ENHANCEMENT OF NUTRIENT REMOVAL IN SBR SYSTEMS THROUGH ACID FERMENTATION OF RAW WASTEWATER

by

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements for the Degree of

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Environmental Engineering Division
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ABSTRACT

Acid fermentation of degritted raw wastewater was investigated under different operational and environmental conditions using a sequencing batch mode of operation. The conditions of the experiments included sludge retention times of 4, 8 and 13 days, influent pH ranges of 7.0-7.6 and 6.1-6.4, mixing periods of 6 h/cycle and 0.25 h/cycle, and hydraulic retention time of 12 h, 9 h, and 6 h. The impact of prefermentation of raw wastewater on enhancement of nutrient removal in SBR systems was explored in conjunction with the fermentation process. This was done by developing a two-stage anaerobic-aerobic SBR system (PAF-SBR) in which the wastewater was first fermented in a sequencing batch reactor named PAF (Primary Acid Fermenter). The effluent from the fermenter was then conducted to another SBR for the purpose of carbon, nitrogen and phosphorus removal. The performance of this system was evaluated against a parallel conventional-SBR which was treating the same raw wastewater but without employing the prefermentation step. Different operational cycles (8 h and 6 h cycles) with various periods of anaerobic, aerobic and anoxic conditions, discontinuous aeration regime, and step feed procedures were tried in biological nutrient removal reactors to increase their efficiency with regard to phosphorus and nitrogen removal. All experiments were carried out at room temperature (20±2°C).

In fermentation studies it was found that acid fermentation of degritted raw wastewater is a stable reliable process. Results also revealed that acetic acid was the main component (78-96%) of volatile fatty acids (VFA) produced under the various investigated conditions.

Sludge retention time (SRT) had a pronounced impact on the solubilization of organic matter and production of VFA (regardless of the experimental conditions). Both processes improved as SRT increased from 4 d to 8 d and further to 13 d.

Overall efficiency of the VFA production diminished as the influent pH range was reduced from its natural range of 7.0-7.6 to the range of 6.1-6.4. This was due to the suppression of activities of the acidogenic bacteria at the lower pH range. Influent pH also affected VFA distribution. Acetic acid production was reduced at the pH range of 6.1-6.4, while production of butyric, valeric and propionic acids was enhanced.

The process of acid fermentation of degritted raw wastewater was affected by the mixing period of each operational cycle. Total solubilization and VFA production was similar under both mixing conditions of 0.25 h/cycle and 6 h/cycle, but the specific rates of solubilization and VFA production were lower at the mixing period of 0.25 h/cycle. Volatile fatty acids composition was also influenced by the duration of the mixing period in each operational cycle.

Reduction of HRT from 12 h to 9 h did not affect the fermentation process significantly. However the decrease from 9 h to 6 h was associated with a considerable reduction in net solubilization and VFA production. Variation in VFA distribution caused by the change in HRT was not statistically significant.

Prefermentation of raw wastewater had a remarkable impact on the improvement of biological phosphorus removal in the SBR systems. Regardless of the operational conditions, soluble phosphorus of the effluent from the PAF-SBR was always below 1 mg/L, while in the parallel conventional-SBR, the concentration ranged from less than 1 mg/L to over 4 mg/L with an average range of 1.5-2.6 mg/L.

An operational cycle of 8 h with a long initial anoxic/anaerobic period of 2-3 h was found to deteriorate effluent phosphorus quality in the SBR receiving fermented wastewater. This was caused by the secondary release of phosphorus during the long anaerobic period of each cycle. Reduction of cycle period from 8 h to 6 h with a short initial anoxic/anaerobic period of 45 min enhanced P-removal significantly. Best results with respect to nitrogen and phosphorus removal were obtained in 6 h operational cycles employing intermittent aeration schemes. Phosphorus removal up to 90-94% was achieved in the PAF-SBR system under such operational conditions leading to an average effluent soluble phosphorus content of 0.3 mg/L. Nitrogen removal efficiencies were 69% in the PAF-SBR system and 65% in the parallel conventional-SBR. Further removal of nitrogen in both systems was limited by lack of availability of carbon source for denitrification. Step feeding did not enhance nitrogen removal as the concentration of SOC and TKN were almost equivalent to those in the feed.

One of the major differences observed between the two parallel BNR systems was related to their sludge characteristics. The sludge in the reactor fed with the fermented wastewater showed excellent settling characteristics. The average effluent SS concentration was less than 20 mg/L in this reactor. On the other hand bulking and deterioration of effluent quality were often problems in the conventional-SBR. The PAF-SBR system produced about 12% less sludge than the conventional-SBR system (based upon production of total dry solids/1000 m^3 of the treated wastewater).

As a result of this research a two-stage anaerobic-aerobic SBR system was developed in which biological removal of nitrogen and phosphorus can be performed efficiently at variable influent concentrations of organic compounds.

TABLE OF CONTENTS

Page

Abstract i
Table of Contents iv
List of Tables ix
List of Figures xi
Nomenclature and Abbreviations xvi
Acknowledgments xix
Dedication xx

Chapter 1 Introduction 1

1.1 Definition of the problem 3

Chapter 2 Literature Review 5

2.1 Biological phosphorus removal 5
2.1.1-Mechanisms of biological phosphorus removal 6
2.1.2-Microbial aspects of the Bio-P removal systems 11
2.1.3-Factors affecting Bio-P removal efficiency 15
2.1.3.a-pH 15
2.1.3.b-Temperature 17
2.1.3.c-Mean cell residence time (MCRT) 19
2.1.3.d-Anaerobic zone and its hydraulic retention time (HRT) 20
2.1.3.e-Presence of NOx in the anaerobic zone 23
2.1.3.f-Substrate 26

2.2 Biological nitrogen removal 31
2.2.1-Nitrification 33
2.2.2-Factors affecting nitrification 34
2.2.2.a-Oxygen 34
2.2.2.b-Temperature 35
2.2.2.c-pH and alkalinity 36
2.2.2.d-Solids residence time 37
2.2.2.e-Carbon 38
2.2.3-Denitrification 39
2.2.4-Factors affecting denitrification 41
2.2.4.a-Temperature and pH 41
2.2.4.b-Carbon source 42
2.2.4.c-Oxygen 44

2.3 Fermentation 45
2.3.1-Acid fermentation of primary sludge 46
2.3.2-Factors affecting sludge fermentation 48
2.3.2.a-pH 48
2.3.2.b-SRT and solids concentration 49
2.3.3-Sludge fermenters : types and problems 50
2.3.3.a-Activated primary tanks 51
2.3.3.b-Static fermenters or thickener/fermenters 51
2.3.3.c-Separate completely mixed fermenters 52
2.3.4-Acid fermentation of raw wastewater 52

2.4 Sequencing batch reactors (SBR) 54
2.4.1-Nitrogen removal 57
2.4.2-Phosphorus removal 59
2.4.3-Combined nitrogen and phosphorus removal 60

Chapter 3 Research objectives and scope of work 63

3.1 Research objectives 63

3.2 Scope of work 64

Chapter 4 Materials and methods 65

4.1 Objectives approach 65
4.1.1-Acid fermentation of raw wastewater 65
4.1.1.a-Step 1 : Effects of sludge retention time (SRT) 65
4.1.1.b-Step 2 : Effects of pH 66
4.1.1.c-Step 3 : Impacts of mixing period 67
4.1.1.d-Steps 4 and 5 : Effects of hydraulic retention time (HRT) 67
4.1.2-Impact of fermentation of raw wastewater on BNR in SBR systems 68
4.1.2.a-Stage 1 : Use of the conventional 8 h-cycle 69
4.1.2.b-Stage 2 : Improvement in P-removal (6 h-cycle, HRT = 9 h) 69
4.1.2.c-Stage 3 : Enhancement in nitrogen removal (step-aeration) 70
4.1.2.d-Stage 4 : Enhancement in nitrogen removal (step-feeding) 71

4.2 Experimental set up and equipments 72
4.2.1-Acid-fermentation reactors (PAFs) 73
4.2.2-BNR-reactors (BNR-SBRs) 74

4.3 Raw wastewater collection 77

4.4 Reactors start up 77
4.4.1-Acid-fermentation reactors 77
4.4.2-BNR-reactors 78

4.5 Sampling and analytical procedures 79
4.5.1-Sampling 79
4.5.2-Analytical procedures 81
4.5.2.a-Different forms of solids (TS, SS, VS) 81
4.5.2.b-pH and alkalinity 81
4.5.2.c-Soluble organic carbon (SOC) 81
4.5.2.d-Chemical oxygen demand (COD) 82
4.5.2.e-Volatile fatty acids (VFA) 82
4.5.2.f-Nitrogen 82
4.5.2.g-Phosphorus 83
4.5.2.h-Head-space methane gas (CH_4) 84
4.5.2.i-Sludge volume index (SVI) 84
4.6.2.j-Microbial examination 84
4.6.2.k-Statistics 84

Chapter 5 Results and discussion 85

5.1 Nature of the wastewater (feed) 85

5.2 Biological acclimation of the reactors 88

5.3 Fermentation studies 93
5.3.1-Step 1 : Effects of SRT (pH of feed = 7.0-7.6) 93
5.3.1.a-Solubilization of particulate organic compounds 94
5.3.1.b-VFA production 99
5.3.1.c-VFA composition 103
5.3.1.d-Quality of the fermented wastewater-effects of SRT 107
5.3.1.e-Conclusion 109
5.3.2-Step 2 : pH reduction (pH of feed = 6.1-6.4) 110
5.3.2.a-Organic carbon solubilization 111
5.3.2.b-VFA production 118
5.3.2.c-VFA composition 122
5.3.2.d-Quality of the fermented wastewater-Low pH 125
5.3.2.e-Conclusion 127
5.3.3-Step 3 : Reduction in mixing period 128
5.3.3.a-Solubilization and VFA production 129
5.3.3.b-Quality of the fermented wastewater-reduced mixing condition ... 134
5.3.3.c-Conclusion 135
5.3.4-Steps 4 and 5 : Effects of HRT 136
5.3.4.a-Solubilization of organic particulates 137

5.3.4.b-VFA production 141
5.3.4.c-VFA speciation 144
5.3.4.d-Quality of the fermented wastewater-effects of HRT 146
5.3.4.e-Conclusion 148
5.3.5-Fermentation process : An overview 148

5.4 Impacts of fermentation of raw wastewater on BNR in SBR systems 152
5.4.1-Stage 1 : Use of the conventional 8 h-cycle 152
5.4.1.a-Phosphorus removal 153
5.4.1.b-Anoxic/anaerobic period 163
5.4.1.c-Nitrogen and SOC removal 167
5.4.1.d-Final effluent 172
5.4.1.e-Conclusion 175
5.4.2-Stage 2 : Improvement in P-removal (6 h-cycle, HRT = 9 h) 176
5.4.2.a-Nutrient removal 177
5.4.2.b-Track studies 182
5.4.2.c-Phosphorus profile 182
5.4.2.d-Nitrogen profile 184
5.4.2.e-Soluble organic Carbon (SOC) profile 187
5.4.2.f-Conclusion 187
5.4.3-Stage 3 : Improvement in nitrogen removal through step-aeration 190
5.4.3.a-Phosphorus removal 192
5.4.3.b-Nitrogen removal 198
5.4.3.c-Track studies 198
5.4.3.d-Nitrogen profile 200
5.4.3.e-Soluble organic carbon (SOC) profile 201
5.4.3.f-Phosphorus profile 204
5.4.3.g-Oxidation-reduction potential (ORP) 207
5.4.3.h-Final effluent 209
5.4.3.i-Conclusion 211
5.4.4-Stage 4 : Improvement in nitrogen removal through step-feeding 213
5.4.4.a-Nutrient removal 214
5.4.4.b-Conclusion 217

5.5 Effects of fermentation on nutrient removal : An overview 218
5.5.1-Effluent phosphorus 221
5.5.2-Effluent nitrogen and SOC 221
5.5.3-Effluent suspended solids 224
5.5.4-Sludge characteristics 225
5.5.5-Reactor dynamics 232

5.6 Potential applicability of the findings 234

Chapter 6 Conclusion 237

Chapter 7 Future Research Recommendations 243

References 246

Appendix A 263
Appendix B 300
Appendix C 317

LIST OF TABLES

Page

Table 2.1 Effect of organic substrate on enhanced BPR 29

Table 4.1 Data on characteristics of wastewater and primary sludge (start-up of fermenters) 78

Table 4.2 Parameters of importance and their sampling schedules 80

Table 5.1 Degritted raw wastewater characteristics over the entire research period (Oct. 30, 1993-July 7, 1995) 86

Table 5.2 Solubilization performance of fermenters under different SRTs (pH_{Feed} = 7.0-7.6) 97

Table 5.3 Acid fermentation performance under different SRTs (pH_{Feed} = 7.0-7.6) 102

Table 5.4 Characteristics of raw and fermented wastewater (impacts of SRT on acid fermentation of raw wastewater; pH = 7.0-7.6) 109

Table 5.5 Solubilization performance of fermenters at different SRTs (pH_{Feed} = 6.1-6.4) 113

Table 5.6 Acid fermentation performance at different SRTs (pH_{Feed} = 6.1-6.4) 121

Table 5.7 Percent VFA distribution at different SRTs (pH_{Feed} = 6.1-6.4) 125

Table 5.8 Characteristics of raw and fermented wastewater (Impact of SRT on acid fermentation of degritted raw wastewater with pH = 6.1-6.4) 126

Table 5.9 Performance of duplicate reactors under the mixing condition of 0.25 h/cycle 129

Table 5.10 Comparison between the performance of the fermenter with 13 days SRT in step 1 (mixing period = 6h/cycle), and the average performance of duplicate reactors in step 3 (mixing period = 0.25h/cycle) 131

Table 5.11 Some of the characteristics of degritted raw wastewater (feed) during steady state conditions in step 1 and step 3 132

Table 5.12 Characteristics of raw and fermented wastewater (Impacts of short mixing period) 134

Table 5.13 Solubilization results at different HRTs 140

Table 5.14 Performance of VFA production at different HRTs 143

Table 5.15 Percent VFA distribution at different HRTs 145

Table 5.16 Characteristics of raw and fermented wastewater (Impacts of HRT) 147

Table 5.17 Summary of the results on acid fermentation of degritted raw wastewater under various environmental and operational conditions tested in this research 151

Table 5.18 SCVFA yields related to the quantity of primary effluent 151

Table 5.19 Characteristics of the feed and the final effluent from the two parallel BNR systems (8 h-cycle) 174

Table 5.20 Characteristics of the feed and the final effluent from the two parallel BNR systems (6 h-cycle with the step aeration regime) 210

Table 5.21 Sludge production and sludge characteristics in the PAF-SBR and conventional-SBR systems 232

Table 5.22 Reaction dynamics in the parallel BNR reactors 233

LIST OF FIGURES

Page

Fig. 2.1 Pathway suggested in the Comeau/Wentzel model for generation of $NADH_2$ in Bio-P bacteria 9

Fig. 2.2 Pathway suggested in the Mino model for generation of $NADH_2$ in Bio-P bacteria 10

Fig. 2.3 Nitrogen transformations in biological treatment units 32

Fig. 2.4 A general operational cycle in sequencing batch reactors 55

Fig. 4.1 Components of an 8 h operational cycle employed in primary acid fermenters during steps 1, 2, and 3 67

Fig. 4.2 Components of an 8 operational cycle in the BNR reactors (B1 & B2) during stage 1 in the research 70

Fig. 4.3 Components of a 6 h operational cycle in the BNR reactors during stage 2 in the research 70

Fig. 4.4 Optimum operational cycle used in the BNR reactors during stage 3 71

Fig. 4.5 Typical schematic of a primary acid fermenter (PAF) developed in this study 74

Fig. 4.6 A view of the two biological nutrient removal (BNR) reactors 75

Fig. 4.7 Detailed components of PAF-SBR system 76

Fig. 5.1 Variation in COD/P ratio of the degritted raw wastewater during the total research period 89

Fig. 5.2 Variation in COD/N ratio of the degritted raw wastewater during the total research period 90

Fig. 5.3 Achievement of steady-state conditions in the fermentation reactors 92

Fig. 5.4 Profile of soluble COD in the feed and effluent from the fermenters at different SRTs (pH of feed = 7.0-7.6) 96

Fig. 5.5 Mean concentration of soluble COD in the effluent from the fermenters at steady-state condition (pH of feed = 7.0-7.6) 96

Fig. 5.6 Total COD solubilization and the specific rate of solubilization as a function of SRT (pH of feed = 7.0-7.6) 98

Fig. 5.7 Profile of VFA concentration in the effluent from the fermenters as compared to the VFA concentration in the feed (impact of SRT)..... 101

Fig. 5.8 VFA production (as HAc) at different SRTs (pH of feed = 7.0-7.6) 101

Fig. 5.9 VFA concentration and the specific rate of VFA production at different SRTs (pH of feed = 7.0-7.6) 102

Fig. 5.10 Solubilization and acid fermentation at different SRTs (pH of feed = 7.0-7.6)..... 104

Fig. 5.11 Effects of SRT on percent distribution of VFA (pH of feed = 7.0-7.6)..... 106

Fig. 5.12 Profile of soluble COD in the feed and effluent from the fermenters at different SRTs (pH of feed = 6.1-6.4)..... 112

Fig. 5.13 Mean concentration of soluble COD in the effluent from the fermenters at steady-state condition (pH of feed = 6.1-6.4)..... 112

Fig. 5.14 Effects of SRT on net soluble COD production under two ranges of pH 116

Fig. 5.15 Specific solubilization rates (effects of SRT at the two pH ranges of the feed) 116

Fig. 5.16 Profile of VFA concentration in the feed and effluent from the fermenters at the low pH range..... 120

Fig. 5.17 Mean concentration of VFA at different SRTs (pH of feed = 6.1-6.4) 120

Fig. 5.18 Total VFA, and VFA specific production rate as a function of SRT (pH of feed = 6.1-6.4)..... 123

Fig. 5.19 Solubilization of particulate organic matter at different SRTs under the two pH ranges of the feed 123

Fig. 5.20 VFA production at different SRTs under the two ranges of pH 124

Fig. 5.21 Effluent VFA concentration under the short mixing period of 0.25 h/cycle 130

Fig. 5.22 Profile of SOC in the effluent from the fermenters versus its concentration in the feed (effects of HRT) 138

Fig. 5.23 Profile of soluble COD in the feed and effluent from the fermenters (steps 4 and 5) 139

Fig. 5.24 Solubilization of organic particulates at different HRTs 140

Fig. 5.25 Profile of VFA concentration in the effluent from the fermentation reactors (effects of HRT) 142

Fig. 5.26 VFA production (effects of HRT) 143

Fig. 5.27 Impacts of HRT on the specific rates of solubilization and VFA production 145

Fig. 5.28 Ortho-P concentration in the final effluent from the two parallel BNR systems (stage 1; 8 h-cycles) 154

Fig. 5.29 Frequency chart on the effluent ortho-P concentration of the BNR systems (stage 1) 155

Fig. 5.30 VFA/ortho-P ratio in the raw, and fermented wastewater (stage 1) 157

Fig. 5.31 Profile of ortho-P concentration in the BNR reactors during operational cycles in stage 1 (typical for the days when the raw wastewater was low in VFA content) 159

Fig. 5.32 Profile of ortho-P concentration in the BNR reactors during operational cycles in stage 1 (typical for the days when the raw wastewater was rich in VFA content) 160

Fig. 5.33 P-release in the BNR reactor of the PAF-SBR system-B1 (stage 1) 161

Fig. 5.34 VFA-uptake in B1 during the initial anoxic/anaerobic period of 8 h operational cycles (stage 1) 165

Fig. 5.35 P-release during the initial anoxic/anaerobic period of 8 h operational cycles (stage 1) 168

Fig. 5.36 Percentage of nitrogen removal (stage 1) 170

Fig. 5.37 Variation in SOC concentration of the degritted raw wastewater (stage 1) 170

Fig. 5.38 Change in SOC concentration of the BNR reactors during 8 h operational cycles (stage 1) 171

Fig. 5.39 Variation in SS and SOC concentrations in the raw wastewater (stages 1 & 2) 178

Fig. 5.40 Profile of SCVFA in the raw and fermented wastewater (stage 2)..... 178

Fig. 5.41 Profile of ortho-P concentration in the raw wastewater and effluent from the BNR systems (stage 2) 180

Fig. 5.42 Results of the track studies on ortho-P and NOx-N concentrations (stage 2) 185

Fig. 5.43 Profile of SOC in the parallel BNR reactors (Stage 2; 6 h cycle)..... 188

Fig. 5.44 Ortho-P concentration in the raw wastewater and effluent from the BNR reactors (stage 2)..... 194

Fig. 5.45 Frequency plot of the effluent ortho-P concentration of the BNR reactors (6 h-cycles) 196

Fig. 5.46 Effluent soluble-P frequency plot of the BNR reactors (6 h-cycles)..... 197

Fig. 5.47 Nitrogen removal efficiencies in the BNR reactors (6 h-cycles)..... 199

Fig. 5.48 Change in SOC and NOx-N concentrations of the BNR reactors (6 h-cycles with step-aeration regime) 202

Fig. 5.49 Change in ortho-P concentration of the BNR reactors (6 h-cycles with step-aeration regime) 206

Fig. 5.50 Change in oxidation-reduction potential of the BNR reactors (6 h-cycles with step-aeration regime) 208

Fig. 5.51 Change in SOC and NOx-N concentrations (step-feeding operation) 215

Fig. 5.52 Suspended solid removal in the PAF reactor (overall view) 219

Fig. 5.53 Increase in SOC content of the fermented wastewater (overall view)..... 219

Fig. 5.54 VFA concentration in raw and fermented wastewater (overall view)..... 220

Fig. 5.55 Ortho-P concentration in the effluent from the BNR reactors (overall view)..... 222

Fig. 5.56 Soluble-P concentration in the effluent from the BNR reactors (overall view) 222

Fig. 5.57 SOC concentration in the effluent from the BNR reactors (overall view) 223

Fig. 5.58 Total soluble nitrogen concentration in the effluent from the BNR reactors (overall view) 223

Fig. 5.59 Effluent suspended solids of the BNR reactors (overall view) 227

Fig. 5.60 SVI in the BNR reactors (overall view) 227

Fig. 5.61 Photographic representation of the sludge in the conventional-SBR 229

Fig. 5.62 Sludge settleability in the BNR reactors (overall view) 231

NOMENCLATURE AND ABBREVIATIONS

3H2MB	3-hydroxy-2-methylbutyrate
3H2MV	3-hydroxy-2-methylvalerate
3HB	3-hydroxybutyrate
3HV	3-hydroxyvalerate
AcA	Acetic Acid = HAc
ATP	Adenosine-Triphosphate
Bio-P	Biological Phosphorus
BNR	Biological Nutrient Removal
BOD	Biochemical Oxygen Demand
C/N	Carbon to Nitrogen Ratio
C/P	Carbon to Phosphorus Ratio
CoA	Coenzyme A
COD	Chemical oxygen Demand
CoV	Coefficient of Variation
DO	Dissolved Oxygen
EBPR	Enhanced Biological Phosphorus Removal
EMP	Embden Meyerhof Parnas Pathway
F.W.W.	Fermented Wastewater
F/M	Food to Microorganisms Ratio
GC	Gas Chromatograph
HRT	Hydraulic Retention Time

M.O.	Microscopic Observation
MCRT	Mean Cell Residence Time
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Solid
$NADH_2$	Nicotinamide adenine dinucleotide
NOx-N	$[(NO_3\text{-}N) + (NO_2\text{-}N)]$
ORP	Oxidation Reduction Potential
PAF	Primary Acid Fermenter
PHA	Polyhydroxyalkanoates
PHB	Poly-ß-hydroxybutyrate
PHV	Polyhydroxyvalerate
R.W.W.	Raw Wastewater
SBR	Sequencing Batch Reactor
SCVFA	Short Chain Volatile Fatty Acids = VFA
SD	Standard Deviation
SOC	Soluble Organic Carbon
SRT	Sludge Retention Time
SS	Suspended Solid
SVI	Sludge Volume Index
TCA	Tricarboxylic Acid
TKN	Total Kjeldahl Nitrogen
TS	Total Solid
TVS	Total Volatile Solid

VFA	**Volatile Fatty Acids = SCVFA**
VSS	**Volatile Suspended Solid**
WAS	**Waste Activated Sludge**

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for their lifetime efforts to teach me the values of knowledge and wisdom

Chapter 1.

INTRODUCTION

Phosphorus and nitrogen are known as the major cause of eutrophication phenomena. Eutrophication is defined as the enrichment of surface water bodies by nutrients and the consequence deterioration of quality due to luxuriant growth of plant life. The process impacts the ecological balance of the bodies of the waters affected.

Discharge of nutrients to the surface waters accelerates the natural eutrophication process. Many sources (natural and manmade) including domestic and industrial wastewaters contribute to the nutrient input of water resources. It has been reported (Randall et al., 1992) that one Kg of phosphorus after discharge can lead to reconstruction of 111 Kg of biomass which corresponds to 138 Kg of COD. Similarly, discharge of one Kg of nitrogen may lead to reconstruction of some 20 Kg of COD in the receiving water bodies in form of dead algae. Excessive nitrogen can also exert oxygen demand on the receiving water through nitrification where 4.3 Kg of oxygen is consumed for each Kg of ammonia discharged. In some cases the problem of un-ionized ammonia may become a problem. Other significant problems are increased chlorine demand of partially nitrified wastewater and health hazard of nitrates in water used for drinking purposes.

Because of the above problems, all new treatment plants have to provide some form of nutrient removal expressed in concentration limits for total and/or soluble phosphorus, total nitrogen, and ammonium nitrogen.

Nutrient removal from wastewater can be accomplished through the application of biological and/or chemical treatment processes. Biological methods are by far the most

common methods in practice due to their advantages such as elimination (or reduction) in use of chemical compounds, reduction in sludge production, reduction in costs of handling and disposal of sludge, and decrease in oxygen requirements (Randall et al., 1992; McClintock et al., 1994).

Biological nutrient removal (BNR) systems could be grouped into two main categories; continuous-flow through systems (such as Bardenpho), and discontinuous-flow through systems (sequencing batch reactors-SBR). In all biological nutrient removal systems, regardless of the flow regime and/or the configuration, the biomass should be subjected to anaerobic, anoxic and aerobic environments if efficient removal of both phosphorus and nitrogen are expected. In continuous-flow methods, the wastewater is clarified and the required sequence of the environmental conditions are provided spatially in different units, or alongside of one reactor. In contrast, in sequencing batch reactors, the flow is semi-continuos, the wastewater is not usually clarified, all unit operation processes occur within one reactor, and the required environmental conditions are time sequenced; changing from anoxic/anaerobic to aerobic. Moreover the total biomass is subjected to any changes in the environmental conditions.

Due to the fundamental differences between the two treatment systems, performance improvements achieved in continuous flow treatment trains may not be applicable to sequencing batch reactors. Even with some of the system enhancements being applicable to sequencing batch reactors, the resulting performance of the system may substantially vary from those obtained in the traditional flow-through treatments.

1.1 DEFINITION OF THE PROBLEM

The success of the biological nutrient removal systems relies upon; 1) alteration of environmental conditions, and 2) type and concentration of organic compounds available for the microorganisms involved in the processes.

Biological phosphorus removal bacteria (Bio-P bacteria) require short chain volatile fatty acids (SCVFA) in the anaerobic zone to replenish their storage of polyhdroxyalkanoates (Comeau et al., 1986; Appeldoorn et al., 1992). Inadequate supply of organic compounds in the wastewater, inefficient production of VFA in the anaerobic zone, and long anaerobic HRT could all lead to secondary release of phosphorus which deteriorates the performance efficiency of treatment systems. Nitrogen removal also becomes limited if adequate supply of easily biodegradable compounds are not present in the wastewater.

To enhance biological nutrient removal and to improve process operation, acid fermentation of primary sludge has been employed in some full-scale plants practicing BNR in conventional flow-through systems. Primary sludge is fermented during this process and the supernatant added to the main flow thus enriching the system with the easily biodegradable compounds; mostly in the form of VFAs. Acid fermentation of primary sludge has been researched and applied in full scale continuous-flow systems during the last decade (Rabinowitz and Oldham, 1985; Elefsiniotis and Oldham, 1993).

Although now de-listed from art to practice, sludge fermentation technology can not be directly applied to the discontinuous processes such as sequencing batch reactors which usually lack primary sedimentation tanks and hence primary sludge. As a result other means of carbon supplimentation need to be found for these systems. One method is

acid fermentation of whole raw wastewater which could increase its total content of easily biodegradable compounds, and hence improve nutrient removal in the SBR systems.

In this research, the feasibility of acid fermentation of raw wastewater under various operational and environmental conditions was evaluated. Furthermore, the impacts of acid fermentation of raw wastewater on BNR in SBR systems were fully investigated. The aim was the development of a SBR system in which biological removal of phosphorus and nitrogen could occur reliably.

Chapter 2.

LITERATURE REVIEW

The content of this chapter has been classified into four major sections covering the following subjects:

- Biological phosphorus removal
- Biological nitrogen removal
- Fermentation
- Sequencing batch reactor

2.1 BIOLOGICAL PHOSPHORUS REMOVAL

Biological phosphorous removal occurs as microorganisms are subjected to alternate anaerobic/aerobic environments (Fuhs and Chen, 1975; Nicholls and Osborn, 1979; Marais et al., 1983). In the anaerobic stage Bio-P bacteria use the energy obtained in the hydrolysis of intracellular polyphosphate to take-up, and store substrate (mostly volatile fatty acids) in the forms of polyhydroxyalkanoates (PHA); especially polyhydroxybutyrate (PHB). Hydrolysis of polyphosphates is associated with the release of phosphorus to the environment. Upon entering the aerobic stage, Bio-P bacteria use oxygen as an electron acceptor and oxidize stored PHB in order to supply their energy and carbon requirements. This process is associated with the excess uptake of phosphates from the environment by Bio-P bacteria. Phosphorus removal occurs when the phosphorus-rich cells are wasted from the system as excess sludge.

2.1.1 MECHANISMS OF BIOLOGICAL PHOSPHORUS REMOVAL

Different biochemical models have been proposed in an attempt to provide a satisfactory explanation for the mechanisms of biological phosphorus removal.

Barnard (1976) indicated that the phosphorus content of the sludge increases as the sludge passes through the anaerobic stage with organic substrates during the routine cycle of the secondary treatment process. Nicholls and Osborn (1979), and Buchan (1983) suggested that the accumulated form of phosphorus is polyphosphates, and that intracellular polyphosphates function as the energy pool for the uptake of substrate under the anaerobic condition. Although both low molecular and high molecular polyphosphates are accumulated in the sludge produced in the anaerobic/aerobic process, low molecular polyphosphates are principally responsible for the release (as energy pool) and uptake of phosphorus (Mino et al., 1984). High molecular polyphosphate was considered to function as the phosphorus source for the growth. Rensink et al. (1981) suggested that volatile fatty acids generated in the anaerobic zone are stored as PHB using energy produced in the hydrolysis of stored polyphosphate in the form of ATP. Marais et al. (1983) provided a model indicating that poly-P accumulation provides a positive advantage over non-poly-P accumulating bacteria because it enables Bio-P bacteria to absorb and store readily biodegradable compounds under anaerobic conditions, which are then utilized under aerobic conditions to obtain energy and carbon, and to replenish the polyphosphate pool by absorbing PO_4^- from the surrounding medium.

The major biochemical models proposed describing enhanced biological phosphorus removal (EBPR) process are : The Comeau/Wentzel Model (Comeau et al.,1986; Wentzel et al., 1986), the Mino Model (Mino et al., 1987), and the adapted

Mino Model (Wentzel et al., 1991). These models are based on acetate or other short chain volatile fatty acids (SCVFA) as the sole external substrate in the anaerobic zone.

According to the Comeau/Wentzel models, shown in Figure 2.1, under anaerobic conditions, the high extracellular acetate concentration allows passive diffusion of acetate into the cell. The intracellular acetate is activated to acetyl-CoA by coupled ATP hydrolysis. Hydrolysis of ATP releases cations (usually K^+ or Mg^{2+}) and anions $H_2O_4P^-$ to the bulk solution. The ATP is regenerated from ADP by transfer of an energy-rich phosphoryl group from polyphosphate to the ADP. Two acetyl-CoA molecules combine to form acetoacetyl-CoA which is then reduced by $NAD(P)H_2$ to form hydroxybutyrate-CoA. Poly-ß-hydroxybutyrate (PHB) molecules are formed by polymerization of hydroxybutyrate-CoA molecules. On the basis of the model suggested by Abu-ghararah et al. (1989), acetyl-CoA is not the only building block for the synthesis of stored organic polymers. The nature of the building blocks and polymers, and their quantities were reported to be dependent on the chemical structure of the organic acids present.

The net result of the anaerobic processes has been summarized by Wentzel et al. (1991) as :

$$9n\ Ac + 9n\ ATP + CoASH \longrightarrow (C_4H_6O_2)_{4n}CoA + 9n\ ADP + 9n\ Pi + 2n\ CO_2 \qquad (2.1)$$

Under aerobic conditions, PHB is broken down and is used for either anabolic and catabolic metabolism. The ATP generated through catabolic reactions is used for cell energy requirements and synthesis of polyphosphates. The rate of phosphorus uptake depends upon the type of the oxidant present (Kerrn-Jespersen and Henze, 1993),

presence of organic substrates (Ubukata and Takii, 1994), and the concentration of extracellular phosphates as well as the unsaturated storage capacity for the intracellular phosphorus (Somiya et al., 1988).

There is a general agreement between the Comeau/Wentzel models, and the other models except for the source of the reducing power $NADH_2$ required to convert acetoacety-CoA to PHB. The Comeau/Wentzel Models (Fig. 2.1) suggest that $NADH_2$ is supplied by the operation of the tricarboxylic acid (TCA) cycle under anaerobic conditions. In the Mino Model which is presented in Fig. 2.2, the intracellular carbohydrate (glycogen) is used via Embden Meyerhof Parnas (EMP) pathway to generate $NADH_2$. Consumption of intercellular carbohydrates has also been confirmed by Arun et al. (1988). In the adapted Mino Model, the Entner Doudoroff (ED) pathway is assumed as an alternative to EMP pathway. Figures 2.1 and 2.2 show the proposed biochemical behaviors under anaerobic conditions. Although all models predict specific molar ratios for anaerobic phosphorus release, acetate uptake and PHB production, a wide range of values have been observed experimentally (Wentzel et al., 1991).

Satoh et al. (1992) highlighted that the metabolism of glycogen for reducing power can also provide energy for the uptake of substrate. They concluded that there are at least two energetic systems concerning substrate uptake under anaerobic conditions; a polyphosphate dependent system (P-system) present in polyphosphate accumulation bacteria, and a glycogen dependent system (Q-system) which causes breakdown of the Bio-P removal process. In the case of P-system polyphosphate is the main source of energy.

Uptake of acetate and propionate is accomplished by the consumption of glycogen,

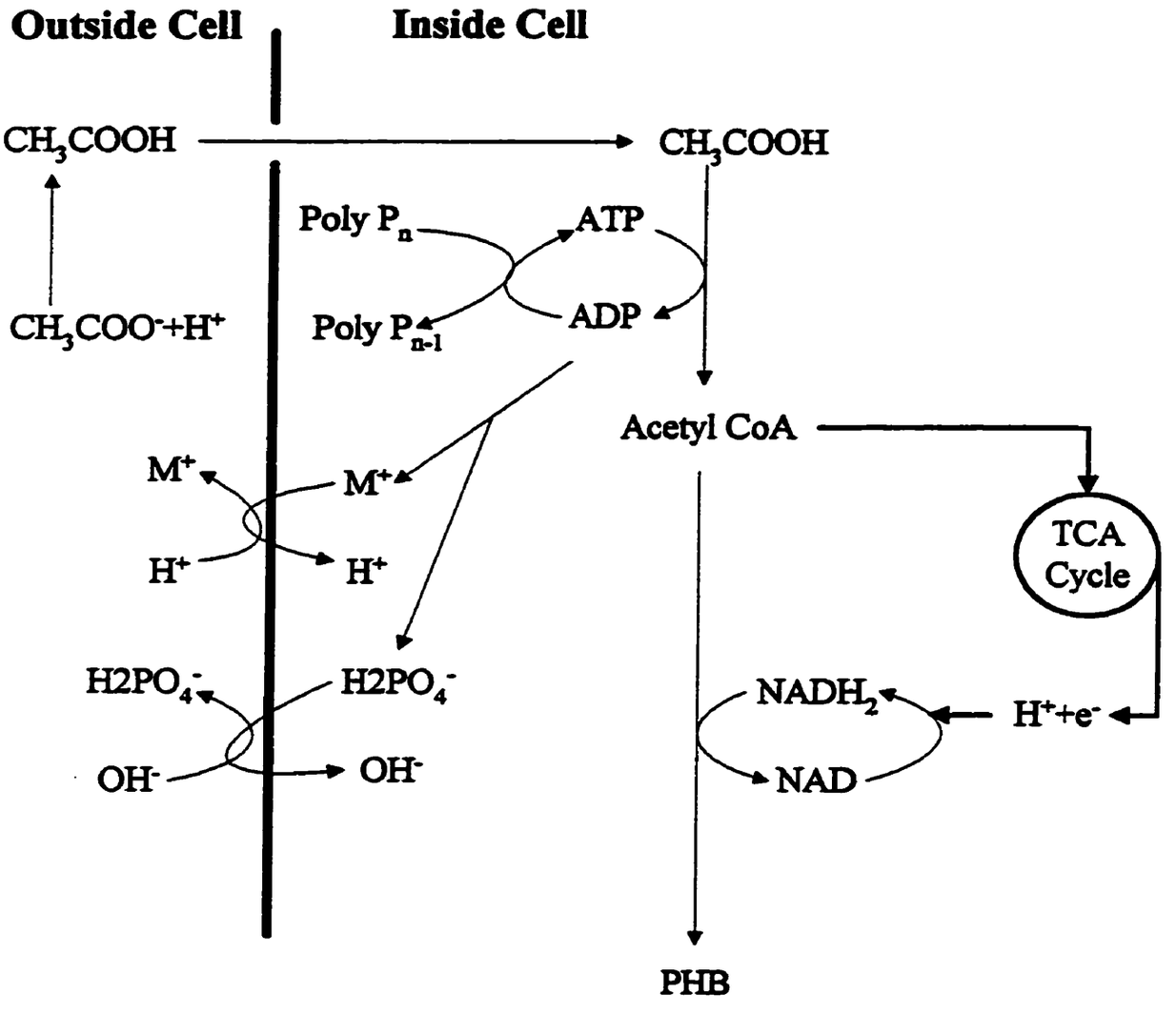

Fig. 2.1 : Pathway suggested in the Comeau/Wentzel model for generation of $NADH_2$ in Bio-P bacteria (Matsuo et al., 1992).

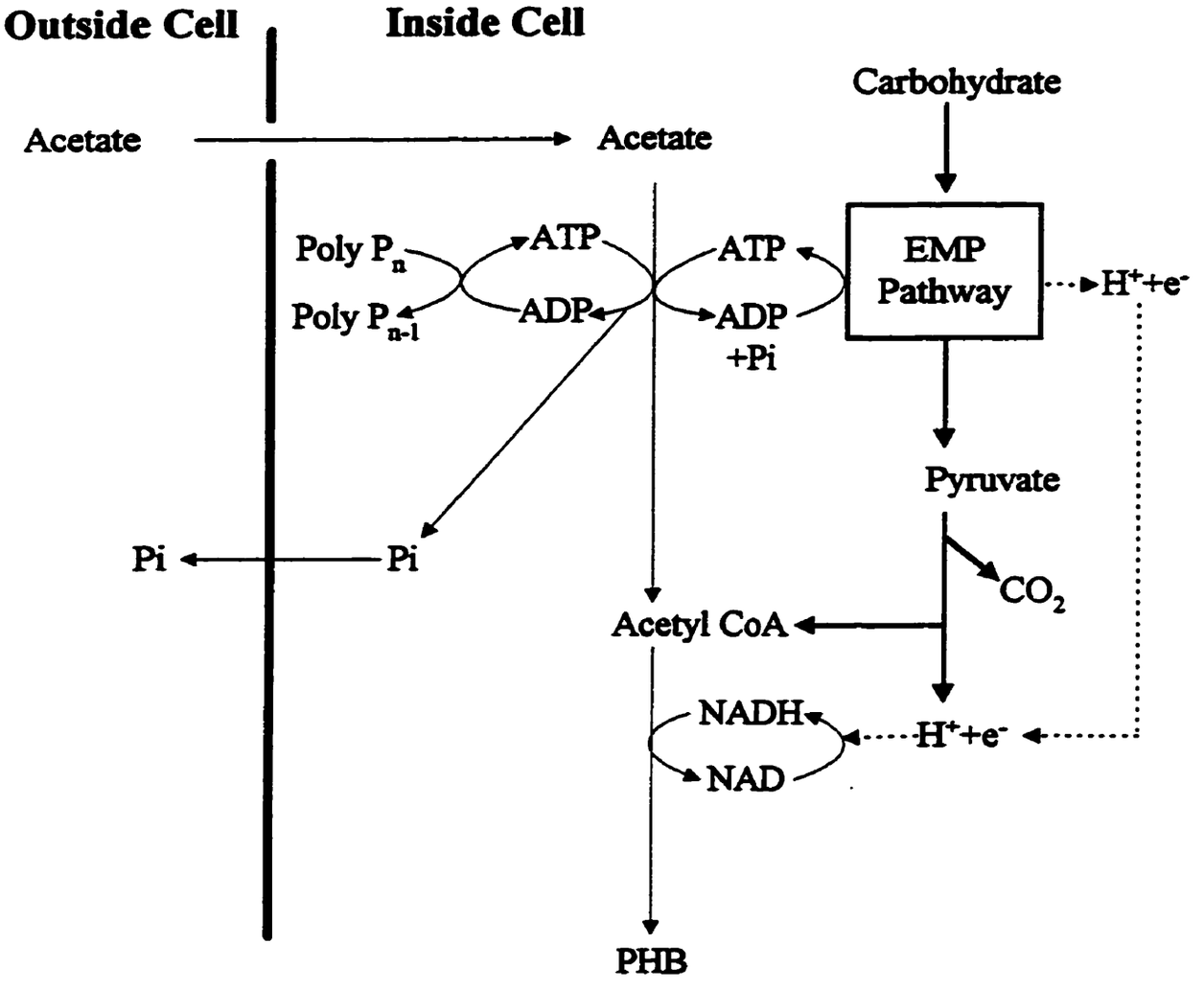

Fig. 2.2. : Pathway suggested in the Mino model for generation of $NADH_2$ in Bio-P bacteria (Matsuo et al., 1992).

and production of some energy in the glycolysis. However the main role of the glycolysis in the P-system is not energy supply but the supply of reducing power. In contrast, in Q-system glycolysis is the main source of energy and microorganisms obtain energy for the substrate uptake under anaerobic conditions by converting glycogen to PHA via acetyl-CoA and propionyl-CoA, and not by the hydrolysis of polyphosphate. Subsequently, bacteria capable of getting energy not by the polyphosphate hydrolysis but by the consumption of intracellular carbohydrates might deteriorate EBPR if they become the dominant group.

2.1.2 MICROBIAL ASPECTS OF THE BIO-P REMOVAL SYSTEMS

Excess biological removal of phosphorus is carried out by different types of bacteria; collectively referred to as "Bio-P bacteria" (Comeau et al., 1986), or "Poly P bacteria" (Wentzel et al., 1991). Bio-P bacteria should be capable of accumulating polyphosphates and glycogen within the cell under aerobic conditions. The former would serve as the energy source for the uptake of organics under anaerobic conditions, while the latter would serve to regulate the redox balance in the cell by providing reducing power for the conversion of organics taken up into reductive polymers (Viswanath et al., 1988).

Excess removal of phosphate by bacteria in activated sludge plants was observed for the first time by Vicker et al. (1967). Fuhs and Chen (1975) discovered that certain bacteria belonging to the genus *Acinetobacter* were responsible for the removal of phosphorus from wastewater. The significant role of *Acinetobacter spp.* in Bio-P removal process has been further confirmed by other researchers (Deinema et al., 1980-1985;

Buchan, 1983; Malnou et al., 1984).

Acinetobacter spp. are Gram-negative, non-motile bacteria which are ubiquitous in nature and can be readily isolated from soil, water and sewage. The genus requires oxygen for catabolic metabolism; however there are some species within the genus which can use nitrate as an electron acceptor when oxygen is not present (Lötter, 1985).

Although *Acinetobacter spp.* have been considered as the major group of bacteria involved in Bio-P removal, there are likewise reports on the importance of other bacterial groups as well. Nakamura et al. (1989), (cited in Appeldoorn, et al., 1992) could isolate a number of Gram-positive bacteria capable of accumulating high amounts of phosphorus. Bacterial population studies of a number of enhanced Bio-P removal plants by Lötter (1985) revealed the predominance of *Acinetobacter* species. However a little more than half the *Aeromonas hydrophila*, *Pseudomonas paucimobilis* and Gram-positive organisms tested were also capable of poly phosphate accumulation. Brodisch and Joyner (1983) in the investigation of microflora composition of three Bio-P removal plants observed minor proportions of the *Acinetobacter* species, while microorganisms of the genera *Aeromonas* and *Pseudomonas* constituted more than 50% of the total aerobic microbial populations. Their results concluded that *Aeromonas* and *Pseudomonas* species as well as some species of filamentous organisms (*Microthrix* and *Nocardia*) most likely contribute to biological phosphorus removal. In an investigation on bacterial populations of nutrient removal plants, Kavanaugh and Randall (1994) found that *Acinetobacter* was not the dominant species in the group enumerated and that both phosphorus and nitrogen removal were carried out by more than one group of bacteria. Aut-ecology study of *Acinetobacter* in the sludge from the Goudkoppies activated sludge plant (South Africa) showed that

Acinetobacter never occurred in numbers sufficiently large to account for the phosphate removal to the extent sometimes reported elsewhere (Cloete et al., 1985). Cloete and Steyn (1988) documented that *Acinetobacter* could account for a maximum of 35% of average P-removal in their system.

In a report by Okada et al. (1991), the isolates of *Micrococcus spp.* and *Pseudomonas spp.* were identified as Bio-P bacteria. The ability of *Pseudomonas vesicularis* in accumulating inorganic phosphate was also indicated by Suresh et al. (1985). Nakamura et al. (1991) isolated a Gram-positive coccus having the ability of excess phosphate accumulation which released phosphorus and took up glucose anaerobically. Wagner et al. (1994) reported a group of Gram-positive bacteria, not *Acinetobacter*, which may play a major role in biological phosphate removal in municipal sewage treatment plants. A Gram-positive coccus was isolated by Ubukata (1994) which was capable of taking up casamino acid while releasing phosphorus anaerobically, and remove phosphate aerobically. He concluded that P-removal bacteria may directly take up amino acids present in the municipal sewage treatment.

Instances have been observed where no biological phosphate removal was achieved in full-scale plants, despite the fact that *Acinetobacter calcoaceticus* was present in relatively high numbers (Brodisch, 1985). It was indicated that high numbers of *Acinetobacter* alone, do not guarantee good phosphate removal, but that other factors must be important. Brodisch noted that there is a positive correlation between the presence of *Aeromonas punctata*, especially in the anaerobic zone, and enhanced phosphate removal. *Aeromonas punctata* is capable of a mixed-acid fermentation, yielding acetate as a major end product.

Cech and Hartman (1990) reported a special type of bacterium which induces the breakdown of enhanced biological phosphorus removal. The bacterium has been named "G bacterium" and grows significantly in the presence of glucose as the carbon source in the anaerobic stage. It does not accumulate polyphosphates, but is capable of taking up glucose without releasing phosphorus under anaerobic conditions. Mino et al. (1994) and Satoh et al. (1994) proposed that the required energy is produced through glycolysis which reduces the necessity for the polyphosphate metabolism, and gives adverse effects on phosphorus removal. The dominance of G bacteria-like microorganisms in a reactor fed with glucose rich feed, was also reported by Carucci et al. (1994). Mino et al. (1994) suggested that glucose may not be the only substrate inducing the growth of "G bacterium" and other substrate such as acetate can be utilized by bacteria like G bacterium. The selective forces to enable the dominance of phosphate accumulating bacteria or "G bacterium" are still to be understood.

Phosphorus accumulating bacteria use oxygen and/or nitrate as an oxidant for the oxidation of organic compounds, and take-up of phosphorus (Comeau et al., 1987; Gerber et al., 1987; Vlekke et al., 1988; Kuba et al., 1993; Kerrn-Jespersen and Henze, 1993). Lötter (1985) isolated some *Acinetobacter spp.* capable of reducing nitrate to nitrogen gas; suggesting the possibility of oxidative metabolism (with P uptake) in the anoxic zone. In the study with laboratory activated sludge systems, Lötter et al. (1986) observed only a small percentage of the *Acinetobacter spp.* capable of complete reduction of nitrate to nitrogen gas (6 to 12%). Juni (1972) was able to separate some strains of *Acinetobacter* capable of reducing nitrate to nitrite. Kerrn-Jespersen and Henze (1993) verified the existence of two groups of Bio-P bacteria; one group capable of utilizing only oxygen as

oxidant and the other capable of utilizing both oxygen and nitrate as oxidant. They concluded that the phosphorous uptake is more rapid under aerobic condition than anoxic condition. Kuba et al. (1993) however showed that the Bio-P bacteria utilizing nitrate as an electron acceptor have the same potential for phosphorus removal as conventional aerobic Bio-P bacteria.

2.1.3 FACTORS AFFECTING BIO-P REMOVAL EFFICIENCY

Biological phosphorus removal is a complex process consisting of a series of anaerobic/aerobic metabolic reactions; each requiring specific sets of environmental/ operational conditions. Many parameters such as type of the treatment process, substrate composition and concentration, duration of the anaerobic period, presence of nitrate in the anaerobic stage, temperature and pH affect the efficiency of the Bio-P process. Change in the influent concentration of organic compounds, existence of saccharides, long periods of anaerobic and aerobic conditions, and very long sludge retention time are among the factors unfavorable for biological phosphorus removal which could encourage the dominance of non-poly P bacteria (Satoh et al., 1994). Biological treatment systems do not show the same ability in removing nutrients. Data on the performances of different treatment processes and configurations indicate considerable variation in the ranges of the efficiencies; with some processes being more efficient than the others (Metcalf and Eddy, 1991; Copper et al., 1994).

2.1.3.a-pH

Information on the effect of pH on biological phosphorus removal is limited, and

inconsistent. Nagashima et al. (1979), (cited in Barnard, 1983a) showed an improvement in phosphorus removal from 42% at pH of 5 to 92% at pH of 8. However in a work by Barnard (1975) similar improvement was not observed when pH was increased under normal conditions. Potgieter and Evans (1983); investigating the impact of pH on P-release in the pH range of 2 to 9, obtained the maximum release at pH of 4. At lower pH values the sludge floc disintegrated. It was suggested that the effect of pH on P-release is most likely concerned with its influence on transport mechanisms across the cell membrane.

The significance of pH in biological phosphorus removal process was recently studied by Smolders et al. (1994), who found out the pH dependency of the ratio between P release and acetate uptake. A metabolic model was developed which divides the acetate uptake into a transport, and storage processes. It was declared that the energy necessary for acetate transport is strongly dependent on pH of the solution. In the pH range of 5.5 to 8.5, the acetate uptake rate remained constant, but the release of phosphorus changed such that the ratio of P-release/acetate uptake varied from 0.24 mg-P/mg COD to 0.73 mg-P/mg COD as the pH was increased. According to the model, at low pH there is no energy associated with transport of acetic acid, thus the observed P-release is only used for conversion of acetic acid to acetyl CoA. Since at low pH less energy is required for the uptake of substrate, the biomass yield and total uptake of substrate might increase, resulting in a higher fraction of Bio-P organisms and a more efficient system. The dependency of the ratio of phosphorus release/acetate uptake on the pH was also shown in a laboratory study by Carlsson et.at. (1996) who found a ratio of 0.35-0.4 mg P/mg COD at neutral pH. Linear regression of pilot plant study however showed the ratio of 0.5 mg

P/mg COD. Deinema et. at. (1985) reported the pH range of 6.5 to 8.2 as the optimum range for phosphorus removal.

2.1.3.b-Temperature

The process of phosphorus removal does not seem to be as sensitive to low temperature as some other biological processes. Successful application of EBPR has been achieved over the temperature range of 5 to 30 °C in nitrifying and non-nitrifying plants (Barnard, 1983a; Hong et al., 1984). Oldham (1979) (cited in Barnard, 1983a) showed that while nitrification suffered at temperatures below 10 °C, phosphate removal did not suffer at 6 °C provided that nitrates formed could be removed and the necessary anaerobic conditions could be maintained. Marklund and Morling (1994) also reported a good phosphorus removal at temperatures down to 5 °C, followed by a sharp decrease in efficiency at lower temperatures. Excellent performance of phosphorus removal at 9 °C has been mentioned for EBPR plant at Kelowna B.C. (Barnard et al., 1985). According to van Starkenburg et al. (1993), phosphorus removal efficiency was high at temperatures of 6 to 10 °C as well as at higher temperatures. A shift in the ratio of mesophilic and psychrophilic organisms in the microbial population was considered as a possible reason for good removal of phosphorus at low temperatures. It was further suggested that the hydrolysis of organic material resulting in the production of volatile fatty acids may become the restricting factor in P-removal process at low temperatures.

The rates of phosphorus release have been demonstrated to reduce as temperature declines. The rates decreased by 2.1-2.6 times for every 10 °C temperature decrease in the range of 10 to 30 °C (Shapiro et al., 1967). Jones et al. (1987) reported an increase

of 75% in phosphorus release at 29 °C as compared to the amount of release at 24 °C.

Temperature dependency of maximum net growth rates for EBPR, anaerobic P-release, COD_{Sol} removal rate in the anaerobic zone, and aerobic P-uptake rate were found to be similar, and could be described by the Arrhenius relationship (Mamais and Jenkins, 1992). Within the range of 10 to 30 °C, a 10 °C drop in temperature resulted in slightly less than twice (1.5 to 1.7) fold decrease in these rates.

Temperature dependency of maximum net growth rates μ_{net} was described by the Arrhenius relationship:

$$\mu_{net} = 14.2 - 4366*(1/T) \qquad (2.2)$$

T = Temperature °K

The temperature correction factor (θ) for reactions rates, was suggested to be 1.049 for all EBPR processes at 10-30 °C, and 1.053 for maximum net growth rate at temperature range of 13.5-20 °C.

Mamais and Jenkins (1992) noted that the optimum temperature for EBPR was in the range of 28-33 °C. At 37 °C aerobic P-uptake appeared to be inhibited. Their results are in good agreement with Juni (1978) and Du Preez et.al. (1978) who reported an optimum temperature for growth of *Acinetobacter spp.* in the range of 29-35 °C and no growth at 41 °C. Boughton et al. (1971) have reported the optimum temperature for phosphorus uptake to be in the range of 24-37 °C.

2.1.3.c-Mean Cell Residence Time (MCRT)

Mean cell residence time (solid residence time or sludge retention time (SRT)), is theoretically defined as a period of time that biomass is retained in a unit operation. MCRT affects the performance of biological phosphorus removal systems through its effects on the growth rate of biomass, and on the net sludge production. Removal of phosphorus in Bio-P systems occurs through production and wastage of excess high P-content sludge.

Bio-P removal bacteria are slow growing bacteria compared to other heterotrophic bacteria in the activated sludge, thus they require long MCRT and can be washed out by operating at low MCRT (Okada et al., 1991; Mamais and Jerkins, 1992). The values reported for specific growth rates of Bio-P bacteria are diverse and depend upon the type of substrate, temperature of the experiments, and whether a mixed culture or an isolated culture has been used in evaluation. The specific growth rates of Bio-P bacteria were estimated at 0.040 d^{-1}, 0.030 d^{-1}, and 0.035 d^{-1} in the SBR activated sludge processes fed with sodium acetate, glucose and polypeptone, and peptone, respectively (Okada et al., 1991). Hao and Chang (1987) in a typical batch study conducted at 25 °C and at pH of 7 with sodium acetate as a medium, reported 15 d^{-1} for the maximum specific growth rate of *Acinetobacter spp.* Okada et al. (1991) also obtained larger values for the isolated bacteria than for the mixed cultures, but revealed that the required MCRT for the accumulation of Bio-P bacteria could not be determined from estimation based on the specific growth rate of isolated bacteria. According to their results, Bio-P bacteria could not accumulate in the reactor operated at MCRT less than 25 days at temperatures of 20±2 °C, which indicated a much larger SRT than the value estimated from specific

growth rate. Rensink et al. (1985) verified that prolongation of SRT stimulates growth of *Acinetobacter* by production of low molecular weight fatty acids, but Brodisch and Joyner (1983) concluded that *Acinetobacter*, being strict aerobe, would not be able to withstand extended anaerobic conditions.

Minimum and optimum MCRT for the biological phosphorus removal systems are a function of temperature. Mamais and Jerkins (1992) found the minimum system MCRT of 2.8, 2.3, 2 days for 13.5 °C,17 °C, and 20 °C respectively. Because of the strict aerobic nature of Bio-P bacteria, they suggested that wash out should be based on the aerobic fraction of MCRT rather than total MCRT. Shao et al. (1991) reported a value of 1.6 days for minimum MCRT at 23 °C. For lower temperatures, McClintock et al. (1991), (cited in Mamais and Jerkins, 1991) found 5 days MCRT of minimum for 10 °C.

In an assessment of the effects of length of anaerobic sludge retention time (0.9 to 6.3 days) on phosphorus removal efficiency, Matsuo (1994) concluded that long anaerobic SRT facilitates good phosphorus removal. Microscopic observations of the failed experiments at low SRT showed the failure was due to proliferation of microorganisms (possibly G bacteria) that appeared capable of anaerobic uptake of dissolved organic carbon. It was considered that a long anaerobic sludge retention time probably aids the poly phosphate accumulators in the competition for food against other heterotrophs that are capable of anaerobic substrate uptake.

2.1.3.d-Anaerobic Zone and Its Hydraulic Retention Time (HRT)

During the late sixties and early seventies some treatment plants in the U.S.A. reported removal of phosphorus in excess of the normal cell requirements (Vacker et al.,

1967; Milbury and McCauley, 1971). All the plants that removed phosphorus successfully were high-rate, non-nitrifying, plug-flow activated sludge treatment plants incorporating coarse to medium bubble aeration systems.

The common characteristics of these treatment plants was the presence of a zone at the inlet where the concentration of dissolved oxygen was practically zero. The necessity of having an anaerobic zone prior to the aeration stage was proved by Barnard (1975), though Fuhs and Chen (1975) suggested that the growth of *Acinetobacter* was a result of the anaerobic/aerobic sequence. Barnard (1975) described that, for excess P uptake, the mixed liquor needs to be subjected to an anaerobic state at some point in the process of such intensity that P release is obtained, then if the mixed liquor is adequately aerated, P uptake will be obtained. According to the descriptions given by Wentzel et al. (1985), the magnitude of biological excess phosphorus uptake is linked strongly to the magnitude of phosphorus release in the anaerobic reactor.

Shapiro et al. (1967) observed the release of phosphorus was triggered by a lack of oxygen and/or a low redox potential, but of these two, redox potential was concluded to have more control on the P-release than oxygen tension. Rapid release was appeared to be triggered off once the redox potential fell to -150 mV.

There are various reports on the function of anaerobic zone in Bio-P removal systems. Nicholls and Osborn (1979) suggested that the main role of the anaerobic stage is to create "stress" conditions which enable Bio-P bacteria for the enhanced P-removal in the following aerobic zone. However the model was opposed by the results obtained by other researches (Rensink et al., 1981; Marais et al., 1983; Comeau et al., 1986). In 1983, Marais et al. hypothesized that in the anaerobic zone some of non-poly-P

heterotrophs (facultative aerobes), absorb the readily biodegradable influent COD and derive some energy by transforming substrates to lower fatty acids and similar forms which are released to the surrounding media. These materials then are available to poly-P bacteria for sequestration. The works of Brodisch (1985), Deinema et al. (1985),and Abu-ghararah and Randall (1991) showed that the anaerobic zone in an activated sludge nutrient removal plant serves as a fermentation step in order to produce substrates required for subsequent enhanced phosphorus uptake, rather than the development of stress conditions. The work of Lötter (1985) gave also support to the hypothesis of those researchers who consider the anaerobic zone essential for the formation of substrate which could ensure proliferation of *Acinetobacter spp.* Ubukata and Takii (1994) in their experiments with the biological phosphorus removal bacteria, concluded that the alternate anaerobic(with organic substrate)/aerobic (without organic substrate) cycle is required for the induction of the enzyme system responsible for excess phosphate accumulation. Matsuo (1992) described that the functions of anaerobic zone especially the uptake and metabolism of organic substances, and the release of phosphate are the key mechanisms in biological enhanced phosphorus removal process, because through the ability to store organic substances for their energy and carbon source, the phosphate accumulating microorganisms can predominate over other organisms.

In general, the traditionally designed anaerobic stage serves two purposes:

1. Fermentation of organic compounds present in the wastewater to volatile fatty acids which is carried out by fermentation bacteria. The rate of the conversion is first order with respect to the active non-poly P organisms concentration, and the readily biodegradable COD concentration (Wentzel et al., 1985).

2. Uptake of short chain volatile fatty acids by Bio-P bacteria and conversion of them to PHA. The basal energy requirement of Bio-P bacteria, and the energy required for the transfer and storage of substrate are obtained by the hydrolysis of polyphosphate content of cell; a process which leads to the release of phosphorus to the environment. The part of the phosphorus release which is associated with the transfer and storage of VFA is referred to as primary release, while the P-release which is not associated with the VFA uptake is defined as secondary release (Barnard, 1994). Secondary release deteriorates the efficiency of phosphorus removal systems, because there is no PHB associated with it.

Wentzel et al. (1988) reported that the rate of uptake of VFA by the Bio-P bacteria appears to be faster than the rate of conversion of organic compounds to VFAs (activities of fermentation bacteria); a matter which has also been pointed out by Barnard (1994). If this is true, then determination of an optimum HRT for the activities of both groups of microorganisms in the anaerobic zone seems almost impossible, aggravated by the variability of the incoming wastewater. Short HRT does not provide sufficient time for the VFA production, and long HRT causes secondary release of phosphorus; both straining the system with the negative impacts on the efficiency of phosphorus removal. Martin and Marais (1975) (cited in Barnard, 1985) proposed that long anaerobic retention times would be detrimental to the phosphorus removal process (it may induce secondary release of phosphorus).

2.1.3.e-Presence of NOx in the Anaerobic Zone

Presence of nitrate in the anaerobic stage has been known to impair the efficiency of the Bio-P removal process. Inhibition of biological phosphorus removal in the presence

of nitrate at full scale plants as well as in pilot plant studies have been reported by several authors (Barnard, 1976; Osborn and Nicholls, 1978; Venter et al, 1978).

The mechanisms of inhibition were described to be related to redox-potential, and denitrification reactions. Barnard (1976) and Venter et al. (1978) mentioned that the presence of nitrate is comparable to the presence of oxygen. The resulting redox-potential would be too high to allow the phosphate removing bacteria to release phosphate in the anaerobic stress condition. Furthermore the redox-potential may be too high for adequate organic acid fermentation (cited in Iwema and Meunier, 1985 from Rensink, 1981). Marais et al. (1983) in their report on the role of non-poly P facultative heterotrophs in absorption and conversion of COD to VFAs pointed out that entrance of nitrate to the anaerobic zone causes the heterotrophs to utilize rapidly some or all of the absorbed material via an oxidative process and accordingly less or no material suitable for Bio-P bacteria utilization is released. This was considered as the reason for reduction in phosphorus removal. Osborn and Nicholls (1978) believed that NO_3 ions block certain metabolic phosphorus release pathways; thus inhibiting P-release. They also reported that short chain organic acids would be consumed by denitrifying bacteria leaving a shortage of these compounds for phosphate removing bacteria. Carucci et al. (1994) observed a higher phosphorus removal efficiency in the absence of competition for organic substrate between P-accumulating and denitrifying bacteria. Kuba et al. (1994) pointed out that for ideal P-removal systems, electron donors (COD) and electron acceptors (oxygen and /or nitrate) should not be present simultaneously. Presence of nitrate and electron donors in the anaerobic zone disturbs the process because energy then can be obtained from the denitrification process. Indeed with nitrate or nitrite present, readily available substrate

could be used by denitrification instead of being stored as PHB in the cells.

Comeau et al. (1990) and Jenkins and Tandoi (1991) showed the inhibition of phosphorus release as the result of transfer of nitrate into the anaerobic zone which is in agreement with the results obtained by earlier researchers (McLaren and Wood, 1976; Osborn and Nicholls, 1978). Contrary to them Hascoet et al. (1985), Iwema and Meunier (1985), Manning (1986), and Kuba et al. (1994) observed a decrease in ortho-P release, and not a total inhibition of the P-release, under anoxic conditions.

Hascoet et al., (1985) suggested that the observed release may partially originate in that part of biomass which is unable to reduce nitrate. Kuba et al. (1994) concluded that nitrate does not block phosphorus release (as was suggested by Osborn and Ncholls, 1987), rather it affects acetate uptake and increases its consumption rate. In accordance to their findings, the reduction of phosphorus release by nitrate is due partly to the presence of denitrifying Bio-P bacteria, which utilize acetic acid for denitrification, not for phosphorus release. It was also described that observed reduction in release of phosphorus may be associated with simultaneous uptake of phosphorus by phosphate accumulating denitrifying bacteria.

There is a relation between the amount of phosphorus released at the presence of nitrate into the anaerobic zone, and the concentrations of easily biodegradable organic compounds. Hascoet et al. (1985) reported the importance of initial amount of COD on the impact of nitrate on P-release and phosphorus removal efficiency, and suggested that the amount of nitrate admissible in the non-aerated zone should be a function of the flow of organic matter added to this zone. The effects of initial nitrate and acetic acid concentrations on the specific P-release were demonstrated by Iwema and Meunier (1985)

and Kuba et al. (1994). Their results indicated that, despite the presence of nitrate, denitrifying phosphorus bacteria were found to release phosphorus as long as acetic acid was present. The release however decreased with increasing initial nitrate concentrations and increased with increasing acetic acid concentrations. PHB was always produced when nitrate and acetic acid were present simultaneously, but after removal of acetic acid, PHB degradation and phosphorus uptake occurred.

2.1.3.f-Substrate

Marais et al. (1983) stated that for any fixed process configuration the magnitude of the excess P-removal is linked directly to the magnitude of the readily biodegradable influent COD concentration; the higher the concentration of these compounds, the higher the P-release, uptake and removal. Barnard (1983a) suggested a COD/TKN ratio of 10 to 1 or above for nitrogen and phosphorus removal which is in agreement with finding of Malnou et al. (1984) who observed a COD/TKN ratio of at least 8 is necessary to obtain a stable phosphorus removal performance.

In general, though biodegradable compounds in whole enhance nutrient removal, the overall efficiency of Bio-P removal depends on the composition and concentration of individual components. Type and concentration of the substrate present in the anaerobic zone control process efficiency through their crucial role in determining the relative abundance of microbial populations, type and amount of organic polymers stored in the bacterial cells, and the amount of phosphorus released to the solution.

Many experimental observations have shown the ability of anaerobic-aerobic acclimatized sludge in uptake of various kinds of organic substrate (Arvin and Kristensen,

1985; Manning, 1986; Comeau et al., 1987; Viswanath et al., 1988; Abu-ghararah and Randall, 1989; Satoh et al., 1992). Fukase et al. 1987 reported that when acetate is fed to anaerobic-aerobic acclimatized sludge, under anaerobic conditions, PHB is accumulated within the cell. The importance of acetate in PHB formation has been also confirmed by Bordacs and Chiesa (1989). Comeau et al. (1987) observed accumulation of poly β-hydroxyvalerate (PHV) by Bio-P bacteria when fed with substrates such as propionate, valerate, butyrate and lactate under anaerobic conditions. They stated that PHV production is significantly higher in the case when substrate consists of odd number of carbon atoms. Wiswanath et al. 1988 noted small or negligible amount of synthesis of intracellular PHB for the cases of malate, lactate, pyruvate, propionate, and succinate. It was recently verified by Satoh et al. (1992) that 3-hydroxybutyrate (3HB) and 3-hydroxyvalerate (3HV) are not the only polyhydroxyalkanoates stored in Bio-P bacteria fed with short-chain fatty acids. Other compounds such as 3-hydroxy-2-methylbutyrate (3H2MB) and 3-hydroxy-2-methylvalerate (3H2MV) were also synthesized under such conditions. Polyhydroxybutyrates were the main products of acetate feeding, while 3HV and 3H2MV were the two comparably significant products from propionate feeding.

Release of phosphorus in the anaerobic zone is controlled by many parameters including type of substrate present, HRT (Barnard, 1994), presence of oxygen and/or nitrate, and the amount of stored intracellular phosphorus (releasable phosphorus) (Somiya et al., 1988).

The effect of different substrates on release of phosphorus in the anaerobic zone has been studied by many investigators (Potgieter and Evans, 1983; Rensink et al., 1984; Malnou et al., 1984; Deinema et al., 1985; Manning, 1986; Abu-ghararah and Randall,

1991; Randall et al., 1994; Ubukata, 1994). The results of Potgieter and Evans (1983) indicated that acetate and propionate greatly enhanced phosphorus release while formate also had a meaningful effect compared to butyrate, hydroxybutyrate and glucose. It was found that acetate stimulates PHB formation to a much greater extent than glucose. Effect of acetate, propionate, butyrate and methanol on P-release was investigated by Meganck et al. (1985). After one hour of anaerobiosis, the quantity of phosphorus release was 30 mg/L for acetate, 10 mg/L for propionate and butyrate, and 6 mg/L for methanol. A blank test with no organic matter added showed only 2 mg/L of phosphorus release. Rensink et al. (1984) found that combined addition of acetate and ethanol has a significant stimulatory effect on the initial rate of phosphate release. Manning (1986) noted acetate allows for a quick release of phosphorus, but glucose and amino acids allow a slow and reduced levels of phosphorus release. He pointed out that more complex carbohydrates and fatty acids require significant lag periods before releasing of phosphorus.

It is well established that the Bio-P bacteria have preferences (for their growth and proliferation) in the substrate pool; with short chain volatile fatty acids (especially acetate) being in favor (Fuhs and Chen, 1975; Nicholls et al., 1985; Comeau et al., 1986; Gerber et al., 1986; Jones et al., 1987; Appeldoorn et al., 1992). Rensink et al. (1985) and Winter (1988) showed that adding acetate to the wastewater improved phosphorus removal significantly. Lötter (1992) in an investigation on the growth of *Acinetobacter* isolates on a variety of carbon sources proved that not only growth but also polyphosphate accumulation is stimulated by short chain carbon compounds such as acetate and butyrate, which are products of bacterial fermentation. The impacts of different types of VFAs on the amount of phosphorus release and subsequent phosphorus uptake have been studied

by Abu-ghararah and Randall (1991). They noticed that the amounts of phosphorus release and uptake were related to the number of carbon atoms and degree of branching of fatty acids. Acetic acid caused the greatest release and the greatest uptake of phosphorus. The amount of phosphorus removal per unit COD added was reported to decrease as the number of carbons in VFA molecule increased. Branched molecules of VFAs were superior to their linear isomers (Abu-ghararah and Randall, 1991; Randall et al., 1994). The relative efficiencies of the various VFAs in BPR process are shown in Table 2.1. Due to the large differences observed in BPR efficiencies , Abu-ghararah and Randall (1991) concluded that the efforts to quantify expected phosphorus removal in terms of total VFA or COD utilized in the anaerobic zone are only approximate, and the actual value can vary considerably.

Table 2.1 : Effect of organic substrate on enhanced BPR (after Abu-Ghararah and Randall, 1991).

Short- Chain Volatile Fatty Acids	mg/L P-Uptake * / mg/L COD Utilized	mg COD-Utilized / mg P-Removed
Formic Acid	0	-
Acetic Acid	0.37	18.8
Propionic Acid	0.10	31.5
Butyric Acid	0.12	39.0
Isobutyric Acid	0.14	36.1
Valeric Acid	0.15	94.0
Isovaleric Acid	0.24	23.5

* : P-uptake under aerobic condition.

Synthesis of intracellular glycogen but not of PHB under glucose feeding was reported by Fukase (1982). Glucose, propionate, and an amino acid rich substrate were

reported to be detrimental to phosphorus removal process (Randall et al., 1994).

Deterioration of phosphate removing capacity of anaerobic/aerobic sludge as the result of change in dominance of microorganisms has been discussed by Satoh et al. (1992) and Matsuo et al. (1992). They emphasized the importance of substrate characterization in this matter. Cech and Hartman (1990) reported the breakdown of enhanced phosphorus removal as the result of proliferation of "G" bacterium in the presence of glucose as the carbon source in the anaerobic stage of the process. Kavanaugh and Randall (1994) found that the population mix in biological nutrient removal plants shifts with the dominant substrate fed, and with temperature. In fact with propionate as the dominant VFA in the feed, the dominant species was a coliform-type organism.

Satoh et al. (1992) explained that under the conditions that utilization of glycogen (glycolysis) is encouraged (e.g. presence of glucose as substrate in the anaerobic zone), the ATP generation by breakdown of polyphosphates may not be necessary. Under such conditions, growth and proliferation of non-polyphosphate bacteria could occur which impairs the Bio-P removal efficiency. It has been suggested (Satoh et al., 1994; Mino et al., 1994) that non-polyphosphate bacteria obtain their energy through glycolysis. By using this mechanism, these microorganisms are able to take up substrate and store it as PHA and/or glycogen without the ATP supply from polyphosphates. It was implied that the microorganisms concerned in the anaerobic/aerobic process should have a very sensitive sensor for changing their enzymatic system depending on the change of substrate. In this relation the production of short-chain fatty acids such as acetate or propionate in the preliminary stage is considered very important for stable operation of Bio-P removal

process of domestic wastewater (Satoh et al., 1992). Cooper et al. (1994) have recommended that variability in the performance of different Bio-P removal systems can be reduced by enriching the feed with short chain fatty acids.

2.2 BIOLOGICAL NITROGEN REMOVAL

Nitrogen in wastewater occurs in different forms mainly organic nitrogen and ammonia. In wastewater treatment plants, nitrogen compounds undergo many changes and transformation including ammonification, nitrifacation, denitrification, and assimilation processes. A summary of these transformations are presented in Figure 2.3.

The two major transformations responsible for nitrogen removal are assimilation, and the dissimilatory metabolic process of nitrification-denitrification. Assimilatory reactions incorporate nitrogen in the forms of amino acids and nucleotide building blocks, which are then used in the synthesis of proteins, ribonucleic acid and deoxyribonucleic acid and result in the growth of the biomass. Thus some of the nitrogen is removed from the biological treatment system through wastage of extra biomass. Intracellular nitrogen content of the biomass has been found in the range of 9% to 14% of the cell mass, depending upon the environmental and operational conditions of the system.

Most of the nitrogen removal is however accomplished by the dissimilatory reactions of nitrification-denitrification. In the nitrification step ammonia is converted to nitrate; merely a change of the form. Nitrogen is not removed from the system in this process. In the following step; denitrification, nitrate is converted to gaseous form (N_2) and leaves the system.

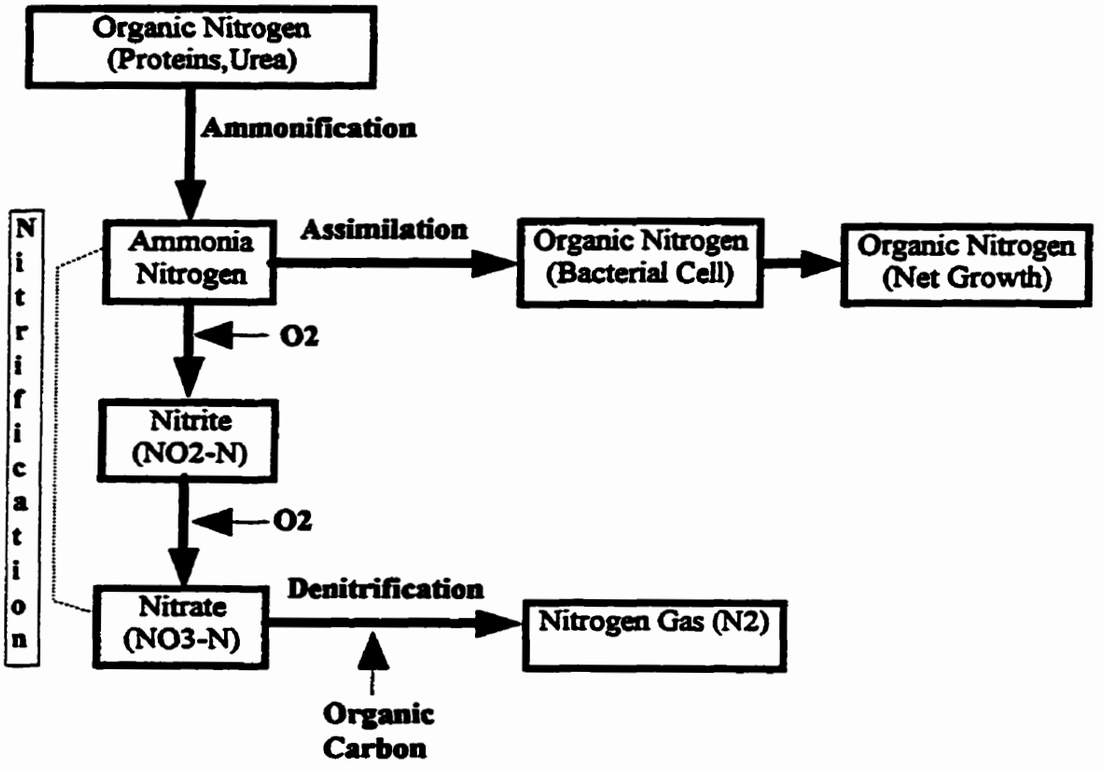

Fig. 2.3 : Nitrogen transformations in biological treatment units. Nitrogen is removed through assimilation in biomass, and by nitrification-denitrification processes.

2.2.1 NITRIFICATION

Nitrification is biological oxidation of ammonia to nitrate. The process consists of two sequential steps, each is carried out by certain groups of microorganisms, which collectively referred to as nitrifiers.

Nitrifiers are mostly autotrophs (they use CO_2 as carbon source), eventhough Randall et al. (1992) noted that some heterotrophic bacteria, fungi and actinomycetes were capable of nitrification. They reported that in wastewater treatment processes autotrophs are the dominant groups, and that the heterotrophic nitrification rates are about one tenth of the autotrophic nitrification rates.

The first step of nitrification is called nitritification and involves oxidation of ammonia to nitrite. The members of the genera *Nitrosomonas* and *Nitrosococcus* are responsible for this step (Metcalf and Eddy, 1991; Randall et al., 1992). Nitritification is followed by nitratification; a process in which nitrite is converted to nitrate by the members of genera *Nitrobacter* and *Nitrocystis*. Approximate equations for these transformations are as follows (Metcalf and Eddy, 1991; Anon, 1993a):

- First step; oxidation of ammonia

$$55\ NH_4^+ + 76\ O_2 + 109\ HCO_3^- \longrightarrow C_5H_7O_2N + 54\ NO_2^- + 57\ H_2O + 104\ H_2CO_3 +$$

58-84 Kcal/mole of ammonium (2.3)

- Second step; oxidation of nitrite to nitrate

$$400\ NO_2^- + NH_4^+ + 4\ H_2CO_3 + HCO_3^- + 195\ O_2 \longrightarrow C_5H_7O_2N + 3H_2O + 400\ NO_3^- +$$

15.4-20.9 Kcal/mole of ammonium (2.4)

Conversion of ammonia to nitrite is slower than the oxidation of nitrite to nitrate. Thus the overall nitrification is usually limited by the performance of *Nitrosomonas* (Metcalf and Eddy, 1991).

The nitrification equation as summarized by Oleszkiewicz (1995) is :

$$NH_4^+ + 1.89\ O_2 + 0.0805\ HCO_3^- \longrightarrow 0.0161\ C_5H_7O_2N + 0.952\ H_2O + 0.984\ NO_3^- + 1.98\ H^+ \quad (2.5)$$

The above equation shows that nitrification produces H^+, which consumes alkalinity in the system. From the equation, conversion of one gram of NH_4-N utilizes about 4.6 gram of oxygen, destroys about 7.14 grams of alkalinity (as $CaCO_3$), and produces about 0.1 gram of biomass. It should be emphasized that the actual oxygen consumption, alkalinity destruction and the yield observed will be different in full scale systems where presence and activities of other groups of microorganisms affect these values.

2.2.2 FACTORS AFFECTING NITRIFICATION

Nitrifiers are among the most sensitive groups of the microorganisms involved in the wastewater treatment. Dissolved oxygen, temperature, pH, total alkalinity, BOD_5/TKN ratio, NH_3-N concentration, presence of toxic compounds and sludge retention time are among the parameters affecting nitrification kinetics.

2.2.2.a-Oxygen

Dissolved oxygen is essential for the nitrification process. It acts as an electron acceptor in the biochemical reactions involved. There are different numbers reported for

limiting dissolved oxygen (DO) concentration. Adams and Eckenfelder (1974) recommended 2.5-3 mg/L for design purposes, but reported achievement of nitrification at dissolved oxygen concentration below 1 mg/L in lab-scale reactors. Metcalf and Eddy (1991) indicated that the DO concentrations above 1 mg/L are essential for nitrification to occur. If DO levels drop below this value, oxygen becomes the limiting nutrient and nitrification slows or ceases. EPA (1993) suggested levels greater than 2 mg/L to prevent the possibility of dissolved oxygen limitation. It was reported by Stenstrom and Song (1991) that the concentration of oxygen in the bio-floc is dependent on the bulk DO concentration, bulk mixing, turbulence intensity, size and shape of the floc, and the oxygen uptake rates of both heterotrophs and nitrifying organisms in the floc. They found that during organic shock loads, the limiting DO was as high as 4 mg/L.

2.2.2.b-Temperature

Temperature is one of the most important factors in regulation of the activities of nitrifying bacteria. The optimum temperature for *Nitrosomonas* is 35 °C while *Nitrobacter* has the optimum in the range of 35-42 °C (EPA, 1993). The optimum range of nitrification reported by Adams and Eckenfelder (1974) is 28 °C to 32 °C with the cessation of nitrification below 5 °C. However the work of Oleszkiewicz and Berquist (1988) on nitrification in the range of 2 °C to 15 °C indicated the feasibility of the process at temperatures as low as 2 °C.

Nitrification kinetics have been reported to exhibit Arrhenius behavior, but the temperature range of the study affects the pattern of change (Henry, 1974; Painter, 1983; Oleszkiewicz and Berquist, 1988). At lower temperature, deviation from Arrhenius

behavior was noted by Henry (1974). Oleszkiewicz and Berquist (1988) observed a discontinuous Arrhenius behavior in the nitrification kinetics when temperature was dropped to lower than 7 °C. Randall and Buth (1984) reported that there exists a lower, critical temperature below which the rate of nitrite formation will exceed that of nitrate, indicating the possibility of nitrite accumulation and toxicity due to the nitrous acid formed. They reported that the inhibitory effect of temperature decrease is more pronounced for *Nitrobacter* than *Nitrosomonas*. According to the EPA (1987), in treatment processes with nitrification, denitrification and phosphorus removal; nitrification has been found to be the most temperature sensitive reaction.

2.2.2.c-pH and Alkalinity

The effect of pH on nitrification is not clearly established in the literature. It is reported that the actual response of the biological system to pH depends on the duration of acclimation. A combination of other factors often synerigistically affects the growth rate of bacteria; thus the impact tends to be case specific (Oleszkiewicz, 1995).

McCartney (1988) reported that the optimum pH for nitrification is in the range of 8 to 9, while nitrifying bacteria are active in pH range of 6 to 10. However, Painter (1983) found the highest rate of nitrification at the pH of 7. The results of his research indicated that under temperature of 25 °C, no nitrification occurred at pH of 6 with SRT of greater than 20 days and HRT of 8 hours. Wild et al. (1971) reported a rate of 15% of the optimum at pH of 6; the optimum nitrification occurred at pH of 8.4. Sears (1995), indicated little loss in efficiency (10%) at a pH of 5.5 and a temperature of 12 °C, with almost complete destruction of alkalinity.

The adverse effects of the upper pH limit are related to the presence of free ammonia, and that of the lower limit are due to the accumulation of free nitrous acid (Anthonisen, 1976). The equilibrium present between free ammonia and NH_4^+ shifts towards production of free ammonia at higher pH levels. Nitrous acid (HNO_2) exists in equilibrium with nitrite NO_2^-, but in greater proportion at lower pH.

Alkalinity is consumed during nitrification reactions. It was shown that for each mg of ammonia nitrogen oxidized to nitrate nitrogen, about 7.14 mg of alkalinity is destroyed. Inadequate quantity of alkalinity will result in a drop of the pH, which in turn may affect the activities of the nitrifiers. Scearce et al. (1980) stated that there are three reactions which affect alkalinity in a nitrifying system: 1) oxidation of ammonia to nitrate which consumes 7.14 mg of alkalinity per mg of ammonia nitrogen, 2) synthesis of new cells which removes 3.59 mg of alkalinity per mg of ammonia nitrogen removed, and 3) conversion of non-ammonia TKN to ammonia, which adds 3.59 mg of alkalinity per mg of ammonia nitrogen formed.

2.2.2.d-Solids Residence Time

The optimum solid residence time or sludge retention time (SRT) for a biological treatment system depends upon the types of microorganisms involved, their growth rates and environmental conditions.

The major crucial parameter in a mixed culture is the growth rate of the slowest group of bacteria. Nitrifying bacteria; being autotrophic, have slower growth rates than heterotrophs and demand a longer SRT for their proliferation. They are also more sensitive to stress than heterotrophs and easily affected by many environmental and

operational parameters. The ratio of the maximum specific growth rate of heterotrophs to autotrophs is about 13.6 at 20 °C (McCartney, 1988). Consequently the growth rate of the nitrifiers is the limiting factor and the SRT of the biological system must be chosen on the basis of nitrifiers' growth rate if nitrification is to occur. Downing et al. (1964) indicated that below a certain SRT (SRT_{min}), the nitrifying population would be washed out and the system would lose nitrification capacity. The optimum required SRT for nitrifying systems varies with the present operational and environmental conditions. All nitrogen removal reactors were suggested to have SRT greater than 5-8 days, which is considered safe for nitrifiers to be retained in the system at 20 °C (Oleszkiewicz, 1995).

2.2.2.e-Carbon

In wastewater treatment systems, nitrifiers compete for oxygen with the heterotrophs. The presence of biodegradable organic compounds, by reducing the availability of oxygen, intensifies the competition and leads to the reduction in the activity of the nitrifying population. Van Niel et al. (1993) showed that nitrifiers can not compete with aerobic heterotrophs for oxygen and other nutrients in the presence of substantial amount of organic compounds. The higher the BOD_5/TKN ratio, the greater the amount of substrate for the heterotrophs, and the higher their demand for oxygen. Hanaki et al (1990) studied the impact of the activity of heterotrophs on nitrification in suspended growth reactors. They concluded that the influent COD has no direct effect on nitrification, but the activity of the heterotrophs utilizing the COD does. They hypothesized that assimilation of ammonia is preferred to nitrification, and heterotrophs in assimilating ammonia, reduce the concentration of ammonium available for the nitrifiers.

The number and extent of activity of the nitrifying bacteria is governed by the ratio of BOD_5/TKN. According to Metcalf and Eddy (1991), the percentage of nitrifying bacteria present in biological systems varies from 35 to 2.5 at BOD_5/TKN ratios of 0.5 to 9, respectively. In general, biodegradable organic compounds should be mostly consumed before significant amounts of nitrification occur. Practical confirmation of this phenomenon is observed in two-stage biological treatment systems where nitrification in the second stage following the carbon removal in the first stage, proceeds at a much higher rate and stability than in combined one-reactor carbon and nitrogen removal systems.

2.2.3 DENITRIFICATION

Denitrification is the process of reduction of nitrate to reduced forms such as NO, N_2O and nitrogen gas. The process is accomplished biologically under "anoxic" conditions. The denitrifying microorganisms; denitrifiers; are ubiquitous in nature as well as in the activated sludge systems (EPA, 1975). They are facultative anaerobes which use organic carbon as the source of energy and carbon, and oxidized forms of nitrogen (NO_x) as the alternative electron acceptors to oxygen, and are most effective in the absence of oxygen. They comprise several genera of bacteria listed in Metcalf and Eddy (1991) as *Achromobacter*, *Aerobacter*, *Alcaligenes*, *Bacillus*, *Brevibacterium*, *Flavobacterium*, *Lactobacillus*, *Micrococcus*, *Proteus*, *Pseudomonas*, and *Spirillum*. Payne (1981) reported that *Pseudomonas* is the predominant group of denitrifiers in wastewater treatment systems. In the last few years, some reports were published on the phosphorus removing bacteria (e.g. *Acinetobacter*) capable of utilizing nitrate as an electron acceptor

instead of oxygen (Vlekke et al., 1988; Kerrn-Jespersen and Henze, 1993; Kuba et al., 1993; Barker and Dold, 1996). Kuba et al. (1993) showed that these bacteria have the same potential for phosphorus removal as the conventional aerobic phosphorus removing bacteria. Barker and Dold (1996) achieved denitrification rates comparable to other heterotrophs, whereas Wentzel et al. (1989) indicated minimal denitrification rates with phosphorus removing bacteria.

Though denitrifying bacteria are heterotrophs, Zitomer and Speece (1993) reported the denitrifying capabilities of *Paracoccus denitrificans*, and *Thiobacillus denitrificans* which are autotrophic bacteria.

Denitrification is a four-step process. The first step is the conversion of nitrate to nitrite which is followed by the production of nitric oxide, nitrous oxide, and nitrogen gas (Metcalf and Eddy, 1991). The general conceptual model is:

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \qquad (2.6)$$

The last three compounds are gaseous products that are dissimilate from the system and released to the atmosphere. The final gaseous product in a well performed denitrification is nitrogen gas with no detectable amount of NO and NO_2 in the atmosphere.

A stoichiometric equation describing denitrification process and using methanol as a carbon source was suggested by EPA (1993) as:

$$NO_3^- + 5/6\ CH_3OH + 1/6\ H2CO_3 \longrightarrow 1/2\ N_2 + 4/3\ H_2O + HCO_3^- \qquad (2.7)$$

The equation reveals the consumption of carbonic acid, and production of bicarbonate; meaning that alkalinity is produced during the conversion of nitrate to nitrogen gas resulting in an increase in pH. About 3.57 mg of alkalinity (as $CaCO_3$) is

produced as the result of reduction of one mg of nitrate nitrogen to nitrogen gas. This indicates the restoration of almost 50% of alkalinity lost in nitrification reactions.

Utilization of oxygen from nitrates to stabilize organic compounds in raw wastewater in systems with a pre-denitrification step results in oxygen savings (Oleszkiewicz, 1995). Assuming a typical pre-denitrification system with waste activated sludge containing 10% TKN and 35 mg/L of nitrogen in the influent, he estimated an oxygen saving of 20% when compared to the systems applying carbon and nitrogen oxidation prior to denitrification. Randall et al. (1995) reported that up to 62.5% of the energy required to provide oxygen for nitrification can be recovered by using nitrate as the electron acceptor in stabilization of the influent COD.

Recently, Mulder et al. (1995) discovered a new pathway for the reduction of nitrate to nitrogen gas. The conversion which was named Anammox, involves the anaerobic oxidation of ammonia with nitrate serving as electron acceptor. The reaction was described as:

$$3NO_3^- + 5\ NH_4^+ \rightarrow 4N_2 + 9H_2O + 2H^+ \qquad (2.8)$$

2.2.4 FACTORS AFFECTING DENITRIFICATION

Kinetics of denitrification reactions are affected by many parameters mainly the presence of oxygen, type and concentration of carbon source, concentration of nitrate and the pH and temperature of the reactions' environment.

2.2.4.a-Temperature and pH

Temperature affects denitrification according to the Arrhenius equation, where the

temperature correction coefficient was found to be 1.03-1.2 (for endogenous rate), depending on the literature source (EPA, 1993). However, the Arrhenius behavior is influenced by the temperature range of study, and different temperature range limits for Arrhenius behavior of denitrification have been reported in the literature (Hagar, 1995).

The optimal pH for denitrification lies between 7 to 8 with different optimums for different bacterial populations (Metcalf and Eddy, 1991). A linear decrease in the efficiency was found by other researchers as pH declined from 7 to 4, or as pH increased from 8 to 9.5 (cited in Randall, 1992).

2.2.4.b-Carbon Source

Denitrifiers, being heterotrophs, require organic compounds in their metabolic reactions. Henze et al. (1994) referred to the carbon source as the dominating rate limiting factor, and showed that the detailed composition of the wastewater influences significantly the microbiology and the reaction rates in biological wastewater treatment processes. Barnard (1975) classified the carbon compounds of raw wastewater to three types according to their impact on denitrification rates: easily degraded compounds, slowly hydrolyzed compounds, and endogenous carbon compounds. Henze et al. (1994) concluded that the rate of hydrolysis of slowly degradable COD (e.g. complex carbohydrates, proteins) will in many cases limit the denitrification rates. The directly metabolizable (e.g. acetic acid), and the easily degradable fractions (e.g. lower amino acids), though they may induce high rates, are often present in too small amounts to make a difference. The denitrification capacity of raw wastewater then can be very limited due to the low concentrations of the above compounds. The denitrification rates for directly

metabolized, easily degradable, and slowly degradable components of the wastewater were reported to be 10-20 g-N/Kg VSS.h, 2-4 g-N/Kg VSS.h, and 0.2-0.5 g-N/Kg VSS.h respectively.

Henze et al. (1994) documented that the capacity of a carbon source to serve as electron donor for nitrate removal depends on its type, its concentration, and the actual design and operation of a treatment plant. They found that the $\Delta COD/\Delta N$ ratio is 3.5-4.5 for denitrification process where no part of the carbon source is lost through oxidation by oxygen. However the ratio could vary in the range of 4 to 15 depending on design and type of the process. Abufayed and Schroeder (1986) recommended a COD/N ratio of greater than 7 for an efficient denitrification process. The C/N ratio of 4-6 g BOD_5/g N_{Total} was suggested by Rusten and Eliassen (1993) for total nitrogen removal. Caponetto and Oleszkiewicz (1993) found that approximately one gram of SOC is utilized in denitrification of one gram of nitrate nitrogen. A general expression for the carbon required for denitrification is given by Oleszkiewicz (1995) as:

$$COD/N = 2.86/(1-1.134*Y_{net}) \quad (2.9)$$

The formula includes the net biomass yield and assumes that one gram of VSS is equivalent to 1.42 gram of COD and that biomass contains of 10% nitrogen.

Addition of easily degradable compounds improves denitrification rates. Isaacs et al. (1995) showed that the addition of acetate or hydrolysate (derived from biologically hydrolyzed sludge) to the anoxic zone resulted in an instantaneous increase in the denitrification rate. Different types of carbon sources such as methanol, ethanol, glucose, acetate, propionate, various organic acids and salts, and even industrial wastes have been used to enhance biological nitrogen removal (Manoharan et al., 1989; Winter, 1989;

Carley and Mavinic, 1991). The conclusions indicated that the denitrification rate is affected by the type and dose of organic carbon utilized. These factors influence the type of bacteria that develop, bacterial growth rate, nitrate reduction rate and the degree of accumulation of intermediate by-products (Carley and Mavinic, 1991; Tam et al., 1992). McCarty (1969) considered methanol as the best source due to its economical cost and low sludge yield. Methanol is used in many locations as the most cost effective form of readily degradable carbon. The use of purchased carbon source such as methanol, however has a drawback of continuous price increases (Oleszkiewicz, 1995; Wilson, 1995). Bell (1994) reported an increase in the cost of methanol from $0.4/US-gal in 1993 to $1.55 by the end of 1994.

In recent years, researchers have tried to find methods to increase the concentration of easily biodegradable compounds of wastewater without addition of an external source of carbon. Acid fermentation of primary sludge and discharge of the fermented supernatant to the main stream of the biological nutrient removal units has been one of the practices.

2.2.4.c-Oxygen

In denitrifying systems, dissolved oxygen concentration is the critical parameter. The presence of dissolved oxygen will suppress the enzyme system needed for denitrification (Grady and Lim, 1980; Metcalf and Eddy, 1991). Grady and Lim (1980) described the impact of oxygen inhibition on the enzymatic system of denitrification. They stated that lack of oxygen in the denitrification environment is necessary for the synthesis of the nitrate reduction enzymes. The findings of Körner and Zumft (1989), and Von

Schulthess et al. (1994) also confirm the interference of oxygen in the denitrifiers' enzyme system.

Grady and Lim (1980) further stated that the determination of oxygen's effects on denitrification becomes more complicated by the influence of sludge floc structure on the extent of oxygen inhibitory impact. They explained that large flocs most likely have an interior zone devoid of oxygen which allows denitrification in an aerobic media.

Dawson and Murphy (1973) showed the inhibition of denitrification activity of a *Pseudomonas* culture at DO levels of 0.2 mg/L. Oleszkiewicz (1995) reported that practically the rate of denitrification is seldom affected at oxygen levels below 0.5 mg/L provided the oxidation reduction potential stays at or below 0 mV. Denitrification rates at DO concentrations of 0, 0.5, 1, 2, and 4 mg/L were measured by Von Schulthess et al. (1994). They noted that higher production of N_2O was associated with higher concentrations of oxygen, while production of NO was minimum under such conditions. As the concentration of DO was reduced to 0 mg/L, the maximum production of NO and N_2 were observed. It was concluded that oxygen inhibits reduction of N_2O more than the reductions of nitrite or nitrate.

2.3 FERMENTATION

Complete fermentation involves the decomposition of organic and inorganic matter in the absence of molecular oxygen. Anaerobic degradation of complex organic material has been described as a multistep process of series and parallel reactions (Kaspar and Wuhrmann, 1978; Gujar and Zehnder, 1983, Metcalf and Eddy, 1991). The process occurs in three steps; hydrolysis, acidogenesis, and methanogenesis. In the first step, complex

polymeric materials are hydrolyzed by extracellular enzymes to soluble products which could be transported across the cell membrane. These compounds then are fermented to identifiable intermediate compounds such as short chain fatty acids and alcohols through acidogenesis. Finally, methanogenesis occurs from carbon dioxide reduction by hydrogen, and acetate. The first part of the process is carried out by "hydrolytic bacteria" and the second part by "acidogens" or "acid formers". Both groups consist of facultative and obligate anaerobic bacteria (Metcalf and Eddy, 1991; Elefsiniotis, 1993).

2.3.1 ACID FERMENTATION OF PRIMARY SLUDGE

In acid fermentation of primary sludge, the process is carried out to the second step and attempts are made to prevent methanogenesis. The objective of acid fermentation of primary sludge is the conversion of complex organic compounds to lower molecular mass compounds mainly volatile fatty acids. These simple compounds then can be used to enhance biological nutrient removal. Fermentation increases the relative amount of directly and easily biodegradable fractions of the wastewater in the expense of hydrolysis and acidification of easily and slowly biodegradable compounds.

Osborn et al. (1986) showed that the presence of adequate concentrations of readily biodegradable COD, in particular VFAs is important to provide the substrates required for the Bio-P removal bacteria. They reported that in many wastewaters such substrates would not be present in adequate concentrations and supplementation from other sources would be required. A report by Brinch et al., (1994) explains that in the process of hydrolysis of primary or pre-precipitated sludge, direct degradable organic compounds are produced, which compensate for the low C/P and C/N ratios in the

influent and speed up the nutrient removal reactions rates. Pitman et al. (1983), proposed addition of supernatant liquor from a high rate digester to the feed of treatment plant in order to improve biological nutrient removal. Nicholls et al. (1985) in a full scale study confirmed the beneficial effects of high rate anaerobic products in biological nutrient removal. An improvement in phosphorus removal was observed in a five stage nutrient removal process when primary acid digester supernatant was added to the process feed (Nicholls et al., 1987). Significant improvements in phosphate removal were observed at three of the Johannesburg's activated sludge plants where acid fermentation of primary sludge and subsequent discharge of the fermentation products into the influent sewage streams were practiced (Pittman et al., 1992). They however announced that the nitrogen, phosphorus and suspended solids loads to the nutrient removal units were increased, which is the disadvantage of this operation.

Rabinowitz and Oldham (1985), reported that the fermentation of primary sludge can be used successfully to produce volatile fatty acids. The use of a separate fermenter for the production of VFAs was first proposed by Barnard in 1977, and is becoming a fairly standard practice at locations with colder climate and/or more dilute sewage (Kelona and Penticton, BC). Acid fermentation of primary sludge supplies volatile fatty acids which then could be added to the anaerobic zone of conventional Bio-P removal systems. This will reduce the hydraulic retention of the anaerobic zone and prevent or decrease the release of secondary phosphorus (Barnard, 1994; Randall,1994). The net benefits are a more economical design and higher nutrient removal efficiency.

2.3.2 FACTORS AFFECTING SLUDGE FERMENTATION

Many parameters related to environmental, operational and system conditions affect fermentation kinetics. Temperature, pH, solids residence time (SRT), hydraulic retention time (HRT), solids concentration, and type of the system are among the parameters of importance in the fermentation process. Results on temperature effects in the range of 14 to 23°C (Skalsky and Daigger, 1995) and 10 to 30 °C (Gupta, 1985) show that higher temperatures enhance fermentation process and result in higher production of volatile fatty acids.

2.3.2.a-pH

The role of pH in production of VFAs and their concentration distribution have been emphasized by many researchers. Eastman and Ferguson (1981), and Pavlostathis and Giraldo-Gomez (1991) concluded that the rate limiting step in the conversion of waste solids to fermentation products is the hydrolysis of particulate matter to soluble substrates. Furthermore, according to the results obtained by Eastman and Ferguson (1981), the distribution of volatile fatty acids changes with the operational conditions, especially variation in pH. Increased values of pH from 5.14 to 6.67 improved the solubilization of the particulate substrate. Zoetemeyer et al. (1982), (cited in Gupta, 1985) found that the relative production of individual fatty acids depends on the dilution rate, and more strongly on the pH value. Elefsiniotis & Oldham (1993, 1994a, 1994b) studied the effects of HRT (6 to 15 hours), SRT (5 to 20 days), pH (4.3-6.2), and system configuration on acid phase fermentation at ambient temperature. They indicated the importance of pH in VFAs production, and in distribution of VFAs produced. Within the pH range of 4.5 to

6.1, the effect of pH was negligible; while a drastic drop in VFAs production was observed at pH levels above 6.1. Low pH ranges (4.3-4.6) encouraged the production of propionic acid, and pH values in the range of 5.9-6.2 favored butyric acid formation. The authors pointed out that degradation of carbohydrates, proteins, and lipids; each follows an individual trend with respect to pH variation. The highest degradation of proteins occurred at pH of 4.5, with a significant decrease at higher pH levels. Lipid solubilization was not affected by pH changes up to 5.1, however a moderate decrease was shown at higher pH. Carbohydrate degradation increased steadily with increasing pH in the range investigated (4.3-6.2). A similar trend has been observed by Eastman and Ferguson (1981) in continuous flow reactors treating primary sludge at pH between 5.2 and 6.5. Gupta (1985) reported that a change in pH in the range of 5.6 to 7 did not affect VFAs production, but it influenced the relative concentration of acetic and propionic acids.

2.3.2.b-SRT and Solids Concentration

The literature on optimum SRT for acid fermentation of primary sludge is not very clear. Different optimum SRTs have been reported by different authors. This is possibly due to the difference in experimental conditions and types of the sludge used in the experiments. Gupta (1985) suggested SRTs of 9 days for temperatures of 10 and 20 °C, and 6 days for 30 °C. Daigger (1993) reported that in bench-scale fermenters operated at 17 °C to 20°C, VFAs production varied slightly over SRT of 2 to 6 days. He concluded that mean cell residence time of 2 days should produce adequate performance and that little benefit would be obtained by operation at longer cell residence time. On the other hand Elefsiniotis and Oldham (1994a) observed a sharp decrease in VFAs production at

18 to 20 °C as SRT was lowered to 5 days. The increase in VFAs production approached almost a plateau at SRT of 10 days or longer. The rate of VFAs production ranged from 0.06 to 0.12 mg/mg VS . d (Elefsiniotis and Oldham, 1994a). Production rates were based on the reactor volatile solids concentrations, not feed volatile solids concentrations. Highest production rates occurred at SRTs between 15 and 20 days and at an HRT of 12 hours. Skalsky and Daigger (1995) observed a change in VFA yields between approximately 6% and 26% of feed volatile solids under SRTs of 2 to 6 days, fermenter solids concentrations between 0.43% and 2.6%, and temperature between 14 °C and 23 °C. Higher VFAs yields were obtained at higher SRTs, lower fermenter solids concentrations, and higher temperature. They concluded that dilute fermenters (less than 1% solids) produce slightly higher yields. Improvement in hydrolysis, and substrate uptake, and the reduction of inhibitory effects of fermentation products were suggested to be the reasons for achievement of higher VFA yield in the dilute fermenters.

2.3.3 SLUDGE FERMENTERS : TYPES AND PROBLEMS

Acid fermentation of primary sludge requires three different steps (GonCalves et al., 1994) including: primary settling in which separation of particulate organic matter occurs, fermentation of settled particulates, and clarification of fermented sludge. These processes and operations can take place within a minimum of two reactors (Comeau, 1990; cited in Gon Calves et al., 1994).

The configurations of fermenters vary depending on the strength of the wastewater, degree of fermentation in the sewage system, and the availability of structures and space in the retrofitted treatment plants (Barnard,1994). In general, there are three

types of fermenter units which have been identified by Oldham et al. (1992) and Barnard (1994) as activated primary tanks, static fermenters, and separate completely mixed fermenters. The characteristic feature of each will be briefly discussed in the following sections.

2.3.3.a-Activated Primary Tanks

This method which was proposed by Barnard (1985) consists of primary sludge recycling around the primary sedimentation tank. There are many problems associated with this type of fermentation. Rabinowitz et al., (1994) summarized these problems as; high solids loading to the primary clarifiers, difficulty in controlling the SRT of the fermenting sludge mass, tendency to promote methane and sulfide formation, build up of fibrous material in the sludge which can cause blockage of pumps and pipelines, and inadequacy to discharge the VFAs produced directly to the BNR process.

2.3.3.b-Static Fermenters or Thickener/Fermenters

In static fermenters, primary sludge is transferred to a combined fermenter/thickener, and the fermented supernatant is then fed to the nutrient removal bioreactor. This method which has been used in Kelowna (Oldham et al, 1992) is the simplest process to operate (Pitman, 1991), but results in low VFA. Volatile fatty acids production in Kelowna was reported to be about 21g/m^3-plant influent (Oldham and Abraham, 1994). The main disadvantage of using thickener as a fermenter is the lack of direct control over SRT, though the detection of sludge blanket can serve as a means of controlling the system adequacy (Barnard, 1994).

2.3.3.c-Separate Completely Mixed Fermenters

The completely mixed system includes a vessel for retaining the primary sludge for a specific period of time before passing it to the thickener for removal of some of the liquid rich in VFAs content. This type of fermenters produce the best results however with an increase in the number of reactors and complexity of the operations (Gon Calves et al., 1994). Oldham and Abraham (1994) reported VFA production of 58g/m^3-plant influent in Kalispell, Montana. One of the major problems of complete mixed fermenters is sludge thickening. The fermented sludge does not thicken easily to more than 3.5%; resulting in a watery sludge to the digesters or sludge dewatering systems (Barnard, 1994). This is accompanied by a carry over of solids to the biological nutrient removal units. Another problem is build-up of methane fermentation in the completely mixed fermenters. Barnard (1993) emphasized that provision must be made for periodic removal of all sludge, or for occasional aeration to counteract such tendencies.

Odor and corrosion problems, methane formation, blockages in pumps and pipelines, and the formation of stable scum blankets on the surface of quiescent units are among the major operating problems associated with the operation of full scale primary sludge fermenters (Rabinowitz et al., 1994).

2.3.4 ACID FERMENTATION OF RAW WASTEWATER

Acid fermentation of primary sludge has been employed in some full scale plants practicing BNR in conventional flow-through treatment systems, e.g., the three stage anaerobic-anoxic-aerobic process in Kelowna B.C.

Sludge fermentation technology cannot be directly applied to discontinuous

processes such as sequencing batch reactors (SBR) which usually lack primary clarifier and hence primary sludge.

In order to bring the effluent phosphorus down to the levels lower than 1 mg/L, chemical treatment may have to be used in SBR systems. Chemical methods though very efficient , produce large quantities of sludge, and increase the cost of treatment substantially. Another possible option is to find and improve a biological method that plays in the SBR system a role similar to the role of sludge fermenters in continuous flow-through systems.

Existing primary sludge fermentation acts mainly on the particulate fraction of the wastewater, a large proportion of which consists of slowly degradable organic compounds (Henze et al., 1994). The majority of the rapidly hydrolisable compounds are present in the soluble fraction of the wastewater. The soluble components can be used to produce VFAs and enhance biological nutrient removal. The potential of the soluble part of the wastewater in VFAs production is not being used in the existing fermenters.

The concept of acid fermentation of raw wastewater which covers both, the particulate and soluble organic components, could be applied to SBR system. The concept is new and there has not been any information available on the topic at the beginning of this research (September, 1993). However very recently Gon Calves et al. (1994) reported fermentation of domestic wastewater in pilot-scale upflow sludge blanket reactors. They studied the role of HRT (1.1-4.3 hours) on the performance of the system at 20±1 °C. The optimum condition obtained at HRT of 2.8 h. They pointed out that the fermentation efficiencies were superior to those of the existing fermentors.

No association has yet been reported between the SBR reactors and the concept of

primary fermentation of the wastewater. Likewise the impacts of other environmental and operational parameters on the fermentation of raw wastewater, and the role of prefermentation of raw wastewater in enhancement of BNR removal in SBR systems have not been reported and should be explored.

2.4 SEQUENCING BATCH REACTORS (SBR)

A sequencing batch reactor system is an activated sludge system in which each reactor accomplishes in time what a traditional activated sludge accomplishes in space in a series of continuous flow reactors. The system operates in a cyclic manner; each cycle consists of periods of fill, react (with or without aeration), settle, decant and idle. Figure 2.4, demonstrates the general performance of a sequencing batch reactor in one complete cycle.

The use of fill-and-draw processes for treating wastewater have been in development and use since the turn of the century. Most sewage treatment studies between 1881 and 1912 used fill-and-draw tanks. In 1914 the value of aeration was demonstrated and between then and 1920 several full-scale SBR systems were operated. After 1920 however, the emphasis moved to continuous flow conventional systems. In the late 1950s and early 1960s interest was revived in the SBR systems with the development of the new technology and equipment (EPA, 1986).

The sequencing batch reactor system is known to have several advantages over conventional continuous flow systems (Irvine et al., 1977; Silverstein and Schroeder, 1983; EPA, 1986; Chin, 1988). They are easy to operate, and are much more flexible than conventional activated sludge systems. Cycle period and thus hydraulic retention time can

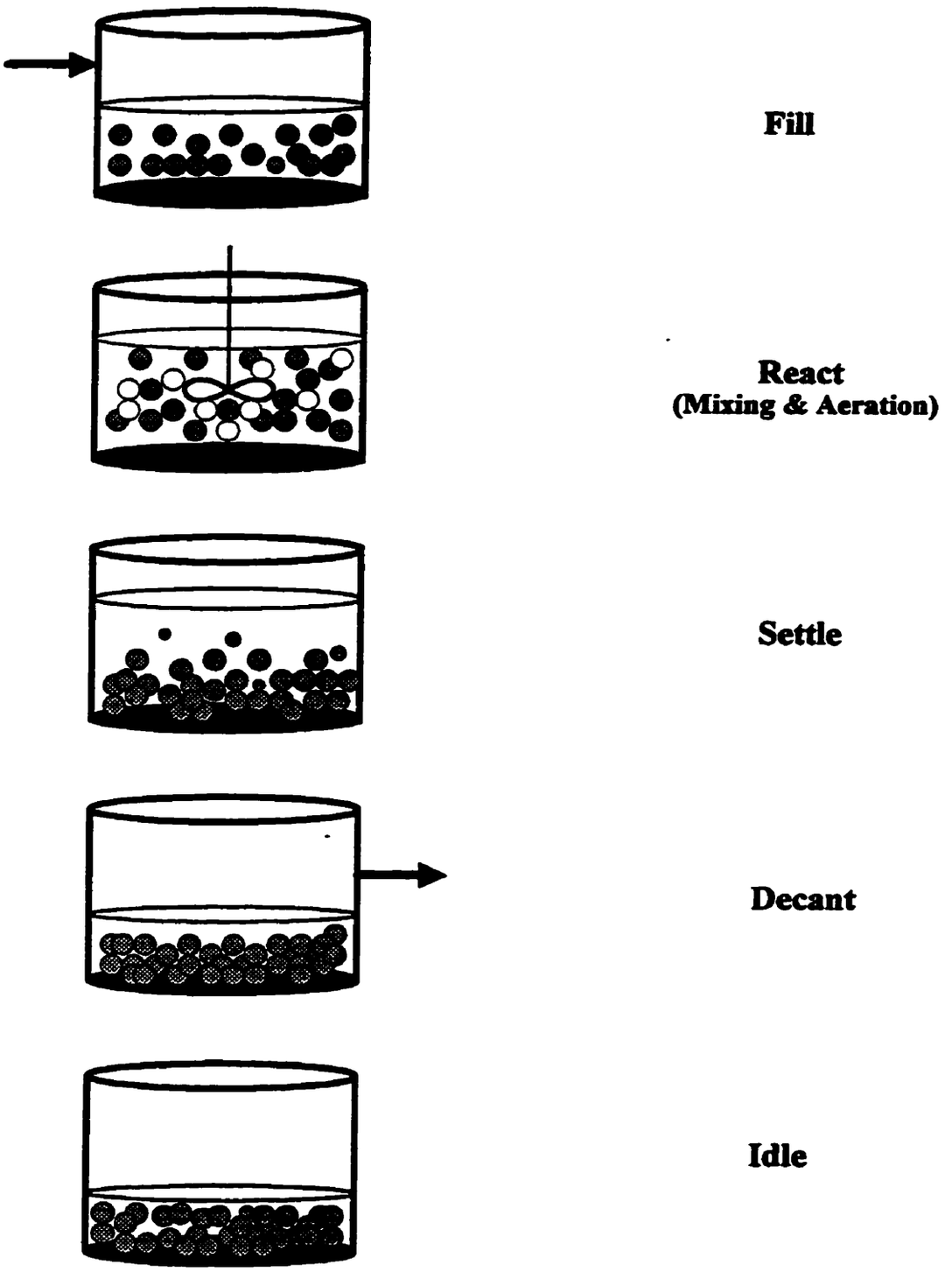

Fig.2.4 : A general operational cycle in sequencing batch reactors. Each cycle usually consists of periods of fill, react, settle, decant and idle.

be easily changed to match the variation in the influent flow and composition. Hoepker and Schroeder (1979) stated that batch reactors behave as ideal plug-flow reactors with respect to kinetic responses. Furthermore, flow equalization and attenuation of peak loads are intrinsic in batch processes. Thus sludge bulking is rarely observed and large fluctuations in influent loading hardly affect the process performance. The system could be managed to provide either a continuously low reactor substrate concentration, or an alternating high-low concentration substrate profile by varying the operational strategies during fill period. This gives the advantage of incorporating selector mechanisms for controlling filamentous growth and bulking problems. Silverstein (1984), (cited in Jones et al., 1990) discovered that lack of mixing during fill period saves energy and controls growth of filamentous organisms. Sheker et al. (1994) observed a significant improvement in sludge settleability by adapting the anoxic fill strategy as comparison was made with oxic (aerobic) fill strategy.

Since SBR systems are time oriented, fill, mixing and aeration patterns may be altered to accommodate for specific operating conditions (anaerobic, anoxic, and aerobic environments) and to yield carbon, nitrogen and phosphorus removals.

The advantages of the system and the vast improvement in electronic control devices have caused increasing use of such systems in many locations during the past two decades. The first full-scale SBR facility was built in Culver, Indiana in 1982. According to EPA (1992), there are about 170 SBRs operating in US, of them approximately 40 were designed to include nutrient removal. Irvine et al. (1983) reported an excellent performance for the Culver treatment plant in removing the carbonaceous material. The high capability of SBR systems with regard to carbon removal has been emphasized in

almost all the papers published since then.

Barth (1985) stated that for wastewater flows up to 19000 m3/day, the SBR process is favored over the continuous flow process due to total life cycle cost savings, ease of operation, flexibility in operation and reliability.

2.4.1 NITROGEN REMOVAL

Irvine et al.(1987) showed the feasibility of nitrogen removal in SBR systems. Since then sequencing batch reactors have been successfully applied throughout the world for carbon removal, nitrification and denitrification (Jones et al., 1990).

As with continuous flow systems, the problem with denitrification is mostly associated with an imbalance between availability and demand of electron donors. Often the availability of electron donors as well as the quantity of oxidized nitrogen that are being reduced limit the denitrification capacity of the system. Many attempts have been made to increase the efficiency of the SBR systems in removing nitrogen.

Wilderer et al. (1986) reported that the extent of denitrification can be improved by a second fill strategy; a method which may end up with a high ammonia content in the effluent. Abufayed and Schroeder (1986) advised the use of primary sludge in SBR systems as a an excellent source of carbon, and demonstrated the enhancement of denitrification process through this method.

Tam et al. (1994) pointed out the importance of addition of an anoxic stage following the aeration stage, and usage of an external carbon source in SBR systems. The results of their work clearly indicated that the usage of a readily available carbon source enhanced overall nitrogen removal efficiency in the modified sequencing batch reactor

running at 12 h cycle period. They reported that methanol; the most commonly used carbon substrate, was found to be the least effective carbon source when compared with sodium acetate and propionate. The necessity of addition of a supplementary readily biodegradable COD during the anoxic phase to obtain complete removal of nitrogen was confirmed by Demuynck et al. (1994). They explained that in wastewaters having low C/N ratio, all BOD is normally removed before nitrification is completed. Thus addition of an extra carbon source is necessary to guarantee full denitrification during the anoxic stage. The extent and rates of denitrification reactions depend on the type and amount of organic compounds used to derive denitrification process (Abufayed and Schroeder, 1986; Tam et al., 1994). Demuynck et al. (1994) further observed that a sequence of short aerobic/anoxic phases enhances nitrogen removal and reduces the consumption of extra carbon source. Vuoriranta et al. (1994) obtained about 80% removal of total nitrogen at 13 °C without any addition of supplementary source of carbon. The feed was a strong wastewater (TCOD=590 mg/L) and the operational parameters consisted of the cycle period of 1 day, HRT of 86 h, and organic loading of 0.03 to 0.04 Kg BOD_7/Kg MLSS . d. A three-stage SBR system was developed by Jones et al. (1990) in which the organic carbon was first sequestered into biomass, and later was used in denitrification process. The system capacity for nitrogen removal was limited to 75%. Lack of mixing during the initial fill period improved the performance of the system and the settling characteristics of the sludge.

Oleszkiewicz et al. (1988) studied nitrification-denitrification in SBR systems at temperature ranges of 15 to 7 °C, and 5 to 2 °C. Decreasing temperature resulted in a gradual deterioration of the nitrogen removal efficiency and rate. The nitrification

efficiency declined from 90-94% at 15 °C to 54-55% at 2 °C. Nitrification efficiency was improved to 90% at 2 °C by increasing the cycle length from 8 h to 12 h, lowering the F/M ratio to 0.07, and extending SRT to beyond 60 days. McCartney and Oleszkiewicz (1990) in their study on the effect of low temperatures on carbon and nutrient removal in SBR concluded that significant nitrification is not achieved below 4 °C. The highest specific nitrification rates were 4.41, 2.05, and 1.02 mg/g VSS.h at 10, 6, and 4 °C, respectively. The specific denitrification rate reduced from 8.0 mg/g VSS.h at 10 °C to 1.5 mg/g at 4 °C. Nitrification was found to be the most temperature sensitive reaction, followed by denitrification with carbon removal being the least sensitive. No enhanced Bio-P removal was achieved in the temperature range of study (0.5 to 10 °C).

2.4.2 PHOSPHORUS REMOVAL

The first classical work on phosphorus removal in SBR was presented by Manning (1986). In lab-scale reactors, he applied different operational strategies during the fill periods to investigate the effects of substrate (concentration), oxidized nitrogen, and dissolved oxygen on the performance of SBR systems. All reactors, using synthetic feed, included a basic 8 h operating cycle divided into a 2 h fill period, 4 h aeration period, and 2 h for settle, draw, and idle. Spiked feeding at the beginning of the fill period together with the application of continuous mixing during the anoxic/anaerobic, was realized the best strategy on the basis of the results obtained for different performance parameters such as phosphorus removal, sludge settleability, and COD removal rate. Continuous feeding produced the same effluent phosphorus concentration (less than 0.5 mg/L) as the spiked filling, but the rate of COD removal in the anoxic/anaerobic period was reduced, and

sludge settleability deteriorated significantly. Sludge volume index (SVI) reached 500 mL/g under continuous fill, while SVI associated with spike fill rated from 60 to 80 mL/g, indicating the importance of mode of operation of SBR systems in settling characteristics. The results further revealed excellent phosphorus removal during periods of high SVI.

Manning verified that fermentation products are a major substrate for the phosphorus removing bacteria, and that the presence of oxidized forms of nitrogen in the anaerobic stage initiates a competition between denitrifiers and phosphorus removing bacteria which results in reduction of phosphorus release.

Feasibility of low temperature biological phosphorus removal was explored by Marklund and Morling (1994) in a full-scale SBR treatment plant near the Arctic circle. The wastewater temperature varied between 3 °C and 10 °C, being mostly below 5 °C. The system operated with cycle periods of 6 to 12 h, HRT of 12 to 24 h, and SRT of 15.5 to 21 days. Effluent soluble phosphorus concentrations were usually less than 1 mg/L at water temperatures down to 5 °C, but a sharp increase to greater than 2 mg/L was evident at 4 °C. Biochemical oxygen demand (BOD) removal varied between 70% and 90%. These reductions were achieved at supernatant suspended solids of 20-30 mg/L.

2.4.3 COMBINED NITROGEN AND PHOSPHORUS REMOVAL

Early investigation on nitrogen and/or phosphorus removal in SBR systems was performed by Alleman and Irvine (1980). Their work led to the conclusion that the processes of nutrient removal in SBR systems are possible, if the operational conditions are properly modified. Some operational modifications such as different combinations of anoxic/anaerobic/aerobic stages in the operational cycles were tried in a research by Okada

and Sudo (1986). They showed that the presence of an anoxic/anaerobic condition during the fill period improves nutrient removal. It was however suggested that an optimum time period should be sought for the anoxic/anaerobic stage in order to achieve successful operations and sludge settleability. Denitrification was not improved by the introduction of a second anoxic period of 1.25 h. The shortage of hydrogen donor both inside and outside the sludge was considered responsible for preventing denitrification in the second anoxic period. No release of phosphorus was observed during this period.

Bortone et al. (1992) in treating clarified piggery wastewater in lab-scale reactors realized the benefits of having secondary anoxic stage and step feeding. Though nitrogen removal was found to be limited by lack of adequate carbon, they proposed that distribution of feed between denitrification phases allows a better use of the organic source for the denitrifiers. With HRT of 10 days, SRT of 28 days and step feeding, about 88-93% of nitrogen and about 95% of phosphorus were removed.

In a modified SBR unit, Goronszy and Rigel (1990) achieved an effluent phosphorus and nitrogen concentrations of less than 1 and 5 mg/L, respectively. Sludge recycle was employed, and the formal anoxic period did not exist.

Rusten and Eliassen (1994) explored the effects of a wide range of operational and cycle parameters to optimize biological nutrient removal in a small full scale treatment plant at average temperatures 9-10 °C. An equalization tank was used prior to the main reactors. The maximum obtained nitrogen removal was 60 to 65% at HRT of about 32 hours and SRT of 14.3 to 19.2 days. Phosphorus removal was about 46% under these conditions and occurred only if the settled sludge was completely denitrified prior to the first fill. They confirmed that denitrification was limited by the lack of soluble carbon in

the wastewater. The applicability of SBR for nutrient removal was tested by Imura et al. (1994) using a manufactured SBR to treat a wastewater from apartment houses. Nitrogen removal of 81.4% and phosphorus removal of 96.3% were reported at HRT of 22 hours.

Optimization of nutrient removal has been attempted at Dauphin Borough Wastewater Treatment Plant, by changing the periods of mix-fill, react-fill (McClintock and Frazier, 1994). The change in each sets of the parameters lasted for one month. The best performance occurred with mix-fill, and react-fill of 90 minutes each. The process led to total-P concentration of less than 0.5 mg/L and total nitrogen concentration of 5.5 mg/L.

In a report by EPA (1992), performance of nutrient removals in existing SBR treatment plants have been evaluated. The report stated that: "The plants appear to achieve denitrification when properly designed and achieve phosphorus removal without chemicals to less than 1 mg/L, although data on both processes are limited". The available data on seven plants showed an average effluent P concentration in the range of 0.5 to 4.27 mg/L.

In summary, sequencing batch reactors are relatively recently introduced systems that show promise for the removal of both nitrogen and phosphorus. However, limited information exists concerning their design, operation, performance and costs when compared to the conventional flow-through systems.

Chapter 3.

RESEARCH OBJECTIVES AND SCOPE OF WORK

Sequencing batch reactors (discontinuous flow-through systems) provide treatment conditions totally different from the continuous flow-through systems. In SBR systems, various functional groups of microorganisms are kept in one tank, and the treatment process proceeds on timely sequenced manner, rather than occurring in spacely divided tanks. As a result the research findings on treatment optimization of continuous flow-through systems may not be applicable to the SBR systems, eventhough the basic mechanisms of the biological removal of carbon, nitrogen and phosphorus are the same in all biological treatment systems.

As the review of literature showed, concurrent biological removal of phosphorous and nitrogen in SBR systems may be feasible but has not been investigated thoroughly, particularly in performance kinetics and design criteria. As well, the process of acid fermentation of raw wastewater and its role in enhancement of nutrient removal in SBR system has not been explored yet. Consequently, a detailed research in this area could provide valuable information for performance and design improvements of SBR systems.

3.1 RESEARCH OBJECTIVES

This study was initiated with the following objectives :

1. To investigate the feasibility of acid-phase fermentation of degritted raw wastewater under various environmental and operational conditions.
2. To study the effects of acid fermentation of raw wastewater on biological nutrient

removal of SBR systems.

3. To optimize biological phosphorus and nitrogen removal in the SBR systems while applying the process of acid fermentation of raw wastewater.

3.2 SCOPE OF WORK

The scope of research on fermentation of raw wastewater covered the following aspects :

- Effects of different SRT : 4 days, 8 days, and 13 days.
- Effects of different pH levels of the wastewater : natural pH range of the wastewater (7.0-7.6), and low pH range of 6.1-6.4.
- Impacts of mixing period : 6 h mixing/cycle, and 0.25 h mixing/cycle.
- Effects of HRT : 12 h, 9 h, and 6 h.

In optimization of biological nutrient removal in the SBR systems, the impacts of following parameters were investigated.

- Total Cycle length
- Duration of anoxic/anaerobic period, aeration period, and settling period in each cycle.
- Step-aeration regime (to improve nutrient removal, and to minimize the aeration period).
- Step feeding strategy (to enhance denitrification process).

Chapter 4.

MATERIALS AND METHODS

4.1 OBJECTIVES APPROACH

The objectives of the research, also the variables involved in experiments were too diverse to be approached simultaneously. The scope of this study covered two broad subjects of fermentation of raw wastewater, and the impacts of fermentation on biological nutrient removal. The research initiated with experiments on acid fermentation of degritted raw wastewater. However, after achieving some insight on the fermentation process, the study of BNR began and continued concurrent with some further studies on the fermentation part. To keep the matter simplified the studies performed in fermentation, and those on biological nutrient removal will be described separately.

4.1.1 ACID FERMENTATION OF RAW WASTEWATER

4.1.1.a-Step 1 : Effects of Sludge Retention Time (SRT)

The objective of this stage was to investigate the performance of acid fermentation of raw wastewater under different SRTs. Degritted raw wastewater was fermented in three reactors (F1, F2 & F3) having SRTs of 13 days, 8 days, and 4 days respectively. The feed to the reactors (degritted wastewater) had its own natural pH of 7 to 7.6 during this period of the experiments. These reactors were named Primary Acid Fermenters (PAF).

It is necessary to mention that at the time this research was initiated, there was not any operational data available in the literature with regard to the acid fermentation of raw

wastewater. As a result, the experiment in this step began with only one reactor (F1). Reactor F1 with SRT of 13 days was set on Oct. 30, 1993 to investigate the behavior of the fermentation process. After the success of the system was established, the other reactors; F2 and F3 with SRTs of 8 and 4 days were started on Dec. 17, 1993 and Jan. 14, 1994, respectively.

Reactors F1, F2 and F3 employed suspended growth, and were operated in an anaerobic-SBR mode with three cycles per day (8 h/Cycle) and HRT of 12 hours. Each cycle consisted of 6 hr of mix & react (with 15 minutes of fill at the start of each hour), followed by 1 hr & 20 minutes of settle, 20 minutes of decant, and 20 minutes of idle. The operational cycle of the fermentation units at this step of the experiments is shown in Figure 4.1.

4.1.1.b-Step 2 : Effects of pH

This section of the research dealt with feasibility and behavior of acid fermentation of raw wastewater at low pH condition of the feed (degritted raw wastewater). Reactors in step 1 were running in this step, too. All environmental and operational conditions remained the same as in step 1 except for the pH of feed which was reduced to the range of 6.1-6.4 using a solution of 6 N hydrochloric acid.

At the end of this period, one of the reactors with the worst performance (F3) was discarded, and the other two reactors (F1 & F2) were kept for further investigations throughout the research.

4.1.1.c-Step 3 : Impacts of Mixing Period

The objective of this step was to determine the efficiency of the fermentation process as a reduction in mixing period was applied. The two reactors (F1 and F2) remained from step 2, were set to operate as duplicate in this step. The reactors were running at 3 cycle/day with HRT of 12 h; similar to previous steps. The major operational change in this step was a reduction in mixing period from 6 h per cycle to 0.25 h per cycle. SRT of both reactors was also set at 12 days. The degritted raw wastewater used as feed kept its own natural pH.

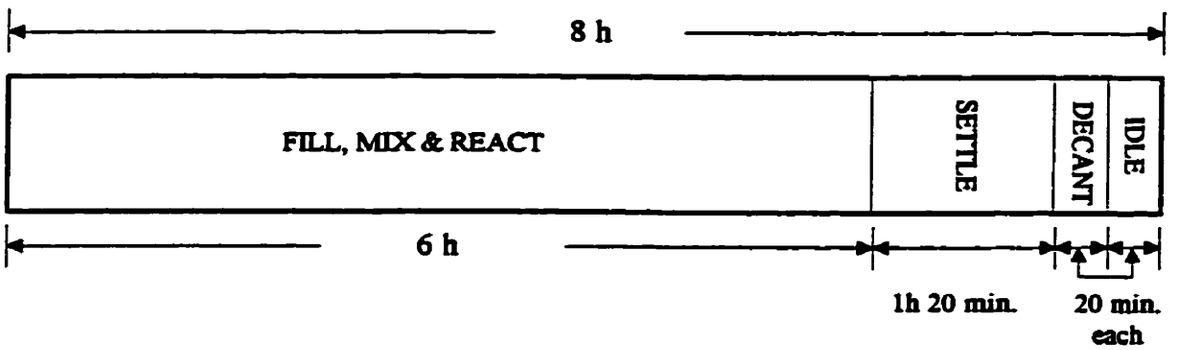

Fig. 4.1 : Components of an 8 h operational cycle employed in primary acid fermenters during steps 1,2 and 3.

4.1.1.d-Steps 4 and 5 : Effects of Hydraulic Retention Time (HRT)

The change in performance behavior of fermentation process with regard to variation in HRT was investigated in subsequent steps 4 and 5. In step 4 a comparison was made between HRT of 12 h and 9 h using reactors F2 and F1. Hydraulic retention time of fermenter (F1) was programmed at 9 h (4 cycle/day with 6 h/cycle), while the other reactor (F2) was kept at its previous HRT of 12 h (3 cycle/day). The 6 h cycle consisted of 4 h of react (with 15 minutes of fill at the start of each hour), and a total of 2

hours for settle, decant and idle periods. Mixing was applied for only 0.25 h during the last portion of the react period. Distribution of the time for settle, decant and idle were the same as those in previous steps of the research.

In step 5, reactor F2 was changed gradually (was reduced to 9 h HRT for several days) to HRT of 6 h (6 cycle/day) and its performance was compared to the parallel reactor (F1) with HRT of 9 h. The cycle length in reactor F2 was 4 hours; consisted of two hours of react (with 15 min of fill period at the beginning of each hour), and the total periods of 2 hours for settle, decant and idle.

Sludge retention time and mixing period of both reactors during steps 4 and 5 were kept at optimized values obtained from previous steps of the research; meaning 12 days for SRT and 0.25 h/cycle for the mixing period.

4.1.2 IMPACT OF FERMENTATION OF RAW WASTEWATER ON BNR IN SBR SYSTEMS

Research on biological nutrient removal began concurrent with step 3 in fermentation studies.

Two new parallel sequencing batch reactors were set (B1 and B2) for the purpose of biological nutrient removal. One reactor (B1) was fed with the fermented effluent from PAF reactors, and the other reactor (B2) was directly fed with the degritted raw wastewater. The first system which consisted of a fermenter (PAF), and B1 was called PAF-SBR system. In this system, degritted raw wastewater was fermented first (in a PAF reactor), and then was treated for nutrient removal in B1. The parallel system which was called conventional-SBR, consisted only of B2, and treated degritted raw wastewater

directly for nutrient removal.

The objectives were to investigate the effects of prefermentation of the raw wastewater on behavior of biological nutrient removal in sequencing batch reactors, and to optimize nutrient removal in the new developed two-stage SBR system (PAF-SBR) consisting of a fermenter and a BNR-SBR.

Experiments on biological nutrient removal were conducted in four sequential stages as follows:

4.1.2.a-Stage 1 : Use of The Conventional 8 h-Cycle

A comparison between the performance of the PAF-SBR system, and the conventional-SBR system was made in this stage. Both BNR reactors (B1 and B2) were run at a cycle period common in SBR systems (8 h cycle). The reactors were operating at 3 cycle/day with HRT of 12 h. Each operational cycle during this stage (Figure 4.2) included 20 min of fill without mixing, 2 h of anoxic/anaerobic period with mixing, 4 h of aeration with mix, 1 h and 20 min of settle followed by 20 min of decant.

4.1.2.b-Stage 2 : Improvement in P-removal (6 h-Cycle, HRT = 9 h)

Major changes were made in the operational cycles of the BNR reactors (B1 and B2) to optimize phosphorus removal efficiency. Total length of initial anoxic/anaerobic period was reduced from 2 h and 20 min in previous stage to 45 min in this stage which permitted the operation of BNR reactors at 4 cycle/day with HRT of 9 h. Each cycle, as indicated in Figure 4.3, was composed of 20 min of fill without mixing, 25 min of anoxic/anaerobic with mixing, 3 h and 40 min of aeration with mix, 1 h and 15 min of

settle and finally 20 min of decant. Comparison of Fig. 4.3 with Fig. 4.2 could clear out the nature of alterations made in this stage.

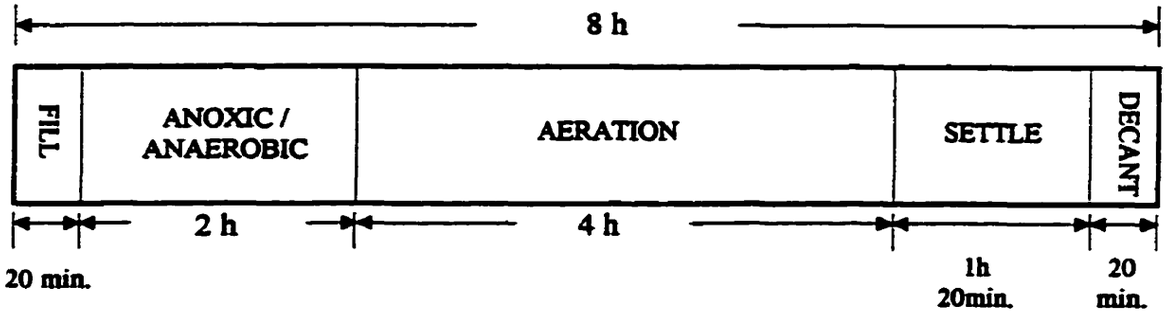

Fig. 4.2 : Components of an 8 h operational cycle in the BNR reactors (B1 & B2) during stage 1 in the research.

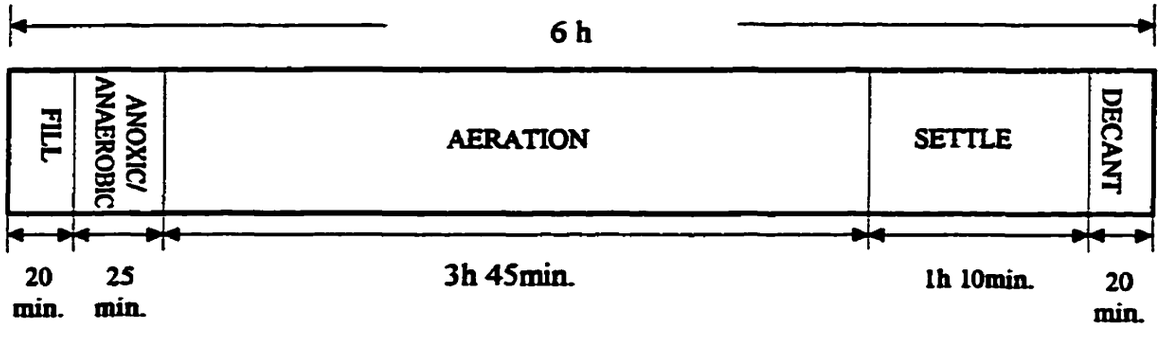

Fig. 4.3 : Components of a 6 h operational cycle in the BNR reactors during stage 2 in the research.

4.1.2.c-Stage 3 : Enhancement in Nitrogen Removal (Step-Aeration)

Nitrogen removal was enhanced in BNR reactors (B1 and B2) by introduction of an anoxic period in the operational cycle. This was done by stopping the aeration system for a pre-determined period of time. By this mean, the total time period of anoxic condition in each cycle was increased. Different combination of aerobic/anoxic periods were tested to obtain the optimum operational periods in each cycle (Figure 4.4).

Hydraulic retention time (HRT) and No. of operational cycle/day were kept similar to previous stage (HRT of 9 h, 4 cycle/day). Each cycle, as depicted in Fig. 4.4 consisted of 45 min of anoxic/anaerobic period including 20 min of filling time (same as in stage 2), followed by 1 h of aeration, 1h and 45 min of anoxic period, 1 h of further aeration, 1 h and 10 min of settling and 20 min of decant. Mixing was provided during the periods of anoxic/anaerobic, aeration and anoxic conditions. The major change in this stage was associated with the total aeration period which was cut to almost half as compared to the total aeration period in stage 2.

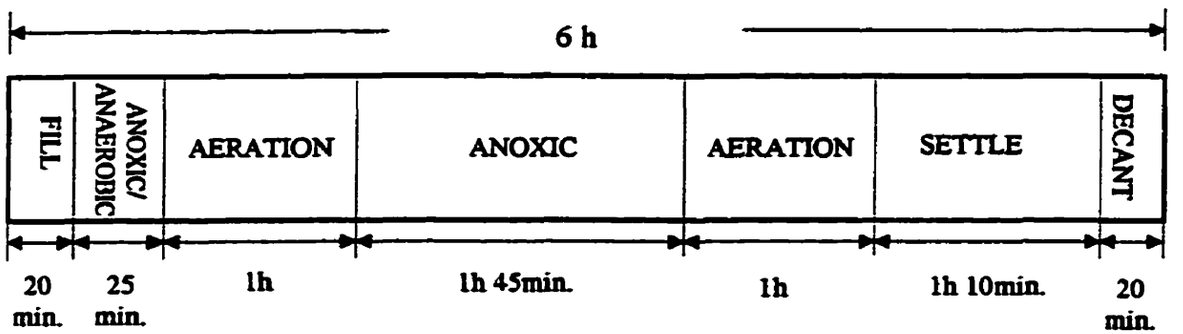

Fig. 4.4 : Optimum operational cycle used in the BNR reactors during stage 3.

4.1.2.d-Stage 4 : Enhancement in Nitrogen Removal (Step-Feeding)

The step-aeration schedule in step 3 was modified to some extend in this stage to reduce the chance of phosphorus release during the anoxic period. Furthermore a step-feeding procedure was tried to improve nitrogen removal and reduce total nitrogen content of effluents to levels below 5 mg/L. The new step-aeration scheme included the sequence of 1 h aeration, 1 h anoxic, 30 min aeration, 45 min anoxic, and 30 min final

aeration periods. As it is observed the total aeration/anoxic periods in each operational cycle remained the same as in stage 3. However they were divided to shorter time intervals in this stage to reduce the possibility of development of anaerobic conditions which would otherwise lead to the release of phosphorus. During step-feeding, a portion of total feed in each cycle was kept and added to the reactor at the beginning of last anoxic period. This stage of research was applied only to the PAF-SBR unit.

The sludge retention time of the biological nutrient removal reactors was kept at 10 days during all stages of this study to ensure the growth and proliferation of nitrifying bacteria in the reactors. Due to their slower growth rate, nitrifying bacteria demand longer SRTs than those required for the growth of heterotrophic bacteria (see section 2.2.2). Oleszkiewicz (1995) suggested SRTs of greater than 5-8 days for the proliferation of nitrifying bacteria in biological systems operating in 20 °C.

4.2 EXPERIMENTAL SET UP AND EQUIPMENTS

The experiments in this research were carried out at room temperature (20±2°C). The reactors in all stages of the research had each a total volume of 4 liter and a working volume (liquid volume) of 3 liter. During the decant period 2/3 of the volume (2 liter) was withdrawn from each reactor which would be replaced by the same amount of feed at the beginning of the next cycle.

Plexiglass cylinders, with the inner diameter of 10 cm were used to make the reactors. The heights of the reactors were 50 cm. The influent and effluent ports were located at the heights of about 30 cm and 13 cm, respectively. A sampling port which was also used for the wastage of excess sludge was placed at the height of 20 cm in each

reactor.

Pumpage of the influents and effluents were done by Cole Parmer # 7553-80 peristaltic pumps with Masterflex 7017-21 pump heads equipped with size # 17 masterflex tubing. Cole Parmer # 7553-71 Masterflex Speed Controllers were used to control the speed of the pumps.

Tygon tubing (size # 17) conveyed liquids from the influent buckets to the pumps, and from the pumps to the reactors. The same type of tubes transferred effluents from the reactors to the pumps, and from the pumps to the effluent buckets. Connections between tygon tubing and pump tubing or reactors were made with the help of the PVC plastic connectors. Effluents from the reactors were discharged to 10 liter plastic buckets. Experimental trains were assembled in Environmental Engineering Laboratory, Department Civil and Geological Engineering, University of Manitoba.

4.2.1 ACID-FERMENTATION REACTORS (PAFs)

The rectors for acid-fermentation process were sealed using a rubber O-ring in addition with silicon water proof sealant. A Cole Parmer Ultraclean Teflon gas bag # H-01409-14 filled with nitrogen gas was connected to the head space of each reactor to allow for level changes within an enclosed head space. Mixing was provided by a Cole Parmer # 4515 magnetic stirrer. The reactors' operation was controlled by a programmable electronic timer.

A schematic of Primary Acid Fermenter with the connected components are shown in Figure 4.5.

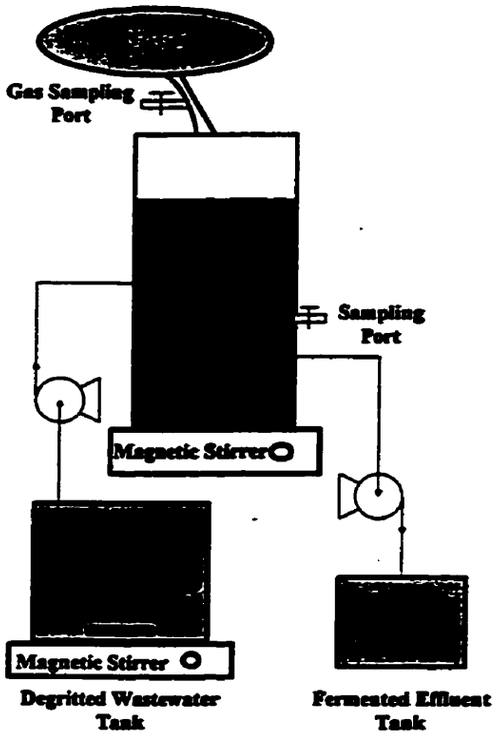

Fig. 4.5 : Typical schematic of a primary acid fermenter (PAF) developed in this study.

4.2.2 BNR-REACTORS (BNR-SBRs)

The two parallel reactors (B1 and B2) used for BNR were open on top, and each received mixing action by a mechanical stirrer. The stirrer was made of a 50 cm stainless steel rod equipped with two 4.5 cm mixing blades at its end. The stirrer was connected to a Cole Parmer Pump # 7553-20 which was installed inversely at 8 cm distance from the top of the reactor and could provide 6 to 600 RPM. A view of these two reactors in operation is observed in Figure 4.6.

One of the BNR reactors (B1) was fed with the fermented wastewater (effluent from PAF reactors). The arrangements in this system is shown in Figure 4.7. The other BNR reactor (B2) was fed directly from the degritted raw wastewater storage tank.

A diffused aeration system composed of a Cole Parmer Aeration Pump # 7530-40 and a stone diffuser, supplied the air during aeration periods. Dissolved oxygen in the reactors were kept between 2 to 4 mg/L and was monitored with a Fisher YSI model # 51B DO meter. The reactors' ORPs were measured by a Cole Parmer Chemcadet pH meter/controller set to read millivolt potential, using a Canlab CA 73950-014 ORP probe (Ref. electrode; Ag/AgCl). All operational processes in BNR reactors were controlled by Digital Lamp and Appliance Timers # 52-8851-2 purchased from Canadian Tire.

Figure 4-7 shows different components of the PAF-SBR system. The parallel system (Conventional-SBR) consisted only of one reactor with no prefermentation process prior to it.

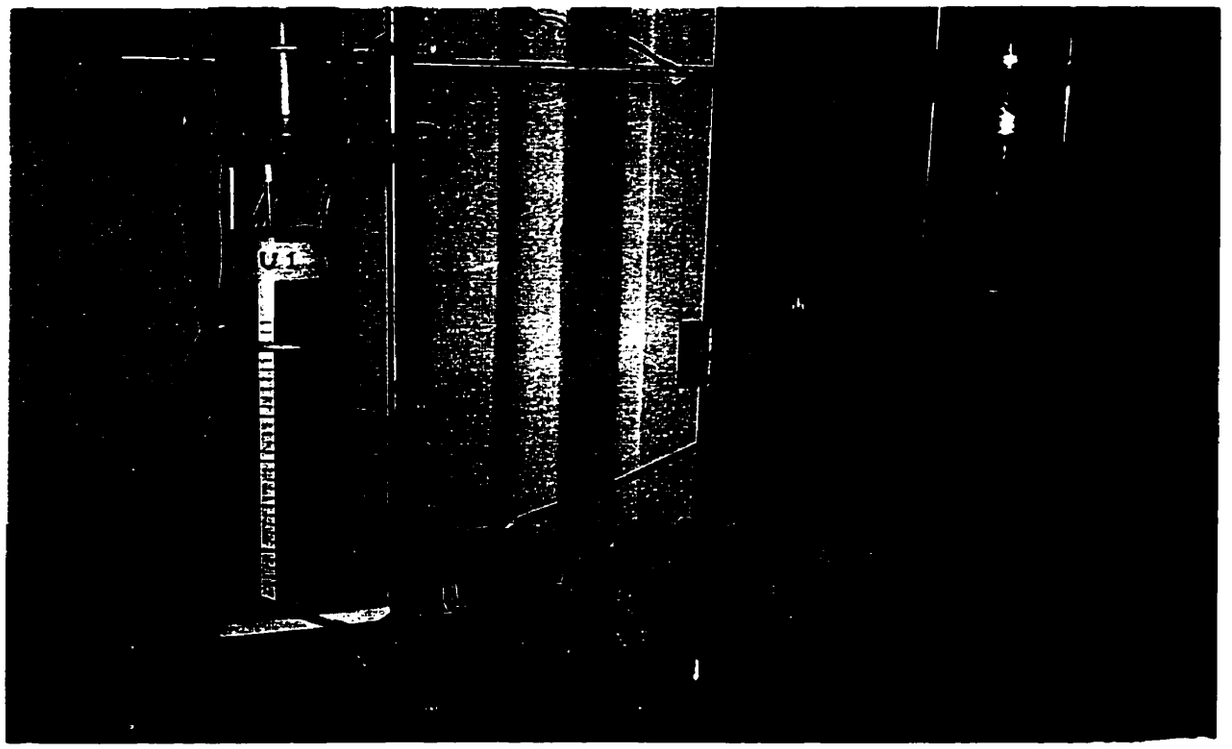

Fig. 4.6 : A view of the two biological nutrient removal (BNR) reactors.

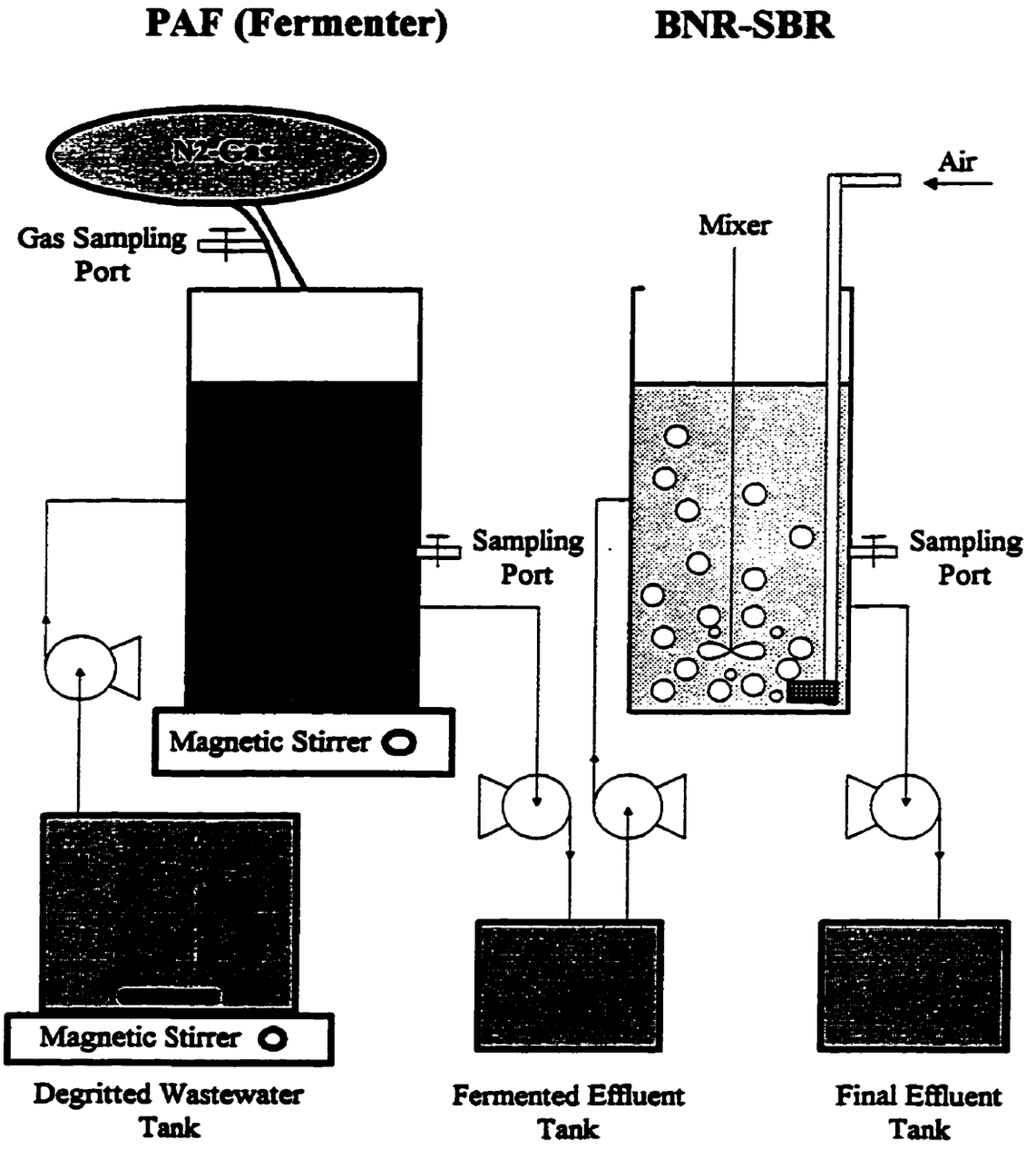

Fig. 4.7 : Detailed components of PAF-SBR system. This system included two reactors in series. The first reactor (PAF) was a SBR-fermenter in which the wastewater was acid fermented. The effluent from the PAF reactor was then conducted to a conventional SBR for enhanced removal of nutrients. Nutrient removal in this system was checked against a system which was only composed of a conventional SBR fed directly on degritted raw wastewater.

4.3 RAW WASTEWATER COLLECTION

Degritted raw wastewater was collected directly from an aerated grit chamber at the South-End Water Pollution Control Center, city of Winnipeg, and delivered by courier to the Environmental Engineering Laboratory on Monday, Wednesday and Friday. Collection was done at around 1:00 PM..

The wastewater buckets were stored in a cool chamber at 4° C to minimize microbial activities and to prevent the change in characteristics of the wastewater. The wastewater then would be transferred daily to a 22 liter magnetically stirred plastic container which was kept in a refrigerator by the reactors, and provided the feed for the reactors. The contents of the buckets were shaken thoroughly prior to emptying them to the feed container.

The SEWPCC receives wastewater mostly from residential areas, also some septic discharges from different sources. Septic discharges are carried by trucks to a station located at the treatment plant and discharged to the sewage inflow line

4.4 REACTORS' START UP

4.4.1 ACID-FERMENTATION REACTORS

Fermentation reactors (PAFs; F1, F2, and F3) were started by filling them up to the volume of 3 liter with a mixture of degritted raw wastewater and primary sludge. Degritted raw wastewater and primary sludge were mixed in such proportions to result in suspended solid concentration of about 3000 mg/L in each reactor. Proportions of each components were determined on the basis of their suspended solids concentrations (Table 4-1). The purpose of adding primary sludge was to seed the reactors with the

fermentation microorganisms. The reactors then were sealed and the operational cycles were initiated as they have been programmed.

Primary sludge was collected from the North End Water Pollution Control Center (city of Winnipeg), and delivered to the laboratory three days before the start up of each reactor and kept at room temperature. Analysis of the volatile fatty acids showed partial fermentation of primary sludge and ensured the activities of the fermentation bacteria. Some characteristics of the primary sludge and degritted raw wastewater used for start up of each reactor is shown in Table 4.1.

Table 4.1 : Data on characteristics of wastewater and primary sludge (start-up of fermenters) .

Fermentation Reactors	W.W. S.S. (mg/L)	Primary Sludge S.S. (mg/L)	Primary Sludge VFA (mg/L)
F1	214	26140	2260
F2	199	19760	1860
F3	184	23300	2525

4.4.2 BNR-REACTORS

The initial contents of the two BNR reactors were prepared by mixing a Bio-P removal sludge with degritted raw wastewater for one reactor , and with the fermented wastewater for the other reactor. Each reactor was filled to the volume of 3 liters with the designated mixture, and the operational cycles were started. The amounts of seed, raw/or fermented wastewater used in the start up of each reactor were calculated on the basis of their suspended solids concentrations in such an order to result the initial suspended solids

of about 1500 mg/L in each reactors. The concentrations of suspended solids in degritted raw wastewater, fermented wastewater and the sludge were measured to be 160, 98, and 11250 mg/L, respectively.

The sludge for seeding biological nutrient removal reactors was supplied by the University of British Columbia Bio-P Pilot Plant. It was delivered to the laboratory three days prior to the start up of the reactors. During this period the sludge was kept at 4 °C in a cool chamber.

To control SRTs of the reactors (acid-fermentation and BNR reactors), the excess sludge in each reactor was wasted once per day through its sampling port. The wastage was done at the end of the react period, before the reactors undergo the settling phase.

4.5 SAMPLING AND ANALYTICAL PROCEDURES

4.5.1 SAMPLING

The samples were obtained from three different sources in order to evaluate the performance of reactors. The sources were :

1) Influent (degritted raw wastewater) : samples were taken directly from the well mixed daily feed container.

2) Reactors : samples were taken from the sampling ports of the reactors.

3) Effluents : samples were taken from the effluent container after the content was well mixed.

Sampling Schedule and the parameters of importance are summarized in Table 4-2. Handling and preservation times before analysis were kept to a practical minimum. Samples for determination of solids, pH, alkalinity, VFA, COD were tested immediately

after the collection times. For oxidized forms of nitrogen (NO_3+NO_2) and ortho-phosphates, the analysis were done within 24 hours of the samplings. Other samples for the analysis of soluble organic carbon (SOC), ammonium, Kjeldahl nitrogen, other forms of phosphorus, and sulfates were preserved; as indicated in the Standard Methods (APHA. et al., 1992). The analyses of the soluble parameters were performed on the filtered samples. All sample filtrations were done using Whatman glass microfibre No. 934-AH filters in the filtration process.

Table 4-2 : Parameters of importance and their sampling schedules.

Parameters	# of Sampling/Week
Solids	3 times
pH & Alkalinity	3 times
VFA	3 times
COD	2 to 3 times in Steps 1 &2, and once during the rest of the research period
SOC	3 times
Ortho-P	3 times
Soluble & Total-P	2 to 3 times in Steps 1 & 2, and once during the rest of the periods
Nitrogen (Different Forms)	2 to 3 times in Steps 1 & 2, and once during the rest of the periods
MLSS, MLVSS	3 times
SVI	Once in Stages 1 through 4
CH_4	Occasional Sampling in Step 1
Microbial Observation	Occasional Sampling

4.5.2 ANALYTICAL PROCEDURES

The majority of the analytical tests were conducted in accordance with Standard Methods (APHA. et al., 1992). When other testing procedures were performed, they are discussed in details in the following sections.

4.5.2.a-Different Forms of Solids (TS, SS, VS)

Analysis for TS, SS, and VS were performed as outlined in methods 2540 B, 2540 D, and 2540 E of Standard Methods (APHA. et al., 1992). Samples for TS and SS were dried to constant weight in a Fisher Isotemp (Model 230F) at 104 °C. Subsequently by igniting the residues at 550 °C in a muffle furnace (CIC instrumentation, model DTP-56PN-E, FK), the volatile solids were measured.

4.5.2.b-pH and Alkalinity

pH of the samples were measured by a Fisher Accumet pH meter, model No. 230. The pH meter was calibrated daily using the standard buffer solutions of pH of 4.0 and 7.0. Total alkalinity was determined by titration of the samples to an end point of 4.5 with 0.02 N sulfuric acid; following the procedure 2320 B in Standard Methods (APHA. et al., 1992).

4.5.2.c-Soluble Organic Carbon (SOC)

Samples for SOC determination were passed through 0.45 μ Whatman 934-AH microfibre filters. The filtrate was acidified with phosphoric acid, purged with pure oxygen for 2 minutes and finally injected to a TOC analyzer (Dohrmann DC 80,

Dohrmann Div., Santa Clara, California).

4.5.2.d-Chemical Oxygen Demand (COD)

The total and filtered samples were analyzed for COD using the Closed Reflux, Colorimetric Method outlined in Standard Methods, section 5220 D (APAH. et al., 1992).

4.5.2.e-Volatile Fatty Acids (VFA)

Samples for VFA were analyzed using a Hewlet Packard HP 5890A GC (Gas Chromatograph) which was equipped with a flame ionization detector (FID) and HP-FFAP (cross linked) capillary column of size 10 m × 0.53 mm × 1.0 μm. The injection, oven and detector temperatures were set at 150 °C, 85 °C and 170 °C respectively. Hydrogen was used as the carrier gas at a flow rate of 13-15 mL/min.

The samples were filtered and 1 μL of the filtrate was injected to the GC. Volatile fatty acids analyzed include : acetic, propionic, iso-butyric, nano-butyric, iso-valeric, and nano-valeric. The system was calibrated in the range of 0-600 mg/L Total-VFA prior to the injection of samples.

4.5.2.f-Nitrogen

Oxidized forms of nitrogen (NO_3+NO_2) were measured in filtered samples using automated Cadmium reduction method following section 4500-NO_3 F in Standard Methods (APHA. et al., 1992). Analysis were done within 24 hours of sample collection.

Samples collected for ammonium and organic nitrogens, were preserved with concentrated sulfuric acids and stored at 4 °C. Ammonia nitrogen was analyzed by the

automated phenate method (section 4500-NH_3 H. in Standard Methods), using a continuous-flow Tecator Autoanalyzer; KJELTEC AUTO, model No. 1030.

The Semi-Micro-Kjeldahl Method, section 4500-N_{org} C (APHA. et al., 1992) was employed in measurements of Kjeldahl nitrogens. Filtered and unfiltered samples were used to determine the soluble or total Kjeldahl nitrogen (TKN), respectively. Samples were first digested in a Tecator Block Digester (model No. 1015) with concentrated H_2SO_4 and K_2SO_4 to convert organically bound nitrogen to ammonium. The samples then were analyzed using Tecator KJELTEC Autoanalyzer.

4.5.2.g-Phosphorus

Analysis for ortho-phosphate was performed in the same day, after collection of the samples. Samples were filtered, and analyzed by the automated version of Stannous Chloride Method (section 4500-P D, Standard Methods) using a Technicon Autoanalyzer II. In this method Molybdophosphoric acid is formed and reduced by stannous chloride to intensely colored molybdenum blue. Standards of known concentrations were analyzed in the same fashion as the samples. Peak heights of the samples were compared to the peak heights of the standards to obtain the concentrations.

Soluble and total phosphorus were determined in filtered and unfiltered samples respectively. Samples were preserved with concentrated HCl and stored at 4 °C prior to the analysis. Soluble and total phosphorus were measured in accordance with the Persulfate Digestion Method outlined in section of 4500-P B of Standard Methods (APAH, et al., 1992). All organically bound phosphorus is liberated and oxidized to ortho-phosphate, which then can be measured by the Stannous Chloride Method.

4.5.2.h-Head-Space Methane Gas (CH_4)

The head-spaces of fermentation reactors (PAFs) were monitored occasionally for the methane content. A Gow-Mac gas chromatograph with series 550 thermal conductivity detector was employed for this purpose. The GC was equipped with Porapak Q Column (80/100) and Helium was used as a carrier gas at a flow rate of 60 mL/min. A 1 mL sample of the head-space gas was injected into the GC. The apparatus was calibrated by standard methane gas at different percentages composition.

4.5.2.i-Sludge Volume Index (SVI)

Sludge volume index was calculated by measuring the settled volume of sludge after 30 minutes in 100 ml graduated cylinder and dividing this volume by the mass of solids.

4.5.2.j-Microbial Examination

Microbial observations were made by preparing microscopic slides of the reactors' MLSS contents. The slides then were examined under 10 and 40 magnification power using a Leitz LABORLUX phase-contrast microscope. The abundance of filamentous organisms was assessed by microscopic observations (M.O.) as per the method proposed by EPA (1987).

4.5.2.k-Statistics

Statistical analysis of the collected data in this research utilized Quattro Pro for Windows (version 5.0) and the statistics book by McClave and Dietrich (1994).

Chapter 5.

RESULTS AND DISCUSSION

5.1 NATURE OF THE WASTEWATER (FEED)

The efficiency of the BNR processes is influenced by the characteristics of the raw wastewater. Thus an understanding of the nature of the wastewater is essential in the design and operation of BNR systems.

The inflow to the South End Water Pollution Control Center is composed mostly of the wastewater from the residential area, though some septic discharges, and the wastewater from some industries are also included. To evaluate the wastewater characteristics, regular analyses were performed on various physical and chemical parameters of the wastewater brought to the lab. A statistical summary of the results, is presented in Table 5.1. The detailed data on wastewater characteristics is given in Appendix A, Table A1.

The range of variation for most parameters were quite large. The variations, however were much higher in some parameters than others. The coefficient of variation; CoV for alkalinity and TVS, and different forms of nitrogen and phosphorus was around 20%; considerably lower than the variations observed for VSS, SOC, and COD. The day to day variations in the wastewater were due to various sources such as: rainfall and infiltration, discharge of septage, equipment failure in the grit chamber and clean up of different units in the treatment plant.

The average ratio of VSS/TVS indicated that about 46% of the organic matter were present in the form of particulate and 54% in the form of dissolved constituents. The

Table 5.1 : Degritted raw wastewater characteristics over the entire research period (Oct. 30, 1993-July 7, 1995).

PARAMETER	RANGE	MEAN	SD*	CoV(%)**
pH	7.0-8.8	7.5	0.3	3.47
Alkalinity as $CaCO_3$	180-460	303	48.2	15.90
TS	350-1348	792	175.2	22.12
TVS	170-592	350	70.6	20.19
SS	58-786	217	89	40.97
VSS	42-473	165	55.9	33.89
SOC	19-164	40	15.3	38.64
COD_{Sol}	58-265	131	42.7	32.58
COD_{Tot}	252-848	427	97.1	22.73
NH_4-N	13.8-39.8	27.1	4.0	14.75
TKN_{Sol}-N	18.8-43.4	32.7	4.3	13.25
PO_4^{-3}-P	1.6-4.9	3.5	0.7	20.73
P_{Sol}	2.4-8.4	4.4	1.0	22.71
P_{Tot}	3.7-12.3	6.5	1.3	20.53

Note : All values in columns RANGE, MEAN and SD are expressed in mg/L, except pH.
* SD = Standard Deviation
** CoV = Coefficient of Variation

total nitrogen in the wastewater was composed of organic nitrogen and NH_3-N. Ammonium on the average constitute about 66% of total nitrogen and 83% of the soluble TKN. Total phosphorus included soluble phosphorus and the phosphorus in the particulate matter. The mean value of soluble phosphorus as the percentage of total phosphorus was 68%, and the amount of ortho-P as a component of soluble phosphorus was 88%.

The suitability of a wastewater for biological nutrient removal treatment is usually determined by one or more of the following indices:

- Ratio of COD/P
- Ratio of COD/N
- Ratio of VFA/P

Randall et al. (1992) reported that a COD/P ratio of greater than 40:1 is required for high removal of phosphorus. A COD/TKN ratio of 10:1 and 8:1 has been suggested by Barnard (1983a) and Malnou et al. (1984), respectively, for biological removal of nitrogen and phosphorus. Presence of VFA is also essential for successful removal of phosphorus. It has been reported that about 6 to 9 mg of VFA is required for removal of one mg of phosphorus (cited in Barnard, 1993).

The data on the ratios of the COD/P, and COD/N in the wastewater used during the course of this study are presented in Figures 5.1, and 5.2. According to the data presented in Figure 5.1, the ratio of total COD/total-P was always greater than the required suggested value of 40:1. The average value of this ratio was about 67:1. The ratio of total COD/total-N (Figure 5.2) was also greater than 10:1 most of the times with the average of about 10:1. Judging on the basis of the total COD data, the wastewater

had more than sufficient amount of carbon for a successful biological removal of nitrogen and phosphorus. In reality, however, the microorganisms involved in the processes absorb only the available soluble fraction of the total COD. Therefore the total COD data could be misleading, unless sufficient time is provided in the treatment process for the solubilization of particulate organic matter, and production of adequate quantity of available carbon compounds.

A more realistic conclusion could be made on the basis of the data obtained for the soluble components of the wastewater. The ratios of COD_{Sol}/P_{Sol} and COD_{Sol}/TKN_{Sol} have been also presented in Figure 5.1 and Figure 5.2 respectively. These ratios were almost always less than the required limits of successful BNR process (40 for the COD/P, and 10 for the COD/N). The filtered COD/P_{Sol} averaged 30.5, and the mean ratio of filtered COD/soluble-N was 4. Moreover, the mean values of the VFA (5 mg/L), and P_{Sol} (4.4 mg/L) indicated that the VFA/P_{Sol} of the wastewater is not adequate for the excess removal of phosphorus.

5.2 BIOLOGICAL ACCLIMATION OF THE REACTORS

The existing populations in a biological treatment reactor undergo acclimation with the changes in the operational and/or environmental conditions. The acclimation period is not constant and is influenced by many parameters such as: type and characteristics of feed, environmental and operational conditions, type of the seed, and the type and configuration of the treatment system. After the acclimation period, the community reaches a steady-state in which the abundance of the species and their ranges of activities are in relative equilibrium with the existing resources, and the environmental conditions.

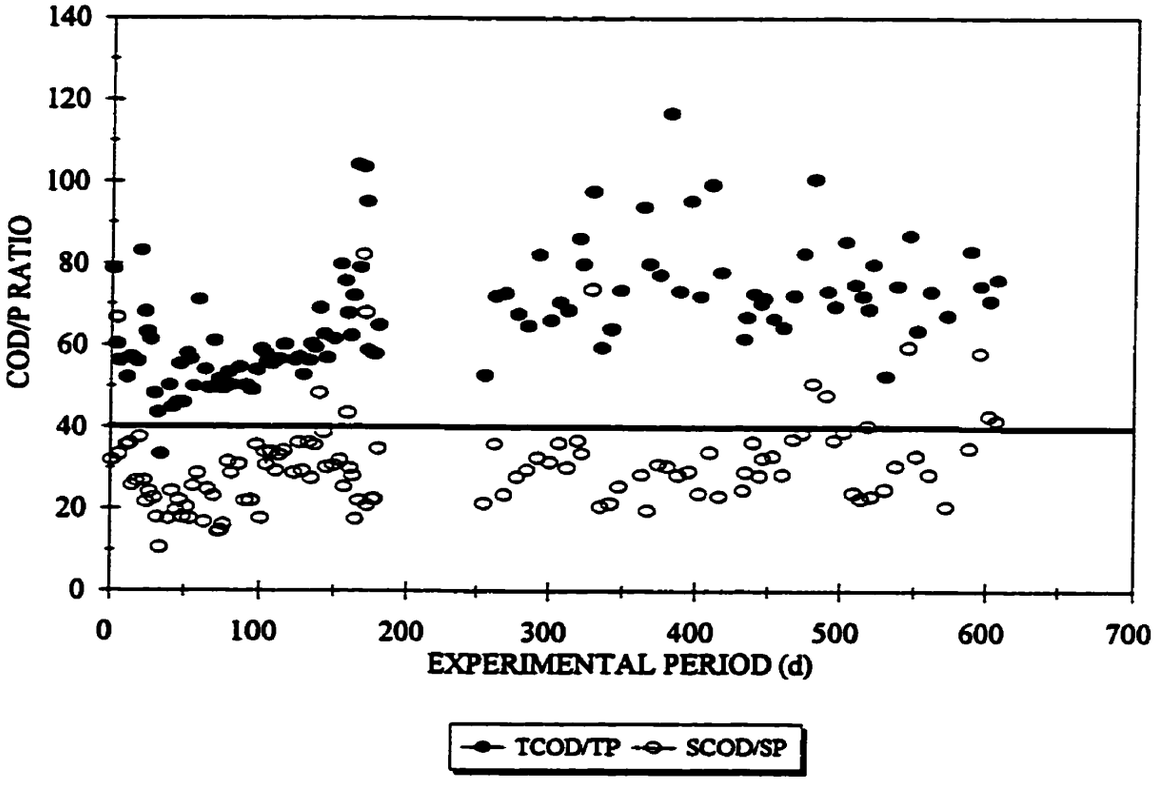

Fig. 5.1 : Variation in the COD/P ratio of the degritted raw wastewater during the total research period.

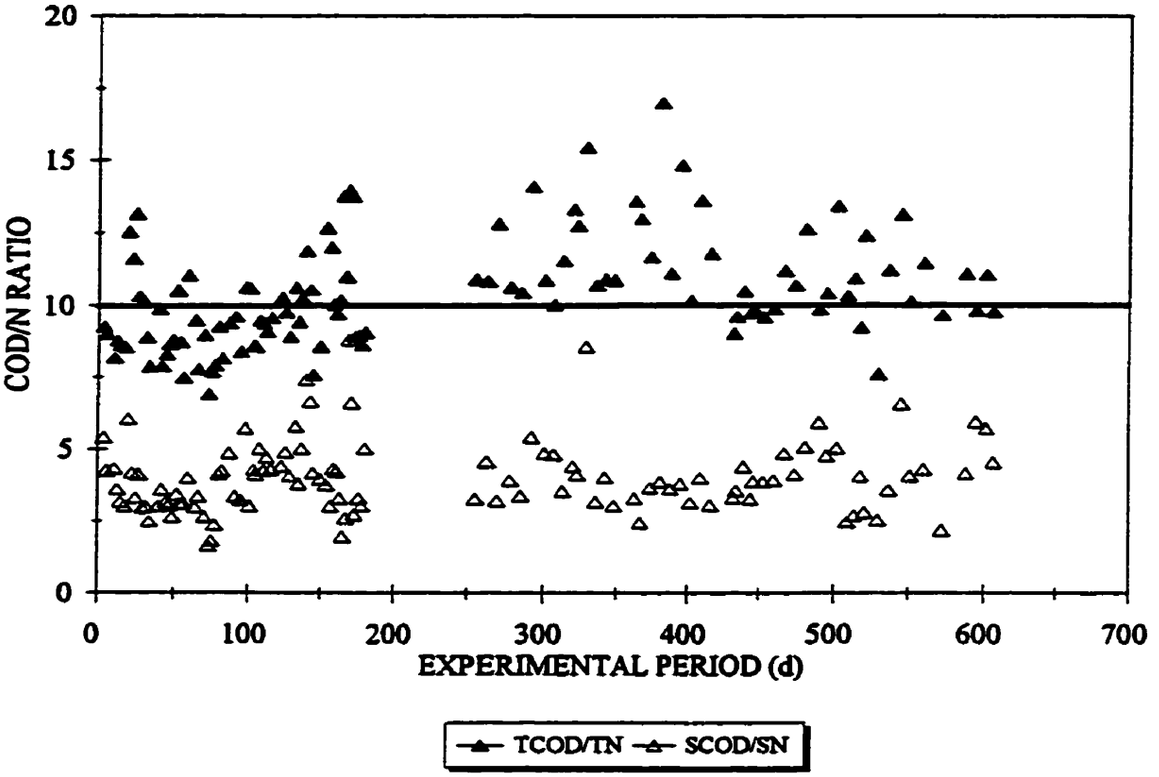

Fig. 5.2 : Variation in COD/N ratio of the degritted raw wastewater during the total research period.

The performance of biological treatment units at steady-state conditions dependents upon the fluctuations of feed quality. It was mentioned in section of 5.1.1. that the variations in characteristics of the wastewater used in this research were considerably large. Due to the highly variable nature of the raw wastewater, some fluctuations in the performance of reactors were observed, even after an acclimation period of 3 to 4 SRT. Consequently, achievement of steady-state conditions in each stage of the research was assumed when coefficient of variation of the performance parameters showed values less than 20%. During fermentation studies, the changes in alkalinity, VFA and SOC production were used to indicate steady-state conditions, while in BNR reactors, the changes in effluent nitrogen and phosphorus concentrations were considered for this purpose.

In the fermentation reactors the initial acclimation took place within the period of 3 to 4 SRT, regardless of the length of the SRT. The initial acclimation periods and the achievement of steady-state conditions for the fermentation reactors are shown in Figure 5.3. The BNR reactors required about three SRT (30 days) to reach steady-state conditions. After establishing a steady-state condition, any further change in the operational or environmental conditions led to the dynamic changes within each reactor. The required length of time for readjustment was however much less than the initial acclimation period. The readjustment periods were usually in the order of two SRT or less; especially when the change was related to the HRT of the systems.

Statistical analysis and performance evaluation were performed on the data collected during the steady-state conditions, when the standard deviations of the observations were within 20% of the mean for most of the parameters.

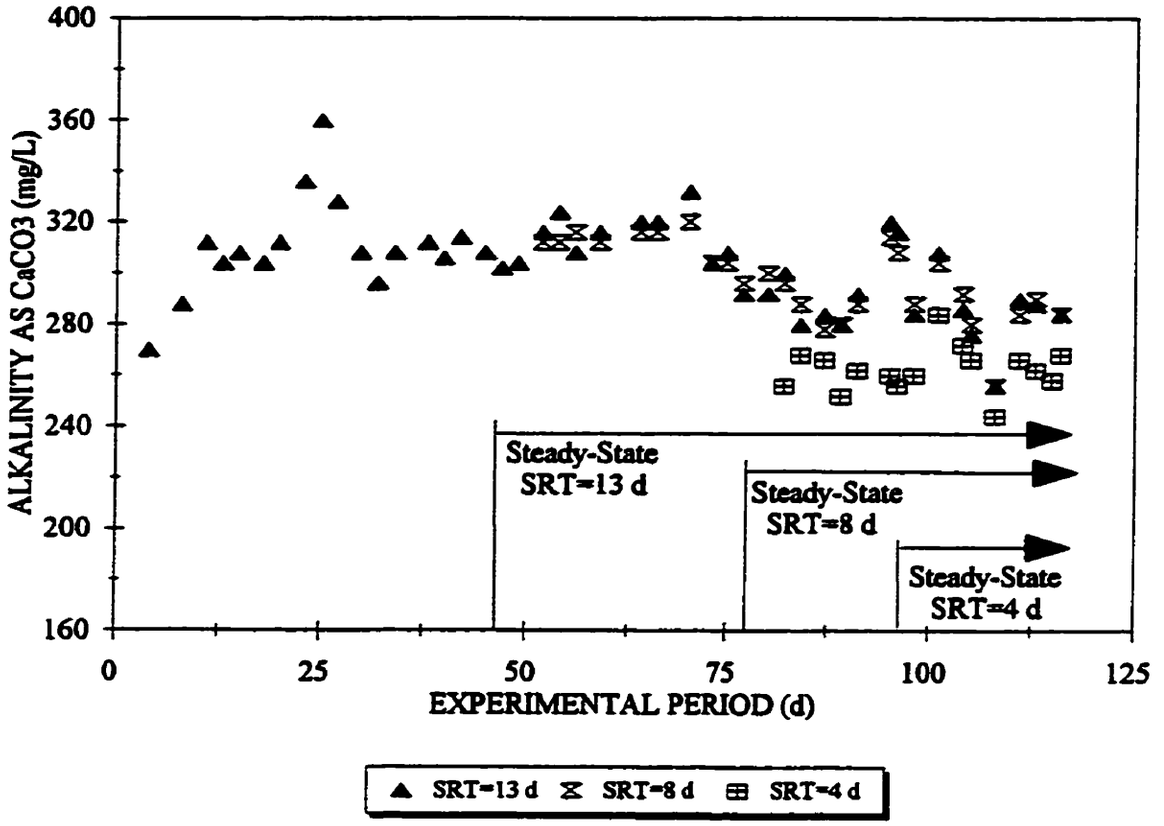

Fig. 5.3 : Achievement of steady-state conditions in the fermentation reactors. Steady-state condition was reached within the period of 3 to 4 sludge retention time. Evaluation of the performance of reactors were made on the basis of the sets of data collected during steady-state conditions.

5.3 FERMENTATION STUDIES

5.3.1 STEP 1 : EFFECTS OF SRT (pH OF FEED = 7.0-7.6)

In wastewater treatment systems "biological treatment" is accomplished by a community not uniform in nature. The heterogeneity is associated with the species diversity and the relative abundance of populations. Some species are present in larger numbers and their activities are so pronounced that the outcome of the community as a "whole" is the reflection of their activities. These populations are referred to as the dominant species. Dominance is not specific to certain populations and varies with many parameters such as temperature, pH, available resources, etc. As one or more of these parameters changes, the distribution of dominant species shifts towards the populations which can use the resources with the highest efficiency. The goal in biological treatment systems is to control the environmental conditions such that the dominancy is distributed among those species which can accomplish the desired type, and degree of treatment.

In the acid fermentation processes the objectives are to maximize the solubilization of particulate organic matter, and to convert the soluble complex organic compounds to simple compounds mostly short chain fatty acids. By this means the availability of carbon for the following biological nutrient removal units is increased. One of the operational parameters which can be used to control the activity of acidogenic bacteria, is the sludge retention time of the system. Sludge retention time is defined as the average amount of time that microorganisms are retained in the reactor, and is controlled by the quantity of the sludge wasted per day. This parameter affects the type of the species which can be present in the system. It also determines the extent of their activities due to its association

with the growth phases. Therefore in the process of acid fermentation it is desirable to achieve a SRT that encourages proliferation of the acidogenic bacteria and suppress the growth of methanogenic bacteria. It is also important that the SRT provide the system with maximum stability and least sludge.

In the studies reported in the literature, different optimum SRTs have been suggested for the acid fermentation of primary sludge (Diagger, 1993; Elefsiniotis and Oldham, 1994a). However with regard to acid fermentation of whole raw wastewater no report was found on the subject of SRT.

In step 1 of this research (Oct. 30, 1993 to Feb. 23, 1994), the effects of three sludge retention times; 4, 8 and 13 days, on the fermentation of degritted raw wastewater was investigated using three parallel PAF reactors (F3, F2. and F1 respectively). The hydraulic retention time of all reactors were 12 h at this step. The raw data for this step are shown in Appendix A, Tables A1 to A4. Data used for statistical analysis and performance evaluation of reactors at steady-state conditions cover those days in the period of Feb. 4, 1994 to Feb. 22, 1994 which have complete analysis for all the parameters.

5.3.1.a-Solubilization of Particulate Organic Compounds

One of the major steps in fermentation of particulate organics is the solubilization process. The process is carried out by extracellular enzymes produced by some of the microorganisms present in the environment. The organic solids are hydrolyzed, and are converted to soluble compounds which act as substrate for the acidogenic bacteria.

About 47% of the total volatile solids of the feed (degritted raw wastewater) in

this step of the study were in the form of particulates. Solubilization of this portion of the volatile solids could contribute significantly to the production of short chain volatile acids.

The efficiency of the solubilization process is estimated using data on different parameters such as : TVS, COD, SOC, TOC. In this section the data on COD were used for discussion on the degree of solubilization of particulate substrate in the fermenters. Total and soluble COD were measured regularly and the data are given in Appendix A.

The concentrations of soluble COD in the feed, and in the effluent of the reactors are shown in Figure 5.4. The increase in soluble COD of the reactors as compared to the concentration in the feed, indicates that solubilization of particulate matter occurred within all three reactors during the experimental period.

Figure 5.5 shows the average concentrations of soluble COD in the effluent from the fermenters at steady-state conditions. Furthermore, Table 5.2 includes other data necessary for the evaluation of solubilization process under different SRTs. Comparisons between the average concentrations of COD at different SRT were made using the Least Significant Difference (LSD) Method (McClave and Dietrich, 1994). Reactors with 13 days and 8 days SRT performed similarly with respect to total solubilization as expressed in mg/L of effluent COD_{Sol}. (Fig. 5.5). A difference of 1.5% observed in the COD concentration, or 5% in solubilization yield (Table 5.2) can be contributed to the experimental errors. The results clearly show that 8 days SRT provided adequate time for the volatile solids in the reactor to be converted to soluble substrate by the biomass. Increase of SRT from 8 days to 13 days did not improve solubilization of organic particulates significantly.

The difference between the concentration of COD in the effluent of the reactor

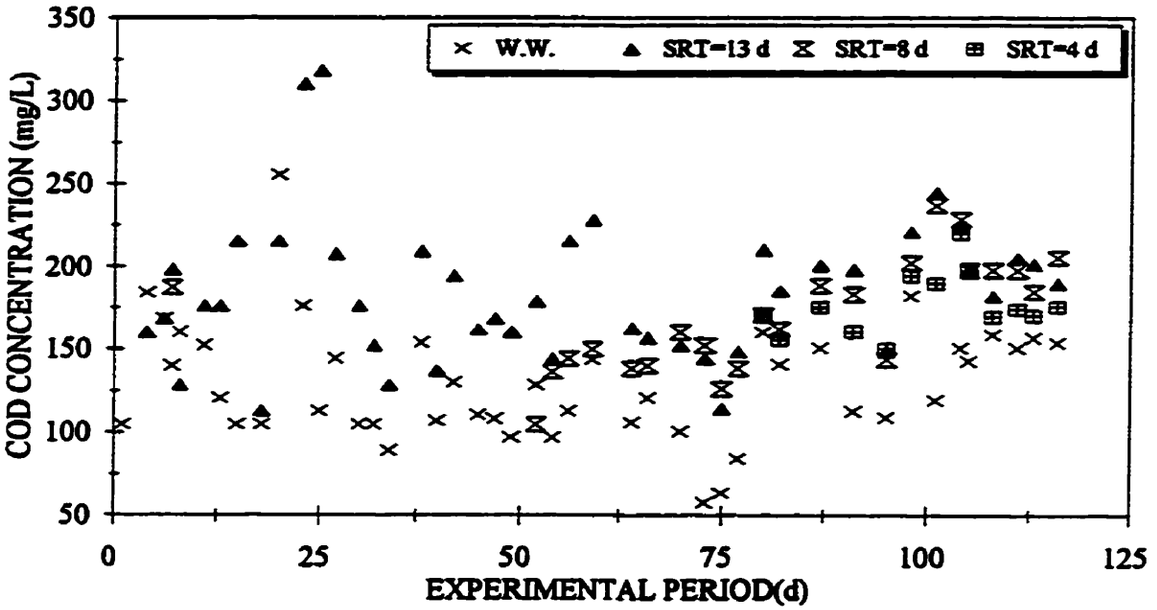

Fig. 5.4 : Profile of soluble COD in the feed and effluent from the fermenters at different SRTs (pH of feed=7.0-7.6).

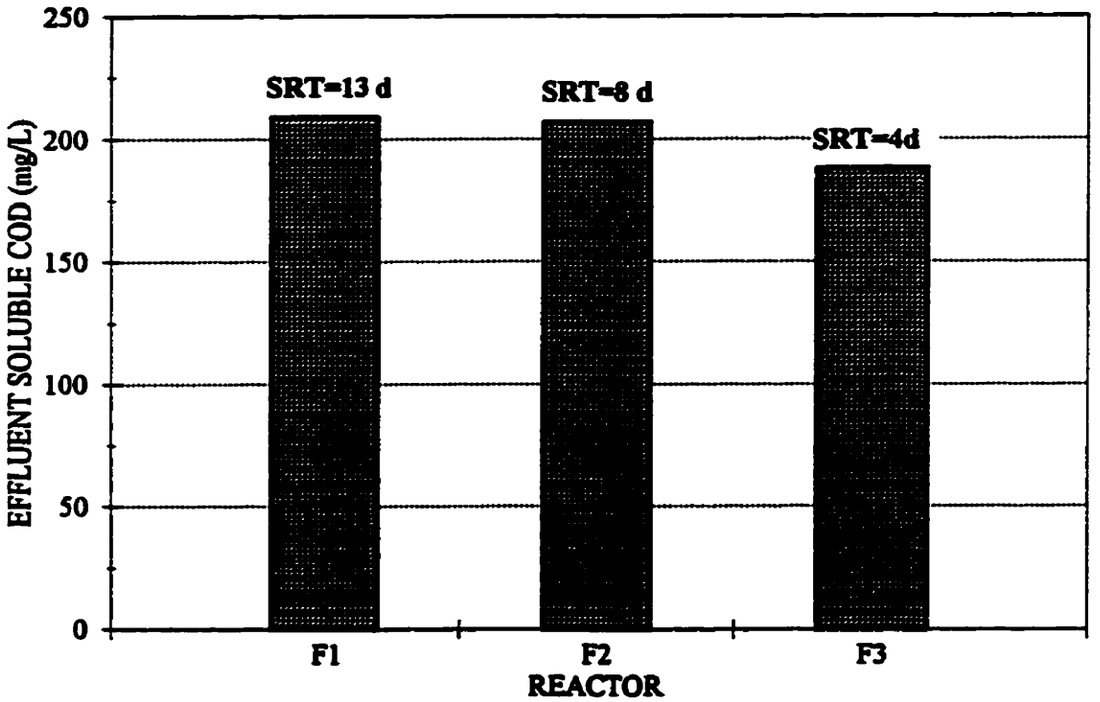

Fig. 5.5 : Mean concentration of soluble COD in the effluent from the fermenters at steady-state condition (pH of feed=7.0-7.6). The highest net COD solubilization was associated with the longest SRT.

with 4 days SRT, and the concentrations of COD in the effluent of other reactors were however significant ($P<0.1$). Solubilization efficiency and yield decreased by 12 and 38% respectively as SRT decreased from 8 days to 4 days. In other words, with 4 days SRT, the microorganisms and the particulate substrate did not remain long enough in the reactor to reach the best efficiency of soluble substrate production.

The results obtained are similar to those reported by Elefsiniotis (1993) in the study of the effects of SRT (range of 5 to 20 days) on fermentation of primary sludge. He observed a sharp drop in solubilization efficiency as the SRT reached 5 days, and a plateau was achieved at longer SRTs of 10 and 15 days.

Table 5.2 : Solubilization performance of fermenters at different SRTs (pH_{Feed}=7.0-7.6).

Reactor	SRT (d)	HRT (h)	Efflu. COD_{Sol} (mg/L)	Solubilization Efficiency %*	Solubilization Yield**
F1	13	12	209	38	0.21
F2	8	12	206	36	0.20
F3	4	12	188	24	0.13

* Solubilization Efficiency : Net Soluble COD as % of Feed COD_{Sol}

** Solubilization Yield : mg Solubilized COD/mg Feed Particulate COD

where : Solubilized COD = Effluent COD_{Sol} - Feed COD_{Sol}

Particulate COD in Feed = Feed COD_{Tot} - Feed COD_{Sol}

Variation in SRT had a profound effect on the specific solubilization rate of COD expressed as mg of net soluble COD per gram of VSS per hour. The net soluble COD concentration and the specific solubilization rate are depicted in Figure 5.6 as a function of SRT. The net soluble COD decreased with the reduction in SRT, as was explained earlier, while the specific rate of solubilization showed a trend of increase. The biomass in reactor

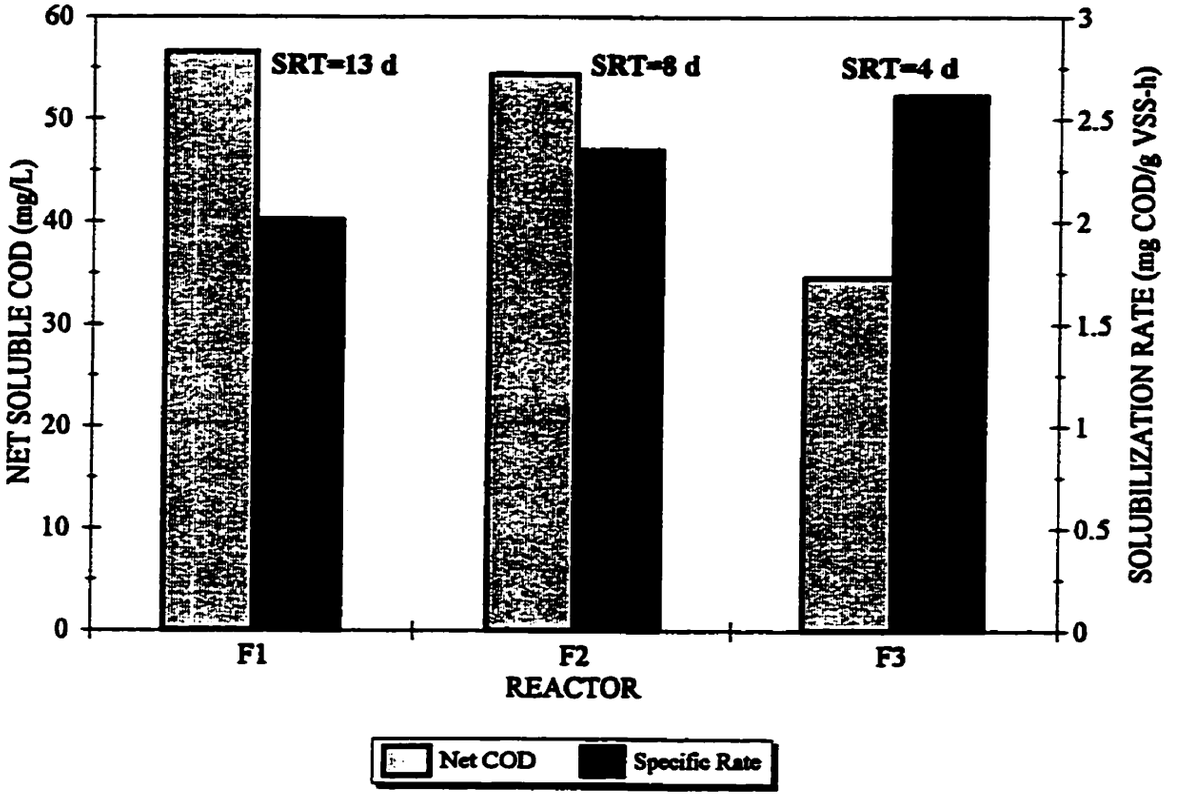

Fig. 5.6 : Total COD solubilization and the specific rate of solubilization as a function of SRT (pH of feed=7.0-7.6). Total solubilization was directly proportional to SRT; increasing as SRT was increased. The specific solubilization rate on the other hand was inversely proportional to SRT; decreasing as SRT was increased.

F3 with SRT of 4 days had the highest specific solubilization rate (2.6 mg COD/g VSS.h), though the production of total net soluble COD was the least in this reactor. The specific rate in this reactor was 23% higher than the rate in the reactor with 13 days SRT, and 12% higher than the rate under 8 days SRT; indicating a significant difference ($P<0.1$) between the reactors in this regard.

The difference observed in the impacts of SRT on net solubilization, and on specific rate of solubilization could be related to the amount of biomass present in the system at each SRT and their degree of activity. At longer SRT, more biomass is present in the system, however the microorganisms are usually in a less active stage of their growth. As a result the biomass produces less soluble material per unit of biomass, but the total solubilization would be higher due to the larger existed biomass in the system.

5.3.1.b-VFA Production

The soluble organic compounds initially present in the wastewater and those generated in the process of solubilization are used by acidogenic bacteria. The result of acid fermentation reactions is the production of a wide variety of compounds; mainly short chain volatile fatty acids (C_2-C_5).

The profiles of total VFA production in the reactors accompanied with the concentration of VFA in the feed are shown in the Figure 5.7. The increase in the concentrations of VFA in the reactors indicated that the conditions necessary for the growth and proliferation of acidogenic bacteria were provided in all three reactors operating with different SRT.

The net VFA production (as acetic acid) at steady-state conditions as a function of

SRT is presented in Figure of 5.8. Variation in SRT had a significant impact on the acid fermentation process. Production of VFA increased with SRT to a maximum value of 47 mg/L at 13 days SRT. The difference observed in acid productions of the reactor with 4 days SRT, and the reactors with higher SRT were significant ($P<0.1$); indicating the importance of operation in SRTs longer than 4 days. A longer SRT allows for the growth of microorganisms with slower growth rate, and provides more time for the solids to remain in the system to undergo solubilization and fermentation process.

The 4 mg/L difference observed between the mean VFA production in the units with 8 days SRT and 13 days SRT, though was not statistically significant, but its impact on the efficiency of Bio-P removal process could be significant. Biological phosphorus removal requires about 6-9 mg of VFA for removal of 1 mg of phosphorus (cited in Barnard, 1993). Thus 4 mg/L of VFA could support removal of 0.5 mg/L of phosphorus which is noteworthy.

Table 5.3 includes data on the behavior of the acid fermentation process with regard to the SRT. Total VFA production and the specific rate of VFA production are also shown graphically in Figure 5.9.

The VFA production yield reduced with the decrease in SRT resulting in minimum VFA production under the operational condition of 4 days SRT. Gon Calves et al. (1994) reported a maximum VFA yield of 0.17 mgVFA/mg Feed COD_{Tot} in the upflow sludge blanket (USB) type reactors operating under different HRT.

In contrast to the VFA yield, the specific VFA production rate increased with reduction of SRT (Figure 5.9). The highest production rate was associated with 4 days and the lowest rate occurred at 13 days SRT. As mentioned in the previous section, the

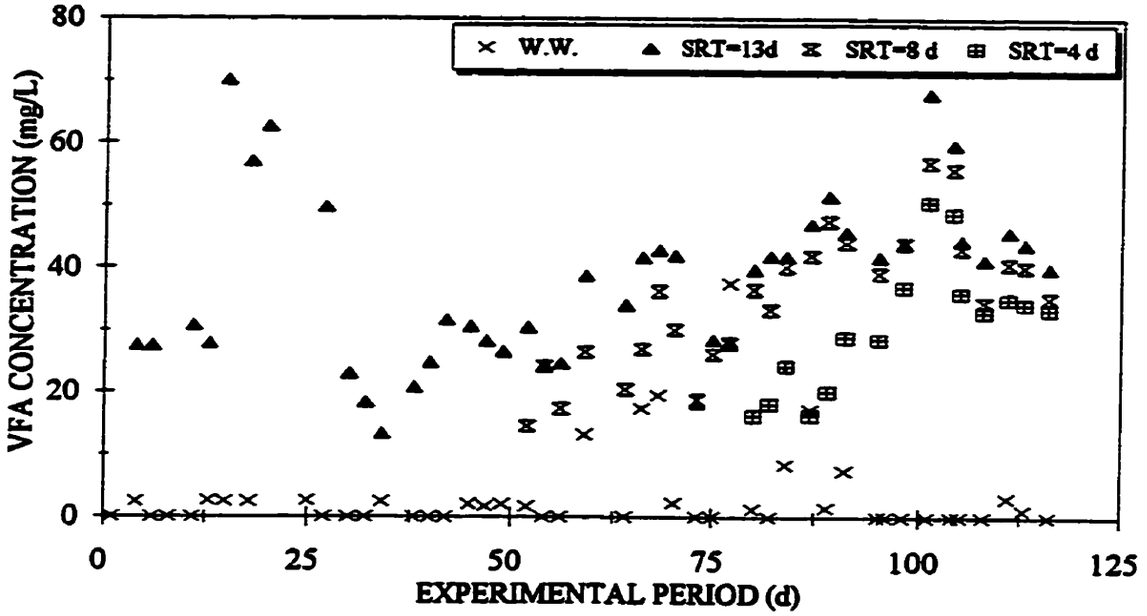

Fig. 5.7 : Profile of VFA concentration in the effluent from the fermenters as compared to the VFA concentration in the feed (Impact of SRT).

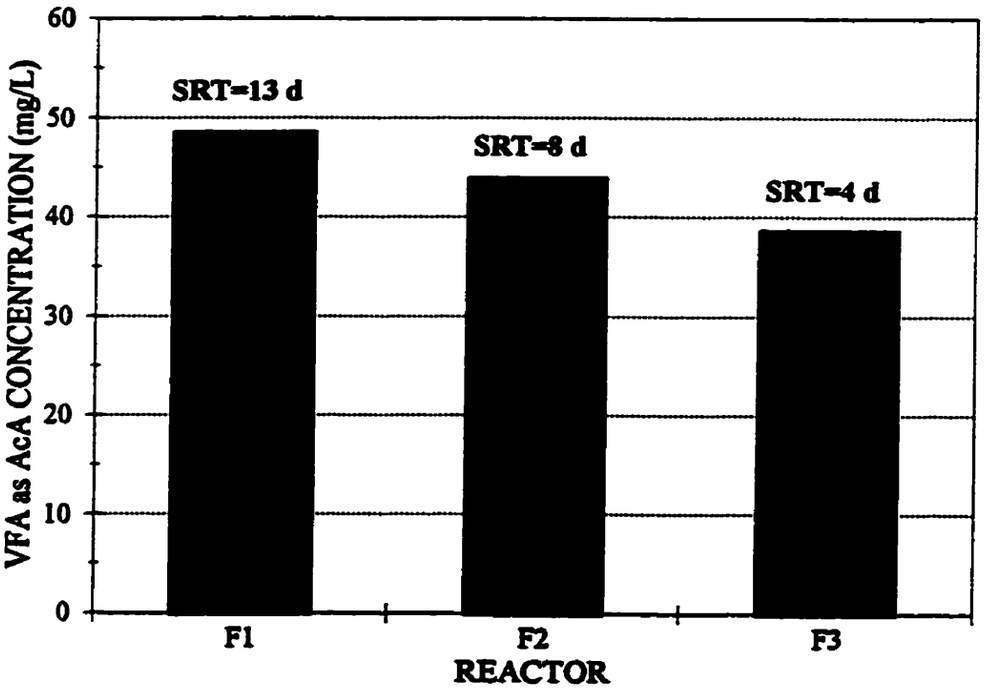

Fig. 5.8 : VFA production (as HAc) at different SRTs (pH of feed=7.0-7.6). Reduction in SRT caused a decrease in the production of volatile fatty acids.

Table 5.3 : Acid fermentation performance at different SRTs (pH_{Feed}=7.0-7.6).

Reactor	SRT (d)	HRT (h)	VFA (mg/L)	Acetic Acid (mg/L)	VFA Yield*	Production Rate **
F1	13	12	48	44	0.12	1.70
F2	8	12	44	41	0.11	1.90
F3	4	12	38	37	0.10	2.90

* VFA Yield : mg VFA/mg Feed COD_{Tot}
** Production Rate : mg VFA/gVSS.h

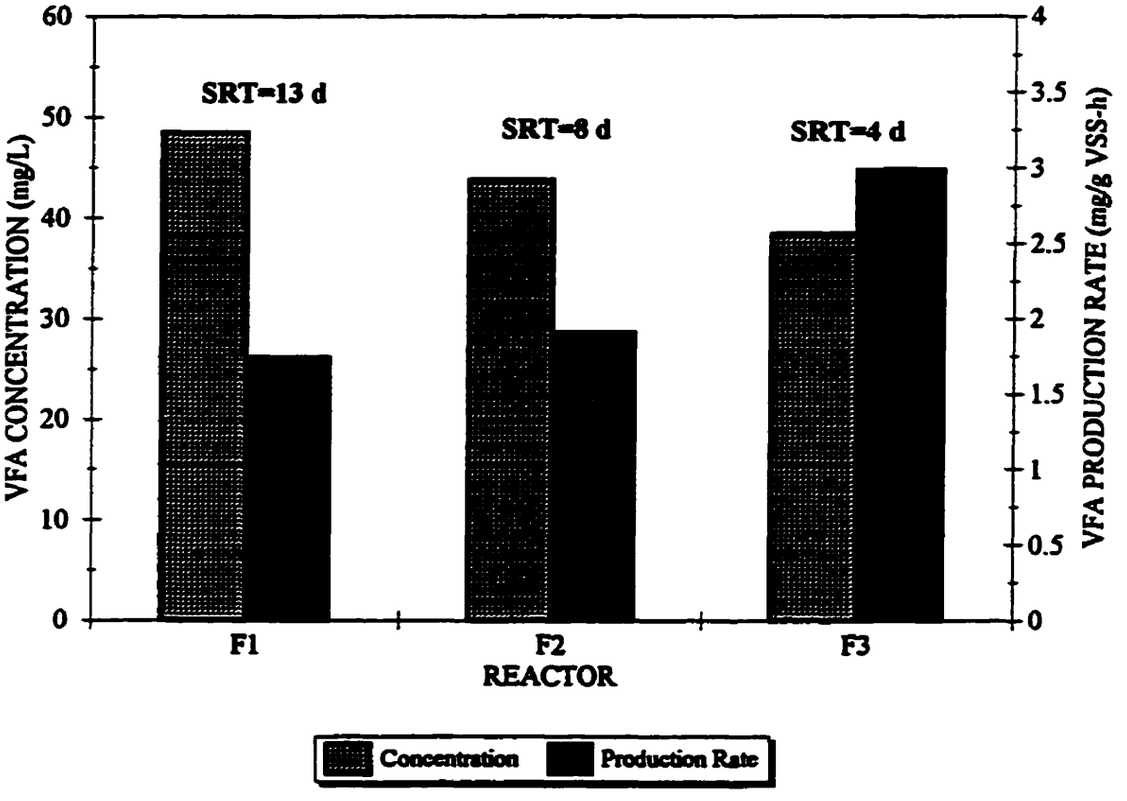

Fig. 5.9 : VFA concentration and the specific rate of VFA production at different SRTs (pH of feed=7.0-7.6). Specific rate was reduced at higher SRTs. In contrast maximum production of VFA occurred under the condition of highest SRT of 13 days.

microorganisms at 4 days SRT are probably in a more active state of growth, thus showing more activity per unit of biomass. The results obtained on the effect of SRT on the VFA specific production rate do not agree with the findings associated with the fermentation of primary sludge. Elefsiniotis (1993) in his research on the fermentation of primary sludge observed an increase in specific VFA production rate as SRT changed from 5 days to 10 and 15 days.

The input of solubilization on VFA production was estimated by calculating the carbon equivalent of VFA in each reactor (based on the chemical formula of component acids) and comparing the calculated value with the net SOC solubilization. It was found that about 55% of VFA in the reactor with 4 days SRT (F3) originated from soluble portion of the feed and 45% from the particulate matter. In reactors with 8 and 13 days SRT, however, solubilization contributed to 65% of VFA production and the remaining 35% came from the soluble compounds originally present in the wastewater. This results show that as SRT increases, the role of solubilization of particulate organic matter in the production of VFA becomes more pronounced.

In general based upon the results obtained on the effect of SRT on the solubilization and fermentation processes (Figure 5.10), it can be concluded that SRT affected both process similarly. An increase in SRT from 4 days to 8 days improved solubilization and acidogenesis significantly. Further extension of SRT from 8 days to 13 days, however did not affect solubilization but enhanced VFA production to some extend.

5.3.1.c-VFA Composition

A knowledge of distribution of different short chain volatile fatty acids formed

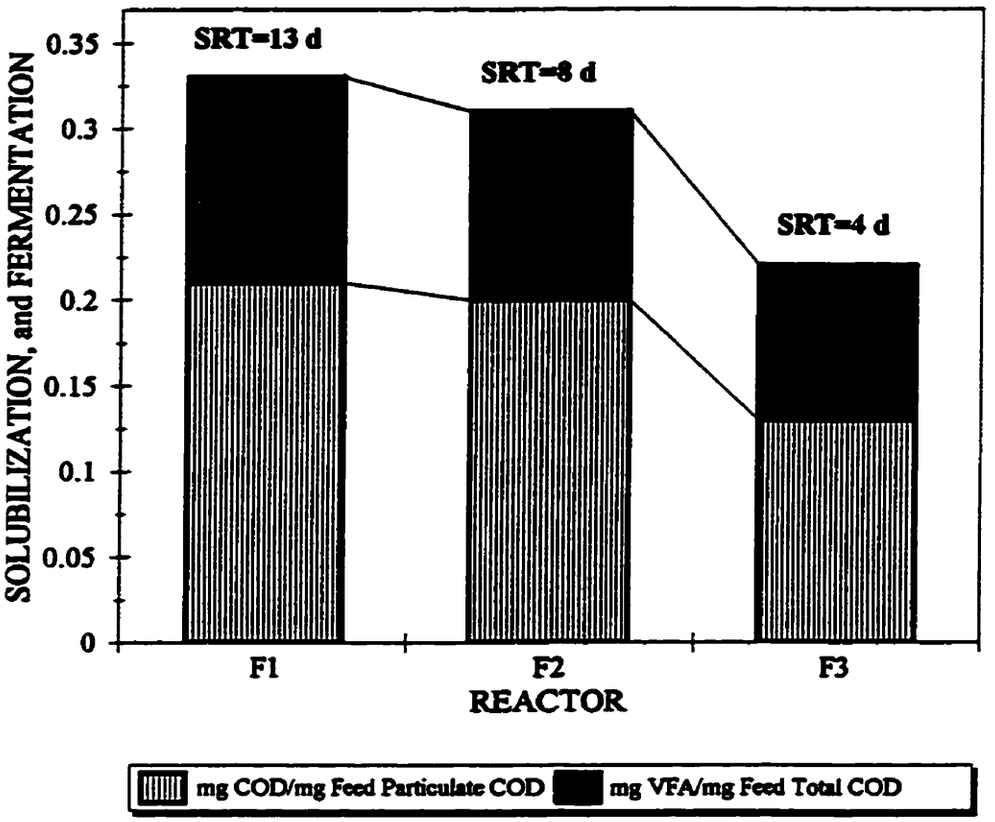

Fig. 5.10 : Solubilization, and acid fermentation at different SRTs (pH of feed=7.0-7.6). Both processes followed the same trend of change; increasing as the SRT increased from 4 days to 13 days.

during the acid fermentation of degritted raw wastewater could provide some information on the quality of the fermented effluent for use in BNR processes.

Acetic acid has been known as the best substrate for the activity of the Bio-P bacteria (Fuhs and Chen, 1975; Comeau et al., 1986; Appeldoorn et al., 1992). In a study on the effects of different types of VFA on the efficiency of Bio-P removal, Abu-ghararah and Randall (1991) pointed out that acetic acid caused the greatest release and the greatest uptake of phosphorus.

The type of carbon source not only affects biological phosphorus removal but it also affects biological nitrogen removal. Henze et al. (1994) dmonstrated the importance of type and concentration of carbon source in nitrogen removal. Directly metabolizable compounds such as acetic acid gave the best results in their experiments.

The VFA components identified in this study include : acetic, propionic, iso-butyric, nano-butyric, iso-valeric and nano-valeric. The distribution of these acids as was affected by different SRT is shown in Figure 5.11. It is observed that acetic acid was by far the most produced component of VFA in all the reactors. The percentage of acetic acid in total VFA was 93% in SRT of 13 days, 94.5% in SRT of 8 days and 96.5% in the SRT of 4 days. The second important component of VFA was iso-valeric acid with the percentage of 4.5 under longest SRT (13 days), and 3.5% in lower SRTs. The remaining percentages of VFA in the reactors were composed mainly of propionic acid (about 2% of total in SRT of 13 days, and 1% in the SRT of 8 days). The average values show a relative reduction in acetic acid with a shift towards production of higher molecular weight fatty acids as SRT increased. Since the production of higher molecular weight volatile fatty acids (butyric and valeric) is mostly the result of anaerobic metabolism of proteins

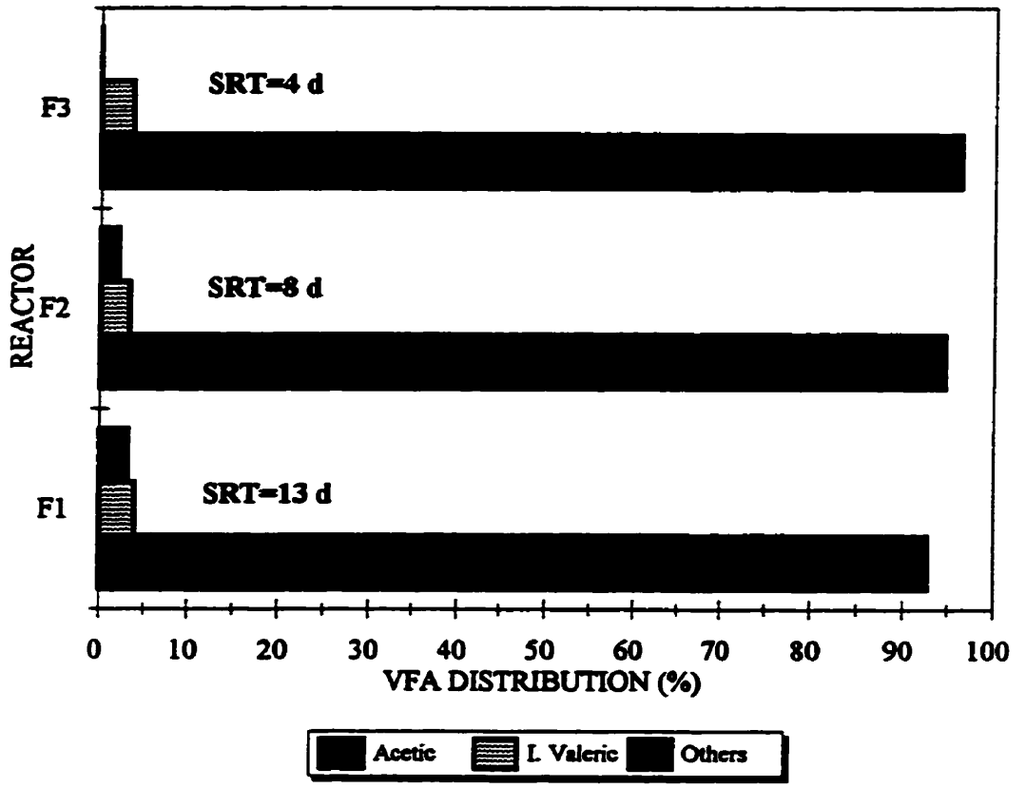

Fig. 5.11 : Effects of SRT on percent distribution of VFA (pH of feed=7.0-7.6). Acetic acid was the most significant component of VFA under the conditions investigated. Its contribution to total VFA production was more than 90% regardless of the SRT.

(Gottschalk, 1986; Elefsiniotis, 1993), the increase in protein dissimilation is most likely the reason for increase in iso-valeric acid at 13 days SRT.

One of the most significant findings of this research is associated with the distribution of VFA produced in acid fermentation of raw wastewater as compared to the values reported in the literature for acid fermentation of primary sludge. A value of 55% was reported for acetic acid production in the acid fermentation stage of sludge digestion process (Randall, 1994). Oldham and Elefsiniotis (1993) obtained 45% acetic acid, and Wentzel et al. (1988) mentioned fraction of 43% acetic acid in acid fermentation of primary sludge. While the percentages of acetic acid reported for acid fermentation of primary sludge vary within the range of 43 to 55%, the obtained percentage of acetic acid in this experiment (using degritted raw wastewater) was higher than 90% regardless of the length of the SRT. The higher production of acetic acid relative to other acids in the case of wastewater is probably due to the availability of soluble portion of wastewater as substrate for the microorganisms. Conversion of the soluble carbohydrates to acetic acid could be the major reason for the increase observed in production of this compound.

5.3.1.d-Quality of the Fermented Wastewater - Effects of SRT

Some of the characteristics of wastewater, as mentioned in section of 5.1.1, are of particular interest in biological nutrient removal due to their direct impact on the performance efficiency of treatment systems. Any improvement in such parameters could cause a higher degree of microbial activity and result in higher nutrient removal efficiency.

Table 5.4 summarizes some of the characteristics of the raw, and fermented wastewater. The pH values of the reactors were very stable after reaching steady-state

conditions, such that the coefficient of variation was in the range of 1.2 to 2.5%. The stability of the pH could be attributed to the buffering capacity which is defined as the degree of resistance to pH changes. High alkalinity content of the raw wastewater, and dissociation of proteins as it is indicated by an increase in the ammonium content of fermented wastewater are the major sources of the buffering capacity of the reactors. In an acid-phase digestion, the net buffering capacity is the result of many inorganic and organic buffer systems such as carbonate/bicarbonate, phosphate, burate, silicate, citrate, and proteins that could be active in the pH range of interest (Elefsiniotis, 1993). The above components were not measured during the course of this experiment, therefore their contribution to the buffering capacity can not be specified.

In general, as it is noticed in Table 5.4, all the parameters of significance in enhancement of biological nutrient removal were improved by the fermentation process. The soluble organic compounds, and the availability of carbon in the wastewater increased as the result of the solubilization, and fermentation reactions. The observed increase in the ratios of COD/P, COD/N, SOC/N, and VFA/P are all evidence of the improvements made in wastewater quality for the purpose of nutrient removal. Comparisons between the means of each of the above parameters under different SRT were made using the LSD method. The mean ratios of COD_{Sol}/P_{Sol} and COD_{Sol}/N_{Sol} changed significantly ($P<0.1$) with the increase in SRT from 4 days to 8 days, but the difference between the mean values at 8 days and 13 days were not meaningful. The most profound effect of fermentation was related to the increase in the VFA content of wastewater. Fermentation in general increased the ratio of VFA/P_{Sol}., but the mean values were significantly different at different SRTs. The highest value of this ratio was obtained at SRT of 13 days.

Table 5.4 : Characteristics of raw and fermented wastewater (Impacts of SRT on acid fermentation of degritted raw wastewater; pH=7.0-7.6).

Parameter	W.W. Mean±SD	F1 (SRT=13 d) Mean±SD	F2 (SRT=8 d) Mean±SD	F3 (SRT=4 d) Mean±SD
pH	7.1±0.1	6.9±0.1	6.8±0.1	6.8±0.2
Alkalinity as $CaCO_3$	251±9.7	284±13.6	285±12.8	265±10.5
VFA as HAc	<1	47±8.3	43±7.3	38±6.4
HAc as %VFA	100	93±5.2	94.5±4.9	96±1.42
VFA/P_{Sol}	0.1 [a*]	8±1.0 [b]	7±1 [c]	6.5±0.8 [d]
COD_{Sol}/P_{Sol}	31±5.4 [a]	35±2.7 [b]	34±2.7 [b]	32±3.7 [c]
COD_{Sol}/N_{Sol}	4.4±0.7 [a]	5.6±0.4 [b]	5.6±0.4 [b]	5.1±0.5 [c]
SOC/N_{Sol}	1.2±0.1	1.5±0.1	1.5±0.1	1.3±0.1
NH_3-N	28±2.3	32±3.3	32±3	32±2.8

Note : Values of alkalinity, VFA and NH_3-N are reported in mg/L.
* : Non-similar letters in the superscript indicate a significant difference between the means ($P<0.1$).

5.3.1.e-Conclusion

Sludge retention time had significant impacts on the acid fermentation of raw wastewater. Solubilization of organic particles, as well as production of volatile fatty acids enhanced as SRT increased from 4 d to 8 d and further to 13 d. The best results from the view point of total solubilization and VFA production obtained at SRT of 13 days, although the differences between the mean values at 8 days and 13 days SRTs were not statistically significant. Acetic acid was the most abundant component of total VFA. More than 90% of total VFA under the investigated SRTs was composed of acetic acid.

5.3.2 STEP 2 : pH REDUCTION (pH OF FEED = 6.1-6.4)

pH is one of the most important parameters involved in regulating the equilibrium in a heterogeneous microbial community. The growth rate of each species is affected directly or indirectly by the pH of the environment. It has been found that many aspects of microbial metabolism such as utilization of carbon and energy sources, efficiency of substrate dissimilation, synthesis of storage material, and the release of metabolic products could be influenced by variation in the pH (Elefsiniotis, 1993). In general each group of microorganisms has its own tolerance and optimum limits with respect to the pH of the environment (Gaudy and Gaudy, 1980). Thus any changes that occur in the pH of the habitat can act as a selective pressure in favor of certain populations living in the community, and lead to a shift in the relative abundance of populations with a change in the net outcome of the community.

Many treatment plants (such as those in Vancouver, BC) may receive wastewater with a pH lower than neutral. The response of this type of wastewater to the process of acid fermentation may be totally different from what was observed in acid fermentation of a wastewater that had its natural pH in the range of 7.0-7.6 (step 1).

Step 2 of this research was performed to investigate the feasibility of acid fermentation of wastewater with a pH lower than neutral. The effects of three SRT; 4 days, 8 days, and 13 days were studied in this regard. Reactors F1, F2, and F3 from step 1, continued under the same operational conditions during this step. However the pH of the feed (degritted wastewater) to the reactors was lowered to the range of 6.1-6.4 by using a solution of hydrochloric acid (HCl). The pH was maintained at 6.1-6.4 for the duration of this step.

The data collected during this period of the research (Feb. 24, 1994 to Apr. 27, 1994) are presented in detail in Appendix A, Table A1 through Table A4. Statistical analysis and performance evaluation of the reactors were done on the basis of the data during steady-state conditions (Apr. 8 - Apr. 27).

5.3.2.a-Organic Carbon Solubilization

The trends of change in soluble COD of the effluent from the three reactors fed with the low pH wastewater are depicted in Figure 5.12. The soluble COD in the effluents of the reactors were higher than the concentration in the feed during the whole period of data collection. The results indicate that solubilization of organic matter occurred in all three reactors under the operational conditions. The solubilization efficiency showed a reduction after the 20th day of the experiment, however the reduction did not last more than 10 days, after that the units returned to their normal capacity which continued until the end of the experimental period.

Total solubilization in each reactor expressed as mg/L of soluble COD is shown in Figure 5.13. The values represent the mean solubilization at the steady-state condition. A significant difference in solubilization of particulate organic compounds was observed between the reactors operating under different SRTs. Solubilization achieved its highest efficiency at SRT of 13 days SRT. The production of soluble COD decreased as the SRT was brought down to lower levels of 8 days, and 4 days. A summary of the mean values of the measured and calculated parameters of solubilization is included in Table 5.5.

The results distinctly reveal the significance of SRT in the dissimilation process of organic particulates under the feed pH of 6.1-6.4. Variation in SRT created a dramatic

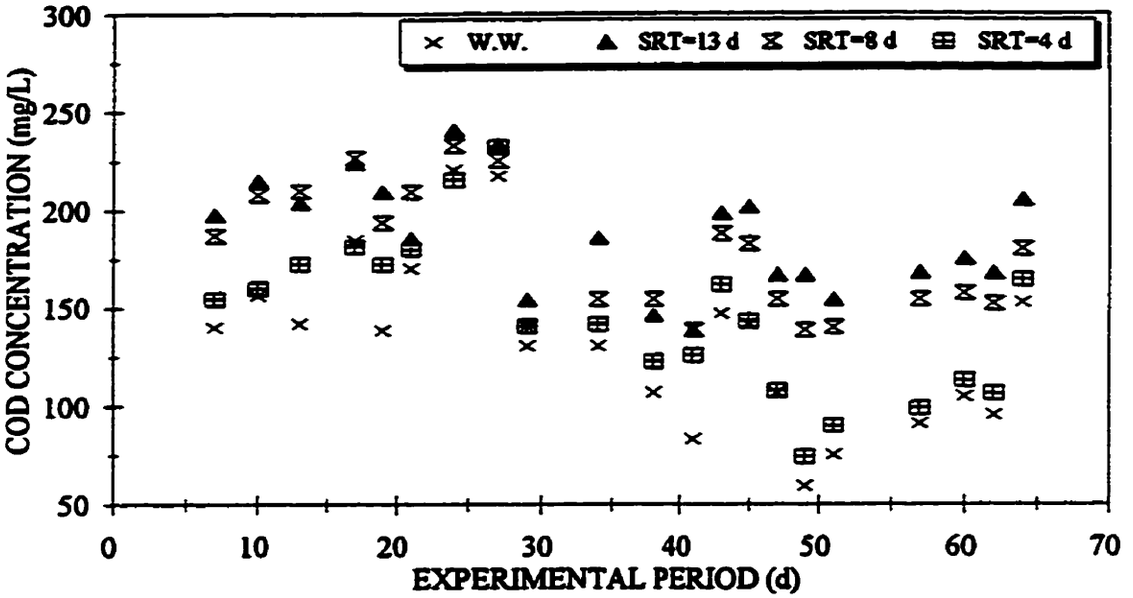

Fig. 5.12 : Profile of soluble COD in the feed and effluent from the fermenters at different SRTs (pH of feed=6.1-6.4).

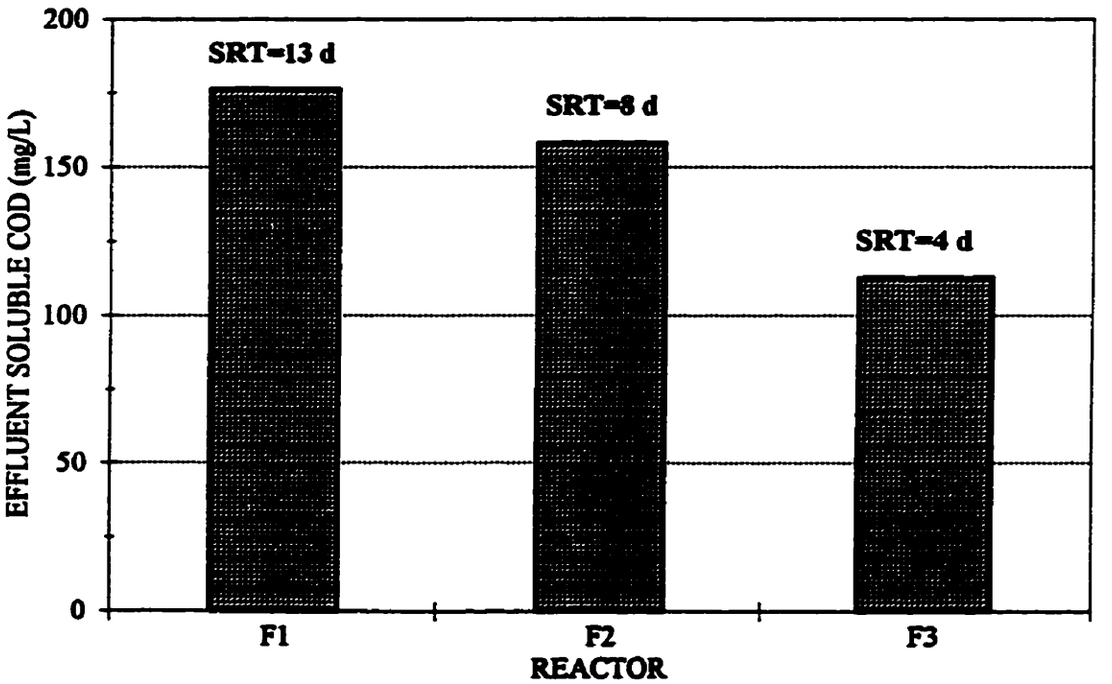

Fig. 5.13 : Mean concentration of soluble COD in the effluent from the fermenters at steady-state condition (pH of feed=6.1-6.4). At low pH condition, SRT played a profound role in the extend of solubilization process. The differences observed between the mean values of net COD production at different SRT were remarkable.

Table 5.5 : Solubilization performance of fermenters at different SRTs (pH_{Feed} = 6.1-6.4).

Reactor	SRT (d)	HRT (h)	Efflu. COD_{Sol} (mg/L)	Solubilization Efficiency %*	Solubilization Yield**	Specific Rate†
F1	13	12	176	69	0.25	2.66
F2	8	12	158	52	0.17	2.08
F3	4	12	113	9	0.03	0.65

* Solubilization Efficiency : Net Soluble COD as % of Feed COD_{Sol}

** Solubilization Yield : mg Solubilized COD/mg Feed Particulate COD

where : Solubilized COD = Effluent COD_{Sol} - Feed COD_{Sol}

Particulate COD in Feed = Feed COD_{Tot} - Feed COD_{Sol}

† Specific Rate : Specific Solubilization Rate as mg net COD/g VSS.h

change in the solubilization performance of the reactors. The reactor with 4 days SRT practically failed in hydrolization and conversion of particulate organic forms to the soluble forms. The solubilization yield was only 0.03 mg COD per mg of feed particulate COD with the specific rate of 0.65 mg COD/g VSS.h. A significant improvement in solubilization efficiency was made as the SRT doubled from 4 days to 8 days. The increase brought up the solubilization yield from the negligible magnitude of 0.03 to the average level of 0.17 mg COD/mg feed particulate COD. Further increase in SRT to 13 days caused a 47% increase in solubilization yield as compared to the yield value at 8 days SRT. The same trend of increase was observed in the specific rate of solubilization. Solubilization rates showed considerable variation with different SRTs; obtaining its maximum value of 2.66 mg COD/g VSS.h in the reactor with the longest SRT (13 days), and its minimum value of 0.65 mg COD/g VSS.h under shortest SRT of 4 days. It should be pointed out that the differences observed between the mean values of the performance parameters were statistically significant ($P<0.01$).

The inefficient performance of the reactor F3 with 4 days SRT was probably due to the removal of microorganisms from the system at a rate faster than their growth rate. A reduction in pH of the wastewater from the range of 7.0-7.6 to the range of 6.1-6.4 could have slowed down the microorganisms growth rate, thus demanding longer SRTs than 4 days for the establishment of an active biomass. The significant increases in the performance efficiencies of the reactors with 8 days and 13 days SRT confirms the former statement. At longer SRTs than 4 days, sufficient time was provided for the growth and proliferation of the biomass. Also the contact time between the microorganisms and substrate increases at longer SRTs. This could be a further reason for the improvements observed in solubilization of particulate matter at SRTs of 8 days and 13 days.

To compare the results obtained from solubilization of particulate organic matter under the two sets of the investigated conditions (step 1 with the pH of feed = 7.0-7.6, and step 2 with the pH of feed = 6.1-6.4), Figures 5.14, and 5.15 were developed. Figure 5.14 shows the net soluble COD production as a function of SRT under different pH conditions of the feed, while Figure 5.15 represent the specific solubilization rates.

The feed (degritted raw wastewater) to the reactors had similar characteristics during the first and second steps of the research. Thus the differences observed between the steps could be related to the change made in the pH of the feed. The average TVS of feed was 332 mg/L during the first step of the experiments, and 359 mg/L during the second step; a difference of about 8%.

Total solubilization, expressed as mg net soluble COD/L, improved under both pH conditions as the SRT increased in the range of 4 to 13 days (Fig. 5.14). However, the degree of impact of SRT on the improvement of solubilization was not the same in both

cases. In the pH range of 7.0-7.6, all the reactors under different SRTs were actively involve in the solubilization of particulate matter. The net soluble COD production in these reactors increased with SRT changing from 4 days to 8 days, and then reached a plateau such that the difference between 8 days and 13 days was not significant. In contrast, with the wastewater of low pH (6.1-6.5), the differences observed in net COD production were all significant. The amount of net COD production at 4 days SRT was very low (less than 10 mg/L), but improved sharply with increasing SRT to 8 days. Increase of SRT to 13 days caused a further relevant improvement in solubilization process. Overall, the impact of SRT on solubilization, as the slopes of the curves in Fig. 5.14 show, was more profound at the lower pH range.

A significant observation was made on the effect of SRT on the rate of solubilization of organic particulates under different pH conditions of the feed. Comparison of the Fig. 5.14, with Fig. 5.15 shows that the trends of change in total solubilization, and in specific rate of solubilization were not the same under the two pH ranges. According to the results shown in Fig. 5.14, total solubilization, regardless of the pH of the feed, benefited from longer SRTs and the trends of change for both pH levels were increasing. However, the impacts of SRT on the specific rate of solubilization were not similar at the two pH ranges(Fig. 5.15). The solubilization specific rate followed a decreasing trend at the feed pH range of 7.0-7.6. In contrast, it showed an increasing trend at the pH range of 6.1-6.4.

One possible explanation for this difference in behavior could be related to the impact of pH on the enzymatic activities of the biomass. Change in pH disturbs the natural balance of the biological system, and can stimulate certain enzymatic activities. It

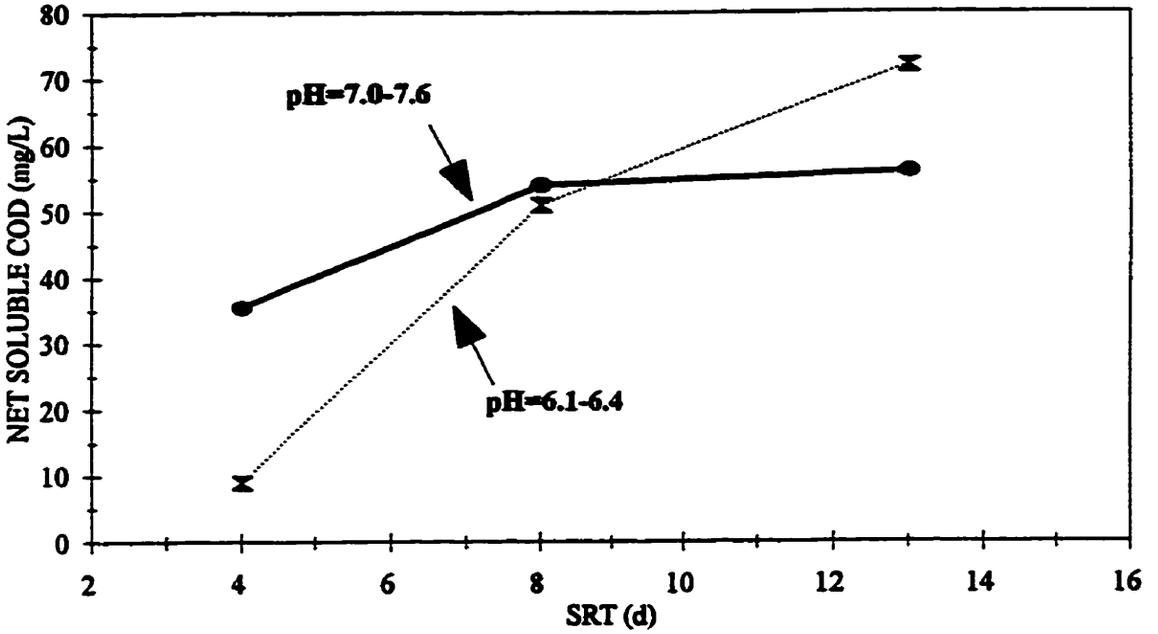

Fig. 5.14 : Effects of SRT on net soluble COD production under two ranges of pH. Increase in SRT enhanced solubilization under both conditions. The extent of improvement, however was not similar in the investigated ranges.

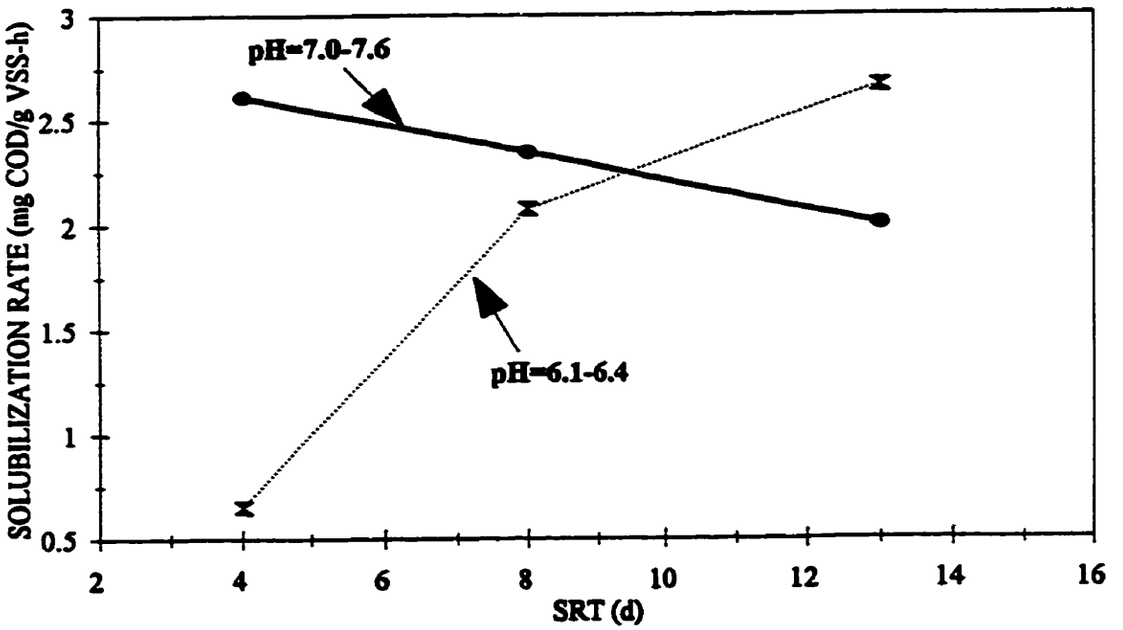

Fig. 5.15 : Specific solubilization rates (effects of SRT at the two pH ranges of the feed). SRT showed a contrasting impact on the specific rate of solubilization under the two pH ranges investigated. At higher pH range, the specific rate declined as SRT changed from 4 days to 8 days, and 13 days. In contrast the trend of change in solubilization rate was increasing at lower pH range; reaching its maximum value at SRT of 13 days.

has been found that hydrolysis of complex carbohydrates reaches a maximum rate at a pH value between 6.0 to 6.5 (Breure et al., 1986), which indicates pH dependency of the activity of the enzymes involved in the process. Elefsiniotis (1993) during acid fermentation of primary sludge, observed a maximum carbohydrate degradation in the pH range of 5.9 to 6.2, which he explained as the major cause of maximum rate of solubilization achieved within this range. A similar trend has been reported by Eastman and Ferguson (1981) in the fermentation of primary sludge at pH between 5.2 and 6.5. On the basis of the information provided in the literature it could be concluded that the solubilization rate of particulate organic matter increases as the pH approaches the range of 6 to 6.5 and this is the result of increase in extracellular hydrolysis of carbohydrate component of particulate organics.

The organic solids in domestic wastewater are composed mostly of carbohydrates (Elefsiniotis, 1993; Metcalf and Eddy, 1992). Consequently, the reduction made in the feed pH during this experiment could have stimulated carbohydrate degradation; enhanced by an increase in SRT from 4 days to 13 days.

In general, it seems that the effect of pH on the growth rate of microorganisms was different from its effect on their hydrolysis activities at the feed pH range of 6.1-6.4. The reduction in pH suppressed microbial growth, while enhancing some of their enzymatic activities. At the pH range of 6.1-6.4, a longer SRT was required for the growth and proliferation of microorganisms as compared to the pH range of 7.0-7.6. This indicates that the microbial growth rate was slower at the feed pH range of 6.1-6.4. In contrast, the enzymatic activities of the biomass with respect to carbohydrates hydrolysis seemed to enhance at the lower pH range. Higher enzymatic activities compensated the

slower growth rate such that the net solubilization at SRT of 8 days at lower pH range (6.1-6.4) was almost equal to the net solubilization at higher pH range (7.0-7.6).

Maximum values for net solubilization and specific solubilization rate occurred at SRT of 13 d using the wastewater with the pH range of 6.1-6.4. Sludge retention time of 13 days provided a sufficient time period for the proliferation of microorganisms, and for the solubilization of complex organic matter. Moreover, the feed pH range of 6.1-6.4 enhanced enzymatic activities. The synergetic impacts of 13 days SRT and low pH range caused the best solubilization performance within the conditions investigated during steps 1 and 2 of this research.

5.3.2.b-VFA Production

The profile of volatile acid production, depicted in Figure 5.16, indicates the presence of acid formers in different reactors. The comparison between Fig. 5.16, and Fig. 5.12 revealed that the change in VFA production of each reactor followed almost the same pattern as that was observed for the solubilization process. A reduction in VFA production occurred in all the reactors between days 26th and 35th which is related to the reduction in the solubilization of volatile solids between days 20th and 30th of the experimental period. After this period of recession, the microbial population in the units with 8 days and 13 days SRTs regained its highly active status in the fermentation process. However, the unit with 4 days SRT did not restore its ability for solubilization and acid formation processes. A combination of low SRT and low pH may have pushed the conditions to the limits of tolerance for the growth and activities of the microorganism involved.

The net concentration of VFA as acetic acid, at steady-state conditions, is shown in Figure 5.17. The importance of SRT in the extent of the activities of the acid formers is clearly demonstrated under the pH condition of 6.1-6.4. The reactor with 4 days SRT was the least efficient unit. The net production of VFA in this unit was practically negligible. VFA production improved substantially with increasing the SRT to 8 days. The average VFA concentration was 31 mg/L in the effluent of this unit as compared to 4 mg/L at 4 days SRT; a significant difference ($P<0.01$).

The maximum production occurred at SRT of 13 days resulting in VFA concentration of 32 mg/L as acetic acid. The excess production of VFA in the reactor with 13 days SRT as compared to the reactor operating under 8 days SRT was also statistically significant. As it was explained in section 5.3.1, a longer SRT allows a longer period of time for the solids and microorganism to remain in the reactor. Also it allows for the growth of microorganisms with the slower growth rate. Therefore solubilization and fermentation of organic compounds improves with longer SRT.

The impact of SRT on acid fermentation under feed pH of 6.1-6.4 was evaluated by the parameters summarized in Table 5.6. All the parameters of importance concerning with acid conversion of complex soluble organic compounds improved as the result of increase in SRT under the investigated conditions of this stage of the research. Maximum values of total VFA production, acetic acid concentration, maximum yield, and specific VFA production rate occurred at the maximum SRT of 13 days. The data in Table 5.6 also confirm the inefficiency of acid formers under the low SRT and low pH conditions. It is observed that the increase in SRT from 4 days to 8 days caused a drastic increase in the mean values of all parameters, which further increased at an SRT of 13 days.

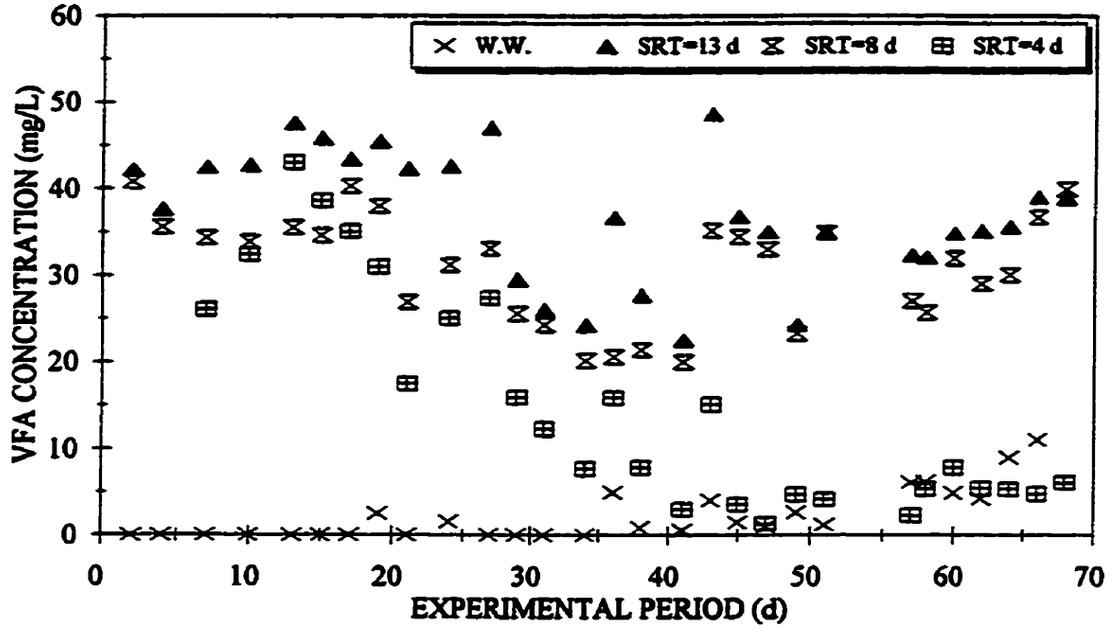

Fig. 5.16 : Profile of VFA concentration in the feed and effluent from the fermenters at the low pH range.

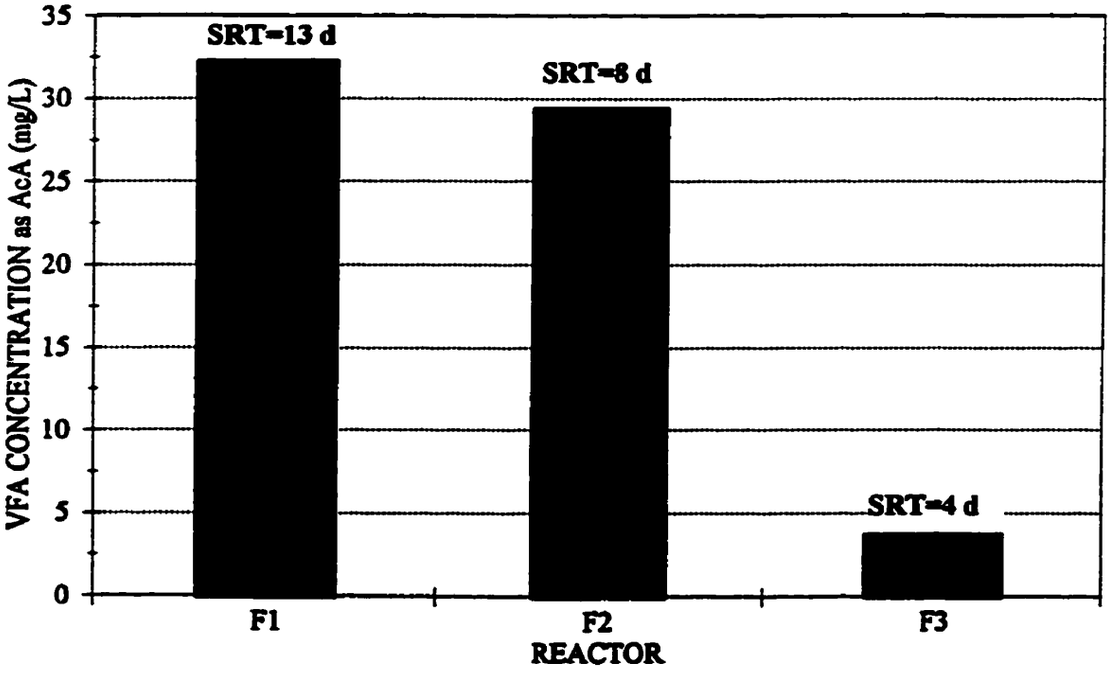

Fig. 5.17 : Mean concentration of VFA at different SRTs (pH of feed=6.1-6.4).

Table 5.6 : Acid fermentation performance at different SRTs (pH_{Feed}= 6.1-6.4).

Reactor	SRT (d)	HRT (h)	VFA (mg/L)	Acetic Acid (mg/L)	VFA Yield*	Production Rate **
F1	13	12	34	29	0.10	1.3
F2	8	12	31	27	0.08	1.2
F3	4	12	4	2	0.01	0.3

* VFA Yield = mg VFA/mg Feed COD_{Tot}
** Production Rate = mg VFA/g VSS.h

The mean values of total production of VFA, and specific rate of VFA production are shown in Figure 5.18. There was a difference between the units with 8 days SRT, and 13 days SRT with respect to total VFA production; being higher at the longer SRT. But both units had almost the same specific rates of VFA production, and the change in SRT did not improve the process. Consequently, the excess VFA produced at 13 days SRT was simply the result of higher biomass concentration, not the result of higher specific rate.

Comparison between the net SOC produced and the carbon equivalent of mean VFA illustrates the contribution of solubilized products in the net VFA production. On the basis of the results obtained for the pH range of 6.1-6.4, about 75% of VFA produced in the reactors with 8 days and 13 days SRTs originated from the solubilized products, and only 25% contribution was made by the soluble compounds which were initially present in the wastewater. The corresponding value for contribution of solubilized products under the pH condition of 7.1-7.6 (step 1) was 65% in the both reactors. It is evident that at the lower pH the role of solubilization in the net output of VFA became more predominant.

The results on solubilization, and VFA production under the two investigated

ranges of pH are shown in Figures 5.19 and 5.20 respectively. In general, regardless of the SRT, total VFA production was lower in the pH range of 6.1-6.4 than in the pH range of 7.1-7.6. In contrast (neglecting the results on solubilization at SRT of 4 days), the solubilization efficiencies were equal (at SRT=8 d), or higher (at SRT=13 d) under the condition of lower pH range.

In general low pH improved solubilization, but suppressed the activities of the acid formers possibly through adverse effects on the acid-generating pathways. In another word, under the feed pH range of 6.1-6.4, the conversion of soluble intermediates to VFA was the rate limiting step in the overall efficiency of acid fermentation process.

Elefsiniotis (1993) observed similar results in acid fermentation of primary sludge in the pH range of 5.9-6.2. Perot et al. (1988) reported maximum concentration of acid-phase products at pH 6.8 using a mixture of primary and activated sludge.

5.3.2.c-VFA Composition

The percent distribution of VFA formed under the low pH condition in different SRTs is summarized in Table 5.7. Although acetic acid was also the most predominant species of VFA at the lower pH, alteration of pH influenced the percent VFA distribution. In general the reduction in pH of the wastewater caused a drop in the percent acetic acid component of VFA.

The total VFA concentration in reactor F3 (4 days SRT) was very low, with acetic acid contributing about 40%. The concentration of other short chain fatty acids in this reactor was not considerable, eventhough the percentages represent high values. The distribution of short chain fatty acids in other reactors with longer than 4 days SRT was

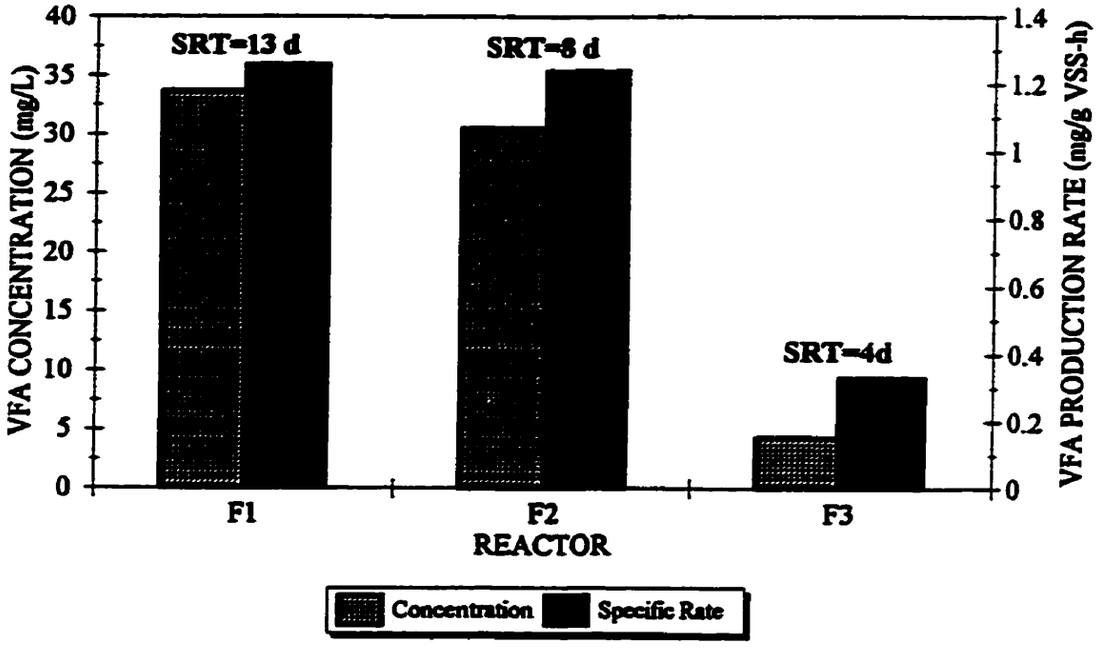

Fig. 5.18 : Total VFA, and VFA specific production rate as a function of SRT (pH of feed=6.1-6.4). Significant improvement in both parameters were observed as the SRT increased to longer time period than 4 days.

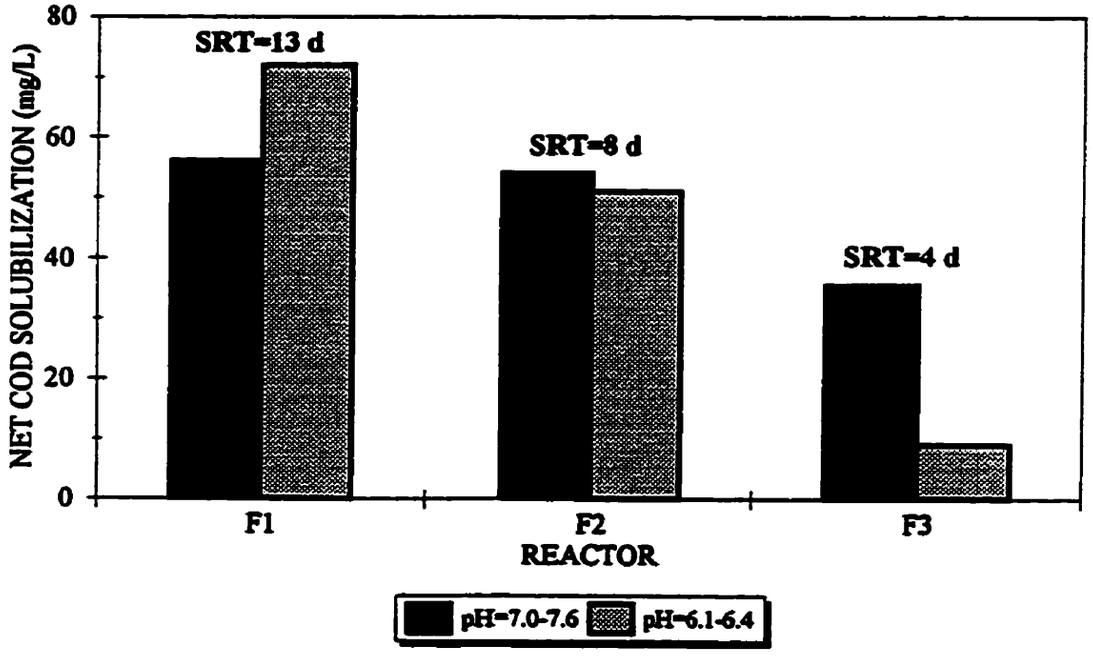

Fig. 5.19 : Solubilization of particulate organic matter at different SRTs under the two pH ranges of the feed. Improvement of solubilization at pH range of 6.1-6.4 over pH range of 7.0-7.6 became significant as SRT approached 13 days.

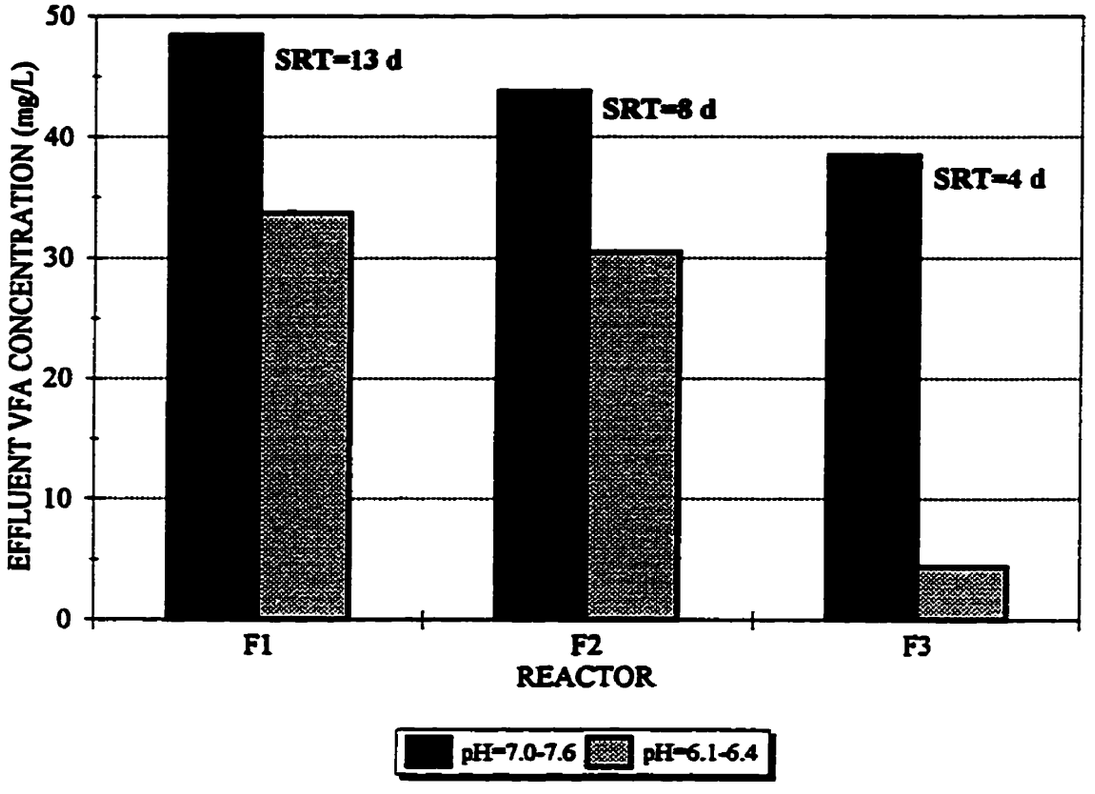

Fig. 5.20 : VFA production at different SRTs under the two ranges of pH. Regardless of SRT, total VFA production was lower in the pH range of 6.1-6.4 than in the pH range of 7.0-7.6.

Table 5.7 : Percent VFA distribution at different SRTs (pH_{Feed}= 6.1-6.4).

Reactor	SRT (d)	VFA (mg/L)	Acetic % VFA	Propionic %VFA	Iso-But. %VFA	N-But. %VFA	Iso-Val. %VFA	N-Val. %VFA
F1	13	34	86.5	3.0	3.0	2.5	3.5	1.5
F2	8	31	88.0	2.5	3.0	2.0	3.5	1.0
F3	4	4	41.0	15.0	6.5	11.0	22.5	4.0

very similar. Total VFA was made of 88% and 86.5% acetic acid in the reactors with 8 days and 13 days SRT, respectively. The second most important component of VFA in these two reactors was butyric acid with mean total percentage of about 5%. Valeric acid constitute about 5% of VFA production, with the last 3% belonging to propionic acid.

Results on percent distribution of VFA under high pH (Figure 5.11) and low pH (Table 5.7) conditions show a decline in the percent production of acetic acid when the pH of the wastewater decreased from 7.0-7.6 to 6.1-6.4. The reduction was about 6.5% in the reactors with 8 days and 13 days SRTs, and was accompanied with the accumulation of higher molecular weight VFAs mainly isomers of butyric and valeric acids. Lower production of acetic acid could be the result of disturbance of the biochemical pathways that lead to the generation of this acid. In contrast, higher production of butyric and valeric acids has most likely resulted from the degradation of proteins which is encouraged at lower pH levels.

5.3.2.d-Quality of the Fermented Wastewater - Low pH

Acid fermentation of the raw wastewater at low pH improved its quality for the purpose of biological nutrient removal. A comparison was made between some of the

characteristics of the wastewater before, and after the application of the fermentation process. The results are summarized in Table 5.8.

Table 5.8 : Characteristics of raw and fermented wastewater (Impact of SRT on acid fermentation of degritted raw wastewater with pH = 6.1-6.4).

Parameter	W.W. Mean±SD	F1 (SRT=13 d) Mean±SD	F2 (SRT=8 d) Mean±SD	F3 (SRT=4 d) Mean±SD
pH	6.1-6.4	6.4±0.1	6.4±0.1	6.5±0.1
Alkalinity as $CaCO_3$	-	185±17.9	183±14	169±15.3
VFA as HAc	3	32±3.4	29±3.6	4±1.7
HAc as %VFA	34	87±2.5	88±2.1	41±21.1
VFA/P_{Sol}	0.9^{a*}	$6.9±0.7^{b}$	$6.3±0.9^{c}$	$0.9±0.4^{a}$
COD_{Sol}/P_{Sol}	$25±5.3^{a}$	$36±3.3^{b}$	$33±2.4^{c}$	$24±4.7^{a}$
COD_{Sol}/N_{Sol}	$3.3±0.9^{a}$	$5.3±0.5^{b}$	$4.7±0.4^{c}$	$3.5±0.9^{a}$
SOC/N_{Sol}	1.3±0.2	1.5±0.1	1.5±0.2	1.3±0.1
NH_3-N	27±1.3	29±1.5	30±1.4	28±1.3

Note : Values of alkalinity, VFA and NH_3-N are reported in mg/L.
* : Non-similar letters in the superscript indicate a significant difference between the means ($P<0.05$).

Although the low pH condition in general impaired overall VFA production (especially at low SRT of 4 days), nevertheless, the process of fermentation did enhance the wastewater quality in the reactors operating under the sludge retention times of 8 days and 13 days.

Solubilization of organic solids and conversion of soluble organic matter to volatile fatty acids were very inefficient in the reactor with 4 days SRT due to the washout of the

biomass. No improvement in the wastewater quality was observed in this reactor as reflected by the mean values of VFA/P_{Sol}, COD_{Sol}/P_{Sol}, COD_{Sol}/N_{Sol}, and SOC/N_{Sol} ratios (Table 5.8). Longer SRTs caused a major improvement in solubilization and fermentation processes as illustrated by the values of the above ratios in the effluent from reactors with 8 days and 13 days SRTs. The difference observed between the mean values of each of the VFA/P_{Sol}, COD_{Sol}/P_{Sol}, COD_{Sol}/N_{Sol} ratios at sludge retention times of 8 days, and 13 days were significant ($P<0.05$); indicating the beneficial effects of longer SRT in the fermentation of raw wastewater when its pH is in the range of 6.1-6.4.

5.3.2.e-Conclusion

Acid fermentation of raw wastewater with a pH range of 6.1-6.4 was found to be a feasible process. The role of SRT on solubilization and fermentation of organic compounds in this pH range was crucial. Solubilization of organic particulates, VFA production, and the related specific rates were improved remarkably as the SRT was increased from 4 days to 8 days. The best results, however, obtained at an SRT of 13 d.

In general, regardless of SRT, the low pH range of 6.1-6.4 improved solubilization but its negative impact on acid formers activity reduced the overall efficiencies of VFA production. Distribution of VFA was also affected by the change in the pH of raw wastewater. The acetic acid percentage of VFA was decreased at the lower pH range.

5.3.3 STEP 3 : REDUCTION IN MIXING PERIOD

One of the components of total costs in treatment plants is the cost associated with the mixing operations. Improvements in the mixing systems' efficiencies and/or duration of mixing periods will certainly be beneficial as the related operational costs will be reduced.

The objective of this step of the research was to investigate the effects of reduction in the mixing period on the performance efficiency of the fermentation process. A change in the mixing regime could affect the system performance as the conditions for microbial activities changes. During the mixing period, the microorganisms are in a more dilute environment. Besides, they are in contact with the soluble portion of the substrate as well as with the solid portion. When the mixing is stopped the solids and the biomass settle down. In the settled sludge, the environment is not as dilute as the media at the time of mixing. Furthermore, the microorganisms are mostly in contact with the solid portion of the substrate. Consequently, a change in the mixing regime could produce a different outcome in the fermentation process of raw wastewater.

To investigate the effects of a reduction in the mixing period, two reactors F1 & F2 from previous steps of the research were reprogrammed. The two reactors were acting as duplicates to improve confidence in the results. Most of the operating parameters were kept the same as in previous runs. The reactors were running at 3 cycle/day, with the HRT of 12 h. The major operational change in this step was the reduction of mixing period from 6 h per cycle to 0.25 h per cycle. In steps 1 and 2, fermentation of raw wastewater produced the best result under the SRT of 13 days. Therefore, SRT of 12 days was chosen for all the fermentation reactors in the current, and in the following steps

of the research. Sludge retention time of 12 days was considered to be close enough to 13 days to provide the optimum condition for the fermentation process.

Data related to this stage are shown in detail in Appendix A, Tables A1 to A4, and cover the time period from July 5, 1994 to Nov. 23, 1994. The data used for the statistical analysis and performance evaluation are those collected during steady state conditions of the reactors (Aug. 20, 1994 - Nov. 23, 1994).

5.3.3.a-Solubilization and VFA Production

The average performances of the duplicate reactors under reduced mixing are shown in Table 5.9. Both reactors were performing very closely, and the observed differences between the mean values of the measured parameters were not statistically significant ($P>0.05$). The profiles of the VFA concentration in the effluent of the two reactors (Fig. 5.21) also verify their similar behavior in acid fermentation process. On average about 81.5% of the total VFA produced in the reactors was acetic acid. The rest was composed of 8% propionic acid, 5.5% valeric acids, and 5% butyric acid.

Table 5.9 : Performance of the duplicate reactors under the mixing condition of 0.25 h/cycle.

Reactor	HRT (h)	SRT (d)	Mixing (h/cycle)	Eff.COD_{Sol} (mg/L)	COD Rate *	Eff.VFA (mg/L)	VFA Prod.**
F1	12	12	0.25	179	1.70	46	1.32
F2	12	12	0.25	185	1.80	48	1.36
			Mean	182	1.75	47	1.34

* COD Rate : Specific Solubilization Rate as mg net COD/g VSS.h
** VFA Prod. : Specific Rate of VFA Production as mg VFA/g VSS.h

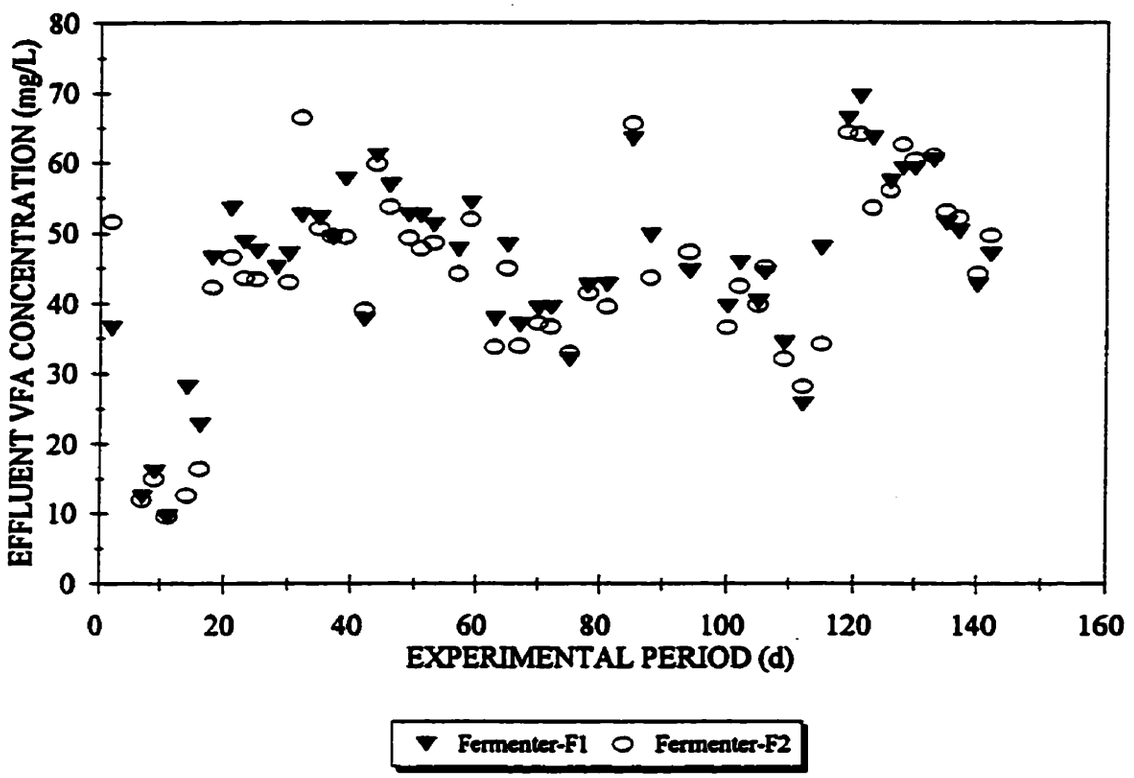

Fig. 5.21 : Effluent VFA concentration under the short mixing period of 0.25 h/cycle. Performance of duplicate reactors in acid fermentation of degritted wastewater was comparable under the reduced mixing condition.

The fermentation process under the new mixing regime of 0.25 h/cycle was evaluated by a comparison made between the average performance of the duplicate reactors in this step (step 3), and the performance of the reactor F1 with 6 h mixing period in step 1. The operational conditions of the reactor F1 during step 1 were similar to the operational conditions of the reactors in this step except for the length of the mixing period in each operational cycle. The data for the comparison are presented in Table 5.10. Some of the differences observed in the feed characteristics during steady-state conditions of step 1 and step 3 are also summarized in Table of 5.11.

Table 5.10 : Comparison between the performance of the fermenter with 13 days SRT in Step 1 (mixing period = 6 h/cycle), and the average performance of duplicate reactors in step 3 (mixing period = 0.25 h/cycle).

Reactor	Mixing (h/cycle)	Net COD_{Sol} (mg/L)	COD Yield*	COD Rate**	VFA (mg/L)	VFA Rate†
F1, Step 1	6	57	0.21	2.00	48	1.74
F1 & F2, Step 3	0.25	63	0.19	1.75	47	1.34

* COD Yield : Solubilization Yield as mg net COD/mg Feed Particulate COD
** COD Rate : Specific Solubilization Rate as mg net COD/g VSS.h
† Specific Rate : Specific Solubilization Rate as mg net COD/g VSS.h

As far as total solubilization and VFA production are concerned, confirmed by the results in Table 5.10, the reactors under the short mixing regime were performing as efficiently as the reactor under the long mixing condition. The net COD production at the mixing condition of 0.25 h/cycle was 63 mg/L, compared to 57 mg/L obtained at the mixing condition of 6 h/cycle. The net VFA concentrations were also comparable; 47 mg/L at 0.25 h mixing/cycle versus 48 mg/L at the mixing period of 6 h/cycle.

However, the average COD yield and the specific rates of solubilization and VFA production were lower in the case of short mixing period, although the feed (wastewater) was stronger in the total carbon content than the wastewater used in step 1. Concentrations of TVS and VSS were higher by 14% and 9%, respectively as indicated by the data in Table 5.11.

Table 5.11 : Some of the characteristics of degritted raw wastewater (feed) during steady-state conditions in step 1 and step 3.

Feed	COD_{Tot} (mg/L)	Particulate COD (mg/L)	TVS (mg/L)	VSS (mg/L)
Step 1	418	266	332	154
Step 3	460	341	379	167

The reasons for observing lower specific rates of solubilization and VFA production in step 3 are probably related to the total amount of substrate physically available for the microorganisms and to some extend to the higher concentration of MLVSS in the reactors. The mixing period during the first step of the research was 6 hours (75% of total cycle period). Consequently, although the wastewater was weaker in carbon content, the microorganisms involved in the solubilization of particulate matter were provided continuous physical contact with the whole spectrum of VSS even the nonsettleable colloidal particles. Likewise, in such conditions, acid formers could use the solubilization products as well as the soluble volatile solids of the feed in the production of VFA. During this step of the research, the mixing period was reduced to 0.25 h (3.2% of the total cycle period). Thus, the quiescent conditions were provided for 97% of the total

cycle time period, yet some of the colloidal particles did not settle out. This non-settleable portion of VSS was outside the domain of the microbial activities in the settled sludge and could not actively participate in the solubilization process. Therefore, while the wastewater was stronger in VSS under this condition, the portion of VSS physically available for the microorganisms has been less; resulting in lower COD yield and lower specific solubilization rate. Similarly, in the case of VFA production, lack of mixing slows down the contact between the microorganisms and the soluble organic matter in the supernatant. Less active participation of soluble volatile solids in biochemical reactions and toxic VFA levels located in sludge could have been the reasons for lower rates of VFA production under the condition of short mixing.

On the basis of carbon equivalents, the net increase in SOC was accountable for the total VFA production under the quiescence condition. In contrast when mixing was provided (step 1), the net increase in SOC was counted for only 65% of the total VFA, and the other 35% was produced by the soluble organic matter originally present in the wastewater. The comparison confirms the above statement concerning the inefficiency of conversion of soluble volatile solids to short chain fatty acids when mixing is not provided sufficiently.

Reduction in the mixing period caused a change in percentage distribution of volatile fatty acids. The obtained acetic acid percentage (81.5%) was lower than the percentages achieved in other investigated conditions, with a shift towards higher percentages of propionic (8%) and butyric acids (5%). The valeric acid content of the VFA was 5.5%; similar to the previous cases. Higher concentrations of substrate and extracellular enzymes in the microenvironments within the settled sludge could have

encouraged degradation of proteins and lipids; resulting in higher production of propionic and butyric acids, and a change in percent distribution of volatile fatty acids.

5.3.3.b-Quality of the Fermented Wastewater - Reduced Mixing

The changes occurred in certain characteristics of wastewater as the result of the fermentation process under the low mixing condition are summarized in Table 5.12. It is observed that all the ratios of interest in biological nutrient removal process were improved, eventhough the mixing period was reduced considerably. The most significant variation, as was found in previous steps of the research, was associated with the ratio of VFA/P_{Sol} which increased from 1.2 in the degritted raw wastewater to the average value of 11 in the effluent of fermenters.

Table 5.12 : Characteristics of raw and fermented wastewater (Impacts of short mixing period).

Parameter	W.W. Mean±SD	Duplicate Reactors (F1 & F2) Mean of the Means±SD
pH	7.6±0.1	7.1±0.1
Alkalinity as $CaCO_3$ (mg/L)	352±37.5	406±38.9
VFA as HAc (mg/L)	5±4.7	44±9.5
HAc as %VFA	45±32.8	81.5±2.0
VFA/P_{Sol}	1.2±0.9 [a*]	11±1.4 [b]
COD_{Sol}/P_{Sol}	32±12.7 [a]	43±11.7 [b]
COD_{Sol}/N_{Sol}	4.1±1.4 [a]	6.0±1.5 [b]
SOC/N_{Sol}	1.4±0.3	1.9±0.23

* : Non-similar letters in the superscript indicate a significant difference between the means ($P<0.05$).

Results from this step of the research clearly show the operational improvement that has been achieved. The mixing period was reduced by 96% without any negative impact on the parameters involved in the biological nutrient removal.

5.3.3.c-Conclusion

The length of the mixing period per cycle influenced some aspects of the fermentation process. The specific rates of solubilization of particulate matter and VFA production declined as the result of a reduction in mixing period from 6 h/cycle to 0.25 h/cycle. Regardless of the slower rates at 0.25 h mixing/cycle, net solubilization and VFA production were similar in values to those quantities obtained at the mixing condition of 6 h/cycle. Adequate solubilization and VFA production improved the wastewater characteristics for the purpose of biological nutrient removal.

The distribution of VFAs was also affected by the change made in the mixing regime. Production of propionic and butyric acids was enhanced under the short mixing condition. Acetic acid, however was the most abundant component of the VFA and constitute about 81.5% of total VFA production.

5.3.4 STEPS 4 AND 5 : EFFECTS OF HRT

Hydraulic retention time (HRT) is the average period of time that a molecule of wastewater remains in the reactor, and is defined by the volume of the reactor divided by the influent flow rate (Metcalf and Eddy, 1991). It actually determines the effective time of contact between microorganisms and the wastewater. It also affects the total daily load of solids to the reactors; hence controlling the relative mass of the microorganisms in the MLVSS of reactors, even at a constant sludge retention time. As a result, through its influence on the relative mass of microorganisms, and on the contact time between substrate and biomass, HRT controls the efficiency of biological treatment processes and has been considered as one of the major parameters of importance in the design and operation of such systems. The role of HRT as an operational parameter is of great importance in the SBR systems. These systems are flexible in manipulation of the operational cycles that allows for a change in the HRT.

The objective of this part of the research was to investigate the effects of HRT on the efficiency of acid fermentation of degritted raw wastewater. The experiments were carried in two steps; step 4 and step 5. In step 4 a comparison was made between HRT of 12 h and 9 h using reactors F2 and F1, respectively. In step 5, reactor F2 was changed to HRT of 6 h and its performance was compared to a parallel reactor (F1) with HRT of 9 h. The sludge retention time and mixing period in the reactors were kept at the values obtained from previous steps of the research; meaning 12 days for SRT and 0.25 h/cycle for the mixing period.

The experimental period in step 4 lasted from Nov. 24,1994 to Jan. 18, 1995, while Step 5 was performed from Jan. 25, 1995 to Apr. 12, 1995. The data related to this

part of the research are also covered in Appendix A, Tables A1 to A4. Collected data over the period of steady-state condition was used for performance evaluation. This period for step 4 was from Dec. 19, 1994 to Jan. 18, 1995 and for step 5 was from Mar. 3 to Apr. 12, 1995.

5.3.4.a-Solubilization of Organic Particulates

Profiles of the variations of the SOC and COD concentrations in the effluents of reactors versus the concentrations of these parameters in the degritted raw wastewater are shown in Figures 5.22 and 5.23, respectively.

The significant increase observed in the SOC and soluble COD concentrations of the effluents over their concentrations in the raw wastewater were the result of the solubilization of particulate organic matters. Solubilization reactions proceeded in the reactors regardless of their HRT. The trend of change in solubilization products concentration within each reactor, as depicted in the related Figures 5.22 and 5.23, followed exactly the same trend of change that was associated with the strength of the raw wastewater.

Variation in HRT showed some influence on the net soluble COD production as well as on the specific solubilization rate. Data for solubilization performance evaluation are summarized in Table 5.13. The results are also graphically presented in Figure 5.24.

According to the presented data, the maximum values of net soluble COD and solubilization rate were obtained at HRT of 9 h. The increase in HRT to 12 h, in step 4, caused a decrease in total solubilization, and in its specific rate. The difference between COD yield and total solubilization at 9 h and 12 h, however were not significant ($P>0.05$).

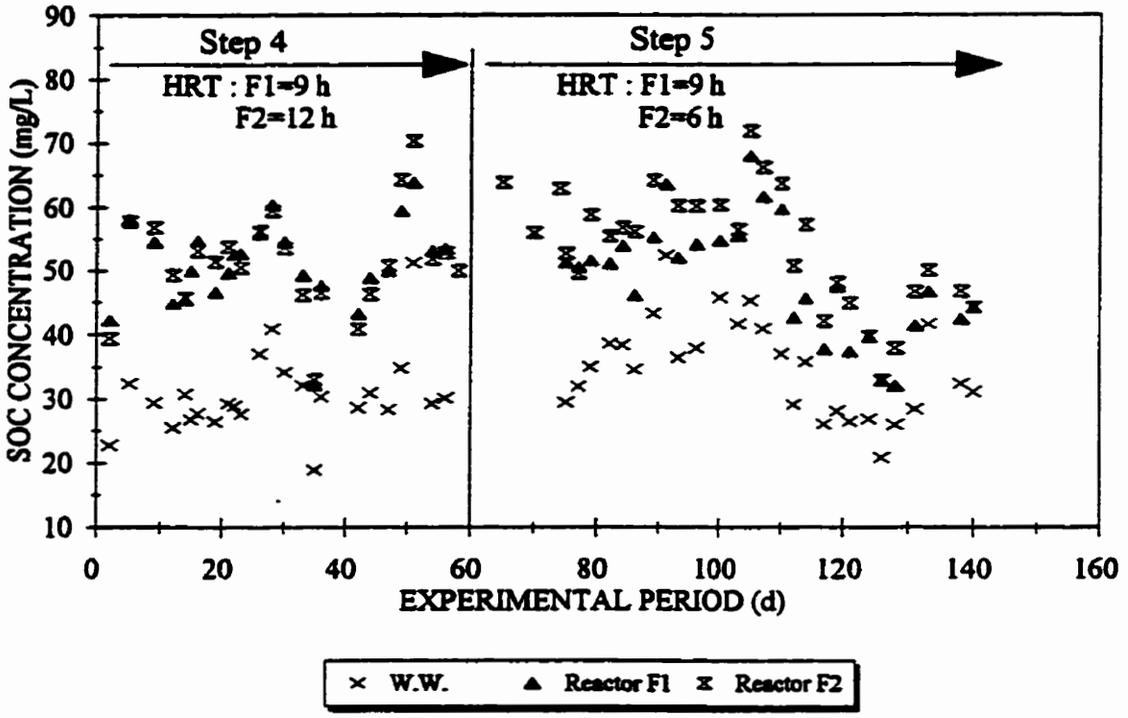

Fig. 5.22 : Profile of SOC in the effluent from the fermenters versus its concentration in the feed (effects of HRT). Remarkable amount of solubilization occurred in the reactors regardless of their HRTs.

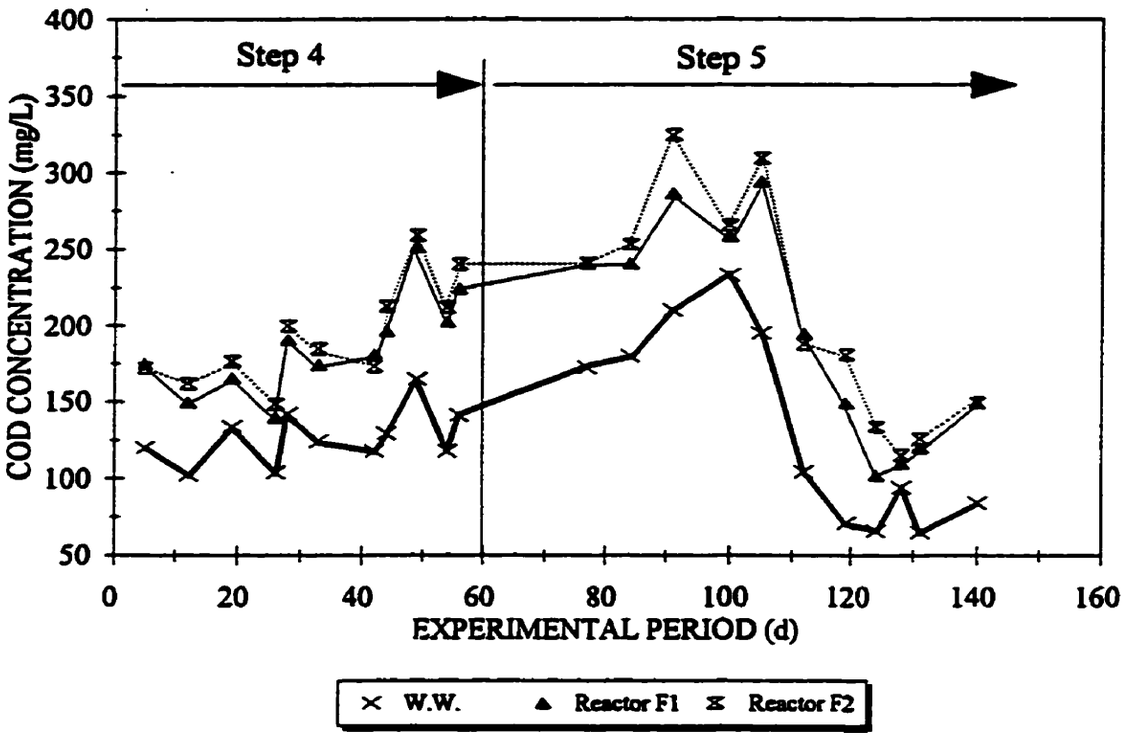

Fig. 5.23 : Profile of soluble COD in the feed and effluent from the fermenters (steps 4 and 5). The change in the effluent followed the variation in the feed.

Table 5.13 : Solubilization results at different HRTs.

Step in Research	Reactor	HRT (h)	Net COD_{Sol} (mg/L)	Solubilization Yield*	Specific Rate†
Step 4	F1	9	74	0.24	2.19
	F2	12	65	0.21	1.74
Step 5	F1	9	70	0.25	2.26
	F2	6	58	0.21	2.00

* Solubilization Yield : mg net COD/mg Feed Particulate COD

where : Solubilized COD = Effluent COD_{Sol} - Feed COD_{Sol}

Particulate COD in Feed = Feed COD_{Tot} - Feed COD_{Sol}

† Specific Rate : Specific Solubilization Rate as mg net COD/g VSS.h

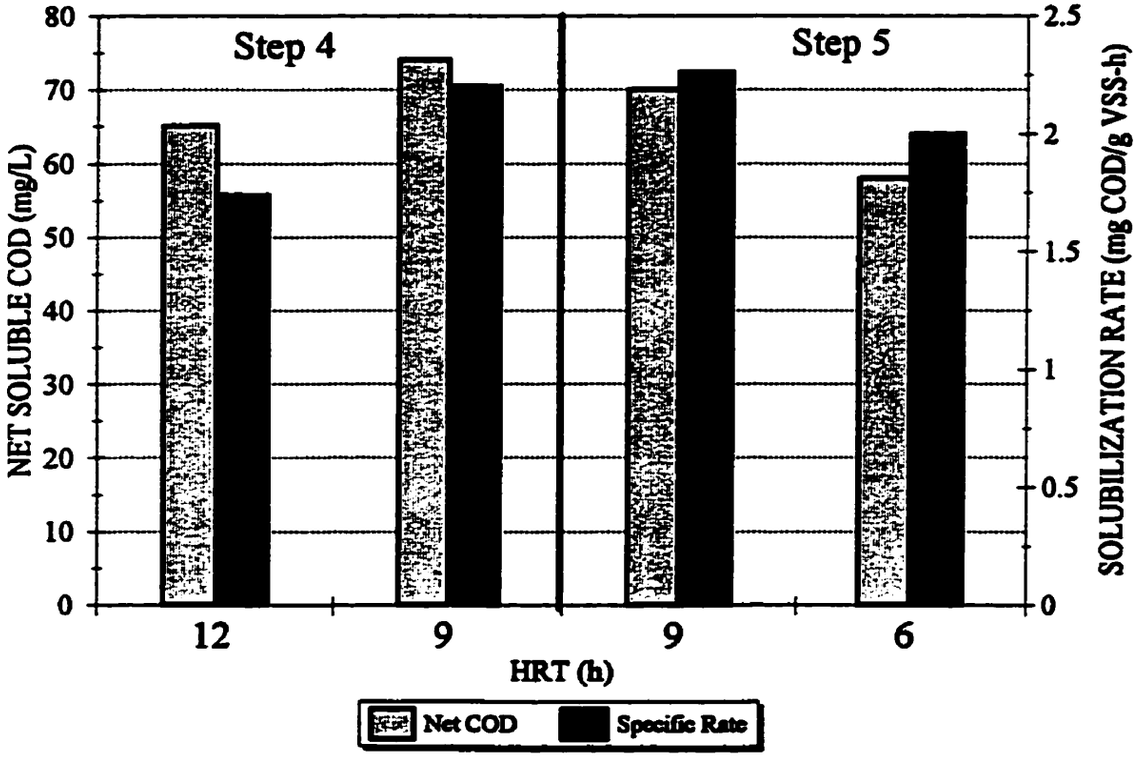

Fig. 5.24 : Solubilization of organic particulates at different HRTs. Net soluble COD production and solubilization specific rate achieved their maximum values at HRT of 9 h.

Reduction in solubilization and its specific rate was also observed during step 5 of the research as the HRT was changed from 9 h to 6 h. The decline noticed at the longest HRT (12 h) was probably caused by lower daily load of VSS to the reactor which limited the amount of substrate for the biomass. The reduction observed in solubilization of particulate organic matter at shortest HRT of 6 h, however, could be the result of the limited contact time between the colloidal particles and the microorganisms, and/or high VSS daily load which could reduce the biomass content of the MLVSS in the reactor.

5.3.4.b-VFA Production

The profiles of the reactors' effluent VFA concentrations are presented in Figure 5.25. High concentrations of VFA in the effluent from the reactor as compared to the mean concentration of 5.5 mg/L in feed, indicate that the conditions for growth and activity of the acid producing bacteria have been favorable under different HRTs.

The data related to the performance of VFA production in the reactors at steady-state condition are summarized in Table 5.14. The VFA production (as acetic acid), and the specific rates of VFA production as a function of HRT are furthermore presented in Figure 5.26.

The change in HRT from 12 h to 9 h did not affect the performance of the acid producing bacteria. The two parallel reactors in step 4; F2 with HRT of 12 h and F1 with HRT of 9 h, were producing almost the same net concentration of VFA. The VFA yields in these two reactors were identical, and the differences observed in total VFA production and the specific rates were not statistically significant ($P>0.05$). In contrast, a reduction of HRT from 9 h to 6 h (step 5) caused a statistically significant decline in VFA yield and

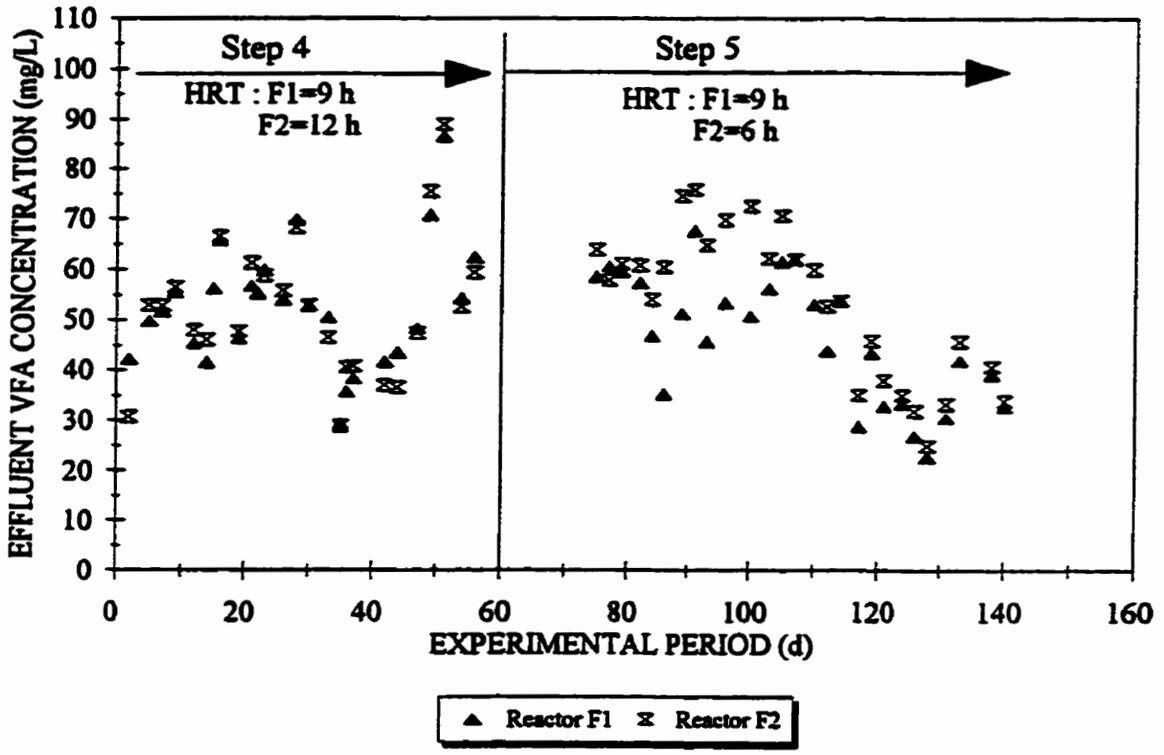

Fig. 5.25 : Profile of VFA concentration in the effluent from the fermentation reactors (effects of HRT). High concentrations of VFA in the reactors indicated favorable conditions for the growth and proliferation of acid producing bacteria.

Table 5.14 : Performance of VFA production at different HRTs.

Step in Research	Reactor	HRT (h)	VFA (mg/L)	Acetic Acid (mg/L)	VFA Yield*	Production Rate **
Step 4	F1	9	52	42	0.12	1.57
	F2	12	53	41	0.12	1.61
Step 5	F1	9	49	38	0.12	1.63
	F2	6	42	35	0.10	1.48

* VFA Yield : mg VFA/mg Feed COD_{Tot}
** Production Rate : mg VFA/g VSS.h

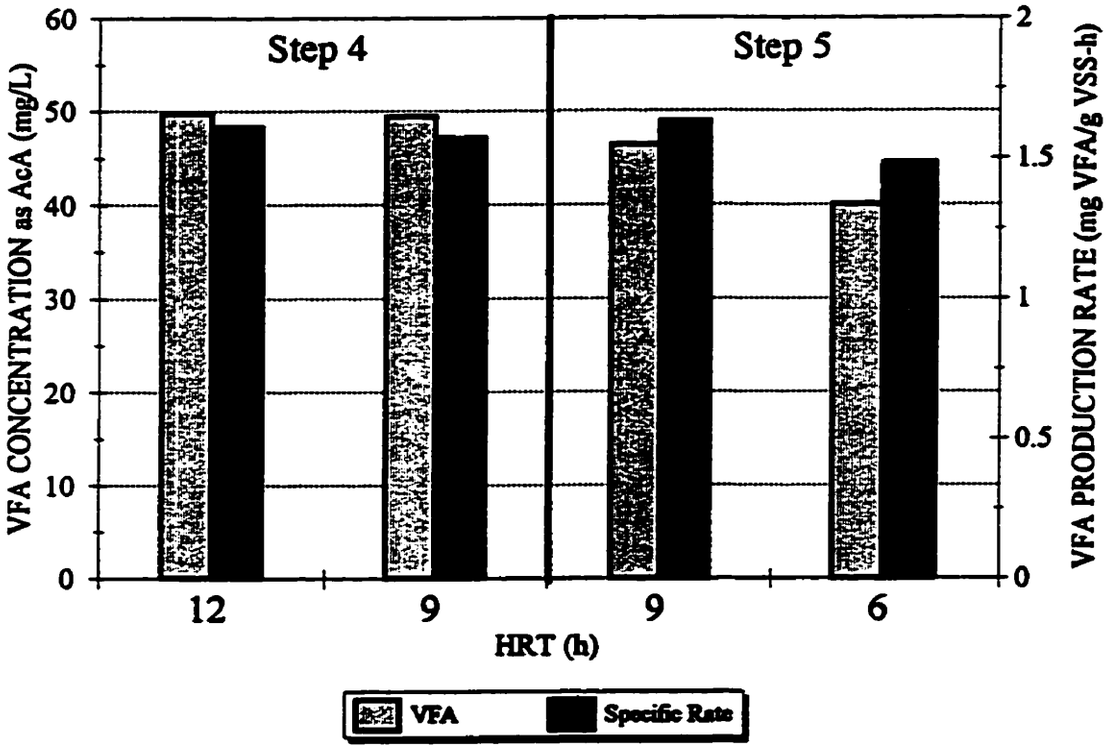

Fig. 5.26 : VFA production (effects of HRT). No significant difference in VFA production was observed between reactors operating at 12 h, and 9 h hydraulic retention time. Reduction of HRT from 9 h to 6 h, however, decreased specific rate and total production of volatile fatty acids.

total VFA production. The specific rate of VFA production was approximately 10% lower at HRT of 6 h revealing a nonsignificant difference. The lower rate of VFA production at the shortest HRT is mainly due to the limited time available for substrate assimilation by the acid former bacteria.

A comparison between the specific rates of solubilization and VFA production as a function of HRT is made in Figure 5.27. Hydraulic retention time of 9 h, as depicted by the average specific rate values in the figure, provided the optimum condition for the process of acid fermentation of degritted raw wastewater. At this HRT, solubilization and acid formation processes showed their best overall performances. Figure 5.27 also clearly indicates that the variation of HRT within the investigated range did not affect the activity of acid formers as much as it influenced the activity of the microorganisms involved in the solubilization process. In contrast to the results obtained in this research, Elefsiniotis (1993) in his research on impact of HRT (range of 6 to 15 h) on fermentation of primary sludge reported maximum solubilization and VFA production at HRT of 12 hr.

5.3.4.c-VFA Speciation

The percent distribution of components of VFA produced at different HRTs are shown in Table 5.15. The most significant component of VFA was acetic acid with the lowest percentage (78.5%) obtained at HRT of 12 h, and highest percentage (84.4) at HRT of 6 h. Propionic acid was the second most abundant fatty acid present in the reactors, followed by valeric and butyric acids percentages.

In general, some variations were noticed in percentage distribution of volatile fatty acids at different HRTs, but the differences were not statistically significant ($P>0.05$).

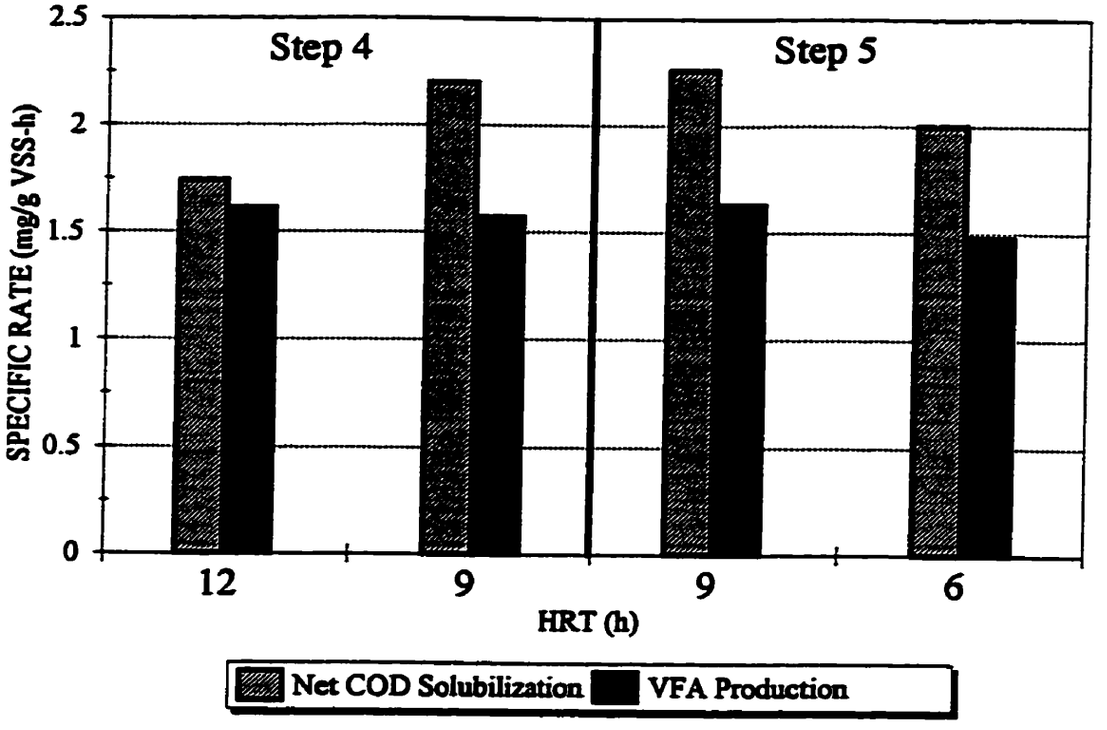

Fig. 5.27 : Impacts of HRT on the specific rates of solubilization and VFA production. Change in HRT did not affect VFA production significantly. The impact of change on solubilization rates was however considerable. Best results were obtained at HRT of 9 h.

Table 5.15 : Percent VFA distribution at different HRTs.

Step in Research	HRT (h)	VFA (mg/L)	Acetic % VFA	Propion. %VFA	Iso-But. %VFA	N-But. %VFA	Iso-Val. %VFA	N-Val. %VFA
Step 4	9	52	80.2	10.0	2.2	2.5	4.1	1.0
	12	53	78.5	11.5	2.3	2.7	4.0	1.0
Step 5	9	49	81.3	8.3	2.2	2.5	4.7	1.0
	6	42	84.4	6.8	1.9	1.8	4.1	1.0

The VFA distribution patterns in all the reactors were very similar to the distribution obtained in step 3; under the condition of low mixing period (0.25 h/cycle). On the basis of the results, it can be concluded that VFA speciation was under the control of mixing regime and was not affected by the variation in HRT within the investigated range of 6 to 12 h.

5.3.4.d-Quality of the Fermented Wastewater - Effects of HRT

The quality of the raw wastewater changed as it was subjected to the fermentation process under various HRTs. The influence of HRT on the final characteristics of fermented effluent from the reactors is shown in Table 5.16. The quality characteristics of the wastewater important in biological nutrient removal; shown in Table 5.16 by the ratio of VFA/P_{Sol} and other ratios representing C/P and C/N, improved significantly during the fermentation process. The highest impact was observed on the ratio of VFA to phosphorus which increased about 10 fold in all reactors regardless of their HRT.

Fermentation in general enhanced the wastewater quality for the purpose of biological nutrient removal. However, variation in HRT did not influence the extend of improvements significantly. Similar values were resulted for the ratios of VFA/P_{Sol}, COD/P_{Sol} and COD/N_{Sol} at different HRT tested in steps 4 and 5 of the research. Variation of HRT from 12 h to 9 h in step 4, and from 9 h to 6 h in step 5 did not make a significant change in the mean values of these ratios, though total solubilization and VFA production in the reactor with the shortest HRT (6 h) was less than the other reactors. Proportionality of solubilization of phosphorus and nitrogen, with solubilization of carbon and VFA production is the reason for observing similar values for the above ratios.

Table 5.16 : Characteristics of raw and fermented wastewater (Impacts of HRT).

Step 4 (12 h vs 9 h) Parameters	W.W. Mean±SD	F1 HRT=9 h Mean±SD	F2 HRT=12 h Mean±SD
pH	7.6±0.2	7.1±0.2	7.1±0.1
Alkalinity as $CaCO_3$	296±24.6	340±26.5	340±26.2
VFA as HAc	3±3.0	49±14.9	50±14
HAc as %VFA	44.5±29.7	80±3.7	78±3.5
VFA/P_{Sol}	0.7±0.6 [a*]	10.5±2.4 [b]	10.5±1.7 [b]
COD_{Sol}/P_{Sol}	30.5±3.5 [a]	39.8±5.7 [b]	37±4.8 [b]
COD_{Sol}/N_{Sol}	3.7±0.4 [a]	5.4±0.7 [b]	5.2±0.6 [b]
SOC/N_{Sol}	0.9±0.1	1.4±0.2	1.4±0.1

Step 4 (9 h vs 6 h) Parameters	W.W. Mean±SD	F1 HRT=9 h Mean±SD	F2 HRT=6 h Mean±SD
pH	7.5±0.1	7.1±0.1	7.1±0.1
Alkalinity as $CaCO_3$	264±30.3	295±36.0	289±31.6
VFA as HAc	8±6.5	47±13.1	40±11.1
HAc as %VFA	75±19.4	81±5.3	84±5.7
VFA/P_{Sol}	1.4±0.8 [c*]	10.9±2.6 [d]	9.2±2.0 [d]
COD_{Sol}/P_{Sol}	30±7.5 [c]	41±5.7 [d]	39±6.9 [d]
COD_{Sol}/N_{Sol}	3.5±1.0 [c]	6.0±1.4 [d]	5.7±1.7 [d]
SOC/N_{Sol}	1.1±0.1	1.7±0.3	1.5±0.2

Note : Values of alkalinity, VFA and NH_3-N are reported in mg/L.
* : Non-similar letters in the superscript indicate a significant difference ($P<0.05$) between the means of each parameter during that specific step of the research.

5.3.4.e-Conclusion

The influence of HRT on acid fermentation of raw wastewater was less pronounced than that of SRT and pH. Reduction of HRT from 12 h to 9 hr did not affect total solubilization, total VFA production, specific rate of VFA production and distribution of VFA significantly. Total solubilization and total VFA production were significantly lower at HRT of 6 h as compared to HRT of 9 h, although the differences in the specific rates were not significant. Percent distribution of volatile fatty acids were also similar in HRTs of 6, and 9 h. On the basis of the results, it could be concluded that the optimum fermentation performance occurred at HRT of 9 h.

Fermentation of degritted raw wastewater at different HRT caused remarkable improvements in the characteristics of importance in biological nutrient removal. The extent of improvement, however, was independent of HRT within the investigated range.

5.3.5 FERMENTATION PROCESS : AN OVERVIEW

Detailed explanation of the research on acid fermentation of degritted wastewater under various environmental and operational conditions have been provided in the previous sections. This section, however covers only the overall summary of the fermentation process, and a discussion on the stability and reliability of the developed system (PAF; primary acid fermenter) with regard to its application as a part of the biological nutrient removal systems. Furthermore, the performance of the PAF fermenters is evaluated on the basis of the VFA production in these units (acid fermentation of raw wastewater), versus the VFA production reported for fermenters performing acid fermentation of primary sludge.

The conditions applied to acid fermentation of raw wastewater during steps 1 to 5 of this research and the results obtained on VFA production, percent distribution of VFA components, and the ratio of VFA/P_{Sol} under each set of conditions are presented in Table 5.17. The data are the result of the research over the period of 17 months (Oct. 30, 1993 to April 12, 1995).

The stability and reliability of the PAF reactors; as shown by the effluent average VFA concentration data was very steady. The fermenters, except under one set of conditions, were producing enough VFA to bring up the ratio of VFA/P_{Sol} into the range of 6 to 9 required for an efficient removal of phosphorus (cited in Barnard, 1993). The results also indicate that the developed system was stable under changing environmental and operational conditions. Consequently its application as an integrated part of a biological treatment system to enhance biological nutrient removal was found to be reliable.

Acetic acid is the best substrate for Bio-P bacteria and its presence in the influent to the anaerobic zone of biological phosphorus removal system is highly desirable. The results (Table 5.17) indicate that in acid fermentation of the whole wastewater the conditions are more favorable for the production of acetic acid than the conditions created in acid fermentation of primary sludge. The acetic acid content of VFA produced by acid fermentation of primary sludge has been reported to be in the range of 43% (Wentzel et al., 1988) and 55% (Randall, 1994). In contrast, the percent contribution of acetic acid in this research ranged from 78% to 96% under various operational conditions investigated except in the reactor operating with SRT of 4 days under the low pH condition (Reactor F3 in step 2).

Table 5.18 shows the VFA production observed in various lab scale, and in some full scale primary sludge fermenters. The VFA production is given as its equivalent concentration in the treatment plant influent. Comparison of the VFA values in Table 5.17 and Table 5.18 confirms that the PAF reactors were more efficient than the conventional static/complete-mix fermenters (on the basis of the equivalent concentration in the treatment plant influent). Their behavior approached the performance of complete-mix fermenter with thickener (Kalispel) only under the condition of low mixing period (0.25 h/cycle) at HRT of 12 h.

Table 5.17 : Summary of the results on acid fermentation of degritted raw wastewater under various environmental and operational conditions tested in this research.

Steps in Research	Reactor	SRT (d)	pH	Mixing (h/cycle)	HRT (h)	VFA as HAc (mg/L)	HAc as %VFA	VFA/P
1	F1	13	Natural	6	12	47	93	8
	F2	8		6	12	43	94	7
	F3	4		6	12	38	96	6.5
2	F1	13	6.1-6.4	6	12	32	87	6.9
	F2	8		6	12	29	88	6.3
	F3	4		6	12	4	41	0.9
3	F1	12	Natural	0.25	12	44	81	11
	F2	12		0.25	12	43	82	11
4	F1	12	Natural	0.25	9	49	80	10.5
	F2	12		0.25	12	50	78	10.5
5	F1	12	Natural	0.25	9	47	84	10.9
	F2	12		0.25	6	40	81	9.2

* The average ratio of VFA/P_{Sol} in the raw wastewater was in the range of 0.1 to 1.4.

Table 5.18 : SCVFA yields related to the quantity of primary effluent.

Treatment Plant	SRT/HRT (d/h)	Equiv. Plant Influent VFA as HAc (mg/L)	Reference
Kelowna, Canada (Static Fermenter)	19/14	21	Oldham & Abraham (1994)
Penticton, Canada (Complete mix fermenter)	7/17 (Ferm. only)	17	Oldham & Abraham (1994)
Kalispell, USA (Complete mix fermenter-Thickener)	12/28	58	Oldham & Abraham (1994)
Lab Scale, Univ. of BC, Canada	10/12	51	Elefsiniotis (1993)

5.4 IMPACT OF FERMENTATION OF RAW WASTEWATER ON BNR IN SBR SYSTEMS

The main objectives of this part of research were:

1- Exploration of the effects of the prefermentation of raw wastewater on biological nutrient removal in SBR systems.

2- Optimization of nutrient removal in the newly developed two-stage system of PAF-SBR; consisting of a fermenter and a conventional SBR.

Experiments on biological nutrient removal were conducted in four consecutive stages (see section 4.1.2) which will be discussed in order in the following sections.

5.4.1 STAGE 1 : USE OF THE CONVENTIONAL 8 h-CYCLE

The objective concerned with the effects of prefermentation of raw wastewater on biological removal of nitrogen and phosphorus in the SBR systems was accomplished in this stage.

Two parallel biological nutrient removal systems were operating during this period of research. One a conventional-SBR, comprised of only one reactor (B2), which was fed directly with degritted raw wastewater. The other, a PAF-SBR system consisted of a fermentation unit (F2) and a conventional-SBR (B1). In the latter system, degritted raw wastewater was first fermented in fermenter F2 (PAF), and the effluent from F2 (fermented wastewater) then was conveyed as feed to B1 to be treated for nutrient removal.

The BNR reactors (B1 and B2) were operating in conventional cycle period of 8 h (3 cycles/day). Each operational cycle during this stage included 20 min of fill

without mixing, 2 h of anoxic/anaerobic period with mixing, 4 h of aeration with mixing, 1 h and 20 min of settle followed by 20 min of decant.

The research in stage 1 began on Jul. 5, 1994 and finished on Jan. 14, 1995. The two parallel systems were compared as to their performances and stability of operation with respect to the influent variations. The detailed data related to reactors B1 and B2 are shown in Appendix B, Tables B1 and B2. Data on the raw and fermented wastewater can be found in Appendix A, Tables A1, A2 and A3 (notice the dates). The performance of biological nutrient reactors was evaluated on the basis of the data collected during the steady-state conditions taken on Aug. 1, 1994 to Jan. 14, 1995.

5.4.1.a-Phosphorus Removal

The behavior of the two parallel BNR systems with regard to phosphorus removal is illustrated in Figure 5.28. The figure shows the profile of the ortho-P concentration in the effluent from reactors B1 and B2 during the research period. Reactor B1, fed with the fermented wastewater was much more efficient in removing phosphorus than the reactor fed with the raw wastewater. The concentration of ortho-P in the PAF-SBR system effluent was mostly below 0.5 mg/L after achieving steady-state condition, while in the conventional-SBR the effluent concentration of ortho-P usually exceeded 1.5 mg/L.

The extent of phosphorus removal in both systems is described more clearly by the application of a frequency chart on the effluent concentration of ortho-P (Figure 5.29). It is observed that 50% of the samples taken from the PAF-SBR system had ortho-P concentrations $\leq$ 0.2 mg/L. About 83% of the samples had values less or equal to 1 mg/L in this system. In contrast, the effluent ortho-P concentrations corresponding to 50 and 80

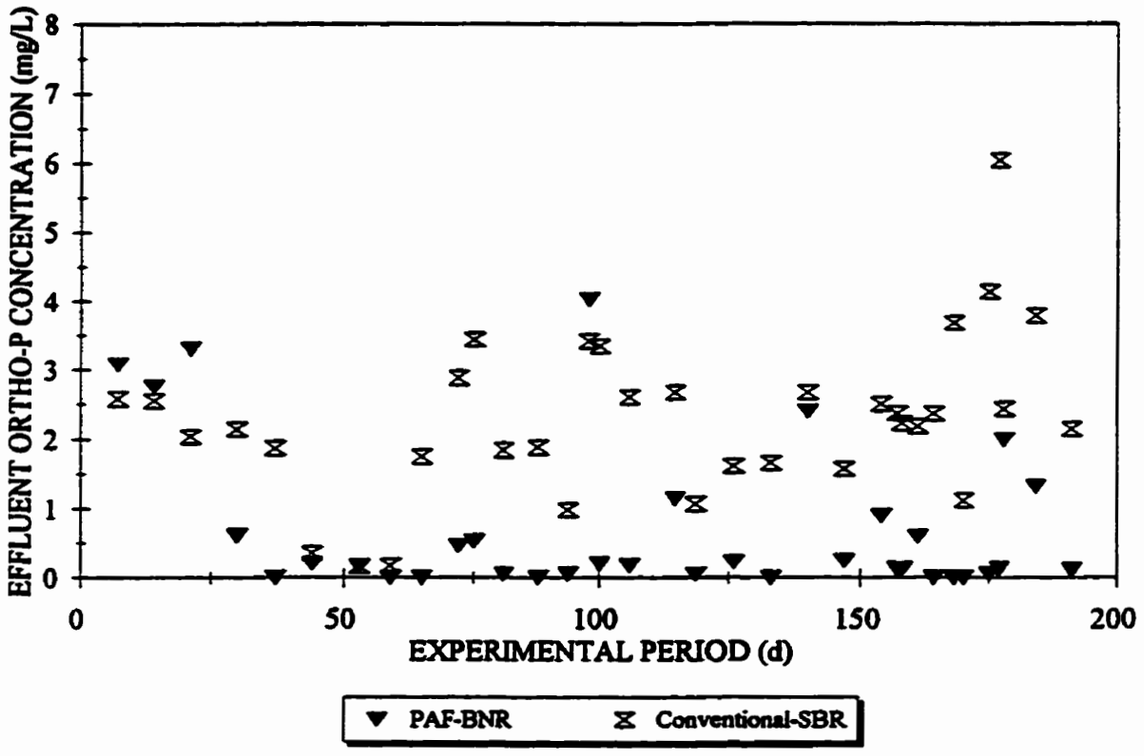

Fig. 5.28 : Ortho-P concentration in the final effluent from the two parallel BNR systems (stage 1; 8 h-cycles). Prefermentation of raw wastewater enhanced P-removal in PAF-SBR system. The conventional-SBR system fed directly with raw wastewater, was significantly less efficient with P-removal.

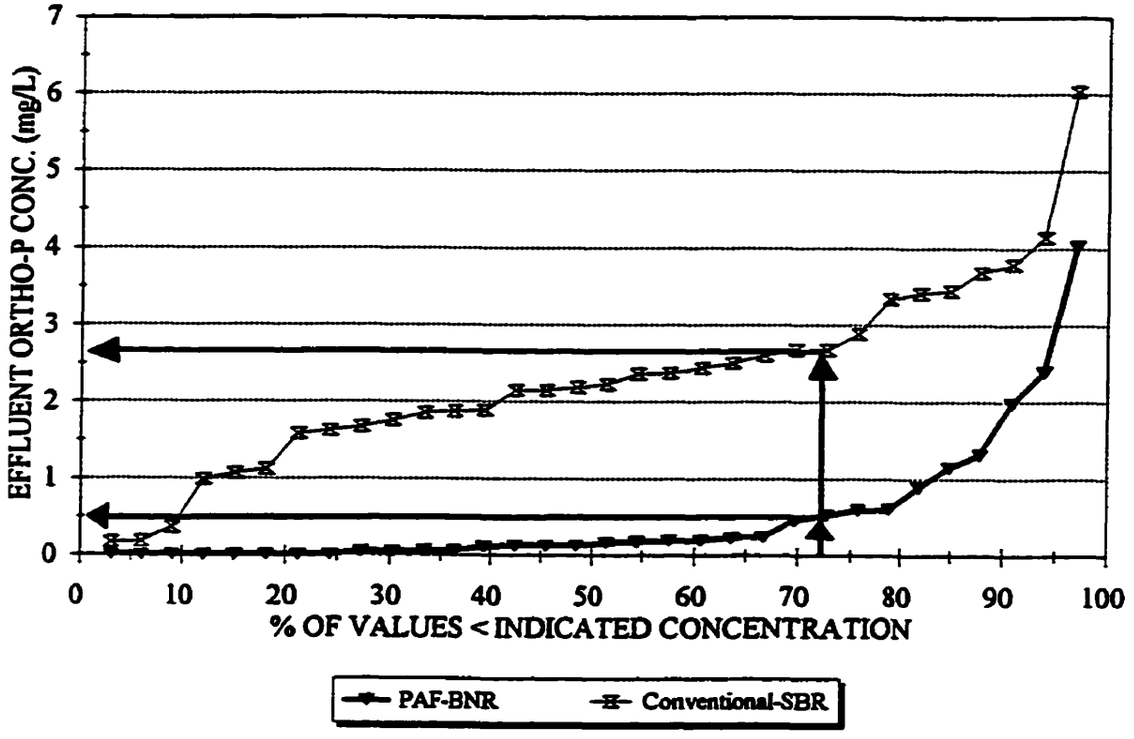

Fig. 5.29 : Frequency chart on the effluent ortho-P concentration of the BNR systems (stage 1). About 72% of the samples taken from the PAF-SBR systems had an ortho-P concentration ≤ 0.5 mg/L, while the corresponding concentration for the conventional-SBR was 2.6 mg/L.

percentile values were 2.2 mg/L and 3 mg/L, respectively in the conventional-SBR system. The difference observed between the systems in removing phosphorus was evaluated statistically and found to be significant ($P<0.01$).

In the PAF-SBR system, the characteristics of the raw wastewater changed during the fermentation process. Complex organic compounds were converted to VFA and other easily biodegradable compounds which play an important role in the enhancement of biological nutrient removal process. Figure 5-30 shows the changes that occurred in the ratio of VFA/ortho-P as the result of the fermentation process. The ratio, as depicted in Fig. 5.30, increased remarkably in the fermentation reactor. The mean concentration of VFA/ortho-P in degritted raw wastewater was 1.1 during this stage of research; indicating the inadequacy of VFA for an efficient removal of phosphorus. The ratio, however increased to 11.5 in the fermented wastewater (effluent from the fermentation reactor F2). As a result the feed (fermented wastewater) conveyed to reactor B1 (BNR reactor in the PAF-SBR system) carried higher concentration of VFA and a higher ratio of VFA/ortho-P than the feed (raw degritted wastewater) used for reactor B2 (conventional-SBR). This was the reason for observing a more efficient removal of phosphorus in the PAF-SBR system.

Track studies were conducted on the trends of change in ortho-P concentration in each BNR reactor (B1 and B2) during their operational cycle. The data on this part is summarized in Tables C1(a), C1(b), and C2, Appendix C.

The results of track studies are shown in Figures 5.31 and 5.32. Figure 5.31 presents the change in ortho-P concentration when the raw degritted wastewater was low in VFA content (3 mg/L), while Fig. 5.32 is the representative of the change in ortho-P

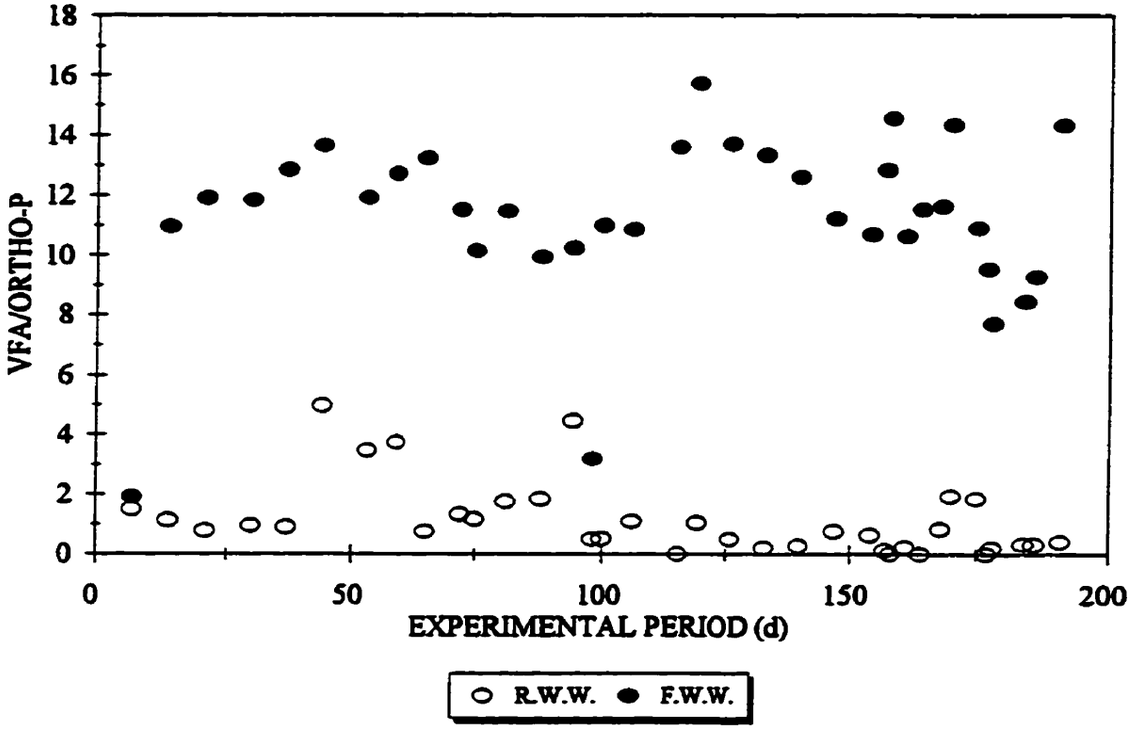

Fig. 5.30 : VFA/ortho-P ratio in the raw, and fermented wastewater (stage 1). The quality of the raw wastewater for BNR process was improved by acid fermentation. The ratio of VFA/ortho-P in the fermented wastewater was remarkably higher than that observed values in the raw wastewater.

concentration when the raw wastewater was relatively rich in VFA (about 16 mg VFA/L).

In both conditions the amount of phosphorus release and uptake in reactor B1 (fed with the fermented wastewater) was much higher than the values observed for B2 which was fed with the raw wastewater.

The type and concentration of substrate present for Bio-P bacteria play an important role in the amount of phosphorus that is released under anaerobic condition, and the amount of phosphorus that is uptaken in the following aerobic condition (Rensink, 1984; Manning, 1986; Abu-ghararah and Randall 1991; Randall et al., 1994). In the PAF-SBR system, prefermentation enriched the wastewater with the best quality substrate : acetic acid. Therefore the Bio-P bacteria, having a supply of VFA during anoxic/anaerobic period, released more phosphorus (primary release of phosphorus) to provide enough energy for uptake, and conversion of VFAs to PHA.

The released phosphorus plus the phosphorus already present in the feed were removed efficiently in reactor B1 during the aeration period of the cycle (Figures 5.31 and 5.32). The phosphorus uptake rate was not constant during the aeration period. It was reduced gradually following a first-order reaction (average rate constant $k = -0.045$) as the concentration of ortho-P in the reactor became limited.

Figure 5.33 shows the amount of P-release in reactor B1 as a function of VFA concentration present in its feed (effluent from fermenter; F2). The amount of P-release was directly proportional to the amount of VFA available for the Bio-P bacteria during the anoxic/anaerobic period. The result is in agreement with the results obtained by Iwema and Meunier (1985) and Kuba et al. (1994) who also observed an increase in P-release as the concentration of acetic acid increased in the environment.

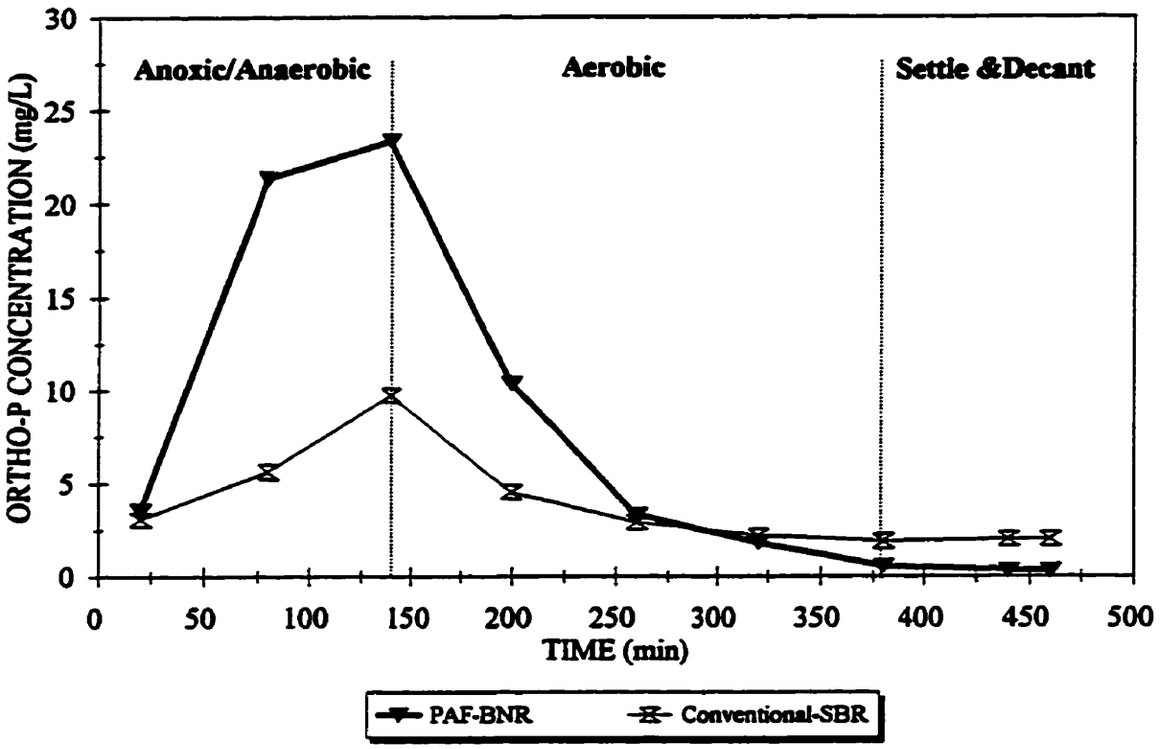

Fig. 5.31 : Profile of ortho-P concentration in the BNR reactors during operational cycles in stage 1 (typical for the days when the raw wastewater was low in VFA content). Due to the low concentrations of VFA in the raw wastewater, the amount of phosphorus release in the conventional-SBR system was low and not adequate to trigger an efficient removal of phosphorus in this system. Phosphorus release and uptake was high in the BNR reactor of the PAF-SBR system as sufficient quantity of VFA was present in its feed (fermented wastewater).

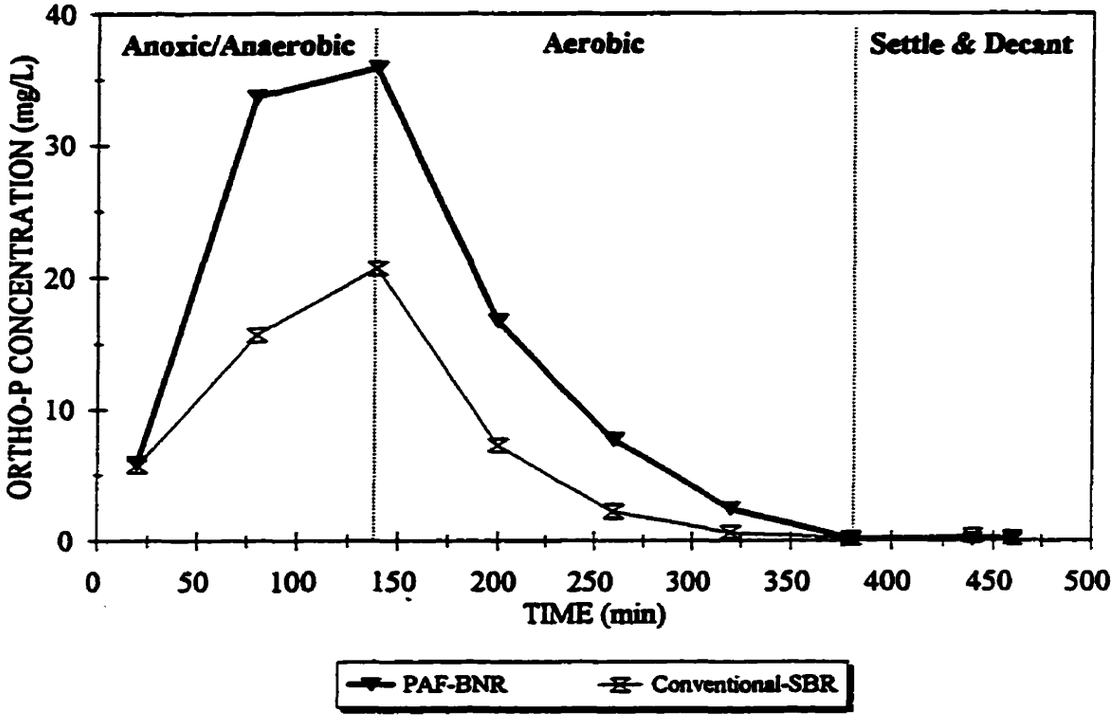

Fig. 5.32 : Profile of ortho-P concentration in the BNR reactors during operational cycles in stage 1 (typical for the days when the raw wastewater was rich in VFA content). Presence of VFA (about 16 mg/L) in the raw wastewater improved the performance of conventional-SBR system. Under such conditions, this system was as efficient as the PAF-SBR system in removing phosphorus.

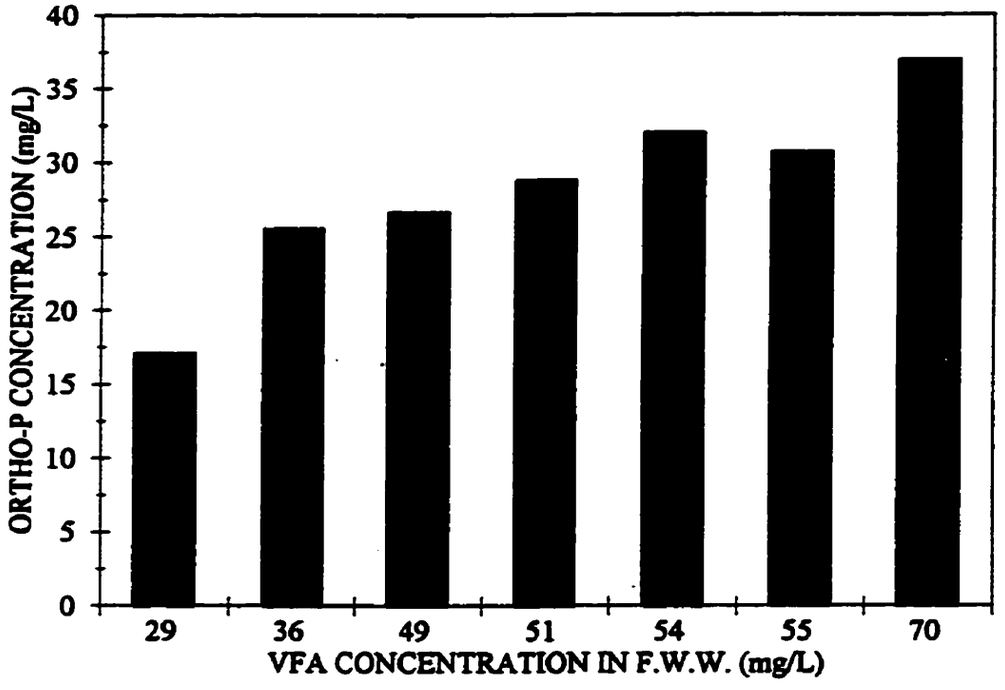

Fig. 5.33 : P-release in the BNR reactor of the PAF-SBR system-B1 (stage 1). The amount of phosphorus release was proportional to the amount of VFA in its feed (fermented wastewater).

The role of SCVFA in release and uptake of phosphorus could be realized if comparison is made among the curves related to the conventional-SBR in Figures 5.31 and 5.32. The amount of P-release and P-uptake in this reactor was dependent on the amount of VFA present in the raw wastewater. The release and uptake of phosphorus under the condition of low VFA (Fig. 5.31) was smaller than the release and uptake observed under the condition of high VFA concentrations (Fig. 5.32). In periods when the VFA content of the wastewater was considerable (about 16 mg/L), the conventional-system removed phosphorus as efficiently as the PAF-SBR system.

In summary the results demonstrated the vital role of SCVFA in biological nutrient removal process. The raw wastewater during this period of the research had a mean COD_{Tot}/P_{Tot} value of 77 (recommended value for high removal of phosphorus is 40:1). However, the conventional-SBR system did not remove phosphorus efficiently except on those occasions that the wastewater was rich in short chain volatile fatty acids. In other words, though enough organic carbon was present in the raw wastewater, the type of carbon was unsuitable for the Bio-P bacteria. Some production of VFA could have happened during anoxic/anaerobic period of cycle in conventional-SBR, but the resulting VFAs were not adequate to provide resources (PHA) for efficient uptake of phosphorus in the aerobic portion of the cycle. In contrast, in the PAF-SBR system, the lack of VFA in the raw wastewater was compensated within the fermentation unit, resulting in success of the following reactor in Bio-P removal process.

5.4.1.b-Anoxic/Anaerobic Period

The effluent quality from the two-stage BNR system (PAF-SBR), shown in Fig. 5.28 deteriorated occasionally and its phosphorus content exceeded even the level of 1 mg ortho-P/L. Deterioration could have been caused by a very dilute wastewater on those occasions or/and a very long period of anaerobic condition, both resulting in secondary release of phosphorus and poor removal efficiency. A search through data on raw wastewater characteristics confirmed the concern about dilute wastewater. The wastewater associated with those occasions of low removal was weak in suspended and dissolved organic matter (SS<200 mg/L and SOC<40 mg/L).

Dilute wastewater could have reduced the efficiency of phosphorus removal through the following sequence of events:

1. High quantity of VFA could not be produced during acid fermentation of dilute raw wastewater in fermenter F2. Thus the effluent from this reactor was not carrying adequate amount of VFA to the biological nutrient removal reactor (B1).
2. Inadequate amount of VFA in the feed, and long anoxic/anaerobic period could have triggered the secondary release of phosphorus in B1 which impaired Bio-P removal significantly.

In order to investigate further the subject of secondary release of phosphorus, and to improve the performance of the Bio-system even in the periods when the wastewater is dilute, several detailed track studies were performed on behavior of ortho-P and VFA concentration during the anoxic/anaerobic part of the operational cycle (data are tabulated in Table C6 and C7 in Appendix C).

The trends of VFA and acetic acid uptake are presented in Figure 5.34. No mixing

was provided during the fill period and the biochemical reactions were minimized by preventing the contact between the settled biomass and the incoming feed in an unstirred environment. At the end of the fill period, mixing was applied, and was kept through the remaining of the cycle period up to the settling time. Almost all of the VFA were uptaken during the first 50 minutes of the anoxic/anaerobic period. The mean specific rate of VFA uptake was 28.5 mg VFA/g VSS.h (equivalent to 27.1 mg of VFA as acetic acid/g VSS.h) as compared to the VFA production rates which were in the range of 1.2-2.9 mg/g VSS.h (See Sections 5.3.1-5.3.4). The comparison shows the significant difference that exists between the rates of the activities of the Bio-P bacteria, and the fermentative bacteria.

The VFA production rates in this research were obtained under controlled laboratory conditions favorable for the fermentative bacteria. In real world, some fermentation of organic compounds occurs in the anaerobic zone of Bio-P removal systems, but the conditions are usually not as favorable. As a result the VFA production rate would probably be lower than those obtained in this research. Hence the difference between the rates of production and uptake of VFA becomes a more critical issue.

The dichotomy of the rates is most probably the major reason for unreliable performance of P-removal in those treatment plants that anaerobic zone is the sole means of production of VFA for the Bio-P bacteria. Because of the differences in the rates of activities of the fermentative bacteria and the Bio-P bacteria, optimization of design and operational conditions in such systems is very difficult if not impossible. The fermentative bacteria, having slow rate, require long HRT for the conversion of complex organic matter to volatile fatty acids. In contrast, the Bio-P bacteria are very fast in removing VFA, and their efficiencies in removal of phosphorus would be impaired by long HRTs, due to the

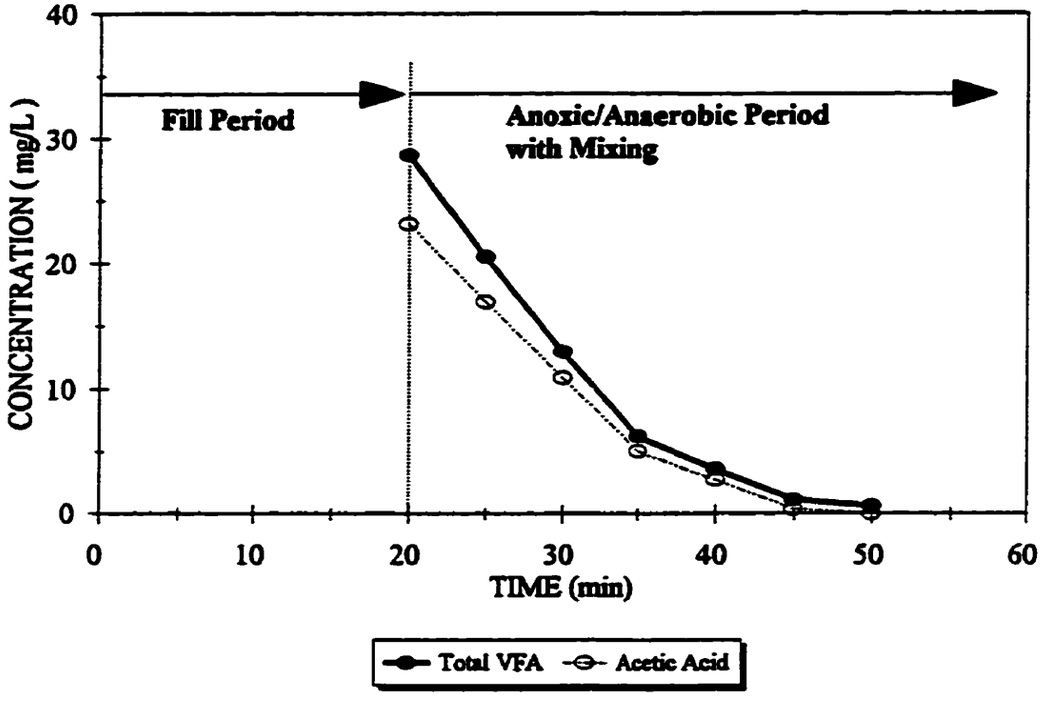

Fig. 5.34 : VFA-uptake in B1 during the initial anoxic/anaerobic period of 8 h operational cycles (stage 1). The VFAs were all removed during the first 50 min of this period.

phenomenon of secondary phosphorus release.

The patterns of phosphorus release in the two Bio-P removal systems are shown in Figure 5.35. The trend of phosphorus release in B1 (fed with fermented wastewater) was steep in the initial 50 minutes of the anoxic/anaerobic period and then diminished significantly during the rest of this period. Comparison of the results of VFA uptake and phosphorus release (Figures 4.34 and 4.35) in the PAF-SBR system indicates that the higher rate of P-release (primary release) occurred in the same time interval that VFAs have been uptaken. The average rate of P-release during this period was 19 mg ortho-P/g VSS.h. The rate afterwards decreased to an average of 1.8 mg ortho-P/g VSS.h (secondary release). High initial release of phosphorus provides energy for the basal requirement of the cells, and for the uptake of substrate (VFA) and storage of them in the form of polyhydroxyalkanoates. After volatile fatty acids were all taken up, the P-release did not stop and continued with slower rate due to the energy requirements of the microorganisms under anaerobic environment.

The rate of release of phosphorus in a conventional-SBR was relatively slow, uniform and almost parallel to the rate of secondary release in the PAF-SBR system. The trend of release did not show any distinct bend (Fig. 5.35); indicating the absence of adequate amount of VFA in the feed to this reactor. The rates of primary and secondary release of phosphorus could not be differentiated in conventional-SBR, as the production and uptake of VFA were occurring concurrently.

Secondary release of phosphorus deteriorates the efficiency of Bio-P removal systems and should be prevented as much as possible. One method is based on optimization of the initial anoxic/anaerobic period of the operational cycles. In a

conventional SBR system, this optimization is not practical , as the time interval between primary and secondary releases of phosphorus is not distinguishable (Fig. 5.35). However, in two-stage system (PAF-SBR), the time of the depletion of VFA and the start of the secondary release is clearly distinct. As the result the anoxic/anaerobic timing in these systems could be controlled to reduce the excess release of phosphorus. According to the results, the anoxic/anaerobic period of 2 h and 20 min for the PAF-SBR system was too long because it induced some secondary release of phosphorus.

Overall, secondary release of phosphorus aggravated with the weak wastewater was the reason for observing deterioration of final effluent quality in PAF-SBR system on certain days of the experiment. Anoxic/anaerobic period of the BNR system with the prefermentation step should be reduced from 2 h and 20 min to about 45 minutes (including the fill period) to match the time period required for the uptake of VFA, and to prevent any secondary release of the phosphorus. This is equivalent to 20% decrease(1 h and 35 min) in total 8 h cycle period in the SBR systems. In continuos-flow systems this reduction accounts for a decrease of one and a half hour in the HRT of anaerobic zone.

In summary, it is evident that the contents of VFA in the influent to Bio-P removal systems can influence the sizing of the units due to its impact on the required HRTs. Thus, it seems necessary to consider the information on this parameter in the design of such systems.

5.4.1.c-Nitrogen and SOC Removal

The performance of the two parallel biological nutrient removal systems in removing nitrogen is observed in Figure 5.36. Nitrogen removal in both systems

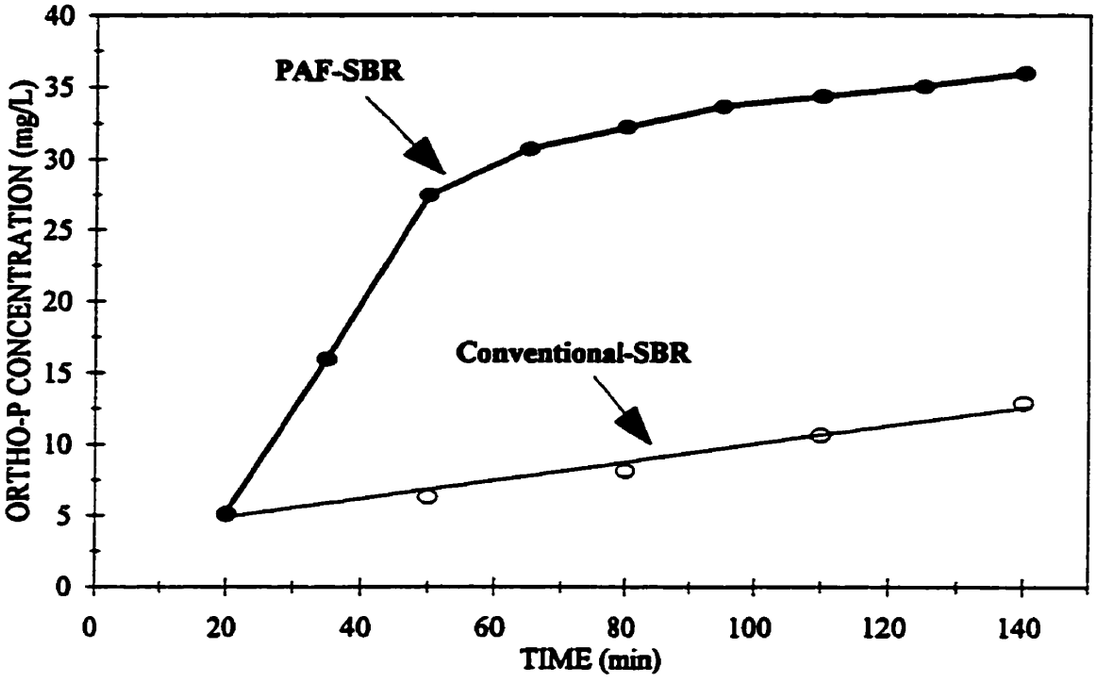

Fig. 5.35 : P-release during the initial anoxic/anaerobic period of 8 h operational cycles (stage 1). The high initial rate of phosphorus release in B1 corresponds to the time period of VFA uptake (See Fig. 5.34). The rate of phosphorus release in the conventional-SBR (B2) was slow, uniform and almost equal to the rate of release in B1 when all the VFA have been used up.

depended upon the strength of the incoming wastewater. The data on soluble organic carbon (SOC) of the degritted raw wastewater is presented in Figure 5.37. The percentages of nitrogen removal (Fig. 5.36) followed the same pattern of change that was observed for SOC content of wastewater. During the initial period of the experiment, when the wastewater was stronger, more nitrogen was removed as the result of presence of higher amount of carbon for the denitrification process.

The mean percentage of total soluble nitrogen removal at steady-state conditions was 46% for PAF-SBR system, and 40% for the conventional-SBR. Higher percentage removal in the former system is the result of higher concentration of available SOC produced in the prefermentation step. Total nitrogen concentration in the effluents of B1 and B2 were 17.5 and 18.5 mg/L respectively; about 90% was comprised by the oxidized forms of nitrogen (NO_3+NO_2). Mean ammonium content of the effluents was negligible.

Instantaneous denitrification, and the denitrification that occurred during the initial anoxic period of each cycle were primarily responsible for the removal of nitrogen. Nitrogen removal in both systems was limited by lack of carbon for the denitrification process, and the limited total amount of time that was allocated for denitrification in each operational cycle.

Profiles of SOC concentration in BNR reactors-B1 and B2, during 8 h operational cycles are presented in Figure 5.38 on the basis of the data in Appendix C, Tables C1(a) and C1(b). The average concentration of SOC remaining in the effluent of these reactors at the end of each cycle was 18 mg/L in B1, and 19 mg/L in B2. These values represent the amount of SOC that has not been biodegraded by the biomass of each reactor. Considering the initial dilution of the feed with the remaining volume of the liquid from the

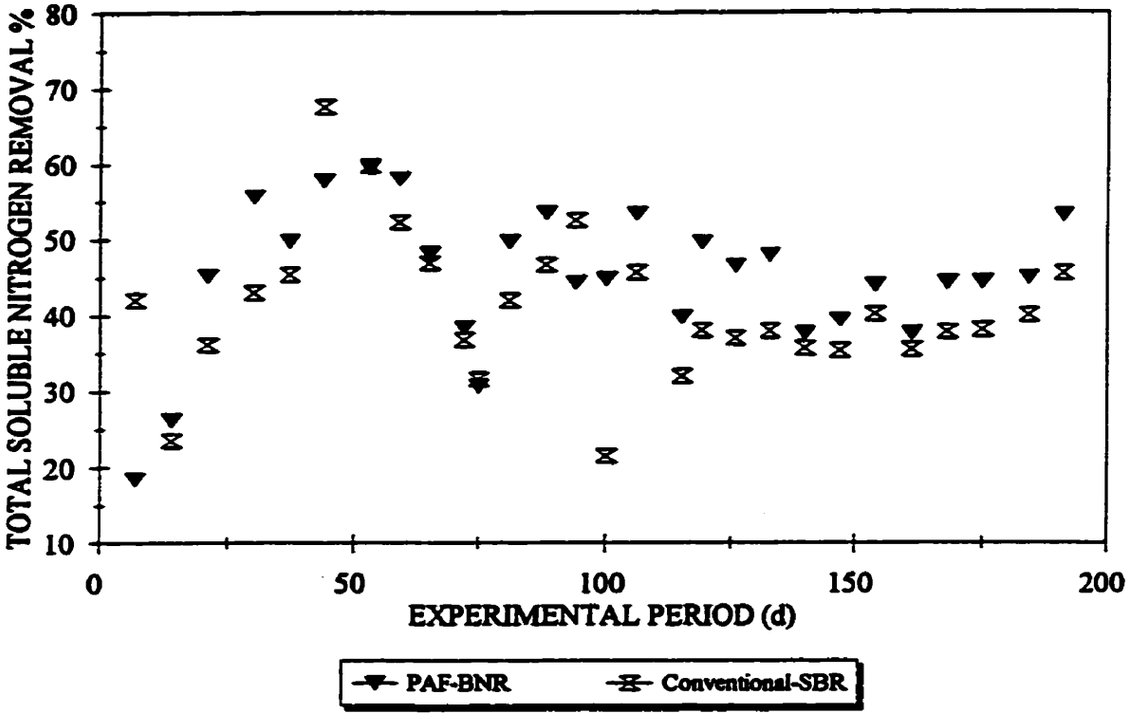

Fig. 5.36 : Percentage of nitrogen removal (stage 1). Nitrogen removal in both systems followed a pattern which was influenced by the pattern of change in the SOC concentration of the raw wastewater (Fig. 5.37).

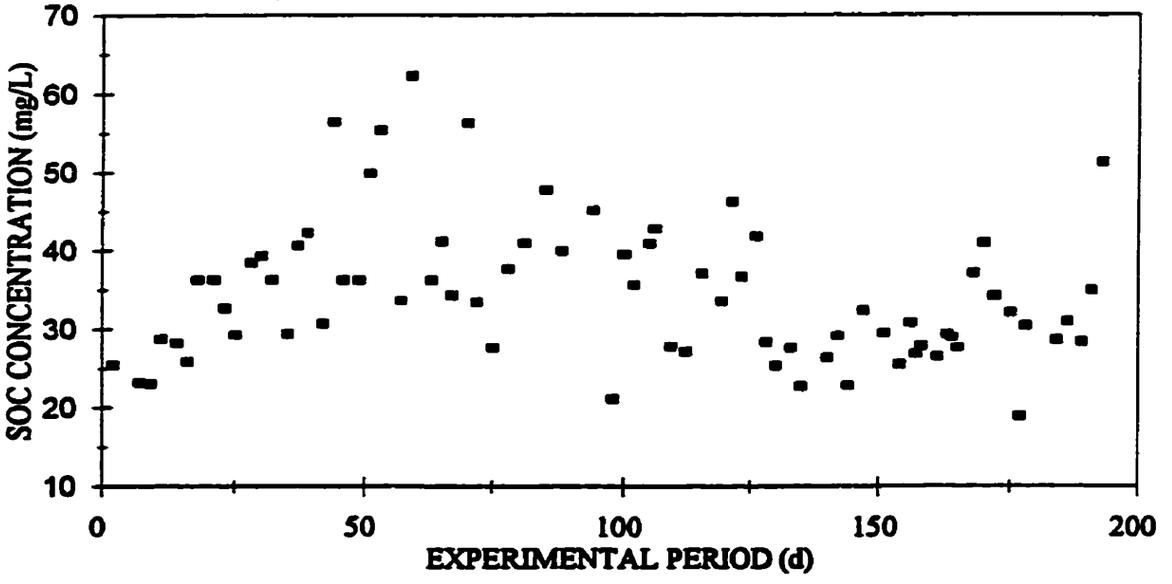

Fig. 5.37 : Variation in SOC concentration of the degritted raw wastewater (stage 1).

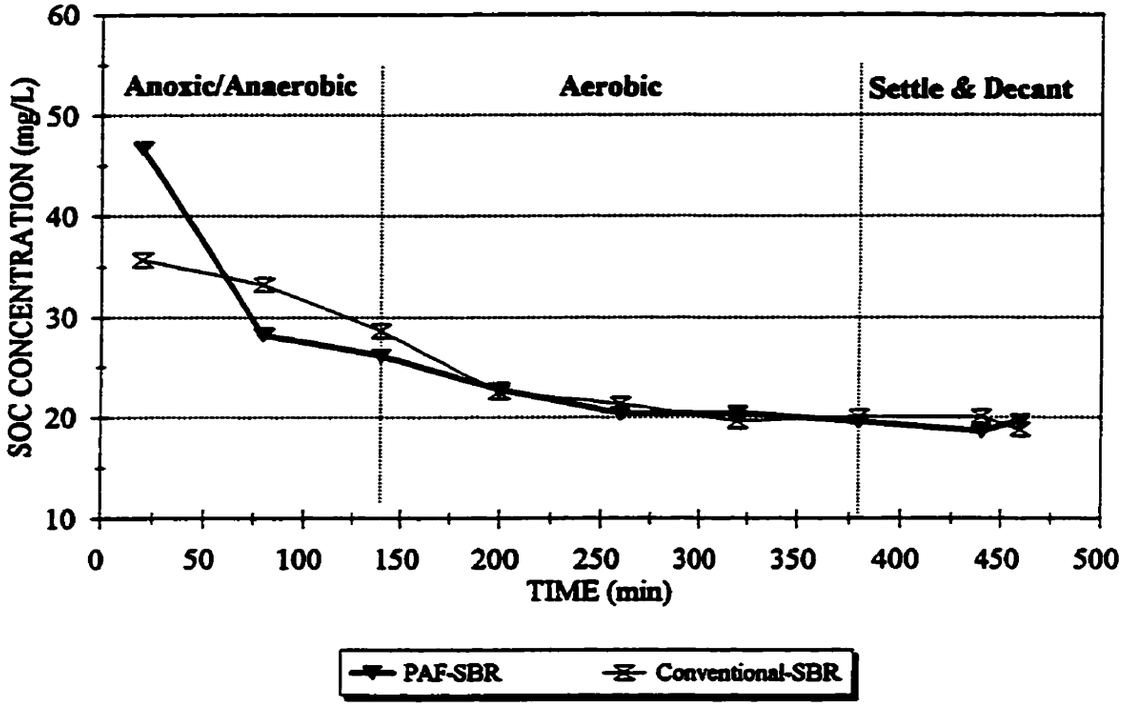

Fig. 5.38 : Change in SOC concentration of the BNR reactors during 8 h operational cycles (stage 1). All biodegradable SOC was removed within the first 4 h of each cycle.

previous cycle, it was realized that about 77% of the biodegradable SOC in reactor B1 (belonging to the PAF-SBR system), and 65% of the SOC in reactor B2 were consumed during the initial anoxic/anaerobic period, and the remaining amounts were mostly uptaken for the aerobic metabolism of microorganisms during the first two hours of aeration. Consequently, any instantaneous denitrification would have been mainly dependent on the endogenous carbon resources. Summarizing the results, it can be concluded that the lack of availability of external organic carbon could have restricted the extent of denitrification process in both BNR systems.

5.4.1.d-Final Effluent

The characteristics of feed, and final effluents in the parallel biological nutrient removal systems tested in stage 1 are presented in Table 5.19.

The fermented wastewater (F.W.W.) served as feed in the BNR reactor of PAF-SBR system was stronger in soluble components than the raw wastewater; R.W.W. (feed to the conventional-SBR). However with regard to the suspended solids, it contained 60% less SS than the raw wastewater. The fermentation unit in the PAF-SBR, in fact, acted as a sedimentation, and a fermentation tank. The efficiency of this reactor in removing suspended solids of the raw wastewater was equivalent to an efficiently designed and operated primary sedimentation tank. A well designed primary sedimentation tank will remove from 50 to 70% of the suspended solids (Metcalf and Eddy, 1991). Removal of SS from the wastewater reduces the load to the following BNR reactor. Moreover, the solubilization and fermentation of organic compounds in the fermentation unit caused an increase in the soluble components, especially in VFA concentration. Alkalinity, SOC,

VFA, and different forms of soluble nitrogen and phosphorus were present at higher concentrations in the fermented wastewater than the raw wastewater (Table 5.19). Total phosphorus and total nitrogen of fermented wastewater, however, showed a reduction due to the removal of suspended solids in the fermentation unit.

The effluent quality of the two BNR reactors indicated that the PAF-SBR system was producing a better quality effluent than the conventional-SBR system. The BNR reactor of PAF-SBR system, in spite of stronger feed (F.W.W) received, demonstrated higher efficiencies in treatment of suspended solids and different forms of nitrogen and phosphorus as compared to the conventional system. The differences observed in the mean values of different forms of nitrogen in the effluent of the two systems were not statistically significant showing the similarity of the behavior of two systems in removal of nitrogen. However the differences in the removal efficiencies of suspended solids and different forms of phosphorus were considerable and statistically significant.

The average concentration of suspended solids in the final effluent of the two-stage SBR was 11 mg/L, while in the conventional-SBR system it averaged 19 mg/L. Judging on the basis of the average concentrations, suspended solids were removed efficiently in both BNR reactors. However, the stability and consistency of the SS removal were not the same in the two compared systems. As verified by the standard deviation, Table 5.19, the concentration of suspended solids in the effluent of the conventional-SBR system was highly variable. The concentration ranged from 5 to 51 mg/L with the mean concentration of 19 mg/L and standard deviation of 13.1 as compared to mean suspended solids concentration of 11 mg/L with standard deviation of 3.8 observed for the PAF-SBR system. The highly variable SS in the effluent of the conventional system was due to the

Table 5.19 : Characteristics of the feed and the final effluent from the two parallel BNR systems (8 h-cycle).

Parameter	R.W.W. Mean±SD	F.W.W. Mean±SD	Effluent (PAF-SBR) Mean±SD	Effluent (Conventional-SBR) Mean±SD
pH	7.1±0.1	7.0±0.1	7.7±0.3	7.7±0.2
Alkalinity as $CaCO_3$	340±40.2	389±44.4	224±48.1	198±47.4
SS	213±62.8	85±16	11±3.8	19±13.1
SOC	35±9	56±9.2	18±2.9	19±3.5
VFA	3.7	47±11.2	-	-
PO_4^{-3}	3.5±0.5	4.2±0.6	0.5 [a*]	2.3±1.2 [b]
P_{Sol}	4.0±0.7	4.5± 0.6	0.6 [a]	2.6±1.3 [b]
P_{Tot}	5.9±0.8	5.5± 0.7	0.9 [a]	2.8±1.1 [b]
NH4-N	26±3.2	28±3.1	< 0.5	< 0.5
(NO_3+NO_2)-N	0.00	0.00	15±2.1 [a]	16±2.7 [a]
Soluble-N	31±3.8	32±3.7	17±2.5 [a]	18±3.2 [a]
Total-N	39±4.4	37±4.2	17.5±2.6 [a]	19±3.3 [a]

Note : All values are expressed in mg/L, except pH.
SD : Standard Deviation of the data
* : Non-similar letters in the superscript indicate a significant difference between the means ($P<0.01$).

changes which occurred in the biological characteristics of sludge. Periodic proliferation of filamentous bacteria caused the loss of solids through the effluent and inconsistent efficient removal of suspended solids. A discussion on some characteristics of the of sludge of the two systems such as settleability will be presented later in a separate section.

In summary, a substantial improvement was observed in the quality of the treated effluent from the PAF-SBR system. The success was related to the fermentation of raw wastewater prior to its treatment for nutrient removal.

5.4.1.e-Conclusion

Prefermentation of raw wastewater enhanced nutrient removal in a two-stage SBR system. Enhancement was due to the presence of easily biodegradable compounds (VFAs) generated during the fermentation process.

The conventional operational cycle period of 8 h (with 2 to 3 h initial anaerobic condition) which is common in SBR systems removing nutrients, was proved to be too long if the wastewater is already rich in VFAs (fermented wastewater). The long initial anoxic/anaerobic portion of the cycle should be shortened to 40-50 min in order to prevent secondary release of phosphorus.

Nitrogen removal in both SBR systems; with and without a prefermentation step, was constrained by lack of availability of organic carbon for the denitrification process and limited anoxic time period of operational cycles

5.4.2 STAGE 2 : IMPROVEMENT IN P-REMOVAL (6 h-CYCLE, HRT = 9 h)

In previous stage of the research with 8 h operational cycle, it was demonstrated that an initial anoxic/anaerobic period of 2 h and 20 min deteriorated the effluent P-removal efficiency in the PAF-SBR system, thus should be reduced. Reduction to 45 min would be expected to reduce any chance of secondary release of phosphorus.

In this stage of the research, the total cycle period of the BNR reactors (B1 &B2) was reduced to 6 h, allowing the reactors to operate with 4 cycle/day and at HRT of 9 h. Each cycle was composed of 20 min of fill without mixing, 25 min of anoxic/anaerobic with mixing, 3 h and 40 min of aeration with mix, 1 h and 15 min of settle and finally 20 min of decant. In this stage a major reduction in anoxic/anaerobic time period of each cycle took place. The configurations of the parallel BNR systems were similar to those in the previous stage. The PAF-SBR system was composed of the BNR reactor B1, and the fermenter F1 which was running at 4 cycle/day at the time. The parallel system, conventional-SBR, did not have the fermentation step and consisted of only B2, the reactor for biological removal of nutrients.

The objective was to improve phosphorus removal, by investigating the efficiency and stability of the process under the new operational cycle conditions where the anaerobic period of the cycle was reduced to 45 min.

The experimental work started on Jan. 15, 1995 and continued up to Mar. 13, 1995. The performance evaluation of the reactors was based on their operation during the steady-state condition (Jan. 25, 1995 to Mar. 13, 1995). The data related to BNR reactors are summarized in Tables B1 and B2 in Appendix B, and the data on raw, and fermented wastewater (effluent from F1) are presented in Appendix A; Tables A1 and A2.

5.4.2.a-Nutrient Removal

The discussion of the effects of the new operational cycle on the removal of nutrients requires some information about the characteristics of the raw wastewater which has been used during the current, and previous stage of the research. Figure 5.39 shows the variations in the suspended solids and the SOC concentration of the raw wastewater. The figure clearly illustrates that during current stage of the research (stage 2), there also were periods in which the incoming raw wastewater was as dilute as during some periods in previous stage (stage 1). During dilute condition periods, the raw wastewater had suspended solids and SOC concentrations of less than 200 mg/L and 40 mg/L, respectively. Dilute wastewater initiates the chain action of reduction in the VFA production, secondary release of phosphorus and finally deterioration of the excess P-removal. During the previous stage, the impact of dilute wastewater was compounded by the long period of anaerobic conditions within the operational cycle, such that the two parameters together impaired the performance of BNR reactors on occasions that the wastewater was dilute. In contrast, deterioration of P-removal in PAF-SBR system was not observed during this stage of the research. The system was continuously producing high quality effluent regardless of the strength of the wastewater. The reasons for the success of the system, as will be discussed in details, were: 1) fermentation process which enriched the raw wastewater with the VFAs, and 2) reduction in the length of the anaerobic period which controlled secondary release of phosphorus.

Figure 5.40 shows the profiles of the VFA concentration in the raw, and fermented wastewater. The fermented wastewater carried significantly higher concentration of VFA in comparison to the raw wastewater. The variation observed in the FVA content of the

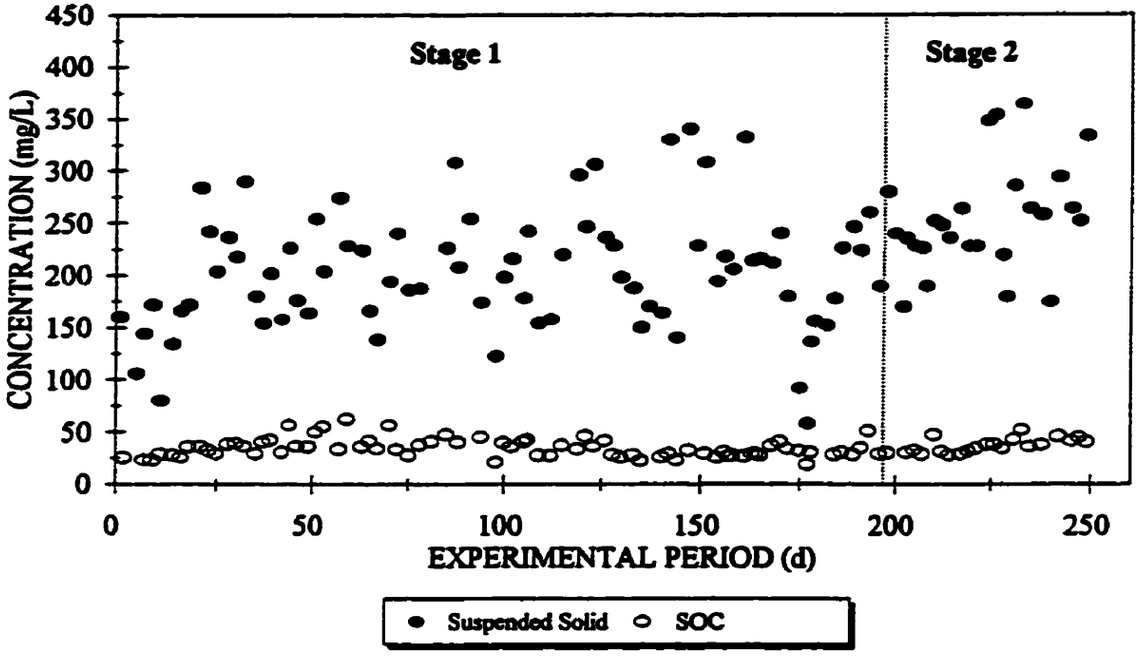

Fig. 5.39 : Variation in SS and SOC concentrations in the raw wastewater (stages 1 & 2). During stage 2 of the research, there were also periods in which the raw wastewater was as weak as those occasions observed during stage 1.

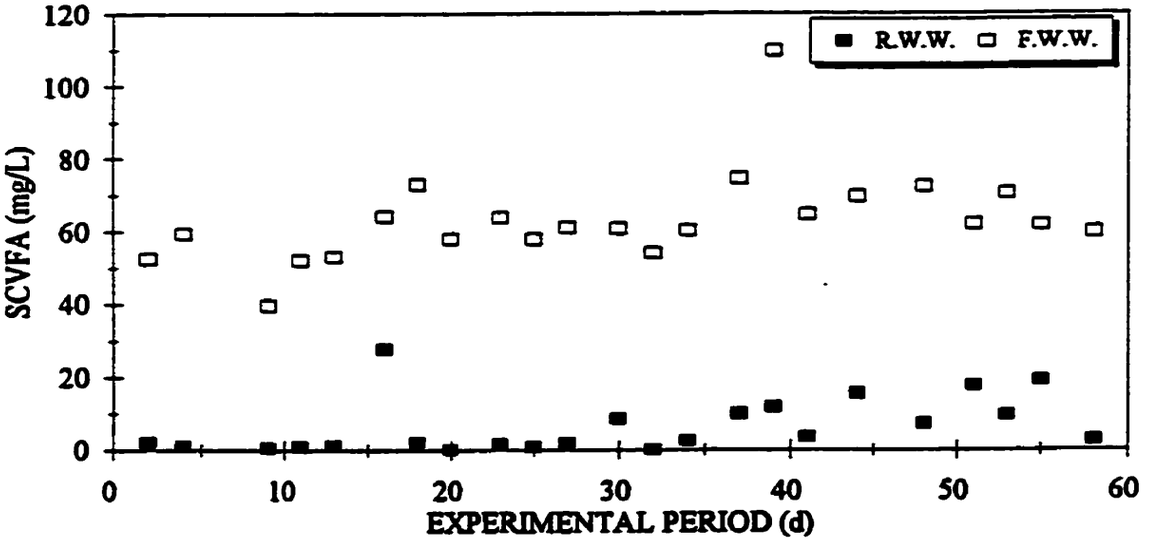

Fig. 5.40 : Profile of SCVFA in the raw and fermented wastewater (stage 2). The concentration of VFA in the fermented wastewater was significantly higher than the concentration in the raw wastewater.

fermented wastewater was due to the variation in the strength of the incoming wastewater. Regardless of the variation in the raw wastewater, the fermenter in the PAF-SBR system always acted as a safety valve for the operation of BNR reactor. The fermentation unit, even on the days that the system received dilute wastewater, produced an adequate supply of VFA because of the solids remained in the reactor from the previous days (SRT >> HRT).

The raw wastewater used during this stage, as shown in Fig. 5.40, was not consistent in its VFA content. The VFA concentration was almost negligible during the first 35 days of the experiment. However, in the last portion of the experiments which was in late February and early March, the raw wastewater was delivered partially fermented, such that the concentration of VFA on some days was as high as 20 mg/L.

The profile of the concentration of ortho-P in the raw wastewater and in the effluent of the two parallel BNR systems are presented in Figure 5.41. The lower concentration of ortho-P in the effluent (from BNR reactors) as compared to the raw wastewater indicates that the Bio-P bacteria were present in both systems, but their efficiencies in removal of phosphorus in the two systems were not comparable. In PAF-SBR system, the excess removal of phosphorus by the Bio-P bacteria produced an average effluent concentrations of 0.2 mg/L and 0.3 mg/L for the ortho-P and soluble-P, respectively. The mean concentration of soluble phosphorus was reduced from 4.7 mg/L in the raw wastewater to 0.3 mg/L in the final effluent of PAF-SBR; corresponding to an average removal efficiency of about 94% in this system. During this stage of the research, the ortho-P concentration of the final effluent in the PAF-SBR system was always less than 1 mg/L, while in the previous stage (8 h cycle), the concentration exceeded 1 mg/L

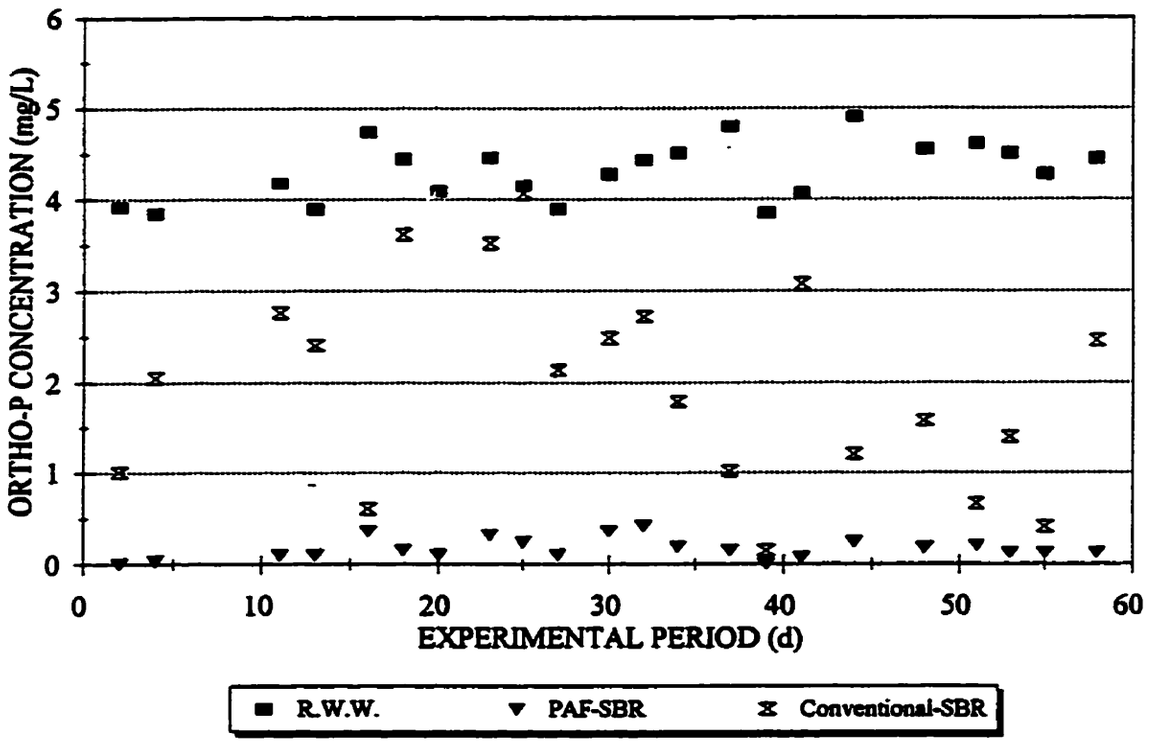

Fig. 5.41 : Profile of ortho-P concentration in the raw wastewater and effluent from the BNR systems (stage 2). Excess biological phosphorus removal was occurring in both systems. The efficiency of phosphorus removal, however was not the same.

on the days that the wastewater had low carbon content. The observed improvement was the result of application of the 6 h operational cycle with a short anaerobic period.

The process of biological phosphorus removal, however was not very efficient in the conventional-SBR system. On the average about 47% of the soluble influent phosphorus (2.2 mg/L) was removed by the biomass in this reactor which is 50% of the phosphorus removal efficiency in the PAF-SBR system. According to Metcalf and Eddy (1991), 10 to 30 percent of the influent phosphorus is removed during secondary biological treatment. Additional uptake of phosphorus in excess of the demands for normal cell maintenance and synthesis is required to achieve low effluent concentration levels. The mean concentrations of ortho-P and soluble-P in the effluent of this system were 2 mg/L and 2.5 mg/L, respectively. Phosphorus removal in the conventional-SBR showed an improvement during the last 25 days of the experimental period (Fig. 5.41). This time period, as can be seen in Figure 5.40, coincided with the time period of observing high concentration of the VFA in the raw wastewater. Consequently, higher removal of phosphorus during this specific period was the result of the presence of VFA in the raw wastewater.

Nitrification in both BNR reactors was almost complete, leading to the NH_4-N concentration of less than 0.5 mg/L in the effluents of the two BNR systems. Soluble nitrogen removal averaged 50% in the PAF-SBR and 42% in the conventional-SBR. The nitrogen removal efficiency was calculated on the basis of total soluble nitrogen concentrations in the feed to the BNR reactors, and in the effluents from these reactors. Total soluble nitrogen in the effluent of B1 averaged 20 mg/L; about 87% being oxidized forms of nitrogen (NO_3-N and NO_2-N). In contrast, the mean concentration of total

soluble nitrogen in the effluent from the conventional-SBR was 23 mg/L including 85% oxidized form of nitrogen. During steady-state condition, the total nitrogen content of the effluents from B1 and B2 averaged 21 mg/L and 27.5 mg/L, respectively.

5.4.2.b-Track Studies

The trends of change in ortho-P, NOx-N, and SOC concentration of BNR reactors (B1 & B2) were investigated to demonstrate the behavior of the systems during the new operational cycle of 6 h.

The results of the ortho-P and NOx-N studies are collectively shown in Figure 5.42, and the outcome obtained for SOC is presented in Figure 5.43. These figures which will be discussed in the following sections are based upon the data in Appendix C, Tables C3(a) and C3(b).

5.4.2.c-Phosphorus Profile

Phosphorus was released in reactor B1 during the initial 45 min of the operational cycle when the reactor was experiencing the anoxic/anaerobic conditions (Fig. 5.42). The high quantity of release in this reactor was due to the presence of VFA in the fermented wastewater which averaged 38 mg/L during the period of track studies. The specific rates of VFA uptake and P release in the last 25 min of anoxic/anaerobic period (when mixing was provided) were 22 mg VFA/ g VSS.h (equivalent to 21 mg of acetic acid) and 16 mg of ortho-P/g VSS.h, respectively. On the average 1 mg of phosphorus was released during uptake of 1.4 mg/L of SCVFA. This is equivalent to the molar ratio of 0.7:1 for the VFA uptake (as acetic acid)/ortho-P release. The molar ratio obtained in track studies

of the previous stage of the research (8 h cycle) was 0.75:1. The ratio of VFA uptake/P-release is not a constant value and varies considerably depending upon the conditions of the experiments, type of substrates present, and the origin and type of sludge. Some of the reported values for the molar ratio of SCVFA decrease to phosphate increase in bulk solution were: 0.7:1 (Arvin, 1985; Comeau et al., 1986), 1:1 (Fukase et al., 1982; Wentzel et al., 1985), and 1.3:1 and 3.4:1 (Mino et al., 1987). The ratios obtained in this research are similar to the ratio reported by Arvin (1985) and Comeau et al. (1986).

Phosphorus uptake occurred during the first 3 h of aeration. The P-uptake rate was not constant and decreased as the aeration proceeded. The behavior of phosphorus uptake in this stage was similar to the behavior observed during the aeration period of stage 1 (Figures 5.31 and 5.32). The highest uptake rate occurred in the first hour of aeration with an average specific rate of 5.7 mg ortho-P/g VSS.h which then diminished to 2.4 mg ortho-P/g VSS.h in second h of aeration. The slowest rate of P-uptake was observed in the 3rd hour of aeration and was equal to 0.9 mg ortho-P/g VSS.h.

Phosphorus fate in the conventional-SBR system was totally different from the PAF-SBR system. The release of phosphorus was negligible due to low concentration of VFA in the raw wastewater (average VFA=3.6 mg/L) in the days of the track studies. Furthermore, the anoxic/anaerobic period was too short (45 min) to allow for considerable conversion of complex organic compounds of feed (raw wastewater) to VFA in this reactor. About 50% of the phosphorus in the solution was removed during the aeration period of this system indicating an incomplete uptake of phosphorus.

5.4.2.d-Nitrogen Profile

Nitrogen compounds in the feed to the BNR reactors were composed of NH_4-N and organic nitrogen. Nonetheless, as it is observed in Fig. 5.42, there were some oxidized forms of nitrogen (NO_3+NO_2) present in both BNR reactors at the start of each operational cycle. These compounds originated from the previous cycle and were present in the volume of the liquid that remained in each reactor after the decanting operation. The oxidized forms of nitrogen then would be diluted with the incoming feed, and finally denitrified during the initial anoxic/anaerobic period of each cycle.

It is interesting that in reactor B1 (BNR reactor of PAF-SBR system), considerable amounts of phosphorus were released even in the presence of nitrate in the solution. The release of phosphorus in the presence of nitrates was reported by several authors (Hascoet et al., 1985; Iwema and Meunier, 1985; Manning, 1986; and Kuba et al., 1994). The release, as was suggested by Hascoet et al. (1985), may have partially originated in a part of the biomass which was unable to reduce nitrates. Iwema and Meunier (1985), and Kuba et al. (1994) showed that despite the presence of nitrate, the Bio-P bacteria release phosphorus as long as acetic acid is present in the environment. P-release was observed under anoxic condition with nitrate concentrations up to 40 mg NO_3-N/L (Iwema and Meunier, 1985). The release was found to be a function of nitrate and acetic acid concentrations; increasing with an increase in the concentration of acetic acid. Contrary to the work of these groups, some other authors including Osborn and Nicholls (1978), Comeau et al. (1990), and Jenkins and Tandoi (1991) reported the inhibition of P-release when nitrate was present in the anaerobic zone of BNR process.

Conversion of NH_4-N to nitrate occurred in both BNR reactors during the aeration

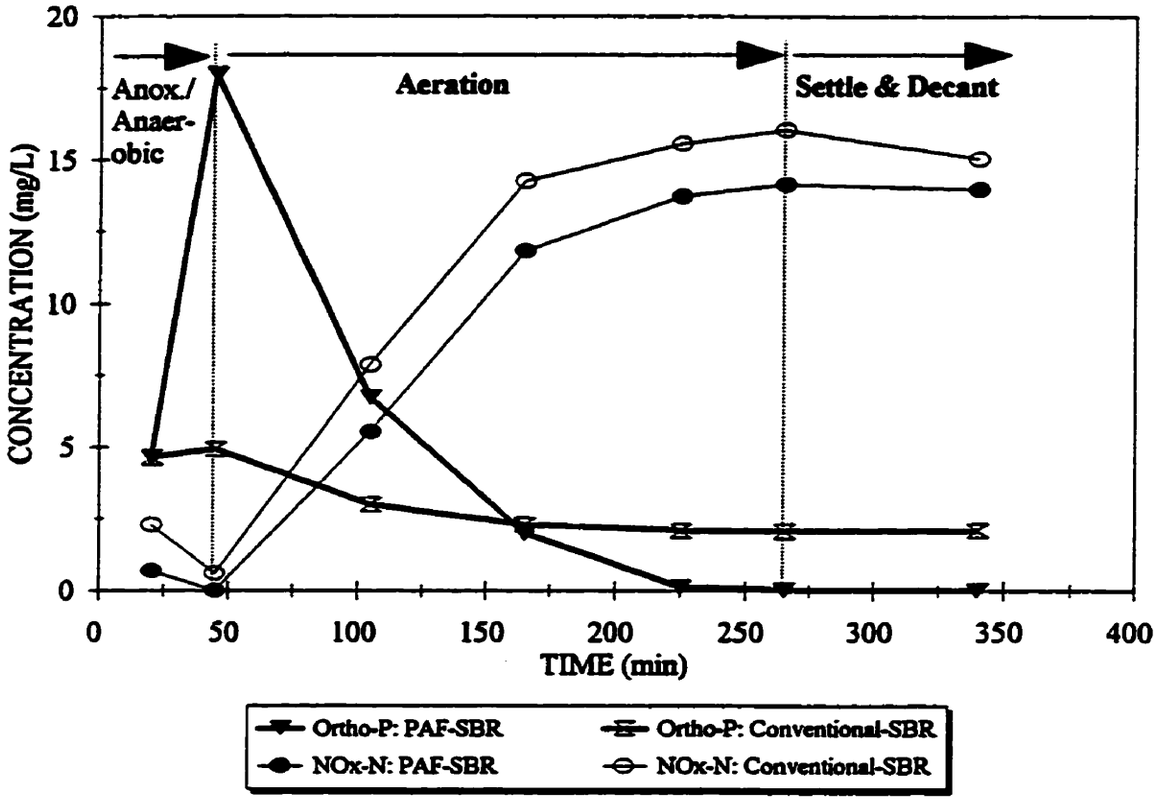

Fig. 5.42 : Results of the track studies on ortho-P and NOx-N concentrations (stage 2). Behavior of the two parallel BNR reactors were similar with respect to the changes in NO_x-N concentration. However, the systems were distinctly different in their ability for release and uptake of phosphorus.

period of each cycle. The rate of nitrification, however, did not remain constant and varied while aeration proceeded. Two distinct periods were observed with respect to the nitrification rates. In the first 2 h of aeration, nitrification rates expressed as oxidized forms of nitrogen were fast (2.98 mg NO_x-N/g VSS.h in reactor B1, and 2.73 mg NO_x-N/g VSS.h), as reflected by the steep parts of the related curves in Fig. 5.42. The rates then diminished to 0.68 mg NOx-N/g VSS.h and 0.43 mg NO_x-N/g VSS.h in B1 and B2, respectively during the last period of aeration as a result of decrease in concentration of substrate (NH_4-N) in the reactors. The average specific rate of nitrification over the whole period of aeration was 1.94 NO_x-N/g VSS.h in reactor B1 and 1.68 NO_x-N/g VSS.h in reactor B2.

Nitrification is a sensitive process, affected by many parameters including temperature, pH, organic carbon, etc. Therefore the specific rate of nitrification varies with the conditions of experiments. Some of the rates observed by other researchers are as follows: McClintock et al. (1993) measured removal rates of 1.97 mg NH_4-N/g MLVSS.h at a temperature of 20°C and a pH of 7.2. Wild et al. (1971) reported a specific nitrification rate of 2.04 NH_4-N/g MLVSS.h at a temperature of 20°C and pH of 6.5. Comparison between the average rates obtained in this experiment and the rates observed by the above authors showed that the average specific rate of nitrification in the PAF-SBR system was very close to the reported values. The specific rate of nitrification in reactor B2 (conventional-SBR) was however lower than these values.

In both BNR reactors, as shown in Fig. 5.42, the amount of denitrification during the settle phase of operational cycle was negligible.

5.4.2.e-Soluble Organic Carbon (SOC) Profile

The behavior of carbon uptake during the 6 h operational cycle is shown in Figure 5.43. The patterns of the change in soluble organic carbon concentration of both BNR were similar to those observed in an 8 h operational cycle during the previous stage of research (Fig. 5.38). All biodegradable soluble organic carbon were removed in the first 3 h of the cycle, leaving a concentration of about 18 mg/L non-biodegradable SOC in the effluents from reactors B1 and B2. In reactor B1, 62% of the biodegradable SOC was removed under initial anoxic/anaerobic condition which lasted for 45 min, and the remaining 38% was reduced during the first 2 h of aeration. The specific uptake rate of SOC was 9.6 mg/g VSS.h during the anoxic/anaerobic portion of the cycle which then gradually diminished in the following 2 h of aeration. The rate finally leveled off due to unavailability of SOC in this reactor.

In reactor B2, the true rate of SOC uptake could not be estimated due to concurrent occurrence of solubilization process. Any change in the concentration of SOC in this reactor was the result of solubilization of particulate organic carbon (increase in SOC), and the uptake of carbon by the biomass (reduction in SOC). As a result the rate of change in the SOC concentration in reactor B2 can not be calculated to specify the uptake rate of SOC by the biomass.

5.4.2.f-Conclusion

Operational cycles with short anaerobic period were essential for efficient phosphorus removal if the receiving influent to SBR systems has been already enriched with VFAs. The consistency of PAF-SBR system in removing phosphorus to

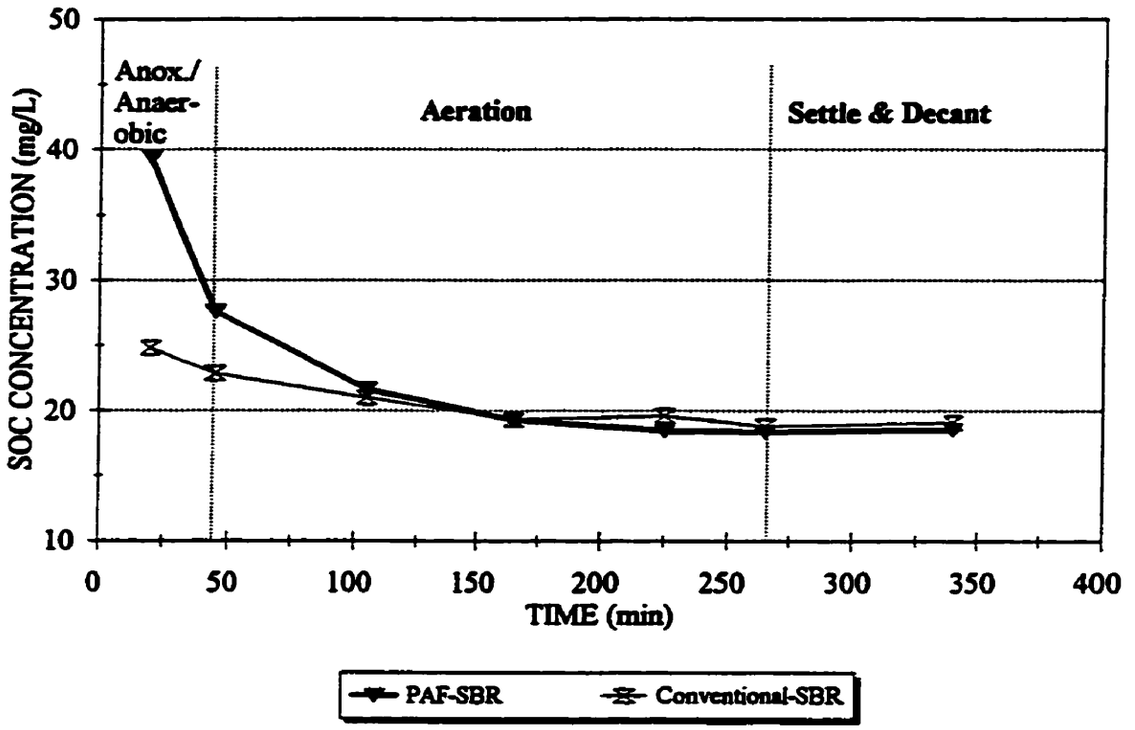

Fig. 5.43 : Profile of SOC in the parallel BNR reactors (Stage 2; 6 h cycle). The behavior of SOC removal during operational cycle of 6 h was similar to the behavior that was observed in 8 h cycle (Fig. 5.38). About 62% of the biodegradable SOC in reactor B1 was removed under the anoxic/anaerobic portion of operational cycles.

concentrations less than 1 mg/L was significantly improved through application of operational cycles of 6 h, with 45 min anoxic/anaerobic condition at the beginning of each cycle. Shortening the cycle from 8 h to 6 h did not damage biological removal of nitrogen or organic carbon.

5.4.3 STAGE 3 : IMPROVEMENT IN NITROGEN REMOVAL THROUGH STEP AERATION

Denitrifying microorganisms are facultative anaerobes (see section 2.2.3). Presence of oxygen suppresses the denitrification enzymatic system and decreases the process efficiency (Grady and Lim, 1980; Körner and Zumft, 1989; Von Schulthess et al., 1994). Thus for a successful biological nitrogen removal, existence of an anoxic period where oxidized forms of nitrogen can act as an electron acceptor in metabolic reactions is essential.

The results of previous stages of this research showed that nitrification was occurring in both biological nutrient removal reactors; B1 and B2. Denitrification efficiencies were however limited partly due to the limited anoxic period of each operational cycle. Operational cycles in stages 1 and 2 of the research did not have any pre-programmed anoxic periods. The only anoxic period was a short period at the beginning of each cycle when the remaining volume of the liquid from the previous cycle was mixed with the feed to the reactor.

The objective of this stage was to enhance biological nitrogen removal through introduction of a pre-programmed anoxic period within the operational cycles of BNR reactors. For this purpose step-aeration was applied such that after the initial anoxic/anaerobic period of 45 min, the BNR reactors were aerated for 1 h in order to nitrify some of the ammonium present in the feed. This period of aeration was followed by 1 h and 45 min of anoxic condition. Aeration was turned off during this period to encourage the use of nitrates in biochemical reactions. At the end of the anoxic period, the reactors were aerated again for one more hour to nitrify the remaining ammonium in

the system. Settle and decant periods followed this step of aeration. The total cycle period was 6 h (4 cycle/day), the same as in the previous stage (stage 2) of the research. Each cycle included a 45 min of anoxic/anaerobic period, followed by 1 h of aeration, 1 h & 45 min of anoxic period, 1 h of aeration, 1 h & 10 min of settling, and finally 20 min for decanting. Mixing was provided at the end of the fill period (first 20 min of each cycle) and kept in action up to the settling period. The only differences between this and the previous stage were the total aeration period, and the aeration regime. In the previous stage of the research the total aeration period of each cycle was continuous for 3 h & 45 minutes. In this stage, the total aeration period was reduced to 2 h which was applied in two intermittent periods of 1h each, with an anoxic period of 1 h & 45 min in between. The HRT and SRT of the reactors remained the same as before : 9 h, and 10 d respectively.

The above operational cycle was the outcome of many track studies performed with different combinations of aerobic/anoxic periods. The results indicated that allocation of less than 1 h for the first period of aeration, did not produce enough NOx to be removed in the following anoxic period. Aeration of more than 1 h also reduced denitrification efficiency due to the oxidation of carbon in the presence of oxygen which intensified the deficit of carbon source for the denitrification process. A period of 1 to 1h & 15 min was necessary for denitrification of all the NOx formed in the first stage of aeration. Finally a second aeration period of 1 h following the anoxic period could nitrify the remaining ammonium to levels less than 1 mg/L. Because a total period of 2 h of aeration seemed sufficient for total nitrification of ammonium, the anoxic period was extended to 1 h and 45 min to reduce aeration and to save as much energy as possible.

Extension of the anoxic period to 1 h & 45 min did not affect nitrogen, and phosphorus removal in the preliminary track studies.

The current stage of research began at Mar. 14, 1995 and continued until Jul. 6, 1995. Reactor B2 (conventional-SBR) was fed with degritted raw wastewater during this period, while B1 (BNR reactor in PAF-SBR system) was fed with the fermented wastewater (effluent from fermenter F1 up to Apr. 13th which was then replaced by the effluent from fermenter F2 due to the equipment failure in F1).

Detailed data on conditions and performance of BNR reactors are presented in Tables B1 and B2 in Appendix B, and the data related to the feed to these reactors (raw, and fermented wastewater) are shown in Appendix A, Tables A1, A2 and A3, respectively. Performance evaluation of BNR reactors in removing phosphorus and nitrogen was based on the data collected during the steady-state condition of the reactors (Mar. 29 to Jul. 6).

5.4.3.a-Phosphorus Removal

The change in aeration regime of BNR reactors did not impact phosphorus removal (Figure 5.44). The data points cover the total time period of previous and present stages of the research and show P-removal efficiencies under the two regimes of continuous, and step-aeration.

It should be pointed out that the raw wastewater used during the current stage of the research was generally weaker than the previous stage, as is reflected by a change in concentration of ortho-P in Fig. 5.44. Snow thaw and spring rains were the major causes of dilution. Other constituents of raw wastewater such as SOC and different forms of

nitrogen also showed a reduction in concentration during this period.

Lower concentration of ortho-P in the effluents of the BNR reactors as compared to the concentration in the raw wastewater indicated that P-removal processes were occurring in both reactors B1 and B2. Phosphorus removal in the conventional-SBR (B2), as indicated by variation in effluent ortho-P concentration, was not consistent. Concentration of ortho-P in the effluent of this system during step-aeration period ranged from 0.5 to 2.7 mg/L with an average of 1.2 mg/L. The mean removal efficiency of this system for soluble phosphorus was 57% which reduced soluble phosphorus concentration from 3.5 mg/L in the raw wastewater to 1.5 mg/L in the effluent. The mean concentrations of ortho-P and soluble-P in the effluent of conventional-SBR system during this stage of research (step-aeration) were lower than their concentrations during the previous stage (2 and 2.5 mg/L, respectively) when 3 h and 45 min of continuous aeration was applied. The lower concentration of phosphorus in the effluent of conventional-SBR under step aeration, however, can not be totally attributed to the change in aeration regime, as the feed to the reactor was also weaker during this stage of experiments.

Contrary to the conventional-SBR system, phosphorus removal in B1 (BNR in PAF-SBR system) was very consistent and stable which resulted in a low degree of variation in effluent phosphorus concentration (Fig. 5.44). Phosphorus removal efficiency in the PAF-SBR system was significantly ($P<0.01$) higher than the parallel conventional-SBR system. The average concentrations of ortho-P and soluble-P in the final effluent of PAF-SBR system during this stage of research were the same as the concentrations in previous stage of the research; being 0.2 and 0.3 mg/L respectively. A reduction of 90% in soluble phosphorus occurred in PAF-SBR system as the concentration diminished from

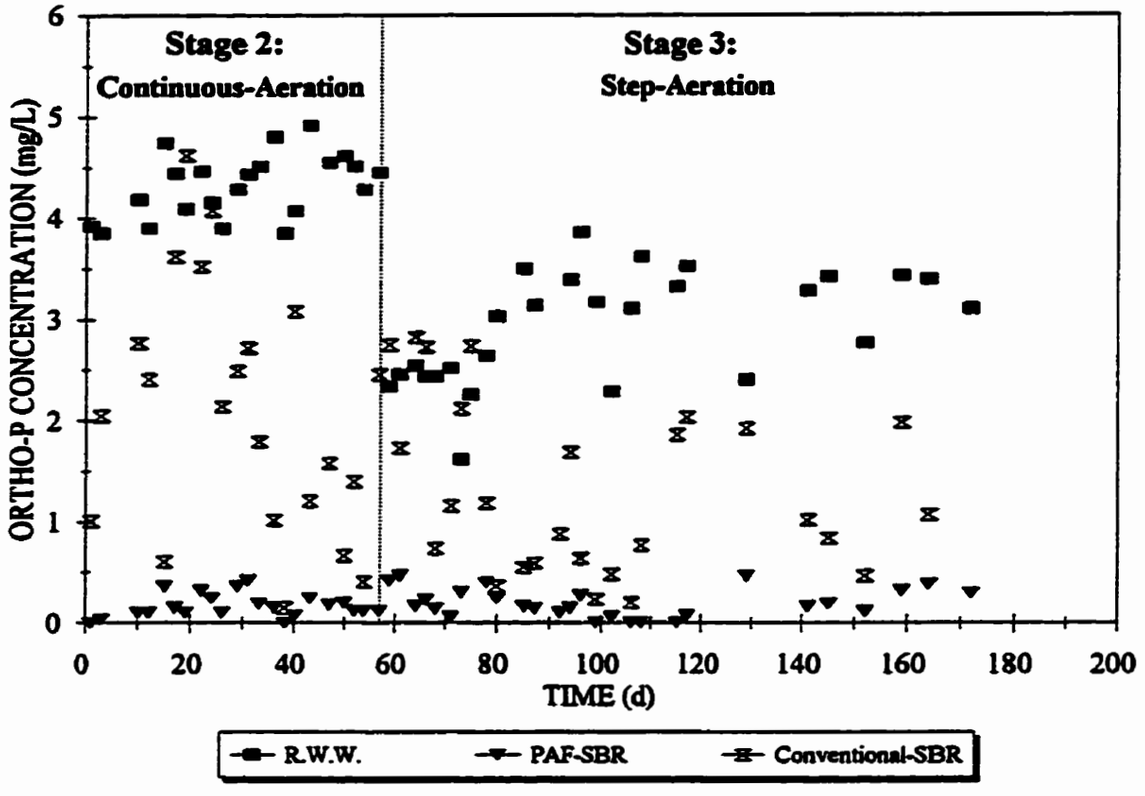

Fig. 5.44 : Ortho-P concentration in the raw wastewater and effluent from the BNR reactors (stage 2). Step-aeration did not deteriorate Bio-P removal in the tested systems.

3.5 mg/L in the raw wastewater to 0.3 mg/L in the system effluent. In conclusion, step-aeration did not deteriorate Bio-P removal in the SBR systems. Phosphorus removal in both parallel reactors under step-aeration conditions was as good as the removal under continuous aeration conditions.

Frequency plots of ortho-P and soluble-P in the effluent of BNR reactors operating under continuous/step-aeration conditions (stages 2 &3 of the research) are shown in Figures 5.45 and 5.46 respectively. The superiority of the SBR system with prefermentation step (PAF-SBR) over the conventional-SBR in removing phosphorus is clearly demonstrated in these figures. Figure 5.45 shows that about 50% of the effluent samples in the PAF-SBR had an ortho-P concentration $\leq$ 0.2 mg/L, while in the conventional-SBR the concentration corresponding to 50% of the effluent samples was 1.5 mg/L. It is also apparent that all the samples taken from the former system had an ortho-P concentration of $\leq$ 0.5 mg/L.

As far as effluent soluble phosphorus is concerned (Fig. 5.46), all samples from the system with prefermentation showed concentrations of $\leq$ 1 mg/L, with 80% of them having concentrations $\leq$ 0.5 mg/L. In contrast, 80% of the samples from the conventional-SBR had values $\leq$ 3 mg/L.

A comparison between Figures 5.45 and 5.29, reveals the extent of improvement made in P-removal capacity of PAF-SBR system by shortening the cycle period of BNR reactor from 8 h (3 cycle/day) to 6 h (4 cycle/day). During experimental period with 8 h cycle period,only 70% of the samples showed ortho-P concentration of $\leq$ 0.5 mg/L (Fig. 5.29). In comparison, in 6 h operational cycles regardless of the aeration regime all 100% of the samples had ortho-P concentrations of $\leq$ 0.5 mg/L.

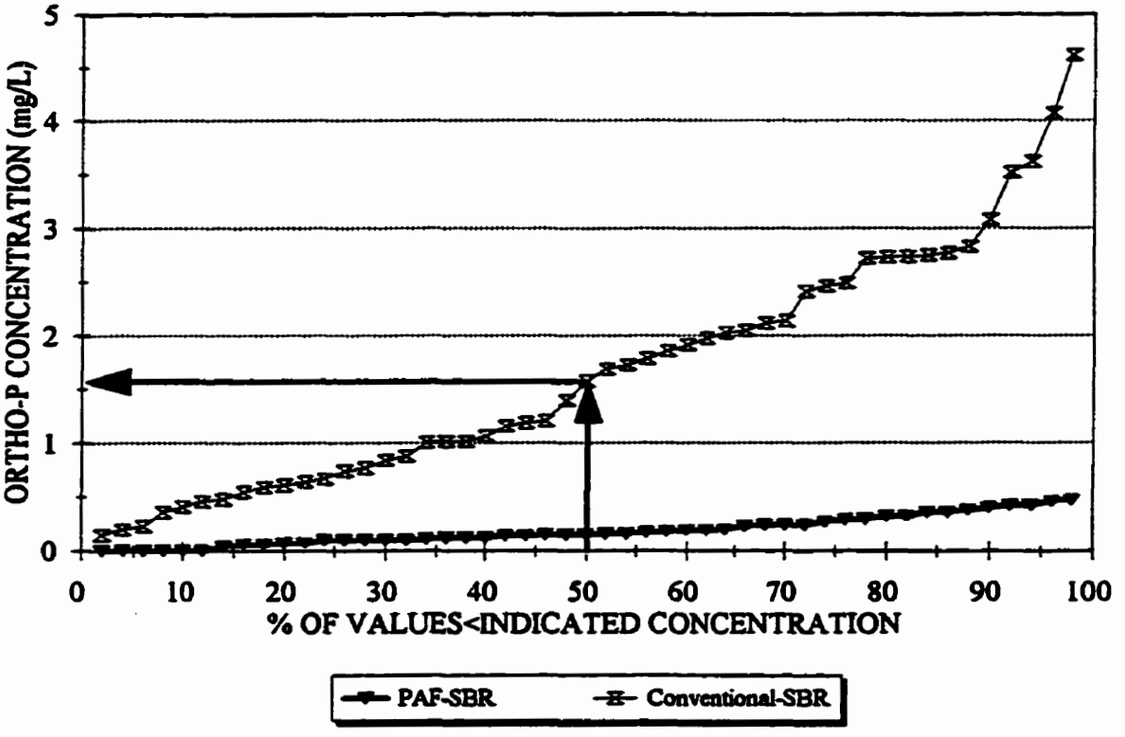

Fig. 5.45 : Frequency plot of the effluent ortho-P concentration of the BNR reactors (6 h-cycles). Regardless of the aeration regime, the reactor fed with fermented wastewater performed remarkably better than the conventional-SBR in removing phosphorus.

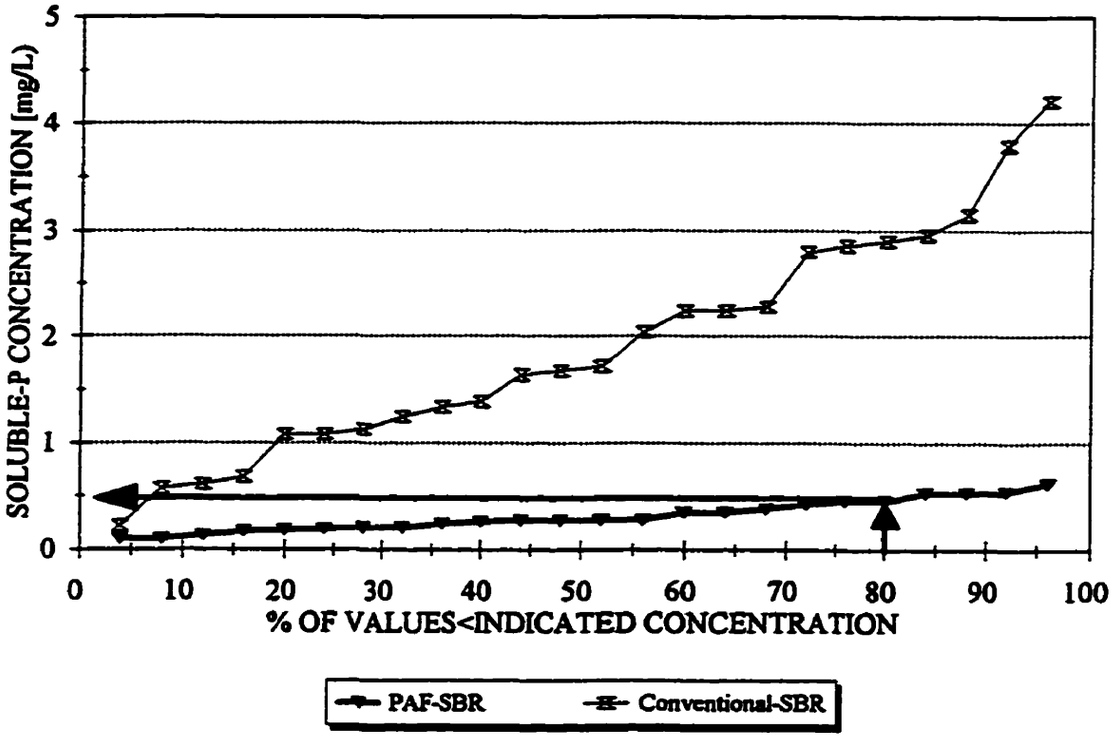

Fig. 5.46 : Effluent soluble-P frequency plot of the BNR reactors (6 h-cycles). About 80% of the samples taken from the final effluent of PAF-SBR system showed soluble-P concentrations ≤ 0.5 mg/L. In contrast, 80% of the samples from the conventional-SBR had values ≤ 3 mg/L.

5.4.3.b-Nitrogen Removal

The addition of an anoxic period in the operational cycle of BNR reactors did not affect Bio-P removal, while improving nitrogen removal significantly.

Nitrogen removal efficiencies (soluble-N removal %) increased from 50% in PAF-SBR system and 42% in the conventional-SBR system to 69% and 65% respectively as the aeration regime changed from being continuous to step-aeration mode (Fig. 5.47). The parallel systems behaved similarly in treating nitrogen constituents of the wastewater under the step-aeration condition. The mean concentration of total soluble nitrogen in the final effluent of both systems was 9.5 mg/L. Oxidized forms of nitrogen (NO_3+NO_2) contributed to 73% of the total soluble nitrogen found in the effluent of PAF-SBR system, and to 60% in the conventional-SBR system. Nitrification occurred very effectively in the BNR reactors during the aeration periods of the operational cycles. This process plus uptake of ammonium in the production of excess biomass reduced the ammonium concentration to levels less than 1 mg/L in the effluents of BNR reactors.

5.4.3.c-Track Studies

Detailed studies on the trends of change in SOC, NOx and ortho-P constituents were performed to understand the dynamics of system processes within the BNR reactors.

The results on SOC and NOx behavior are displayed in Figure 5.48, and for ortho-P, the results are shown in Figure 5.49. Each data point in these figures is the mean value of five observations. The original data related to these sets of track studies are summarized in Tables C4(a) and C4(b) in Appendix C. The following sections cover the discussions on the results obtained during these track studies.

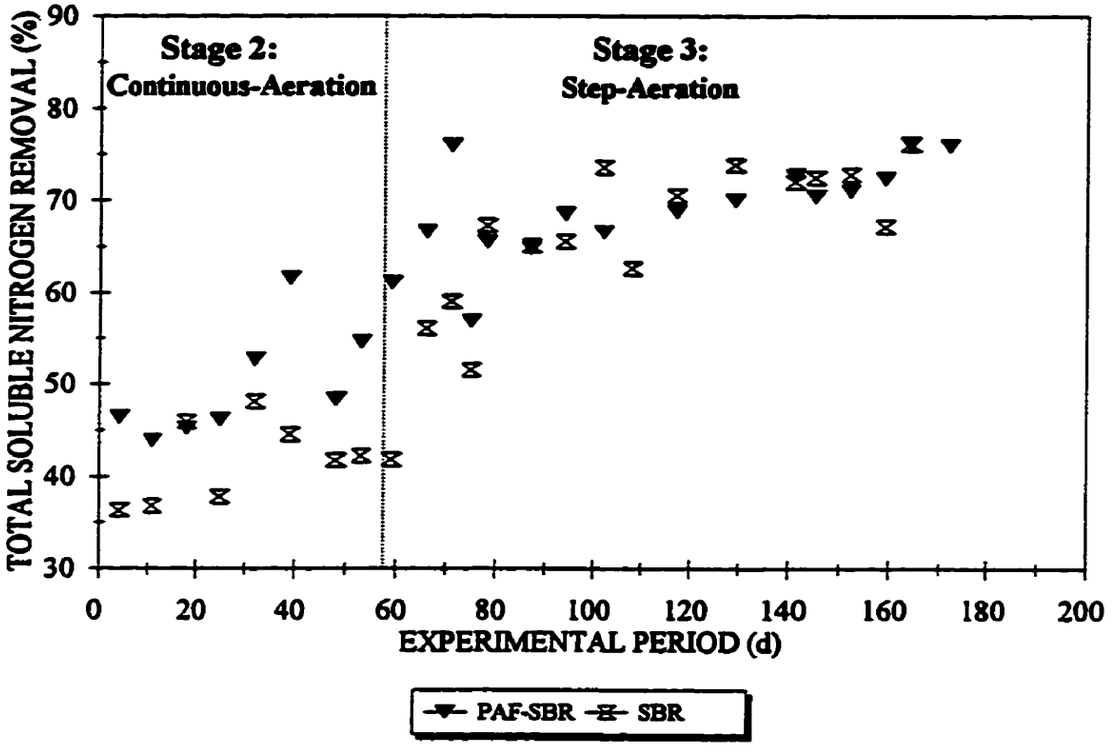

Fig. 5.47 : Nitrogen removal efficiencies in the BNR reactors (6 h-cycles). Nitrogen removal in both parallel reactors improved significantly as continuous aeration was replaced by step-aeration procedure.

5.4.3.d-Nitrogen Profile

The NOx-N concentrations of BNR reactors, as depicted in Fig. 5.48, followed the same pattern of change as the environmental conditions changed sequentially within each reactor.

During fill period (first 20 min of each cycle), the remained liquid volume of the solution in the reactors (from the previous cycle) was diluted by the feed, and its NOx content denitrified completely as a result of presence of available carbon. The first step of aeration provided the conditions for nitrification of some of the ammonium content of reactors. The NOx-N concentration of both reactors was raised to an average of 10 mg/L as the result of the nitrification process. The mean specific rate of NOx-N build up was 3.2 mg/L in the reactor related to PAF-SBR system-B1, and 2.9 mg/L in the conventional-SBR (B2). Most of the NOx contents of the reactors then were denitrified during the anoxic period that followed the aeration period. Denitrification proceeded with an average specific rate of 1.7 mg NOx-N/g VSS.h in both reactors which reduced the mean concentration of oxidized forms of nitrogen to 1.3 mg/L and 2.3 mg/L in reactor B1 and B2, respectively. The reported denitrification rates in the literature vary considerably as the process is affected by many factors such as temperature and carbon resources present in the environment. The effects of different carbon sources on denitrification process have been investigated by different authors (Winter, 1989; Carley and Mavinic, 1991; Tam et al., 1992). Henze et al. (1994) reported denitrification rates of 10-20 g-N/Kg VSS.h, 2-4 g-N/Kg VSS.h, and 0.2-0.5 g-N/Kg VSS.h at the presence of directly metabolized (e.g. acetic acid), easily degradable (e.g. lower amino acids) and slowly degradable (e.g. complex carbohydrates) components of raw wastewater, respectively. At 20 °C with

methanol as the feed, denitrification rate was found to be in the range of 5-14.6 mg NO3-N/g VSS.h (EPA, 1993). In some of the track studies, the NOx concentration reached zero before the anoxic period was ended. In such cases phosphorus was released as anoxic condition turned to an anaerobic condition.

The second and final step of aeration oxidized most of the remaining ammonium in both BNR reactors. Nitrification of ammonium at this stage, reduced the ammonium concentration to less than 1 mg/L in the effluents of reactors. A small quantity of oxidized forms of nitrogen was denitrified during the settle period of operational cycles.

5.4.3.e-Soluble Organic Carbon (SOC) Profile

Almost all of the biologically removable SOC present in the BNR reactor of PAF-SBR system (B1), as illustrated in Fig. 5.48, was removed in periods prior to the anoxic portion of each cycle. Moreover, solubilization of particulate organic material was less likely to occur in this reactor because the process has already been performed in the fermentation reactor located ahead of the BNR reactor. One can speculate that the required source of carbon for the denitrification process in the anoxic period was probably not the mixed liquor. The denitrifiers in this system used most likely their own internal reserves of carbon to accomplish reduction of oxidized forms of nitrogen.

On the average about 60% of the total removal of SOC in reactor B1, occurred during the initial 45 min of each cycle (anoxic/anaerobic period). The rate of removal was slow in the first 20 min (fill period), when mixing was not provided. The rate however increased rapidly during the next 25 min as the action of mixer brought the substrate in close contact with the microorganisms (Fig. 5.48). The results indicate that about 90% of

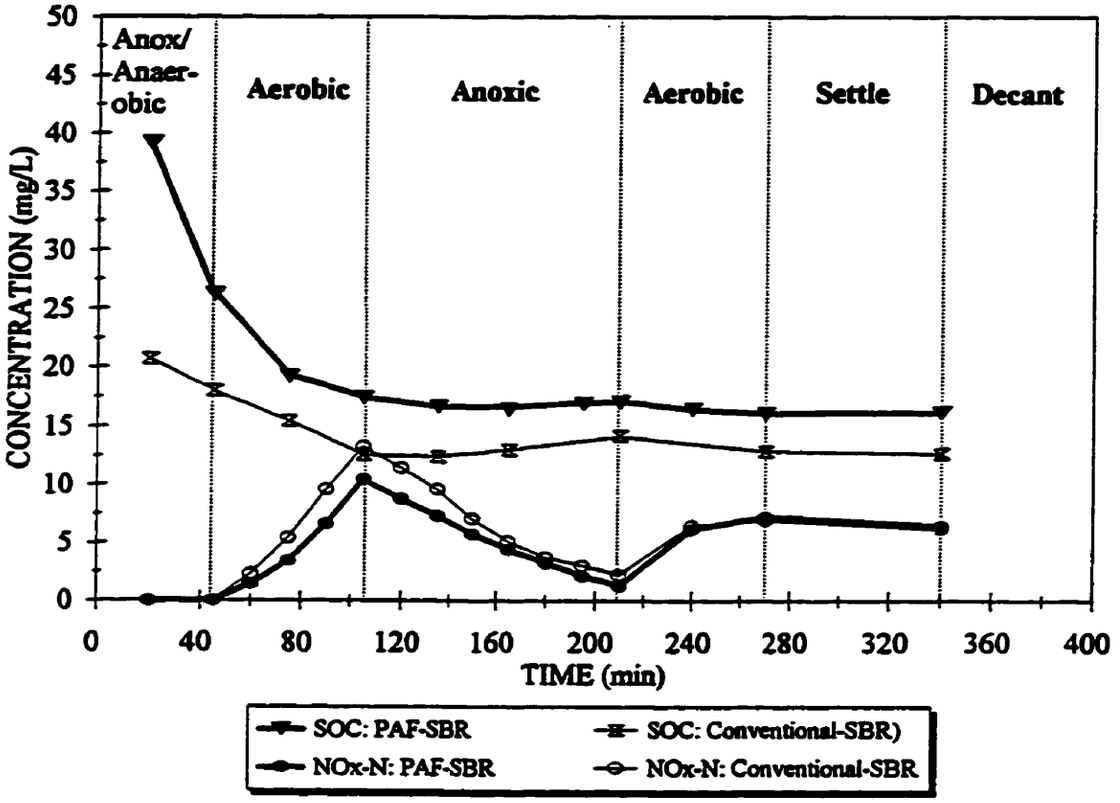

Fig. 5.48 : Change in SOC and NOx-N concentrations of the BNR reactors (6 h-cycles with step-aeration regime). Denitrification proceeded successfully during the anoxic period that followed the first step of aeration. Most of the removable SOC of the both reactors were used up prior to this anoxic period.

total removal of carbon in initial anoxic/anaerobic period occurred in the last 25 min of this interval. Removal of substrate during anoxic/anaerobic period of the operational cycles proceeded at a mean specific rate of 9.5 mg SOC/g VSS.h. Comeau et al. (1987) reported a range of 12-25 mg soluble COD/g VSS.h for specific rate of substrate removal (synthetic feed) during anaerobic stage of Bio-P removal process. The SOC removal efficiencies and the mean specific SOC uptake rate in reactor B1 during this stage were very close to the values obtained from track studies of this reactor in the previous stage (stage 2) of the research.

Contrary to the PAF-SBR system, solubilization of organic particulates in the conventional-SBR occurred within the BNR reactor (B2). Thus the change in SOC concentration in B2 was actually the net result of both solubilization, and the uptake of SOC by the biomass. The observed rate of SOC removal (under initial anoxic/anaerobic) was relatively constant with the mean value of 1.7 mg/ g VSS.h. A comparison of the rates shows that the rate of SOC removal in the conventional-SBR was much slower than the rate in B1; the parallel reactor belonging to PAF-SBR system. The observed low rate was partly due to the lower concentration of readily available compounds in the feed (degritted raw wastewater) and partly due to the concurrent production of SOC (solubilization) in the conventional-SBR which did not allow for the measurement of actual SOC uptake rate. Consequently, the actual rate of SOC removal in the conventional-SBR might be higher than the observed value of 1.7 mg/ g VSS.h.

The SOC content of this reactor, as presented in Fig. 5.48, increased during anoxic period of operational cycles. The increase originated mainly from solubilization of organic compounds and to a less extent from lysis of the microbial cells. As a result the carbon

requirement of denitrification process in the conventional-SBR were supplied by both the external carbon compounds in the environment around the biomass, and the internal carbon reserves of microbial cells.

5.4.3.f-Phosphorus Profile

The profiles of ortho-P concentration in BNR reactors under the step-aeration condition are shown in Figure 5.49. Phosphorus was released in both reactors during the first portion of operational cycle as the reactors became anaerobic. The specific rate of P-release in the PAF-SBR and conventional-SBR were 12 mg/g VSS.h and 3 mg/g VSS.h, respectively.

The quantity of release in the PAF-SBR system was considerably higher than the release in the conventional-SBR because of the presence of higher concentration of SCVFA in the feed to the former system. The concentration of SCVFA in the fermented wastewater (feed to the BNR of PAF-SBR) was 49 mg/L in period of track studies, while the concentration in the raw wastewater (feed to the conventional-SBR) averaged 7 mg/L. The mean ratio of P-release to the amount of substrate utilized during the initial anoxic/anaerobic period of the PAF-SBR system was 1.6 mg ortho-P/mg SOC.

Biological phosphorus uptake occurred during the step-aeration period when the systems were subjected to the aerobic and anoxic conditions (Fig. 5.49). Uptake of phosphorus under anoxic condition indicates that at least some portion of the Bio-P removal bacteria were capable of carrying on denitrification process. The observation is in agreement with the results reported by Kerrn-Jespersen and Henze (1993), and Kuba et al. (1993) who recognized the denitrifying ability of some of the Bio-P bacteria.

Comparison between Figures 5.49 and 5.42 showed the similarity of Bio-P uptake patterns in the current stage (stage 3; step-aeration condition), and previous stage (stage 2; continuous aeration condition) of the research. Phosphorus was removed with the highest specific rate during the first stage of aeration. The rate then diminished remarkably in the following anoxic period. The specific rate of phosphorus removal in the first hour of aeration was 5 mg/g VSS.h in PAF-SBR system and 1.7 mg/g VSS.h in the conventional-SBR. The obtained rate in PAF-SBR system was close to the rate (5.7 mg/g VSS.h) achieved in this system under continuous aeration situation. Uptake rates of phosphorus during the anoxic period were 1.1 and 0.3 mg/g VSS.h in the PAF-SBR system and the conventional-SBR, respectively.

The lower rate of P-uptake during anoxic period is not solely due to the nitrate serving as electron acceptor. Other factors such as lower concentration of ortho-P in the solution and/or reduction of available carbon sources in the medium and within the biomass could have contributed to the decrease in the rate. Reduction in the rate of P-uptake as a function of time was also observed under continuous aeration regime where oxygen serving as the main electron acceptor for biochemical reactions (see section 5.4.2, track studies). In general, the extent and efficiency of phosphorus removal varies considerably depending upon the type of oxidant present (Kerrn-Jespersen and Henze, 1993), type of the organic substrate (Ubukata and Takii, 1994), concentration of extracellular polyphosphates as well as the unsaturated storage capacity for the intracellular phosphorus (Somiya et al., 1988).

In some of the track studies performed, release of phosphorus was noticed towards the end of the anoxic period as NOx-N concentration reached zero. The released

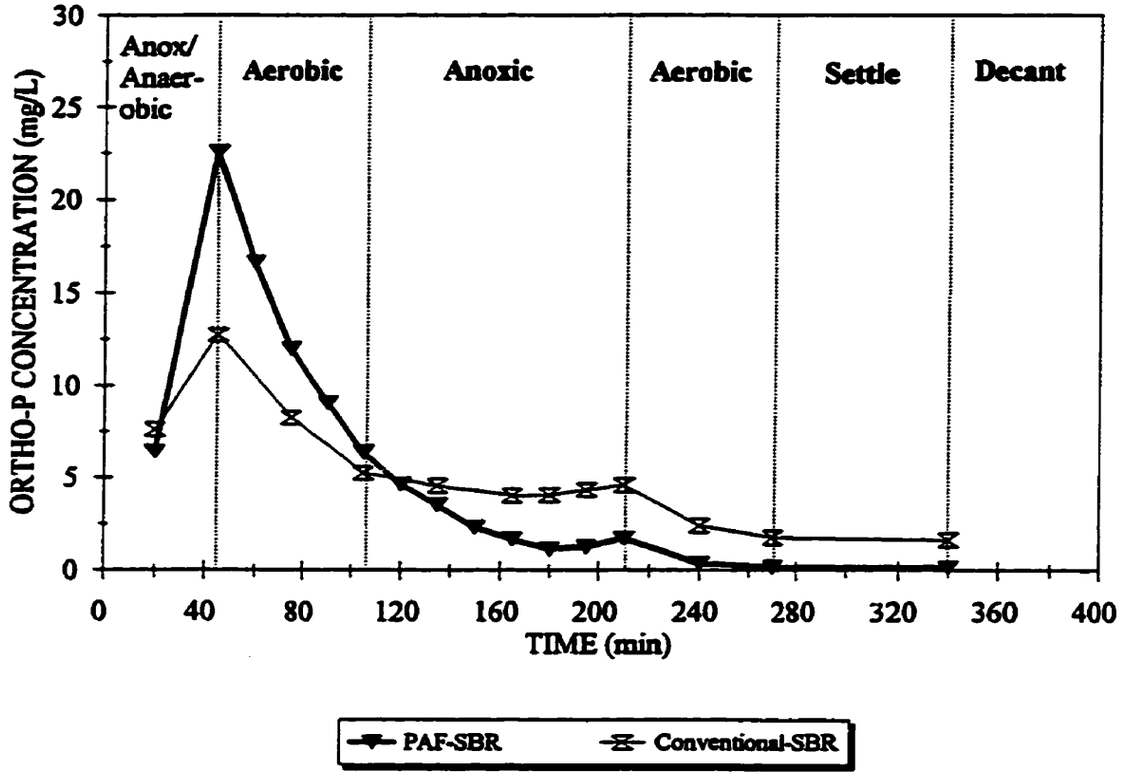

Fig. 5.49 : Change in ortho-P concentration of the BNR reactors (6 h-cycles with step-aeration regime). Patterns of change in reactors were similar to those observed under continuous aeration regime. Biological phosphorus uptake continued as anoxic condition replaced the aerobic condition.

phosphorus, however was uptaken in the final aeration period.

Phosphorus removal efficiency of PAF-SBR system with respect to the utilized substrate was 6.3 mg SOC/mg P-removed. The ratio of utilized substrate per unit of phosphorus removal is not constant and varies with the type of the substrate (Abu-ghararah and Randall, 1991). With acetic acid as substrate, phosphorus removal efficiency was reported to be 18.8 mg COD-utilized/mg P-removed, however the rate was totally different when other SCVFA were used as substrate (Table 2.1, adapted from Abu-ghararah and Randall, 1991).

5.4.3.g-Oxidation-Reduction Potential (ORP)

Profiles of ORP of BNR reactors under sequentially changing environmental conditions are displayed in Figure 5.50. Each data point in the figure is the average of 4 observations, and reflects the relative redox condition of each reactor at different time periods of the operational cycles. The data related to the ORP measurements are shown in Table C8 within Appendix C.

Both reactors, as presented in Fig. 5.50, showed the same trend of variation in the ORP as the environmental condition changed. The initial ORP of the reactors (after the fill period) being -200 mV for the PAF-SBR system, and -150 mV for the conventional SBR, were low enough to induct phosphorus release during the anaerobic portion of operational cycle. According to results reported by Shapiro et al. (1967), rapid release of phosphorus was triggered off once the redox potential fell to and below -150 mV.

The first jump in the ORP of the reactors (after the fill period) was about 35 mV, and was brought about by the action of mixers. The second increase which occurred in

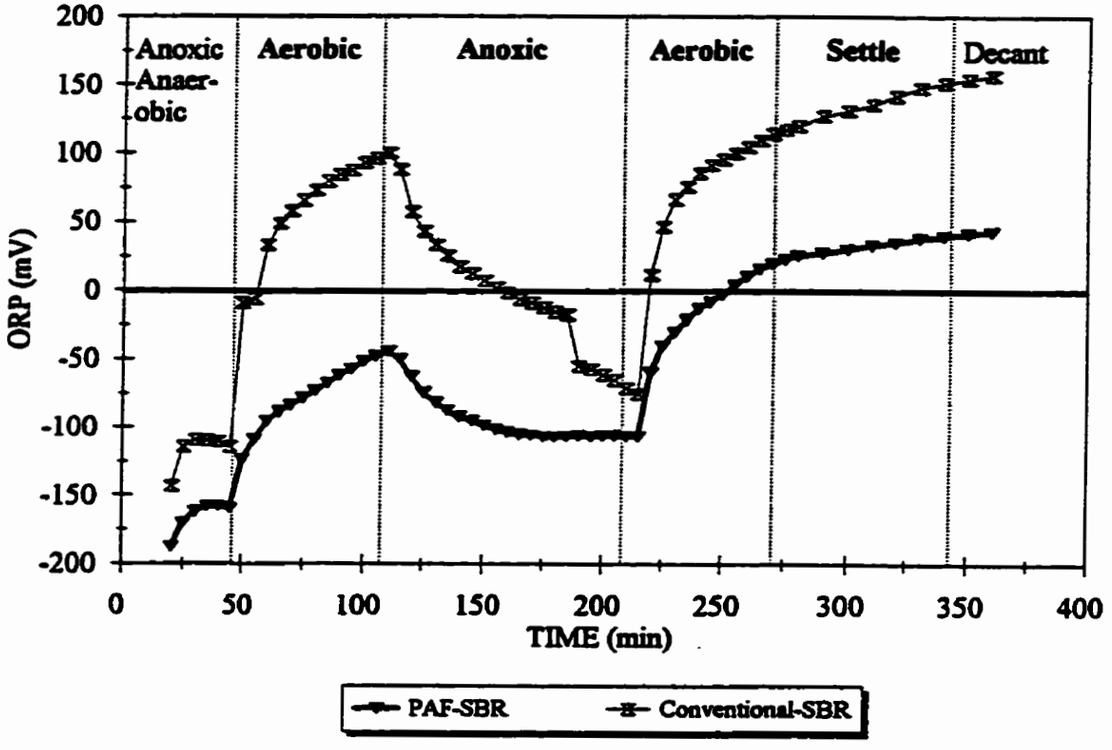

Fig. 5.50 : Change in oxidation-reduction potential of the BNR reactors (6 h-cycles with step-aeration regime). The curves show the relative change in redox potential of reactors as the environmental condition changed sequentially within each operational cycle.

time period of 45-105 min, was the result of the first step of aeration. Oxidation reduction potential increased sharply during the first 5 min of aeration which then followed by a slower rate of increase during the remaining period of aeration.

A decline in ORP was observed as the aeration of reactors stopped and the anoxic condition prevailed within the systems. In the anoxic period, the redox potential of B1 (BNR reactor of PAF-SBR system) decreased to -100 mV, while in the conventional-SBR it reached -75 mV. Both values indicated conditions suitable for the successful occurrence of denitrification process.

The final jump in the ORP resulted from the last step of aeration which raised the ORP of PAF-SBR and conventional-SBR to about +30 and +120, respectively. The increase during settle period was probably due to the settling of the sludge that reduced the concentration of solids around the probe and changed the microenvironment to a more oxidized status.

5.4.3.h-Final Effluent

Performance of BNR reactors at steady-state operation was evaluated based upon their influent/effluent characteristics which are summarized in Table 5.20.

The major differences observed in treatment efficiencies of the PAF-SBR system, and the conventional-SBR system (under step-aeration regime) were related to the following parameters :

- Effluent SS
- Effluent phosphorus
- Effluent total nitrogen

Table 5.20 : Characteristics of the feed and the final effluent from the two parallel BNR systems (6 h-cycle with the step-aeration regime).

Parameter	R.W.W. Mean±SD	F.W.W. Mean±SD	Effluent (PAF-SBR) Mean±SD	Effluent (Conventional-SBR) Mean±SD
pH	7.7±0.2	7.1±0.1	7.7±0.2	7.7±0.2
Alkalinity as $CaCO_3$	316±32.8	358±33.6	237±34.5	218±30.8
SS	218±49.2	71±12.7	12±3.0	111±79.6
SOC	38±13	52±15.9	16.4±2.5	16±2.7
VFA	10	49±19	-	-
PO_4^{-3}	3.0±0.5	3.7±0.6	0.2±0.1 [a*]	1.1±0.7 [b]
P_{Sol}	3.5±0.6	4.2± 0.6	0.3±0.1 [a]	1.5±0.7 [b]
P_{Tot}	5.3±0.7	5.1± 0.8	0.6±0.2 [a]	4.2±2.0 [b]
NH4-N	24±3.2	26.3±3.6	< 1	< 1
(NO_3+NO_2)-N	0.00	0.00	6.8±1.1 [a]	5.6±0.8 [a]
Soluble-N	29.5±3.6	31±3.6	9.3±1.5 [a]	9.4±1.6 [a]
Total-N	37±4.5	35.3±4.3	10±1.5 [a]	14.5±4.0 [b]

Note : All values are expressed in mg/L, except pH.
SD : Standard Deviation of the data
* : Non-similar letters in the superscript indicate a significant difference between the means ($P<0.01$).

The mean concentration of suspended solids in the effluent from the conventional-SBR system was 111 mg/L, as compared to the 12 mg SS/L in the final effluent of PAF-SBR system. High concentration of solids in the effluent of the conventional-SBR was due to the excess growth of filamentous bacteria, which led to frequent bulking and loss of solids in the effluent. As a result, although the system was efficient in removing most of the soluble components of wastewater (e.g. soluble forms of nitrogen), its performance in removing the non-soluble components (e.g. non-soluble forms of nitrogen) was not impressive.

Performance of conventional-SBR system in removal of phosphorus was not also comparable to the PAF-SBR system. The observed differences in the mean concentration of different forms of phosphorus in the effluent from both systems were substantial, and statistically significant. Efficient removal of phosphorus in the PAF-SBR system, as discussed in earlier sections was a direct result of acid fermentation of raw wastewater.

5.4.3.i-Conclusion

Step-aeration did not impair Bio-P removal performance. Phosphorus removal during the discontinuous aeration regime of 1 h aeration, 1 h and 45 min anoxic, 1 h aeration was as effective as in continuous aeration regime of 3 h and 45 min.

Nitrogen removal improved significantly as the result of the step-aeration. Total soluble nitrogen removal was increased by 20% in the PAF-SBR system and by 23% in the conventional-SBR.

Uptake of phosphorus during the anoxic period implied the denitrifying ability of at least some portion of the Bio-P bacteria.

Phosphorus release was observed during the anoxic period of 1 h and 45 min as NOx-N concentration reached zero.

This stage of research led to the savings in aeration costs, and optimization of Bio-P removal and denitrification processes.

5.4.4 STAGE 4 : IMPROVEMENT IN NITROGEN REMOVAL THROUGH STEP-FEEDING

In the previous stage of research, the limitation of external source of carbon for the denitrification process in reactor B1 was demonstrated. Lack of availability of carbon during the anoxic period reduced the denitrification potential. Furthermore, some release of phosphorus was noticed towards the end of the anoxic period. This release, though not affecting nutrient removal efficiency, should be prevented as much as possible due to its possible negative impacts on effluent quality.

The objectives in this stage (which was carried out only for the PAF-SBR system) were :

1- Prevention of P-release during the anoxic period.

2- Enhancement of nitrogen removal by step feeding.

To achieve the first objective, the step-aeration schedule was changed to the sequence of 1 h aeration, 1 h anoxic, 30 min aerobic, 45 min anoxic, and 30 min final aeration periods. As it is observed the total aeration/anoxic periods in each operational cycle remained the same as before (2 h total aeration, and 1 h and 45 min total anoxic periods), however in this stage they were divided into shorter time segments to limit each anoxic period length and to reduce the chance of P-release.

The purpose of the second objective was to explore the possibility of reduction of effluent total nitrogen to levels about 5 mg/L. According to Caponetto and Oleszkiewicz (1994), one gram of SOC is utilized in denitrification of one gram of nitrate nitrogen. The mean concentration of total nitrogen in the effluent of PAF-SBR during previous stage was 10 mg/L; 68% being in the form of NOx-N. To reduce this concentration to 5 mg/L,

about 5 mg/L of SOC was required for denitrification of equivalent amount of NOx-N. The required carbon for denitrifying bacteria, was supplied by step-feeding such that a portion of total feed (enough quantity to produce 5 mg/L of SOC) in each cycle was saved, and was later added to the reactor at the beginning of the last anoxic period.

The new step-aeration/step-feeding procedure was not applied on a continuous time base, rather it was employed in separate cycles in a batch-type manner.

5.4.4.a-Nutrient Removal

Bio-P removal was not affected significantly by the step-feeding procedure. Although some phosphorus (0.30-0.36 mg/L of ortho-P) was added to the reactor as a result of the second feeding step, but it was removed effectively in the following anoxic/aerobic periods such that 88% removal was observed for soluble phosphorus. The mean concentration of soluble phosphorus in the effluent of PAF-SBR system was 0.4 mg/L while total phosphorus concentration averaged 0.8 mg/L.

Contrary to the theoretical prediction, nitrogen removal was not improved remarkably as the result of step-feeding. Total nitrogen concentration of effluent ranged from 8.6 to 9.2 mg/L which is not considerably different from the average 10 mg/L obtained without step-feeding. To shed some light on the subject, track studies were performed on the NOx-N and SOC content of BNR reactor. The results of track studies are presented in Figure 5.51 with detailed data in Table C5, Appendix C.

The changes in SOC and NOx-N concentrations during the sequence of initial anoxic/anaerobic period, first step of aeration, and first step of anoxic condition (identified by numbers 1,2, and 3 in Fig. 5.51, respectively) were similar to those experienced in

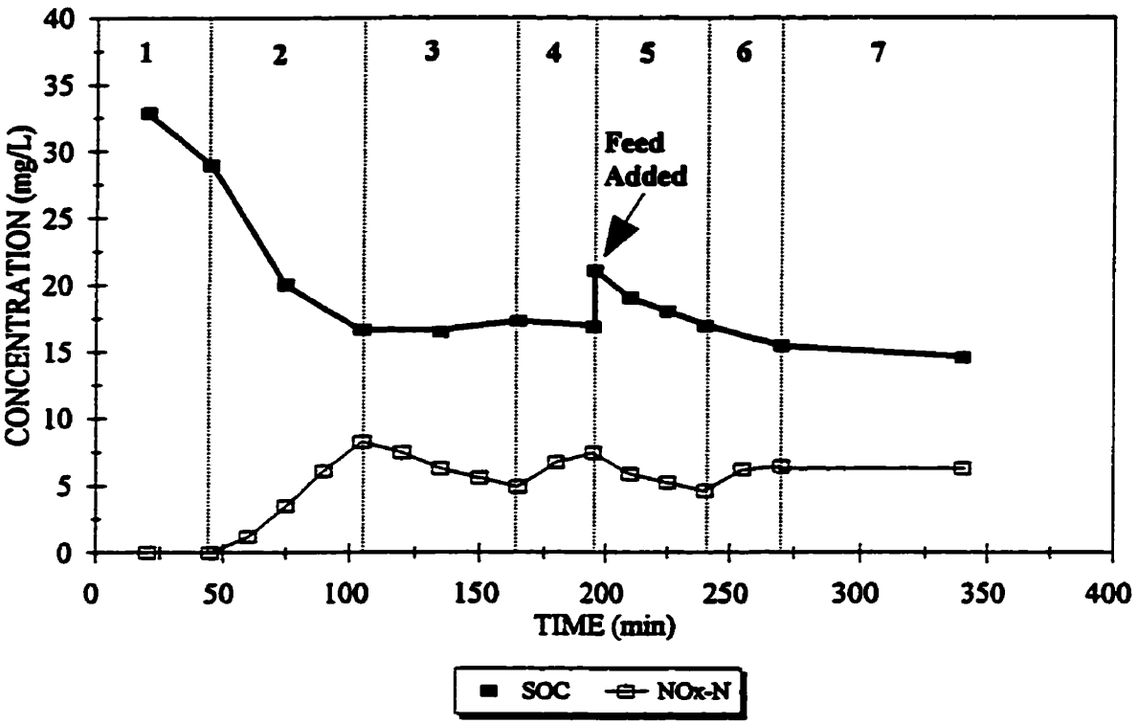

Fig. 5.51 : Change in SOC and NOx-N concentrations (step-feeding operation). Step-feeding did not enhance total nitrogen removal in the system due to similar concentrations of SOC and TKN in the feed.

the former stage of this research (Fig. 5.48). Almost all of the available SOC was removed from the solution by the end of the first step of aeration; before microorganisms were subjected to the anoxic condition (period 3 in Fig. 5.51). Nitrification occurred efficiently during the first aeration period resulting in NOx-N concentration of 8.5 mg/L. Concentration of NOx-N then was decreased (by 35%) as the first anoxic condition overtook the system. The following aeration step (period 4) resulted in further conversion of ammonia to oxidized forms of nitrogen. The change in SOC concentration of system during periods 3 and 4 (Fig. 5.51) were not considerable.

Addition of a fraction of feed to the reactor at the beginning of the last anoxic period (period 5) increased SOC by 4.5 mg/L and enhanced denitrification process. Concentration of NOx-N decreased from 7.5 mg/L to 4.5 mg/L during the above anoxic period as the added SOC was used up in denitrification reactions. Further decrease in NOx-N was limited by the time period of this stage and SOC content of reactor.

The final 30 min of aeration (period 6) were associated with the nitrification of remaining ammonium and increase in concentration of NOx-N to average 6.5 mg/L in the effluent. The change in SOC and NOx-N concentrations during the settle period (period 7) was negligible. The average NH4-N concentration in the final effluent of the reactor was about 1 mg/L.

Step-feeding policy was not successful in improving the total nitrogen removal in the system because of the SOC/TKN_{Sol} ratio of the feed (fermented wastewater). Analysis of the data related to the characteristics of feed showed that the average value of this ratio was 1.1. This value indicates that for each unit addition of SOC to the reactor during step feeding, almost the same quantity of nitrogen was also added to the reactor. The positive

affect of addition of SOC was actually counterbalanced by the negative impact of addition of nitrogen and as a result no significant enhancement in total nitrogen removal was observed.

5.4.4.b-Conclusion

Step-feeding did not improve total nitrogen removal due to the almost equal concentrations of SOC and TKN_{Sol} in the feed. The impact of step-feeding on phosphorus removal was insignificant.

5.5 EFFECTS OF FERMENTATION ON NUTRIENT REMOVAL : AN OVERVIEW

In previous sections of this report the effects of prefermentation of degritted raw wastewater on nutrient removal efficiencies of SBRs have been discussed thoroughly. This section puts together the major results obtained at different stages of the research and highlights (mostly graphically) the performance improvements that have been achieved by the application of prefermentation step. The figures here cover the whole period of BNR studies.

As mentioned earlier in this chapter, the fermentation reactor (PAF) reduced the suspended solids load to the BNR reactor and brought about significant changes in the quality and quantity of the soluble organic component of raw wastewater such that treatment performance of BNR reactor enhanced remarkably. The changes in SS, SOC, and VFA content of degritted raw wastewater caused by the fermentation process are shown in Figures 5.52, 5.53 and 5.54. The fermentation unit has actually accomplished :

1. Reduction of 38-83% suspended solids from the raw wastewater (Fig. 5.52). This reduced the solids load on the BNR reactor, diminished the organic load fluctuations and enhanced the performance and stability of the BNR system.
2. Solubilization of particulate organic matter which was reflected by an increase in soluble organic carbon (SOC) concentration in the fermented wastewater (Fig. 5.53).
3. Acid fermentation of soluble organic compounds into short chain volatile fatty acids (Fig. 5.54), which increased the bio-availability of the carbon sources for denitrifiers and particularly for the Bio-P bacteria.

As a result of the above modifications in the wastewater characteristics, treatment

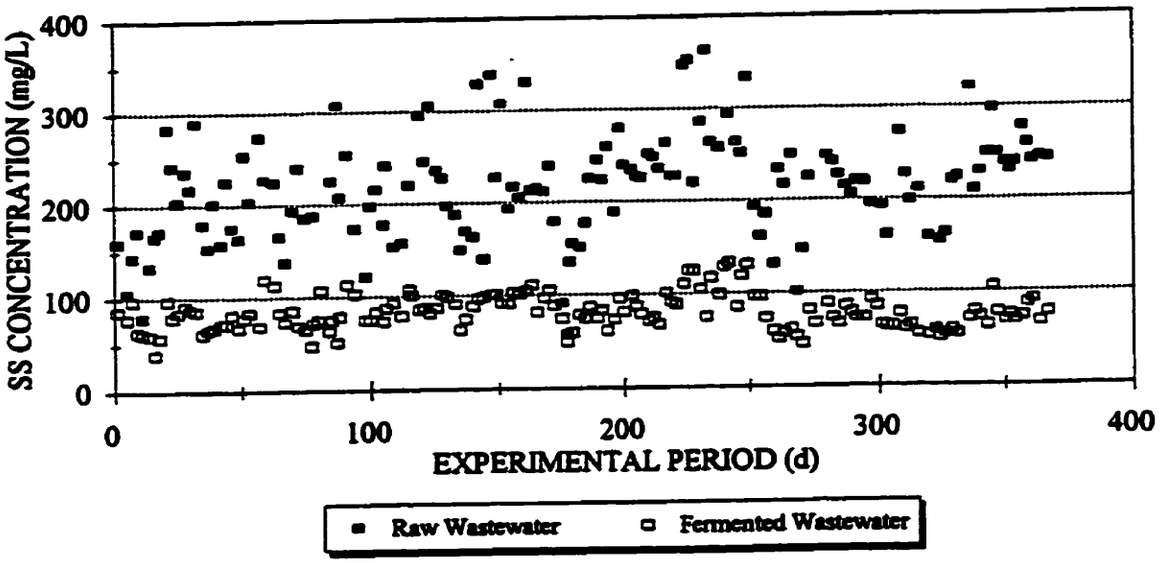

Fig. 5.52 : Suspended solid removal in the PAF reactor (overall view). Fermentation reactor acting also as primary clarifier reduced the suspended solids present in the degritted raw wastewater by an average of 62%.

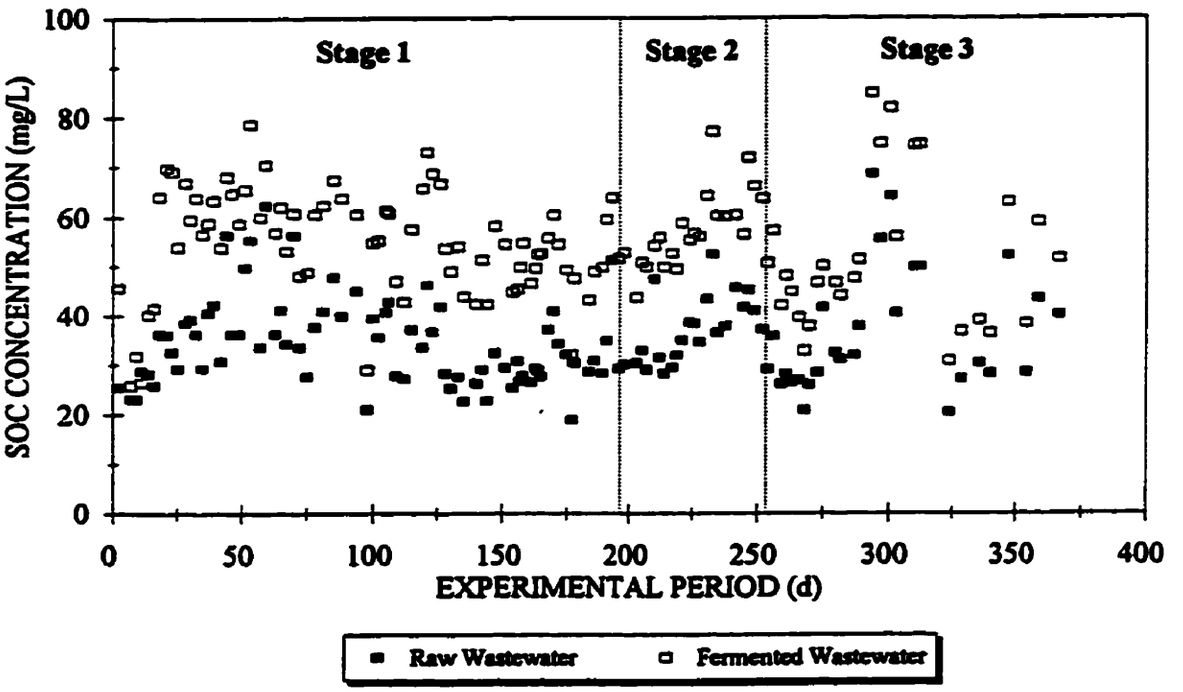

Fig. 5.53 : Increase in SOC content of the fermented wastewater (overall view). Solubilization of particulate organic compounds in the PAF reactor resulted in an increase in SOC of wastewater. (Stage 1 = 8 h cycle, Stage 2 = 6 h cycle with continuous-aeration, and Stage 3 = 6 h cycle with step-aeration).

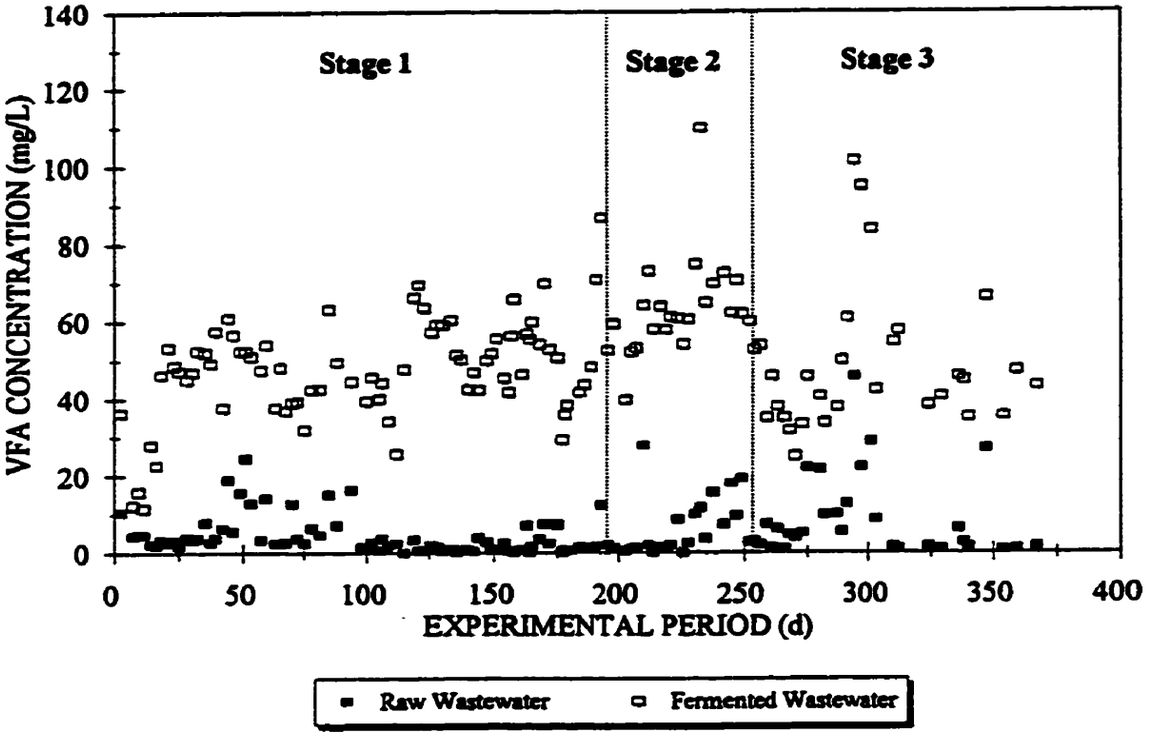

Fig. 5.54 : VFA concentration in raw and fermented wastewater (overall view). Considerable quantity of SCVFA was produced during fermentation process of raw wastewater.

performance of BNR-SBR improved significantly. The impacts of the fermentation process on treatment performance of BNR-SBR are summarized by brief presentation of the following parameters :

- Effluent phosphorus
- Effluent nitrogen and SOC
- Effluent suspended solids
- Sludge characteristics
- Reactions' dynamics

5.5.1 EFFLUENT PHOSPHORUS

Concentrations of ortho and soluble phosphorus in the raw wastewater and in the effluents of the two parallel BNR reactors; one receiving fermented wastewater (PAF-SBR) and the other receiving raw wastewater (conventional-SBR), are shown in Figures 5.55 and 5.56 respectively.

It can be clearly seen that, regardless of the operational conditions, the PAF-SBR system was always significantly more efficient in removing phosphorus than the conventional-SBR. Moreover, fluctuations in the effluent phosphorus concentration of PAF-SBR were remarkably less than the fluctuations observed in the conventional-SBR system, which indicated the greater stability of the PAF-SBR treatment system.

5.5.2 EFFLUENT NITROGEN AND SOC

Figure 5.57 presents the SOC concentration in the final effluents of parallel BNR reactors. Both systems were very efficient in removing the soluble carbon of the

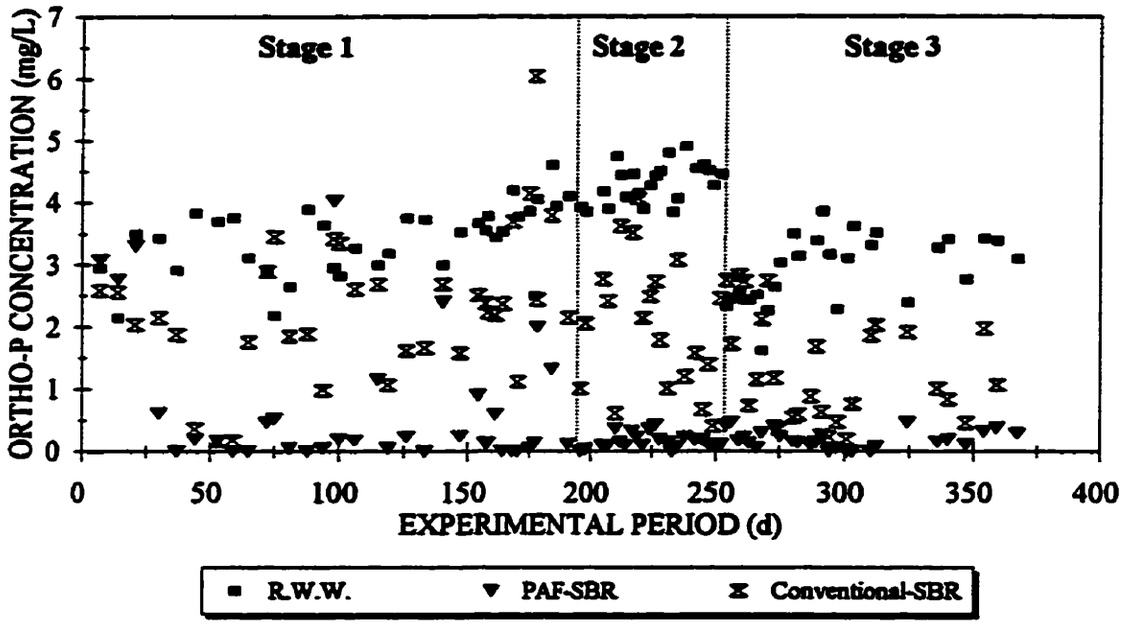

Fig. 5.55 : Ortho-P concentration in the effluent from the BNR reactors (overall view). The difference observed between the performance of PAF-SBR, and conventional-SBR with regard to Bio-P removal was always significant.

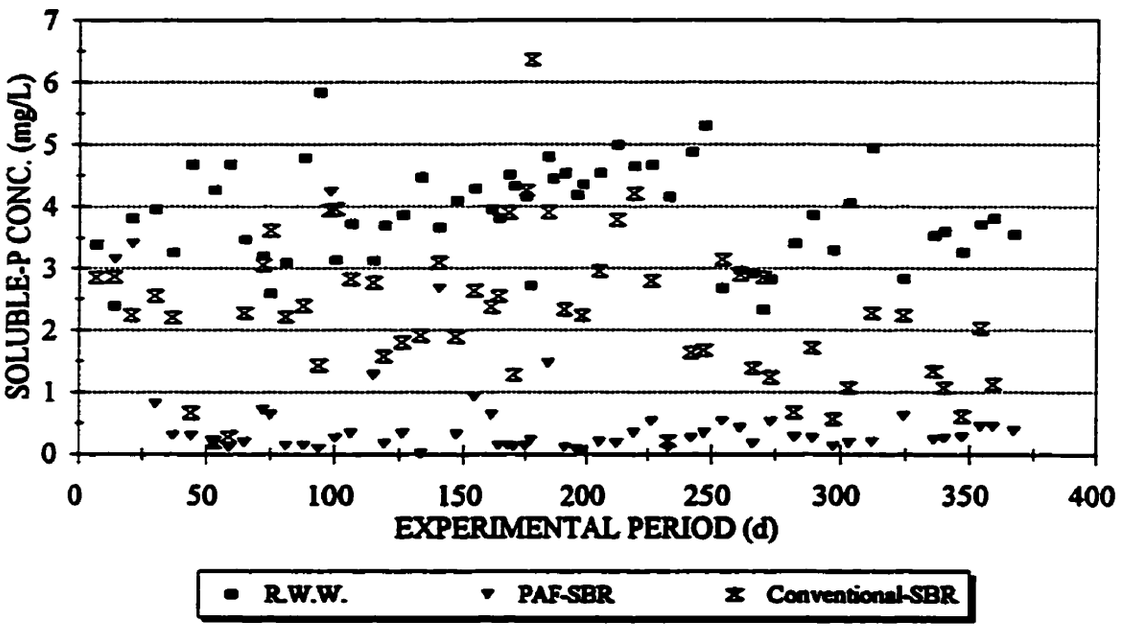

Fig. 5.56 : Soluble-P concentration in the effluent from the BNR reactors (overall view). Total soluble phosphorus concentration in the effluent of PAF-SBR was always less than 1 mg/L while in the conventional-SBR, the concentration varied over a wide range of less than 1 mg/L to greater than 4 mg/L.

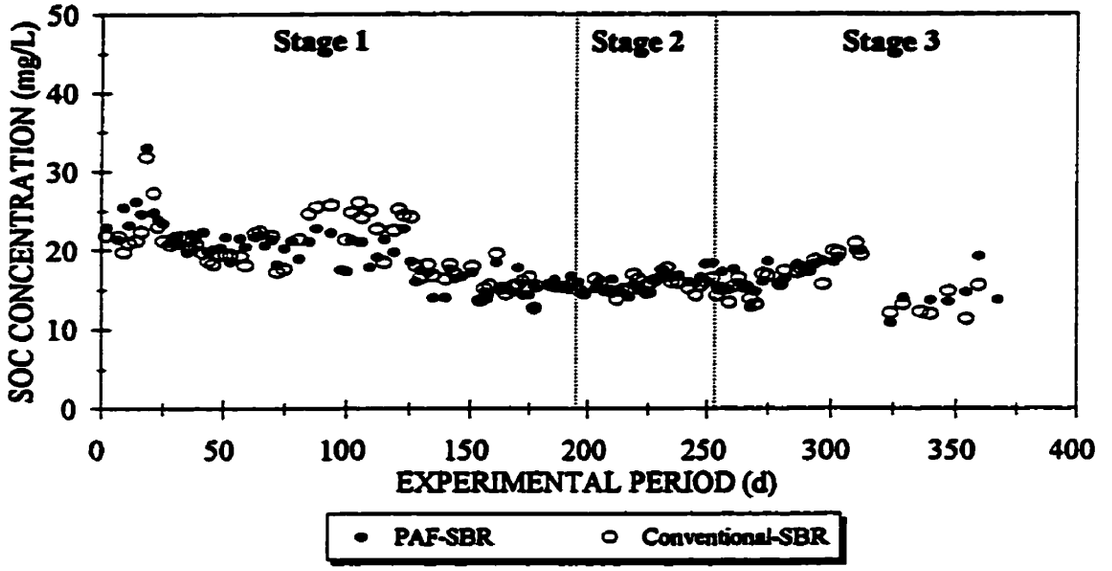

Fig. 5.57 : SOC concentration in the effluent from the BNR reactors (overall view). Removal of biodegradable organic compounds was very efficient in both parallel reactors.

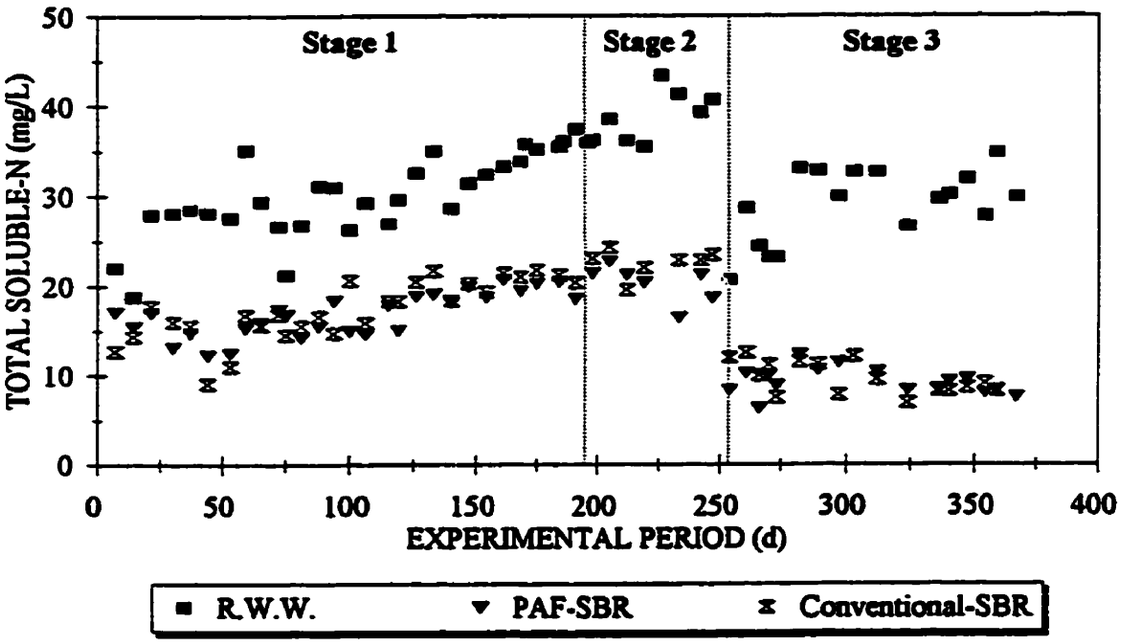

Fig. 5.58 : Total soluble nitrogen concentration in the effluent from the BNR reactors (overall view). The PAF-SBR and the conventional-SBR systems performed similarly in removing the soluble nitrogen content of the wastewater.

wastewater. Actually the conventional system was as efficient as the PAF-SBR system in removal of biodegradable organic compounds under different operational conditions.

The effluent total soluble nitrogen concentrations are shown in Fig. 5.58. In each set of the tested operational condition, removal of total soluble nitrogen in both parallel reactors followed the same pattern. The differences observed in total soluble nitrogen removal of PAF-SBR and the conventional-SBR under different conditions were not significant. In both reactors, the final limiting factor for more efficient removal of nitrogen was lack of availability of carbon sources.

5.5.3 EFFLUENT SUSPENDED SOLIDS

Figure 5.59 shows the effluent suspended solids concentration of BNR reactors over the total time period of research. As the data indicate, the PAF-SBR reactor was very consistent in removal of suspended solids and except for the initial period of start up of the system, the effluent SS of this reactor was less than 20 mg/L during the remaining period of the research.

The effluent suspend solids from the conventional-SBR on the other hand fluctuated, especially during stages 2 and 3 of the research when 6 h cycles (4 cycle/day) were being practiced. Loss of solids in the effluent of conventional-SBR, as will be discussed in the following section, was caused by bulking of the sludge in this reactor. Location of effluent port down at the 1/3 of the height of the reactor from the bottom, also accelerated the loss of the bulking sludge through the effluent.

5.5.4 SLUDGE CHRARACTERISTICS

One of the main goals of activated sludge treatment plants is to produce a well settling sludge which is an enriched mixed consortium of micro- and macro-organisms. Treatment efficiency and the cost of sludge processing are greatly affected by sludge settling behaviors.

In activated sludge systems, the treatment process relies on the development of floc-forming bacteria which will settle under gravity, leaving a clarified supernatant as final effluent. However, not all the bacteria that develop in activated sludge are floc-formers. Many types of filamentous organisms may develop, which can lead to operational problems such as bulking.

A bulking sludge is defined as a sludge that settles and compacts slowly. Many types of filamentous bacteria and fungi can produce a bulking condition in activated sludge (Richard, 1989). A certain limited number of filamentous organisms can be beneficial to the activated sludge process. In fact, lack of filamentous organisms can lead to small, easily sheared flocs (pin-floc) that settle well but leave behind a turbid effluent. Conditions leading to excessive growth of filamentous organisms include; low dissolved oxygen, low F/M ratio, nutrient deficiency, low pH, and septic wastes/sulfides (Richard, 1989).

Sludge volume index (SVI) is used as an indicator of the degree of bulking. A sludge with SVI > 150 mL/g is generally considered as a bulking sludge. However according to Richard (1989), each plant will have a specific SVI value where sludge is lost to the final effluent, which can vary from a SVI , 100 mL/g to >300 mL/g depending on the size and performance of final clarifiers and hydraulic considerations.

Abundance of filamentous organisms can be determined by the microscopic observation (M.O.) of the floc structure. A subjective scoring system (EPA,1987) is used in which filamentous organisms are rated for overall abundance on a scale from 0 to 6; where 0 indicates no filamentous organisms in the floc, and 6 represents excessive growth (abundance of more filaments than flocs).

A comparison between the SVIs of the conventional-SBR and the PAF-SBR is made in Fig. 5.60 (data are presented in Tables B1 and B2, Appendix B). The figure shows the variations in SVIs over the total time interval of the experiments. High SVI values were observed at the start up phase of the conventional-SBR unit. However the SVIs dropped as the reactor stabilized itself at an 8 h cycle period (stage 1). Changing the operational cycle from 8 h to 6 h had an adverse impact on sludge settleability of the conventional-SBR, as is revealed in Fig. 5.60 by an increase in the SVI values during stages 2 and 3 of the research. The SVI varied over the range of 26 to 150 mL/g with the mean value of 64 mL/g. Bulking occurred in this reactor, although the SVI was mostly below 150 mL/g. The problem was occasional at the 8 h cycle, but became more often and more severe in stages 2 and 3, when 6 h cycles were practiced. Severe bulking deteriorated the effluent quality as the concentration of SS in the effluent increased to unacceptable levels. Comparison of the Fig. 5.59 and 5.60 clearly shows the impact of sludge bulking on the effluent quality of the conventional-SBR.

Bulking was created by extensive proliferation of filamentous bacteria. M.O. values of about 5 (>20 filaments per floc) were often observed in the bulking sludge. Low F/M ratio was considered to be the cause of the growth of filamentous organisms in the conventional-SBR. The F/M ratio of this reactor in terms of mg of COD removed per mg

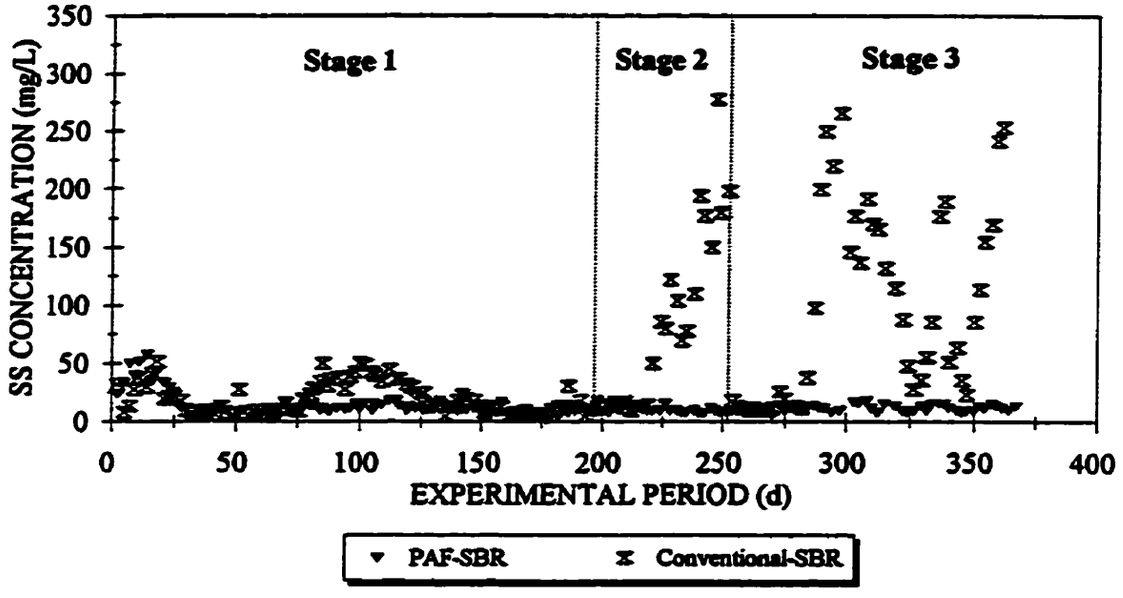

Fig. 5.59 : Effluent suspended solids of the BNR reactors (overall view). While the PAF-SBR produced consistent high quality effluent, sludge bulking deteriorated the conventional-SBR's effluent quality

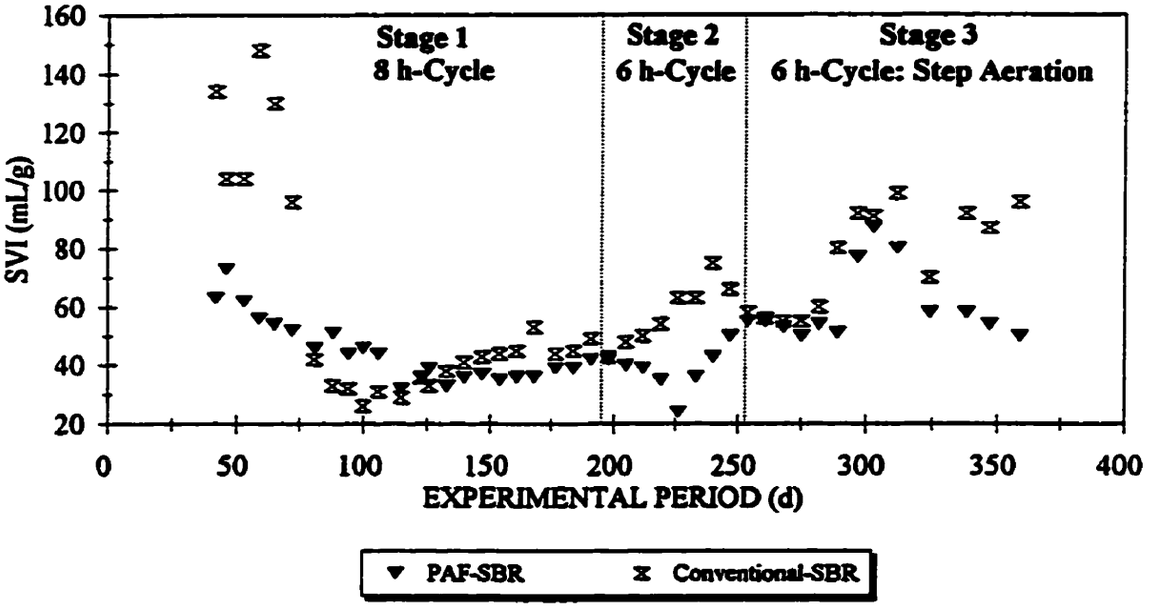

Fig. 5.60 : SVI in the BNR reactors (overall view). Sludge volume index in the conventional-SBR was mostly higher than the values obtained for the PAF-SBR system. Proliferation of filamentous bacteria during stages 2 and 3 of the research created bulking conditions in the former reactor.

of MLVSS per day was in the range of 0.06-0.08.

A representative photograph of the biomass in the conventional-SBR is shown Figure 5.61. Filamentous bacteria, rotifers, flagellates, stalked ciliates, free swimming ciliates and amoeboids were all observed during the course of study. Sludge worms were also present. A species of sludge worm which had a pink coloration in the integument and was characterized by hair-like bristles was developed in the above reactor towards the end of stage 1 of the experiments; between day 170 to day 210, but it disappeared as the system run through the 6 h cycles condition. These worms imparted a pink coloration to the surface of the settled sludge.

The phosphorus content of biomass in the conventional-SBR averaged 3.3%; calculated on the basis of total phosphorus mass balance. The actual biomass phosphorus content was measured on the basis of total phosphorus, soluble phosphorus and dry VSS contents of samples and ranged from 3.4 to 4.5%. Sludge production in this reactor, calculated on the basis of daily production of suspended solids, was 1.4 g dry solids/d which is equivalent to 170 $Kg/10^3$ m^3 of treated wastewater. The sludge production by primary sedimentation tank and waste activated sludge of activated treatment systems have been estimated to be in the range of 180 $Kg/10^3$ m^3 to 265 $Kg/10^3$ m^3.(Metcalf and Eddy, 1991). The reason for lower production of sludge in this research was the F/M ratio of the system which was lower than the usual F/M ratios (0.2-0.4 d^{-1}) applied to most conventional activated sludge systems. From the view point of F/M ratio, the biomass of the conventional-SBR system received an average organic load similar to values common in extended aeration systems (F/M=0.05-0.15 d^{-1}).

Total sludge production in the PAF-SBR system was 1.2 g/day or 150 $Kg/10^3$ m^3

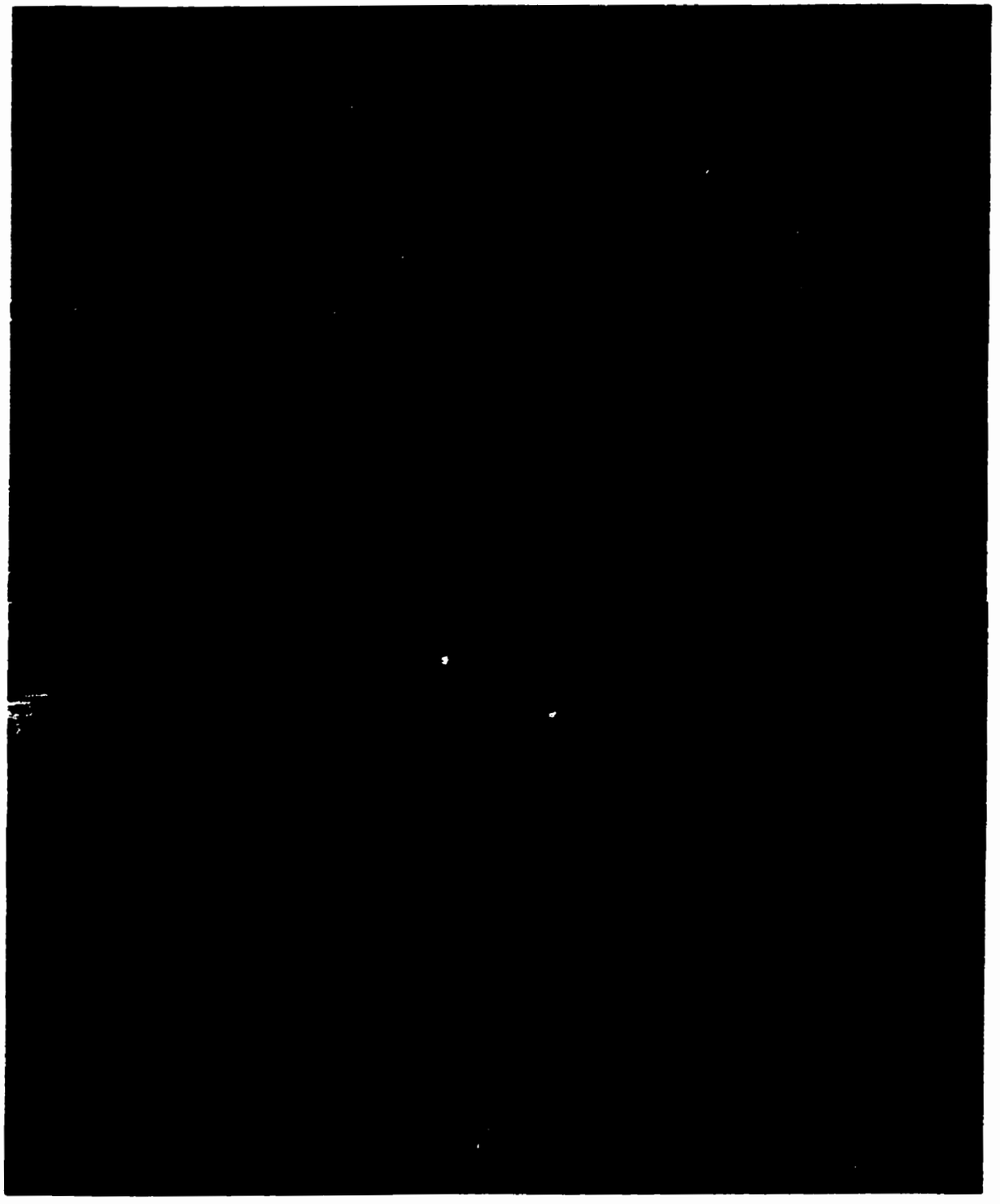

Fig. 5.61. : Photographic representation of the sludge in the conventional-SBR. Excess growth of filamentous bacteria is indicated in this picture. Stalked ciliate and rotifer is also observed.

of treated wastewater; about 12% less than the production in the conventional-SBR. The sludge in the PAF-SBR also had excellent settling characteristics under all the operational conditions tested.

The average calculated phosphorus content of the sludge in reactor B1 (the BNR reactor in the PAF-SBR system) was 8% (on the basis of total phosphorus mass balance) which is quite in agreement with the actual measured values of 7.7 to 8.4%. This is about 2.4 times more phosphorus content than the value achieved for the sludge in the conventional-SBR. Higher phosphorus content could be one of the reasons for observing better settleability of the sludge in this reactor.

The difference between settleability characteristics of the sludge in the parallel BNR reactors (B1 &B2) is reflected in Figure 5.62 which is based on the data in Table C9, Appendix C. The Figure represents the settling velocity of the sludge in the mixed liquor samples during a time interval of 30 min. The sludge volume index in B1 belonging to the PAF-SBR system ranged from 24 to 87 mL/g with the mean value of 48 mL/g.

Regular microscopic examination of the MLSS samples from reactor B1 revealed a stable consistent microbial community in this reactor. Colonial stalked ciliates, free swimming ciliates, rotifers, amoeboids and filamentous bacteria were always present. The M.O. values rarely exceeded 3 (1-5 filaments per floc) in this reactor. Higher F/M ratio (0.12-0.17 d^{-1}) and more availability of substrate in the PAF-SBR probably played an important role in controlling the growth of filamentous bacteria and prevention of bulking condition.

To summing up, the information on sludge production and sludge characteristics of the two parallel systems are given in Table 5.21.

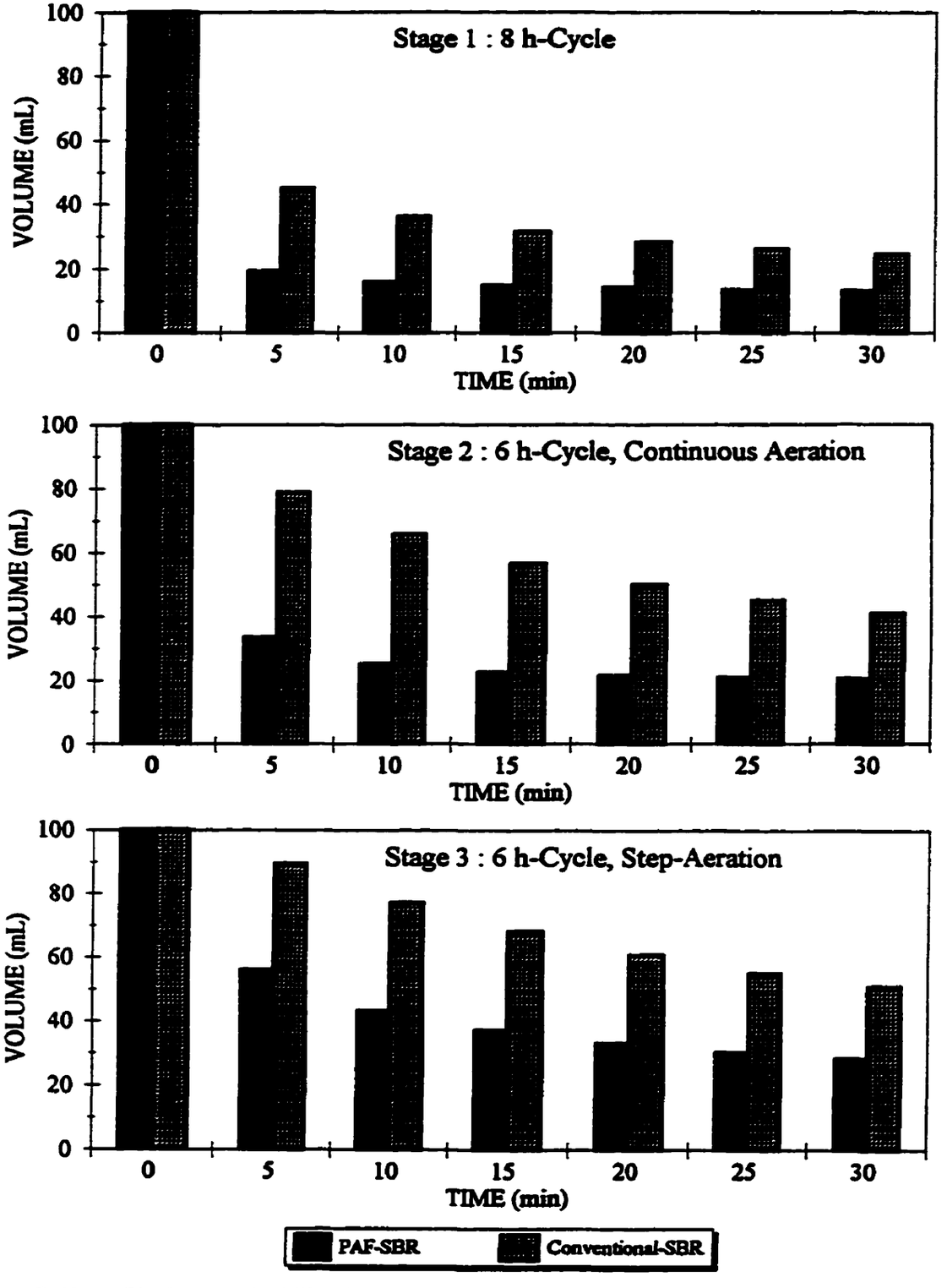

Fig. 5.62. : Sludge settleability in the BNR reactors (overall view). Regardless of the operational conditions, the sludge from the PAF-SBR settled much faster than the sludge from the conventional-SBR.

Table 5.21 : Sludge production and sludge characteristics in the PAF-SBR and conventional-SBR systems.

System	Sludge * ($Kg/10^3 m^3$)	P-Content † (% D.W.)	SVI (mL/g)	Bulking
PAF-SBR	150	7.7-8.4	24-87	No
Conventional-SBR	170	3.4-4.5	26-150	Yes

* : System sludge production in $Kg/10^3 m^3$ of treated wastewater

† : P content of the biomass in BNR reactors; on the basis of dry weight.

5.5.5 REACTOR DYNAMICS

Knowledge of biochemical reaction rates is valuable as they impact the HRT and sizing of reactors. With faster rates, lower HRT is required for accomplishment of reactions. Thus a reduction in total volume of reactors and a decrease in total capital cost of treatment plants will be resulted..

Application of prefermentation of raw wastewater in this research improved reaction rates of BNR processes. Significant differences were observed between the conventional-SBR and the PAF-SBR with respect to some of the reaction rates; as shown in Table 5.22. The values in this table are the summary of the information which have been given, and discussed in details in sections 5.4.1to 5.4.4. As it can be seen the rates of phosphorus release, phosphorus uptake, nitrification, and SOC uptake were remarkably higher in the PAF-SBR than in the conventional-SBR. The systems, however were performing similarly in rates of denitrification processes. Conversion of complex-organic compounds of the raw wastewaterwater to simpler favorable compounds (e.g. VFA) during the prefermentation step, was the main cause of improvement of reaction rates in the following BNR reactor.

Table 5.22 : Reaction dynamics in the parallel BNR reactors.

Reaction Rates	PAF-SBR	Conventional-SBR
VFA-uptake (mg acetic acid/g VSS.h)	22-27	-
P-Release (mg ortho-P/g VSS.h)	Primary release 12-19 Secondary release 1.8	1.1-3
SOC-uptake during anaerobic period (mg/g VSS.h)	9.5	1.7
P-uptake in presence of O_2 (mg ortho-P/g VSS.h)	1st h of aeration 5-5.7 2nd h of aeration 2.4 3rd h of aeration 0.9	1st h of aeration 0.8-1.7 2nd h of aeration 0.3 3rd h of aeration 0.0
P-Uptake in presence of NOx-N (mg ortho-P/g VSS.h)	1.1	0.3
VFA-Uptake/P-Release * (Molar ratio)	0.7-0.75:1	-
SOC-Utilized/P-Removed (mg/mg)	6.3	-
Nitrification (mg NOx-N/g VSS.h)	1st h of aeration 3.0-3.20	1st h of aeration 2.7-2.9
Denitrification (mg NOx-N/g VSS.h)	1.7	1.7

* VFA as acetic acid

** All P-measurements in Table 5.23 have been in the form of ortho-P

5.6 POTENTIAL APPLICABILITY OF THE FINDINGS

This research has led to the development of a new two-stage anaerobic-aerobic SBR system (PAF-SBR) which is remarkably efficient in biological nutrient removal. The system has many advantages over the conventional SBR systems. The practical advantages of the PAF-SBR, and applications associated with the results obtained in this research are presented bellow.

- Reliable biological removal of soluble phosphorus to the concentrations consistently less than 1 mg/L was achieved in the PAF-SBR system-without chemical use. As a result the operational complexity, and the costs associated with the usage of chemicals in the conventional SBR systems could be reduced or eliminated.
- Prefermentation of raw wastewater improved sludge settling characteristics in the following BNR reactor. The process, thus could shorten the sludge settling time, and reduce the HRT and capacity of the tank devoted to settling.
- Acid fermentation of raw wastewater was proved to be remarkably efficient in production of acetic acid. Some 78% to 96% of total VFA as compared to 43-55% HAc in total VFA reported in acid fermentation of primary sludge. This aspect of research has especial significance in enhancement of Bio-P removal process.
- Presence of organic substrates in the aerobic phase severely suppresses the uptake of phosphate (Ubukata and Takii, 1994). It also has detrimental impact on nitrification process. Consequently, as it has been recommended (Ubukata and Takii, 1994; Shin and Jun, 1992), organic compounds should be removed during the anaerobic phase in a phosphate-removing activated sludge system. Shin and Jun (1992) proved that by reducing the substrate concentration before the start of aerobic stage, development of

excess phosphorus removal bacteria was encouraged and their establishment was enhanced. Prefermentation of wastewater prior to BNR systems converts complex organics to the simple compounds which then can be easily removed in the anaerobic zone of BNR reactors. Therefore, in this system the amount of SOC that reaches the aerobic zone is much less than the amounts in the systems without prefermentation step. Results of this research indicated that about 60-62% of biodegradable SOC was removed during the initial anaerobic stage (45 min) of each cycle. This led to savings in oxygen use, better nitrification environment, and a better selection pressure for the Bio-P bacteria as there is less carbon present in the aerobic zone to encourage other heterotrophic populations.

- Efficiency of Bio-P removal process depends on the activities of the fermentation, and Bio-P bacteria. The rates of the activities of these two groups of bacteria were demonstrated in this research to be very different. Thus, reliability of treatment systems in which the two groups of microorganisms co-exist in the same reactor, as is common in the conventional treatment systems, is not sound especially when the anaerobic zone is the sole means of production of VFA. Due to this dichotomy, optimization of the design and operational conditions are difficult. However, if selective separation of the fermentation step is practiced, such as in this research, control of environmental and operational conditions favorable for each group of bacteria would become easier and more practicable. Moreover, separation of fermentation bacteria from the rest of the microbial community would increase the relative abundance of Bio-P bacteria in the BNR reactors which may result in a more efficient and stable process.

- Some parameters such as long sludge retention time (SRT), longer cycle time of anaerobic and aerobic conditions, change in the influent concentration of organic materials and the existence of saccharides could be unfavorable for Bio-P removal and could encourage the dominance of non-poly P bacteria and failure of the system (Satoh et.al., 1994). Brodisch and Joyner (1983) found that the length of anaerobic retention time affects the population dynamics especially with respect to the number of gram-positive organisms. They reported that *Acinetobacter* (usually the dominant Bio-P bacteria) as a strictly aerobic, non-spore forming bacteria would not be able to withstand extended anaerobic conditions. In the PAF-SBR system, the fermentation reactor acts as an equalization tank in the sense that it equalizes solids and organic loads to the BNR reactor. Conversion of organic compounds (including saccharides if they are present in the wastewater) to VFA also occurs in this unit. Therefore, there is no need for long HRT in the anaerobic zone of BNR systems. As a result all the conditions unfavorable for the proliferation of Bio-P bacteria and their activities in the conventional Bio-P removal systems, could be prevented or diminished in the PAF-SBR system due to application of the fermentation step.
- Considerable increase in the reaction rates of the BNR processes were observed in the PAF-SBR system. This indicates that the HRT, and the volume of the BNR reactors could be reduced if the fermentation step is practiced.

Chapter 6.

CONCLUSION

Feasibility of acid fermentation of raw wastewater and the effects of SRT, pH of feed, HRT and mixing period on this process were investigated in this study. Furthermore the role of acid fermentation of raw wastewater on enhancement of biological nutrient removal in SBR systems under different operational conditions were explored. Based on the results of the research, the following conclusions could be made.

1. Acid fermentation of degritted raw wastewater in a sequencing batch (SBR) mode was found to be feasible. The process was flexible, stable and reliable under all the conditions tested, except the condition of low pH (pH of feed = 6.1-6.4) low SRT (4 days).
2. Increase in SRT (using the wastewater with its natural pH; 7.0-7.6), enhanced both solubilization and VFA production. Both processes improved remarkably as the SRT increased from 4 d to 8 d and further to 13 d. VFA production as HAc was 38 mg/L at SRT of 4 d which increased to 43 mg/L at SRT of 8 d, and to 47 mg/L at SRT of 13 d.
3. At the feed pH range of 6.1-6.4, total solubilization, total VFA production, acetic acid concentration, and the specific rates of solubilization and VFA production as a function of SRT all followed the same pattern of change showing a sharp decrease at SRT of 4 days, and increasing with an increase in SRT. The mean VFA production as mg HAc/L of the effluent was 32, 29 and 4 at SRTs of 13d, 8d and 4 d, respectively.

The difference between the mean values were statistically significant.

4. Total VFA production at each level of SRT was lower at the pH range of 6.1-6.4 than at the pH range of 7.0-7.6. Lower pH range improved solubilization of organic particulates but suppressed the activities of the acidogenic bacteria such that the overall efficiency of VFA production was reduced.
5. Percent distribution of VFA was affected by variation in the pH of the feed. Acetic acid percentage of the total VFA was reduced by about 8% (excluding the low pH condition at 4 d SRT) as the pH of the feed was decreased from the range of 7.0-7.6 to the range of 6.1-6.4. Reduction in acetic acid was accompanied with production of higher molecular weight acids such as butyric, valeric and propionic acids.
6. Under short mixing period of 0.25 h/cycle, solubilization of particulate organic matter and production of VFA carried out as efficiently as with the mixing period of 6 h/cycle. However, the specific rates of solubilization and VFA production were lower at the mixing condition of 0.25 h/cycle. Reduction of mixing period also affected the VFA composition; resulting in a decrease in acetic acid production and an increase in propionic and butyric acids.
7. The impact of HRT on acid fermentation of degritted raw wastewater was less pronounced than the effects of SRT, pH and mixing periods. A decrease in HRT from 12 h to 9 h led to a non-significant increase in total solubilization, and solubilization specific rate. VFA production and its specific rate yielded similar values at both HRTs. A further decrease in HRT from 9 h to 6 h caused a significant decrease in total net solubilization and VFA production, although the changes in their specific rates were not significant. The variation observed in VFA speciation at different

HRTs was statistically insignificant. In general, the overall performance of acid fermentation was best at HRT of 9 h with SRT of 12 d.

8. Regardless of the operational and environmental conditions, the parameters of wastewater which are important in BNR process (e.g. VFA/P, COD/P, COD/N, SOC, alkalinity) improved remarkably as the result of the acid fermentation process. The average ratio of VFA/P_{Sol} in the fermented wastewater ranged 6.3-11 (depending on the conditions) as compared to the range of 0.1-1.4 observed in the raw wastewater.
9. Acetic acid was the major component of VFA regardless of the applied conditions. Its percentage in the VFA composition ranged from 78% to 96% (except with the condition of low pH-low SRT). The values were much higher than the range of 43-55% reported in literature for the acid fermentation of primary sludge.
10. Acid fermentation of degritted raw wastewater, in terms of VFA production expressed as mg HAc/L of the influent flow, was more effective than the conventional static, or complete-mix primary sludge fermenters (see Tables 5.17 & 5.18).
11. Significant differences were observed between the performance parameters of PAF-SBR and the conventional-SBR systems. Phosphorus removal, SS removal, and sludge settleability were enhanced substantially in the former system as the result of the application of fermentation step.
12. The operational cycle period of 8 h (with 2 to 3 h allocated to initial anoxic/anaerobic condition) commonly used for sequencing batch reactors designed for BNR, was shown to impair the effluent quality if the feed has already been enriched with the VFA (e.g. fermented wastewater). In such cases, the initial anoxic/anaerobic period should be reduced to 40-50 min to prevent any secondary release of phosphorus.

13. Reduction of total cycle period of BNR reactors from 8 h to 6 h (HRT of 9 h), with allocation of only 45 min to initial anoxic/anaerobic period, improved phosphorus removal in the PAF-SBR system. Phosphorus removal efficiency achieved 90-94% in this system which lead to an average effluent soluble phosphorus concentration of 0.3 mg/L. Operational cycle period of 6 h did not impair nitrogen and carbon removal in both BNR reactors.
14. Nitrogen removal improved as the continuous aeration of 3 h and 45 min in each 6 h cycle was replaced by step-aeration procedure of 1 h aeration, 1 h and 45 min anoxic period followed by 1 h of final aeration. Step-aeration did not impair P-removal efficiencies in BNR reactors. Nitrogen removal efficiencies increased from 50% to 69% in the PAF-SBR, and from 42% to 65% in the conventional-SBR as the result of the step aeration regime. Total soluble nitrogen in the final effluents of the above systems was reduced to an average of 9.5 mg/L consisting of 73% and 60% NOx-N, in the PAF-SBR and in the conventional-SBR respectively. Reactors' effluent NH_4-N concentration was less than 1 mg/L.
15. The impact of step-feeding on enhancement of biological nitrogen removal was insignificant as the result of almost equal concentrations of SOC and filtered TKN in the feed. In both BNR reactors, the final limiting factor in removal of nitrogen was lack of availability of carbon sources.
16. Regardless of the operational condition both BNR reactors behaved efficiently with respect to the SOC removal. About 60-62% of total biodegradable SOC in BNR reactor of PAF-SBR system was removed during the initial 45 min of each cycle.
17. Total soluble-P concentration in the effluent of PAF-SBR was always less than 1

mg/L. All the samples taken during the 6 h operational cycle periods had an ortho-P concentration of ≤ 0.5 mg/L with 80% of them showing also soluble-P concentration of ≤0.5 mg/L. In the conventional-SBR, however, the effluent P-content was very high; fluctuating over a wide range of less than 1 mg/L to greater than 4 mg/L soluble-P with an average range of 1.5 to 2.6 mg/L.

18. Acid fermentation of raw wastewater had a profound influence on the enhancement of sludge characteristics. Regardless of the operational conditions, the sludge in BNR reactor of PAF-SBR system settled much faster than the sludge in the conventional-SBR. The average phosphorus content of the sludge in the former reactor was in the range of 7.7 to 8.4% in contrast to the range of 3.4-4.5% obtained for the sludge in the conventional-SBR. Excellent settling characteristics of sludge in the PAF-SBR resulted in consistent low effluent SS concentration of less than 20 mg/L. Severe sludge bulking occurred in the conventional-SBR system (especially during the 6 h cycle periods of the research) which led to solids escape and deterioration of the effluent quality. Sludge production on the basis of total dry solids/1000 m^3 of treated wastewater was about 12% less in the PAF-SBR system than the conventional-SBR system.

19. A significant difference was observed between the rate of production of VFA by the fermentation bacteria, and the rate of uptake of VFA by the Bio-P bacteria. The uptake rate by Bio-P bacteria was 28.5 mg VFA/g VSS.h in contrast to production rates of 1.2-2.9 mg VFA/g VSS.h. obtained in PAF fermenters under various investigated conditions.

20. The amount of P-release in BNR reactors was a function of the VFA content of their

feed. Primary release of phosphorus ranged 12-19 mg ortho-P/g VSS.h in BNR reactor of PAF-SBR system. The rate of secondary release of phosphorus in this reactor was 1.8 mg ortho-P/g VSS.h. On the average about 1 mg of ortho-P was released for the uptake of 1.4-1.5 mg of VFA. This is equivalent to the molar ratio of 0.7-0.75:1 in terms of VFA uptake (as HAc)/ortho-P release. The mean ratio of P-release to the amount of substrate utilized was 1.6 mg ortho-P/mg SOC. The ratio of SOC-utilized/ortho-P removal was 6.3 mg/mg.

21. Phosphorus uptake rate followed a first-order reaction curve during aeration period. Phosphorus uptake occurred also during anoxic periods indicating the denitrification ability of Bio-P removal population.

22. Volatile fatty acids (VFA) play a vital role in release and uptake of phosphorus. Prediction of the performance of BNR systems just on the basis of the COD/P and/or COD/N of the wastewater without consideration of the quality of the COD could be completely misleading. The ratio of COD_{Tot}/P_{Tot} of the raw wastewater over total time period of this research was always higher (average value 67:1) than 40:1 (recommended value for an efficient removal of phosphorus). However the conventional-SBR system did not remove phosphorus efficiently unless on the days that the wastewater was rich in VFA. The average soluble-P removal efficiency of this system ranged from 35% to 57% depending upon the wastewater characteristics and the operational conditions.

Chapter 7.

FUTURE RESEARCH RECOMMENDATIONS

This research, has thrown some new light on fermentation of raw wastewater and its impacts on BNR of SBR systems. Many questions however, still remain which require research attention. The areas that could be recommended for future studies are as follows :

- The results of this study should be confirmed in a full scale system, subjected to hourly inflow variability.
- Cost analysis is required to compare the developed two-stage SBR system of this research (PAF-SBR) with a conventional-SBR using chemicals in Bio-P removal process.
- The impacts of temperature range on Bio-P removal process is still vague in the literature in the sense that its distinct influence on the fermentation, and Bio-P bacteria have not been studied. The up to now work on temperature effects have been done on the conventional systems where the fermentation bacteria and the Bio-P bacteria co-exist in one sludge. In such systems the assessment of the extent of temperature influence on the activity of each group separately, and determination of final limiting step in total Bio-P removal process is not possible. Experimental work at temperature range of (5 to 30) using a two-stage system (where the fermentation bacteria have been separated from the Bio-P bacteria) could provide the information necessary for many practical applications.

- Research on identification of soluble metabolic intermediates and final products of acid fermentation could be useful in understanding of the mechanisms and pathways involved in acid fermentation, and Bio-P removal processes.
- Although efficient acid fermentation was achieved with mixing period of 0.25 h/cycle, the research did not cover optimization of mixing period in the fermentation reactors. Optimization of the mixing period may lead to a more efficient fermentation process with regard to the solubilization of particulate organic matter and VFA production.
- Hydraulic retention times of less than 6 hours should be investigated in acid fermentation reactors (PAF) to establish the lower break-through range of HRT for such systems.
- Research on acid fermentation of raw wastewater in a continuous flow-through reactor (under controlled conditions of SRT and HRT) is required to expand the application of this process for the conventional continuous-flow through treatment systems.
- Effects of mixing during fill period of BNR reactors were not investigated in this study. The use of mixing operation during fill period could enhance VFA uptake and P-release, and reduce the initial anoxic/anaerobic period of each cycle to even shorter than 45 min developed in this research.
- Determination of the fraction of Bio-P bacteria capable of denitrification, and investigation of the parameters that affect them, can elucidate the conditions required for enhancement of both phosphorus and nitrogen removal.
- It is necessary to study the efficiency of P-uptake versus the stored PHA under

aerobic, and anoxic conditions where other operational and environmental conditions are kept constant. This should further contribute to the better understanding of Bio-P uptake mechanisms.

- Investigation on the effluent Coliform bacteria of PAF-SBR, and conventional-SBR systems are required to reveal the impact of acid fermentation of raw wastewater on destruction of pathogenic bacteria. This will determine whether or not there is a need for further disinfection of the effluent. Various SRTs should be tested in this investigation.

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APPENDIX A

Page

Table A1 - Wastewater (Feed) Characteristics 264

Table A2 - Reactor and Effluent Characteristics (Fermenter-F1) 276

Table A3 - Reactor and Effluent Characteristics (Fermenter-F2) 286

Table A4 - Reactor and Effluent Characteristics (Fermenter-F3) 297

TABLE A1 - WASTEWATER (FEED) CHARACTERISTICS

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
30-Oct-93	1	7.4	252	350	170	214	166	45.7	389.6	105.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.3	0.0				3.29	4.95
31-Oct-93	2																							
01-Nov-93	3																							
02-Nov-93	4	7.3	460	1136	438	614	336	82.0	405.4	184.1	2.5	1.4	1.1	0.0	0.0	0.0	0.0	28.7	0.0	34.0	43.8		2.76	6.73
03-Nov-93	5																							
04-Nov-93	6	7.5	266	584	404	140	110	53.0	400.4	168.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.8		39.4	44.5		5.05	7.12
05-Nov-93	7																							
06-Nov-93	8	7.5	266	584	404	140	110	40.2	389.6	160.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0							
07-Nov-93	9																							
08-Nov-93	10																							
09-Nov-93	11	7.5	276	652	364	158	140	56.1	358.0	152.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.1	0.0	35.1	43.8		4.28	6.86
10-Nov-93	12																							
11-Nov-93	13	7.4	280	684	336	134	112	58.5	373.8	120.9	2.7	2.7	0.0	0.0	0.0	0.0	0.0	22.0		33.3	42.6		3.35	6.54
12-Nov-93	14																							
13-Nov-93	15	7.4	284	736	312	232	132	68.6	358.0	105.1	2.6	2.6	0.0	0.0	0.0	0.0	0.0	24.8	0.0	33.1	41.6		4.09	6.28
14-Nov-93	16																							
15-Nov-93	17																							
16-Nov-93	18	7.4	280	664	268	202	134	59.9	358.0	105.1	2.5	2.5	0.0	0.0	0.0	0.0	0.0	27.7	0.0	34.6	41.9		3.92	6.38
17-Nov-93	19																							
18-Nov-93	20	7.3	284	988	412	268	212	62.9	847.9	255.2	39.1	28.6	0.9	1.8	4.0	2.5	1.2	35.1		42.2	67.6		6.78	10.20
19-Nov-93	21																							
20-Nov-93	22																							
21-Nov-93	23	7.3	292	1128	520	616	348	118.9	721.5	176.2	23.3	16.8	0.6	1.7	1.7	2.0	0.5	34.3		42.0	62.1		6.55	10.60
22-Nov-93	24																							
23-Nov-93	25	7.6	284	936	456	380	232	37.4	571.3	113.0	2.7	2.4	0.0	0.3	0.0	0.0	0.0	28.3	0.0	34.0	43.4		5.24	9.05
24-Nov-93	26																							
25-Nov-93	27	7.3	276	748	336	280	172	38.6	468.6	144.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.7		34.9	45.4		5.98	7.63
26-Nov-93	28																							
27-Nov-93	29																							
28-Nov-93	30	7.1	268	656	306	228	164	33.0	437.0	105.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.4		35.5	43.1		4.64	9.05
29-Nov-93	31																							
30-Nov-93	32	7.2	256	668	304	220	148	35.4	405.4	105.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.1	0.0	35.0	45.6		5.89	9.31
01-Dec-93	33																							
02-Dec-93	34	7.3	264	572	264	138	118	33.8	358.0	89.3	2.5	2.5	0.0	0.0	0.0	0.0	0.0	29.8		35.8	45.5		8.44	10.72
03-Dec-93	35																							
04-Dec-93	36																							
05-Dec-93	37																							
06-Dec-93	38	7.3	270	780	352	298	184	41.6	484.4	154.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0							
07-Dec-93	39																							
08-Dec-93	40	7.3	266	650	300	234	168	35.2	432.5	107.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.2	0.0	35.5	43.8		6.12	8.60
09-Dec-93	41																							
10-Dec-93	42	7.2	256	564	272	204	146	38.4	350.2	130.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.1		36.1	44.4		5.34	7.80
11-Dec-93	43																							
12-Dec-93	44																							
13-Dec-93	45	7.3	260	606	286	210	142	37.6	360.8	110.7	2.1	2.1	0.0	0.0	0.0	0.0	0.0	28.6	0.0	34.9	43.5		5.63	7.84
14-Dec-93	46																							
15-Dec-93	47	7.2	268	586	290	188	138	38.8	372.7	108.2	1.8	1.8	0.0	0.0	0.0	0.0	0.0	32.1		35.3	43.1		4.89	6.73
16-Dec-93	48																							
17-Dec-93	49	7.2	252	544	296	199	153	34.4	373.8	97.2	2.1	2.1	0.0	0.0	0.0	0.0	0.0	34.2		36.7	42.5		5.40	8.11

* Alkalinity as CaCO3

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
19-Dec-93	51																							
20-Dec-93	52	7.3	264	744	368	278	195	40.3	508.1	128.8	1.7	1.7	0.0	0.0	0.0	0.0	0.0	34.9	0.0	37.4	48.3		6.32	8.77
21-Dec-93	53																							
22-Dec-93	54	7.3	272	596	300	178	148	41.9	373.8	97.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.1		31.1	42.9		5.50	6.60
23-Dec-93	55																							
24-Dec-93	56	7.1	260	532	276	121	106		318.4	113.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.8		36.4	42.6		4.41	6.37
25-Dec-93	57																							
26-Dec-93	58																							
27-Dec-93	59	7.1	268	692	364	264	158	43.2	486.2	144.2	13.2	13.2	0.0	0.0	0.0	0.0	0.0	30.1	0.0	35.8	44.0		5.04	6.84
28-Dec-93	60																							
29-Dec-93	61																							
30-Dec-93	62																							
31-Dec-93	63																							
01-Jan-94	64	7.3	260	604	280	133	98	35.8	400.3	106.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.4		35.5	42.3		6.33	7.40
02-Jan-94	65																							
03-Jan-94	66	7.2	268	580	296	119	95	45.9	342.2	120.9	17.4	17.4	0.0	0.0	0.0	0.0	0.0	30.8	0.0	35.7	44.0		4.87	6.90
04-Jan-94	67																							
05-Jan-94	68			976	592	588	473	44.3			19.5	19.5	0.0	0.0	0.0	0.0	0.0							
06-Jan-94	69																							
07-Jan-94	70	7.2	268	724	408	278	223	36.4	500.2	100.6	2.3	2.3	0.0	0.0	0.0	0.0	0.0	32.4		38.0	55.8		4.35	8.19
08-Jan-94	71																							
09-Jan-94	72																							
10-Jan-94	73	7.2	260	544	320	194	141	32.5	342.2	57.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.8		35.0	49.6		4.02	6.61
11-Jan-94	74																							
12-Jan-94	75	7.0	264	520	284	112	94	30.8	334.2	63.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.2	0.0	34.9	43.4		4.32	6.75
13-Jan-94	76																							
14-Jan-94	77	7.1	256	596	296	181	133	35.9	354.4	84.3	37.4	29.4	0.0	4.8	3.2	0.0	0.0	30.6		35.6	44.8		5.23	7.16
15-Jan-94	78																							
16-Jan-94	79																							
17-Jan-94	80	7.4	250	516	358	163	129	48.9	408.3	160.2	1.3	1.3	0.0	0.0	0.0	0.0	0.0	29.4	0.0	38.6	44.1		5.09	7.65
18-Jan-94	81																							
19-Jan-94	82	7.1	252	516	280	142	124	38.6	344.1	141.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.7		33.1	42.2		4.92	6.82
20-Jan-94	83																							
21-Jan-94	84	7.1	256	564	172	176	112				8.5	8.5	0.0	0.0	0.0	0.0	0.0							
22-Jan-94	85																							
23-Jan-94	86																							
24-Jan-94	87	7.1	252	552	304	146	123	42.6	357.7	150.9	17.3	17.3	0.0	0.0	0.0	0.0	0.0	25.2	0.0	30.9	38.1		4.88	6.54
25-Jan-94	88																							
26-Jan-94	89	7.0	256	940	576	495	402				1.6	1.6	0.0	0.0	0.0	0.0	0.0							
27-Jan-94	90				520			37.2																
28-Jan-94	91	7.2	252	604	276	176	115	37.6	410.3	112.8	7.5	7.5	0.0	0.0	0.0	0.0	0.0	26.4		33.3	42.7		5.14	8.15
29-Jan-94	92																							
30-Jan-94	93																							
31-Jan-94	94																							
01-Feb-94	95	7.1	252	576	264	109	93	44.8	340.6	108.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.8		33.7	40.7		4.94	6.92
02-Feb-94	96	7.1	252	432	192	80	52				0.0		0.0	0.0	0.0	0.0	0.0							
03-Feb-94	97																							
04-Feb-94	98	7.2	252	620	320	156	134	46.2	400.9	182.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.0	0.0	31.8	37.7		5.11	7.42
05-Feb-94	99																							
06-Feb-94	100																							
07-Feb-94	101	7.1	272	844	482	464	364	44.8	625.8	119.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.3		39.4	68.5		6.74	12.31

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
08-Feb-94	102																							
09-Feb-94	103																							
10-Feb-94	104	7.2	248	512	272	136	116	42.4	378.8	151.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.1		35.1	44.1		4.44	6.53
11-Feb-94	105	7.2	256	512	288	122	114	41.0	384.0	143.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.0		34.7	41.3		4.65	6.32
12-Feb-94	106																							
13-Feb-94	107																							
14-Feb-94	108	7.0	236	568	328	124	122	43.8	369.6	158.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.3	0.0	31.6	39.0		4.68	6.64
15-Feb-94	109																							
16-Feb-94	110																							
17-Feb-94	111	7.0	250	536	296	132	118	42.9	400.9	151.0	3.1	3.1	0.0	0.0	0.0	0.0	0.0	29.8		35.3	42.8		5.15	7.07
18-Feb-94	112																							
19-Feb-94	113	7.2	246	550	320	130	124	41.8	380.7	156.9	1.2	1.2	0.0	0.0	0.0	0.0	0.0	28.1		33.2	41.9		4.72	6.72
20-Feb-94	114																							
21-Feb-94	115	7.1	250	562	312	134	120																	
22-Feb-94	116	7.1	246	584	348	164	136	39.4	406.7	154.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.8	0.0	35.7	42.5		4.51	6.76
23-Feb-94	117																							
24-Feb-94	118	6.2	108	524	276	152	126				0.0	0.0	0.0	0.0	0.0	0.0	0.0							
25-Feb-94	119																							
26-Feb-94	120	6.4	104	532	240	146	114				0.0	0.0	0.0	0.0	0.0	0.0	0.0							
27-Feb-94	121																							
28-Feb-94	122																							
01-Mar-94	123	6.2	104	610	318	186	122	37.1	396.3	140.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.2	0.0	31.6	38.5		4.86	7.02
02-Mar-94	124																							
03-Mar-94	125																							
04-Mar-94	126	6.2	103	586	320	180	154	42.4	376.8	156.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.6		31.9	38.6		4.32	6.60
05-Mar-94	127																							
06-Mar-94	128																							
07-Mar-94	129	6.3	103	568	308	170	146	38.8	360.2	142.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.7		34.8	40.4		4.86	6.82
08-Mar-94	130																							
09-Mar-94	131	6.1		668	308	234	122	37.4			0.0	0.0	0.0	0.0	0.0	0.0	0.0							
10-Mar-94	132																							
11-Mar-94	133	6.2	101	612	332	198	142	41.3	405.8	184.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.3	0.0	31.8	38.2		5.10	7.21
12-Mar-94	134																							
13-Mar-94	135	6.2	108	700	344	182	150	40.3	422.5	138.6	2.5	2.5	0.0	0.0	0.0	0.0	0.0	30.5		36.2	44.8		5.06	7.01
14-Mar-94	136																							
15-Mar-94	137	6.3	102	704	316	152	102	37.7	398.8	170.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.7		33.8	38.9		4.77	6.72
16-Mar-94	138																							
17-Mar-94	139																							
18-Mar-94	140	6.4	104	736	380	168	156	63.7	517.1	221.0	1.5	1.5	0.0	0.0	0.0	0.0	0.0	27.5	0.0	33.6	43.5		5.15	7.50
19-Mar-94	141																							
20-Mar-94	142																							
21-Mar-94	143	6.2	103	792	324	174	134	56.3	477.7	217.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.8		32.7	45.3		5.62	7.63
22-Mar-94	144																							
23-Mar-94	145	6.2	102	724	300	116	94	35.7	327.9	130.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.6	0.0	31.1	43.2		4.33	5.75
24-Mar-94	146																							
25-Mar-94	147	6.3	113	580	252	130	116	40.3			0.0	0.0	0.0	0.0	0.0	0.0	0.0							
26-Mar-94	148																							
27-Mar-94	149																							
28-Mar-94	150	6.2	114	644	252	120	104	39.3	343.6	130.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.4		33.0	40.1		4.27	5.58
29-Mar-94	151																							
30-Mar-94	152	6.3	107	988	408	334	156	36.1			4.9	1.3	0.5	0.2	0.4	0.0	2.5							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
31-Mar-94	153																							
01-Apr-94	154	6.2	84	812	304	188	116	41.6	387.8	107.1	0.8	0.1	0.0	0.1	0.0	0.0	0.6	22.6	0.0	28.4	30.6		3.35	4.86
02-Apr-94	155																							
03-Apr-94	156																							
04-Apr-94	157	6.2	88	776	284	196	132	34.4	383.1	83.4	0.6	0.2	0.0	0.0	0.0	0.4	0.0	24.2		27.5	31.9		3.28	5.05
05-Apr-94	158																							
06-Apr-94	159	6.3		688	296	160	126	47.0	374.1	147.2	4.0	3.3	0.0	0.2	0.0	0.5	0.0	27.1	0.0	33.9	37.3		3.38	5.52
07-Apr-94	160																							
08-Apr-94	161	6.2	101	668	276	164	122	44.7	356.3	141.8	1.5	0.2	0.0	0.1	0.6	0.6	0.0	27.3		33.4	36.7		4.73	5.71
09-Apr-94	162																							
10-Apr-94	163	6.3	103	826	344	368	240	40.0	395.2	107.1	1.0	1.0	0.0	0.0	0.0	0.0	0.0	27.9	0.0	32.3	38.8		3.81	5.47
11-Apr-94	164																							
12-Apr-94	165	6.2	88	1348	584	786	300	38.2	614.9	59.7	2.6	0.8	0.4	0.2	0.5	0.5	0.3	25.4		30.2	44.7		3.41	5.91
13-Apr-94	166																							
14-Apr-94	167	6.2	102	892	376	356	188	42.6	425.7	75.5	1.2	0.0	0.4	0.0	0.1	0.2	0.6	24.7		29.0	38.7		3.41	5.38
15-Apr-94	168																							
16-Apr-94	169	6.3	174	844	452	204	168	115.5	534.5	264.8	33.7	24.8	2.4	1.0	4.1	0.8	0.7	26.2		30.1	38.3		3.22	5.16
17-Apr-94	170																							
18-Apr-94	171	6.3	182	808	388	172	106	164.4	510.3	214.1	73.5	53.5	11.1	1.2	6.1	1.0	0.6	25.8	0.0	32.4	37.1		3.15	5.36
19-Apr-94	172																							
20-Apr-94	173	6.3	112	692	288	152	126	36.6	359.4	91.3	6.1	1.4	0.7	0.7	1.2	1.0	1.2	28.5		33.3	40.3		4.37	6.10
21-Apr-94	174	6.2	108					36.9			6.2	1.4	0.7	0.6	1.3	1.1	1.1							
22-Apr-94	175																							
23-Apr-94	176	6.2	110	568	336	140	120	37.5	350.4	105.2	4.8	1.0	0.4	0.3	1.0	1.2	0.9	26.3		31.8	39.1		4.68	6.05
24-Apr-94	177																							
25-Apr-94	178	6.3	100	560	300	132	114	35.5	342.7	95.7	4.3	1.6	0.7	0.2	0.6	0.6	0.6	27.5	0.0	31.4	39.8		4.27	5.91
26-Apr-94	179																							
27-Apr-94	180	6.2	113	724	368	184	162	47.9	378.3	152.8	9.0	4.4	0.3	0.8	1.6	1.3	0.6	28.4		30.3	41.7		4.38	5.82
28-Apr-94	181																							
29-Apr-94	182										11.0	6.4	0.3	0.5	1.5	1.4	0.7							
30-Apr-94	183																							
01-May-94	184										13.6	9.1	0.6	0.7	1.3	1.2	0.8							
02-May-94	185	5.8	90	960	476	294	204	50.5										29.8	0.0	32.8	42.9		4.67	6.84
03-May-94	186																							
04-May-94	187	5.7	78	852	456	274	206	49.1										30.2		31.8	43.5		4.26	5.48
05-May-94	188																							
06-May-94	189	5.8	80	812	460	186	156	39.1			7.0	1.2	0.4	1.0	1.6	1.7	1.2	28.6		33.3	41.0		4.83	6.61
07-May-94	190																							
08-May-94	191																							
09-May-94	192	5.9	40	752	436	100	96	36.8			5.6	1.4	0.4	0.7	1.1	0.8	1.2	27.7	0.0	32.3	37.8		4.05	5.45
10-May-94	193																							
11-May-94	194	5.8	80	828	440	196	168	45.5			4.7	2.2	0.7	0.0	0.6	0.8	0.5							
12-May-94	195																							
13-May-94	196	5.9	73	796	460	174	156	42.7			3.0	2.2	0.2	0.0	0.2	0.2	0.2	30.3	0.0	35.4	44.3		4.64	6.20
14-May-94	197																							
15-May-94	198																							
16-May-94	199	5.9	47	772	436	190	140	39.3			3.3	1.4	0.0	0.0	1.4	0.6	0.0	29.2		34.1	42.4		5.15	6.94
17-May-94	200																							
18-May-94	201	5.8	71	840	468	258	224	45.6			3.9	2.2	0.0	0.8	0.0	0.9	0.0							
19-May-94	202																							
20-May-94	203																							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nmo-butyric (mg/L)	Iso-valeric (mg/L)	Nmo-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Jul-94	204					160																		
06-Jul-94	205	7.5	336					25.5			10.6	5.9	0.9	0.0	3.3	0.6	0.0							
07-Jul-94	206																							
08-Jul-94	207																							
09-Jul-94	208	7.5	284	968	260	106	98																	
10-Jul-94	209																							
11-Jul-94	210	7.6	368	1192	376	144	98	23.2	285.7	72.5	4.4	3.3	0.7	0.0	0.1	0.3	0.0	18.7	0.0	22.0	26.2	2.95	3.39	5.42
12-Jul-94	211																							
13-Jul-94	212	7.6	338	772	312	172	152	23.1			4.8	2.3	1.0	0.3	0.3	0.2	0.6							
14-Jul-94	213																							
15-Jul-94	214	7.8	396	1028	328	80	66	28.8			4.6	1.4	1.0	0.4	0.5	0.5	0.9							
16-Jul-94	215																							
17-Jul-94	216																							
18-Jul-94	217	8.1	352	1064	336	134	106	28.2	277.4	86.2	2.4	1.6	0.3	0.6	0.0	0.0	0.0	15.5	0.0	18.8	23.6	2.15	2.4	3.85
19-Jul-94	218																							
20-Jul-94	219	7.7	312	976	328	166	124	25.9			1.8	1.3	0.0	0.2	0.1	0.2	0.0							
21-Jul-94	220																							
22-Jul-94	221	7.5	332	964	364	172	146	36.3			3.3	1.7	0.6	0.4	0.2	0.3	0.0							
23-Jul-94	222																							
24-Jul-94	223																							
25-Jul-94	224	7.5	322	984	448	284	232	36.2	496.7	89.8	2.7	1.2	0.2	0.0	0.5	0.9	0.0	22.1	0.0	27.9	38.7	3.5	3.82	6.82
26-Jul-94	225																							
27-Jul-94	226	7.5	324	840	324	242	164	32.7			3.1	1.5	0.0	0.3	0.7	0.6	0.0							
28-Jul-94	227																							
29-Jul-94	228	7.5	304	1056	404	204	160	29.3			1.7	0.0	0.0	0.4	0.6	0.7	0.0							
30-Jul-94	229																							
31-Jul-94	230																							
01-Aug-94	231	7.3	304	1092	384	236	196	38.5			4.1	2.6	0.0	0.1	0.5	0.9	0.0							
02-Aug-94	232																							
03-Aug-94	233	7.4	308	1028	324	218	182	39.3	396.3	110.6	3.3	0.4	0.0	0.2	0.8	1.3	0.6	22.4	0.0	28.1	37.2	3.43	3.96	5.85
04-Aug-94	234																							
05-Aug-94	235	7.6	272	994	458	290	250	36.3			3.9	1.5	0.0	0.5	0.9	0.9	0.0							
06-Aug-94	236																							
07-Aug-94	237																							
08-Aug-94	238	7.5	300	976	360	180	156	29.4			7.8	4.9	0.0	0.0	2.7	0.0	0.1							
09-Aug-94	239																							
10-Aug-94	240	7.5	326	956	364	154	128	40.7	347.6	96.7	2.6	1.1	0.0	0.4	0.2	1.0	0.0	23.9	0.0	28.5	33.3	2.91	3.26	5.36
11-Aug-94	241																							
12-Aug-94	242	7.4	320	1020	404	202	182	42.3			3.8	1.7	0.0	0.2	1.0	0.5	0.5							
13-Aug-94	243																							
14-Aug-94	244																							
15-Aug-94	245	7.5	328	828	376	158	128	30.8			6.3	3.4	0.8	0.0	0.9	0.7	0.5							
16-Aug-94	246																							
17-Aug-94	247	7.2	354	1032	424	226	190	56.5	542.7	152.4	19.0	12.9	1.1	0.9	1.5	2.1	0.4	26.0	0.0	28.1	38.5	3.83	4.68	6.6
18-Aug-94	248																							
19-Aug-94	249	7.4	308	960	368	176	150	36.3			5.6	1.8	0.0	0.6	1.1	1.7	0.4							
20-Aug-94	250																							
21-Aug-94	251																							
22-Aug-94	252	7.5	308	820	324	164	138	36.2			15.6	10.3	0.0	0.6	1.8	1.8	1.1							
23-Aug-94	253																							
24-Aug-94	254	7.5	316	1064	368	254	194	49.9			24.4	19.9	0.5	0.8	1.5	1.6	0.1							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
25-Aug-94	255																							
26-Aug-94	256	7.5	310	1004	328	204	140	55.4	391.4	134.6	12.8	8.9	0.1	0.4	1.1	1.6	0.8	24.1	0.0	27.5	36.0	3.7	4.27	5.91
27-Aug-94	257																							
28-Aug-94	258																							
29-Aug-94	259																							
30-Aug-94	260	7.5	310	928	344	274	182	33.7			3.4	0.7	0.0	0.0	1.1	1.3	0.3							
31-Aug-94	261																							
01-Sep-94	262	7.4	308	948	332	228	172	62.3	447.0	169.3	14.1	11.4	0.0	0.4	0.5	1.1	0.8	27.4	0.0	35.1	44.6	3.76	4.68	6.33
02-Sep-94	263																							
03-Sep-94	264																							
04-Sep-94	265																							
05-Sep-94	266	7.5	302	988	308	224	172	36.3			2.5	0.9	1.2	0.1	0.1	0.3	0.0							
06-Sep-94	267																							
07-Sep-94	268	7.6	346	900	328	166	146	41.2	400.5	104.6	2.3	1.0	0.0	0.2	0.2	0.9	0.0	24.7	0.0	29.4	34.7	3.12	3.47	5.84
08-Sep-94	269																							
09-Sep-94	270	7.8	364	892	332	138	114	34.3			2.6	1.4	0.6	0.0	0.2	0.5	0.0							
10-Sep-94	271																							
11-Sep-94	272																							
12-Sep-94	273	7.6	332	972	376	194	130	56.3			12.7	10.1	0.0	0.3	1.0	0.8	0.6							
13-Sep-94	274																							
14-Sep-94	275	7.7	346	1032	408	240	194	33.5	459.4	117.7	3.8	1.5	0.2	0.3	0.5	0.9	0.3	21.4	0.0	26.6	34.5	2.87	3.2	5.33
15-Sep-94	276																							
16-Sep-94	277																							
17-Sep-94	278	7.8	372	1000	368	186	166	27.7	357.5	87.7	2.5	0.1	0.1	0.2	0.7	0.8	0.6	18.7	0.0	21.2	28.0	2.18	2.6	4.47
18-Sep-94	279																							
19-Sep-94	280																							
20-Sep-94	281	7.7	382	956	348	188	152	37.7			6.4	4.1	0.0	0.5	1.0	0.8	0.0							
21-Sep-94	282																							
22-Sep-94	283																							
23-Sep-94	284	7.7	326	1148	480	468	282	41.0	582.3	228.6	4.7	2.9	0.3	0.3	0.5	0.6	0.0	21.8	0.0	26.7	37.7	2.65	3.1	5.96
24-Sep-94	285																							
25-Sep-94	286																							
26-Sep-94	287																							
27-Sep-94	288	7.6	334	944	376	226	182	47.7			15.1	10.6	1.0	0.7	1.1	1.1	0.6							
28-Sep-94	289																							
29-Sep-94	290					308	256																	
30-Sep-94	291	7.6	312	800	332	208	182	39.9	424.9	98.9	7.2	5.4	0.3	0.2	0.5	0.7	0.0	26.5	0.0	31.1	39.7	3.89	4.78	7.15
01-Oct-94	292																							
02-Oct-94	293																							
03-Oct-94	294					254	156																	
04-Oct-94	295																							
05-Oct-94	296																							
06-Oct-94	297	7.5	290	776	348	174	148	45.1	417.4	125.2	16.2	15.1	0.3	0.2	0.1	0.5	0.0	26.1	0.0	31.0	38.2	3.64	5.84	6.52
07-Oct-94	298																							
08-Oct-94	299																							
09-Oct-94	300																							
10-Oct-94	301	7.8	334	648	256	122	96	21.1			1.5	1.1	0.2	0.0	0.0	0.2	0.0					2.96		
11-Oct-94	302																							
12-Oct-94	303	7.7	368	896	372	198	162	39.5	372.4	80.2	1.5	0.8	0.3	0.0	0.0	0.4	0.0	21.2	0.0	26.3	34.3	2.82	3.14	5.07
13-Oct-94	304																							
14-Oct-94	305	7.5	376	944	416	216	188	35.6			2.7	1.8	0.0	0.0	0.6	0.4	0.0							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
15-Oct-94	306																							
16-Oct-94	307																							
17-Oct-94	308	7.7	352	876	352	178	154	40.9			0.8	0.0	0.4	0.0	0.0	0.4	0.0							
18-Oct-94	309	7.6	336	880	335	242	190	42.8			3.6	2.1	0.5	0.0	0.0	0.5	0.6	25.3	0.0	29.2	38.6	3.27	3.73	5.73
19-Oct-94	310																							
20-Oct-94	311																							
21-Oct-94	312	7.7	402	960	373	154	126	27.7			1.8	1.7	0.0	0.1	0.0	0.0	0.0							
22-Oct-94	313																							
23-Oct-94	314																							
24-Oct-94	315	7.7	460	1108	424	158	128	27.1			2.3	0.9	1.2	0.0	0.0	0.2	0.0							
25-Oct-94	316																							
26-Oct-94	317																							
27-Oct-94	318	7.7	406	1084	536	220	176	37.1	473.0	89.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.7	0.0	26.9	34.8	3	3.13	5.04
28-Oct-94	319																							
29-Oct-94	320																							
30-Oct-94	321																							
31-Oct-94	322	7.7	372	1012	474	296	232	33.6	509.0	73.0	3.3	2.8	0.0	0.0	0.0	0.5	0.0	25.2	0.0	29.6	39.2	3.18	3.7	6.37
01-Nov-94	323																							
02-Nov-94	324	7.6	368	964	432	246	198	46.2			0.6	0.0	0.0	0.0	0.0	0.6	0.0							
03-Nov-94	325																							
04-Nov-94	326	7.8	376	1044	428	306	166	36.7			0.5	0.0	0.0	0.0	0.0	0.5	0.0							
05-Nov-94	327																							
06-Nov-94	328																							
07-Nov-94	329	7.5	360	968	412	236	200	41.8	496.0	120.0	1.9	0.8	0.0	0.0	0.0	1.1	0.0	26.9	0.0	32.5	42.4	3.75	3.87	6.42
08-Nov-94	330																							
09-Nov-94	331	7.5	320	832	384	228	176	28.3			1.4	0.0	0.0	0.0	0.3	0.7	0.4							
10-Nov-94	332																							
11-Nov-94	333	7.6	352	884	336	198	172	25.3			0.5	0.0	0.0	0.0	0.0	0.5	0.0							
12-Nov-94	334																							
13-Nov-94	335																							
14-Nov-94	336	7.6	352	948	412	188	164	27.6	716.0	136.0	0.8	0.0	0.0	0.0	0.0	0.8	0.0	30.0	0.0	35.0	42.1	3.72	4.47	6.14
15-Nov-94	337																							
16-Nov-94	338	7.6	354			150	118	22.7			0.0	0.0	0.0	0.0	0.0	0.0	0.0							
17-Nov-94	339																							
18-Nov-94	340			918	398	170	144				0.6	0.0	0.0	0.0	0.0	0.6	0.0							
19-Nov-94	341																							
20-Nov-94	342																							
21-Nov-94	343	7.6	404	904	406	164	142	26.3	387.0	104.0	0.8	0.0	0.0	0.0	0.2	0.4	0.2	22.4	0.0	28.6	34.8	3	3.67	5.29
22-Nov-94	344																							
23-Nov-94	345	7.7	420	1232	444	330	158	29.1			0.4	0.0	0.0	0.0	0.0	0.4	0.0							
24-Nov-94	346																							
25-Nov-94	347	7.7	418	984	388	140	124	22.8			3.8	1.0	0.0	1.3	0.0	1.5	0.0							
26-Nov-94	348																							
27-Nov-94	349																							
28-Nov-94	350	7.7	388	1080	468	340	272	32.4	638.0	120.0	2.7	1.2	0.9	0.0	0.0	0.7	0.0	26.8	0.0	31.4	43.0	3.53	4.1	6.69
29-Nov-94	351																							
30-Nov-94	352	7.7	384	964	416	228	186				0.8	0.0	0.3	0.0	0.0	0.5	0.0							
01-Dec-94	353																							
02-Dec-94	354	7.6	364	1020	428	308	256	29.5			0.5	0.0	0.0	0.0	0.0	0.5	0.0							
03-Dec-94	355																							
04-Dec-94	356																							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Dec-94	357	7.6	360	932	368	194	154	25.5	410.5	102.5	2.4	1.7	0.6	0.0	0.0	0.0	0.0	25.7	0.0	32.4	40.4	3.67	4.29	5.7
06-Dec-94	358																							
07-Dec-94	359			912	368	218	180	30.8			0.5	0.0	0.0	0.0	0.0	0.5	0.0							
08-Dec-94	360							26.8			0.5	0.0	0.0	0.0	0.0	0.5	0.0					3.55		
09-Dec-94	361	7.6	350	900	380	206	176	27.8			0.0	0.0	0.0	0.0	0.0	0.0	0.0					3.78		
10-Dec-94	362																							
11-Dec-94	363																							
12-Dec-94	364	7.5	360	972	392	332	210	26.5	576.4	134.0	0.8	0.5	0.0	0.0	0.0	0.2	0.0	26.6	0.0	33.3	42.3	3.44	3.95	5.8
13-Dec-94	365																							
14-Dec-94	366			836	312	214	170	29.3			6.9	4.5	0.9	0.0	0.5	0.6	0.4							
15-Dec-94	367							28.9			0.0	0.0	0.0	0.0	0.0	0.0	0.0					3.54	3.82	6.65
16-Dec-94	368	7.6	328	880	384	216	176	27.6			1.6	1.0	0.6	0.0	0.0	0.0	0.0							
17-Dec-94	369																							
18-Dec-94	370																							
19-Dec-94	371	7.1	322	900	348	212	170	37.1	498.3	104.3	3.5	3.2	0.0	0.0	0.0	0.3	0.0	26.3	0.0	33.8	42.2	4.19	4.51	6.4
20-Dec-94	372																							
21-Dec-94	373			912	368	240	188	41.0	492.3	142.4	7.3	5.0	1.0	0.0	0.3	1.0	0.3	29.3	0.0	35.8	44.3	3.77	4.33	6.98
22-Dec-94	374																							
23-Dec-94	375	7.6	316	804	308	180	150	34.2			2.3	0.0	1.6	0.0	0.0	0.8	0.0							
24-Dec-94	376																							
25-Dec-94	377																							
26-Dec-94	378	7.5	314	720	264	92	80	32.1	360.7	124.6	7.1	5.4	0.8	0.0	0.0	0.7	0.2	28.2	0.0	35.1	43.9	3.86	4.16	5.41
27-Dec-94	379																							
28-Dec-94	380	7.4	228	512	196	58	48	18.9			0.0	0.0	0.0	0.0	0.0	0.0	0.0					2.5	2.72	3.72
29-Dec-94	381			752	284	136	126	30.4			0.7	0.0	0.0	0.0	0.0	0.7	0.0					4.05		
30-Dec-94	382	7.5	314	760	280	156	138				0.6	0.0	0.0	0.0	0.0	0.6	0.0							
31-Dec-94	383																							
01-Jan-95	384																							
02-Jan-95	385			988	368	152	125																	
03-Jan-95	386																							
04-Jan-95	387	7.8	314	856	308	178	138	28.7	378.9	118.3	1.5	0.4	0.0	0.0	0.8	0.3	0.0	30.1	0.0	35.5	42.0	4.6	4.8	6.15
05-Jan-95	388																							
06-Jan-95	389	7.7	292	788	360	226	192	31.0	434.2	129.3	1.2	0.9	0.0	0.0	0.0	0.3	0.0	31.5	0.0	36.1	45.2	3.94	4.45	6.49
07-Jan-95	390																							
08-Jan-95	391																							
09-Jan-95	392	7.5	296	828	352	246	220	28.4			0.9	0.5	0.0	0.0	0.0	0.4	0.0							
10-Jan-95	393																							
11-Jan-95	394	7.8	288	808	356	224	196	34.9	494.7	165.3	1.7	0.9	0.0	0.0	0.0	0.8	0.0	31.2	0.0	37.4	47.1	4.1	4.54	6.81
12-Jan-95	395																							
13-Jan-95	396	7.5	304			260	224	51.3			12.3	7.3	2.4	0.4	1.3	0.8	0.3							
14-Jan-95	397																							
15-Jan-95	398																							
16-Jan-95	399	8.0	288	764	340	190	144	29.3	432.0	118.2	2.0	0.6	0.0	0.0	0.5	0.9	0.0	30.2	0.0	36.0	44.4	3.92	4.19	6.15
17-Jan-95	400																							
18-Jan-95	401	7.8	276	868	400	280	178	30.2	455.5	141.8	1.1	0.5	0.2	0.0	0.0	0.4	0.0	30.4	0.0	36.3	46.0	3.85	4.36	6.37
19-Jan-95	402																							
20-Jan-95	403			784	292	240	214																	
21-Jan-95	404																							
22-Jan-95	405																							
23-Jan-95	406	7.8	276	804	306	235	195	30.5			1.1	0.5	0.0	0.0	0.0	0.0	0.0							
24-Jan-95	407																							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
25-Jan-95	408	7.8	288	844	328	228	176	33.0	453.8	150.1	1.0	0.0	0.8	0.0	0.0	0.2	0.0	31.4	0.0	38.6	47.3	4.18	4.54	6.81
26-Jan-95	409																							
27-Jan-95	410					226	200	29.0			1.3	0.0	0.5	0.0	0.5	0.3	0.0					3.9		
28-Jan-95	411																							
29-Jan-95	412																							
30-Jan-95	413	7.5	284	784	344	252	196	47.6				21.2	3.8	0.5	1.3	0.8	0.4					4.74		
31-Jan-95	414																							
01-Feb-95	415	7.7	284	820	368	248	168	31.5	461.4	142.5		0.9	0.8	0.0	0.0	0.4	0.0	30.3	0.0	36.2	46.7	4.44	4.99	7.17
02-Feb-95	416																							
03-Feb-95	417	7.8	274	772	332	236	196	28.3				0.0	0.0	0.0	0.0	0.0	0.0					4.09		
04-Feb-95	418																							
05-Feb-95	419																							
06-Feb-95	420					264	206	29.5				0.0	0.5	0.0	0.0	1.0	0.0					4.46		
07-Feb-95	421																							
08-Feb-95	422	7.7	268	740	332	228	184	32.0	499.4	172.8		0.0	0.5	0.0	0.0	0.5	0.0	30.1	0.0	35.5	44.5	4.15	4.65	6.92
09-Feb-95	423																							
10-Feb-95	424	7.7	268			228	180	35.0				0.0	0.8	0.0	0.5	0.6	0.0					3.9		
11-Feb-95	425																							
12-Feb-95	426																							
13-Feb-95	427	7.6	256	844	352	348	166	38.6				7.2	0.9	0.0	0.0	0.5	0.0					4.28		
14-Feb-95	428																							
15-Feb-95	429	7.1	278	816	428	354	250	38.5	590.5	180.4		0.0	0.0	0.0	0.0	0.0	0.0	39.8	0.0	43.4	55.1	4.43	4.67	7.15
16-Feb-95	430																							
17-Feb-95	431	7.7	262	636	288	220	186	34.7				1.3	0.0	0.0	0.7	0.5	0.0					4.51		
18-Feb-95	432																							
19-Feb-95	433																							
20-Feb-95	434	7.6	264	708	368	286	210	43.4				8.1	0.0	0.4	0.9	0.6	0.0					4.8		
21-Feb-95	435																							
22-Feb-95	436	7.6	276	832	396	364	238	52.5	651.3	210.8		10.4	0.0	0.3	0.7	0.4	0.0	31.1	0.0	41.3	51.5	3.85	4.16	6.47
23-Feb-95	437																							
24-Feb-95	438	7.8	264	664	344	264	212	36.6				1.5	0.7	0.0	0.9	0.5	0.0					4.07		
25-Feb-95	439																							
26-Feb-95	440																							
27-Feb-95	441	7.6	260	630	320	258	208	38.0				13.3	0.5	0.5	0.6	0.7	0.0					4.91		
28-Feb-95	442																							
01-Mar-95	443																							
02-Mar-95	444																							
03-Mar-95	445	7.4	264	710	376	294	216	45.8	529.8	233.6		5.5	0.0	0.6	0.0	0.9	0.3	31.5	0.0	39.3	53.7	4.55	4.88	7.24
04-Mar-95	446																							
05-Mar-95	447																							
06-Mar-95	448	7.4	254	616	312	264	204	41.7				14.3	1.9	0.0	0.9	0.9	0.0					4.61		
07-Mar-95	449																							
08-Mar-95	450	7.5	256	692	380	252	184	45.3	529.8	195.6		8.7	0.0	0.0	0.0	0.9	0.0	32.2	0.0	40.7	50.8	4.51	5.3	7.62
09-Mar-95	451																							
10-Mar-95	452	7.4	260	696	396	334	240	41.0				15.9	0.8	0.6	0.3	1.5	0.0					4.28		
11-Mar-95	453																							
12-Mar-95	454																							
13-Mar-95	455	7.4	260	620	328	194	166	37.1				1.3	0.0	0.5	0.0	0.8	0.0					4.45		
14-Mar-95	456																							
15-Mar-95	457	7.5	180	708	220	162	108	29.2	339.9	104.5		0.9	0.5	0.3	0.4	0.4	0.5	13.8	0.0	20.7	25.3	2.34	2.69	3.98
16-Mar-95	458																							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
17-Mar-95	459			688	296	186	136	35.9				1.0	0.5	0.0	0.0	0.6	0.0					2.46		
18-Mar-95	460																							
19-Mar-95	461																							
20-Mar-95	462	7.5	222	596	232	132	106	26.1				6.5	0.0	0.0	0.0	0.8	0.0		0.0			2.55		
21-Mar-95	463																							
22-Mar-95	464	7.3	268	610	368	234	178	28.1	371.2	71.1		0.7	0.6	0.0	0.0	0.0	0.0	21.0	0.0	28.7	36.0	2.44	2.97	4.96
23-Mar-95	465																							
24-Mar-95	466	7.7	266	616	248	218	146	26.5				6.1	0.0	0.0	0.0	0.0	0.0					2.44		
25-Mar-95	467																							
26-Mar-95	468																							
27-Mar-95	469	7.4	268	592	200	250	158	26.9	330.0	66.2		0.6	0.4	0.0	0.0	0.0	0.0	19.3	0.0	24.4	30.2	2.52	2.92	4.58
28-Mar-95	470																							
29-Mar-95	471	7.3	264	628	220	102	64	20.9				4.2	0.0	0.0	0.0	0.5	0.0					1.62		
30-Mar-95	472																							
31-Mar-95	473	7.8	304	716	288	148	114	26.0	251.6	94.7		3.4	0.0	0.0	0.0	0.5	0.0	16.7	0.0	23.2	27.2	2.26	2.34	3.65
01-Apr-95	474																							
02-Apr-95	475																							
03-Apr-95	476	7.5	296	700	320	226	164	28.4	384.9	65.5		4.9	0.0	0.0	0.0	0.2	0.0	20.0	0.0	23.2	31.0	2.64	2.83	4.82
04-Apr-95	477																							
05-Apr-95	478							41.7				15.8	3.8	0.4	0.9	0.8	0.4					3.03		
06-Apr-95	479																							
07-Apr-95	480																							
08-Apr-95	481																							
09-Apr-95	482																							
10-Apr-95	483	7.6	292	796	320	248	184	32.4				16.4	2.0	0.4	0.4	1.0	1.2					3.5		
11-Apr-95	484																							
12-Apr-95	485	7.7	300	758	302	242	180	31.2	320.9	84.7		8.7	0.0	0.0	0.7	0.0	0.4	25.7	0.0	33.1	42.1	3.14	3.41	6.1
13-Apr-95	486																							
14-Apr-95	487					228	186																	
15-Apr-95	488																							
16-Apr-95	489																							
17-Apr-95	490					216	174	32.0				6.7	0.6	0.5	0.6	0.9	0.7							
18-Apr-95	491																							
19-Apr-95	492	8.0	292			206	160	37.8	439.8	118.2		4.3	0.0	0.0	0.6	0.5	0.0	24.5	0.0	32.8	39.2	3.39	3.87	5.9
20-Apr-95	493																							
21-Apr-95	494					220	168					10.8	1.0	0.0	0.0	0.8	0.0					3.86		
22-Apr-95	495																							
23-Apr-95	496																							
24-Apr-95	497	7.7	300	832	400	220	174	68.6				15.3	2.5	0.5	26.3	0.9	0.3					3.17		
25-Apr-95	498																							
26-Apr-95	499																							
27-Apr-95	500	7.8	312	816	340	196	166	55.5	510.4	196.7		1.8	0.5	0.5	18.5	0.6	0.3	23.9	0.0	29.9	38.8	2.29	3.3	5.87
28-Apr-95	501																							
29-Apr-95	502																							
30-Apr-95	503																							
01-May-95	504	7.6	310	788	344	194	150	64.1				8.8	0.8	0.6	17.0	1.2	0.4					3.11		
02-May-95	505																							
03-May-95	506	7.8	308	760	300	162	132	40.6	380.2	133.9		8.0	0.0	0.0	0.7	0.0	0.0	24.9	0.0	32.7	37.5	3.62	4.06	5.97
04-May-95	507																							
05-May-95	508																							
06-May-95	509																							

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
07-May-95	510																							
08-May-95	511					274	226																	
09-May-95	512																							
10-May-95	513	8.1	320			228	192	49.9				1.2	0.0	0.0	0.0	0.4	0.0					3.32		
11-May-95	514																							
12-May-95	515	7.7	320	804	328	200	170	50.0	444.5	140.9		1.0	0.0	0.0	0.0	0.0	0.0	26.7	0.0	32.6	38.8	3.52	4.94	6.08
13-May-95	516																							
14-May-95	517																							
15-May-95	518					212	164																	
16-May-95	519																							
17-May-95	520																							
18-May-95	521																							
19-May-95	522					160	130																	
20-May-95	523																							
21-May-95	524																							
22-May-95	525					60	42																	
23-May-95	526																							
24-May-95	527	7.9	384	780	348	156	124	20.6	314.3	58.6		1.2	0.0	0.4	0.0	0.0	0.0	22.5	0.0	26.6	32.5	2.4	2.84	4.68
25-May-95	528																							
26-May-95	529					164	140																	
27-May-95	530																							
28-May-95	531																							
29-May-95	532	8.2	408			220	170	27.3				1.0	0.0	0.0	0.0	0.0	0.0							
30-May-95	533																							
31-May-95	534					224	178																	
01-Jun-95	535																							
02-Jun-95	536																							
03-Jun-95	537																							
04-Jun-95	538																							
05-Jun-95	539	7.8	358			322	250	30.4				2.5	1.4	0.6	0.8	0.6	0.3	24.2	0.0	29.6	37.3	3.28	3.54	5.05
06-Jun-95	540																							
07-Jun-95	541					210	140					1.3	1.1	0.0	0.0	0.2	0.0							
08-Jun-95	542																							
09-Jun-95	543	7.6	332	776	380	230	184	28.3	426.1	126.1		1.2	0.0	0.0	0.0	0.2	0.0	25.9	0.0	30.2	38.4	3.42	3.61	5.28
10-Jun-95	544																							
11-Jun-95	545																							
12-Jun-95	546	7.7	326			250	196																	
13-Jun-95	547																							
14-Jun-95	548					298	220																	
15-Jun-95	549																							
16-Jun-95	550	7.7	332	868	390	250	188	52.2	401.0	190.2		13.1	0.4	2.0	8.5	1.7	1.3	28.0	0.0	31.9	40.9	2.77	3.27	5.38
17-Jun-95	551																							
18-Jun-95	552																							
19-Jun-95	553					240	156																	
20-Jun-95	554																							
21-Jun-95	555					232	172																	
22-Jun-95	556																							
23-Jun-95	557	7.8	300	852	364	240	154	28.5	385.2	159.2		0.7	0.0	0.0	0.0	0.0	0.0	24.6	0.0	27.8	34.8	3.43	3.72	5.62
24-Jun-95	558																							
25-Jun-95	559																							
26-Jun-95	560					278	210																	

TABLE A1 - Continued.....

Date	Day	pH	Alkalinity (mg/L)	TS (mg/L)	TVS (mg/L)	SS (mg/L)	VSS (mg/L)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-Butyric (mg/L)	Nmo-Butyric (mg/L)	Iso-Valeric (mg/L)	Nmo-Valeric (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
27-Jun-95	561																							
28-Jun-95	562	7.7	328	840	376	260	210	43.6	420.5	159.2		1.0	0.0	0.0	0.0	0.0	0.0	29.0	0.0	34.8	43.0	3.39	3.82	5.53
29-Jun-95	563																							
30-Jun-95	564					242	180																	
01-Jul-95	565																							
02-Jul-95	566																							
03-Jul-95	567					246	176																	
04-Jul-95	568																							
05-Jul-95	569																							
06-Jul-95	570	7.6	294			244	196	40.2			0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6	0.0	29.9	39.9	3.1	3.56	5.3

TABLE A2 - REACTOR AND EFFLUENT CHARACTERISTICS (FERMENTER-F1)

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
30-Oct-93	1			3010	2360																			
31-Oct-93	2																							
01-Nov-93	3																							
02-Nov-93	4	7.2	270	2800	2180	176	152	No WAS	75.0	294.7	160.4	27.6	16.1	7.9	1.2	1.1	1.3	0.0	23.0	23.4	27.9		3.64	4.67
03-Nov-93	5																							
04-Nov-93	6	7.2	390	2510	1920	226	134	No WAS	56.2	452.8	168.3	27.6	26.3	0.0	0.0	0.0	1.3	0.0	32.5	36.3	41.4		2.99	5.57
05-Nov-93	7																							
06-Nov-93	8	7.4	288	2250	1760	170	120	No WAS	44.0	278.9	128.8		24.1	0.0	0.0	0.0	1.2	0.0	28.4	34.4	39.1		3.28	5.44
07-Nov-93	9																							
08-Nov-93	10																							
09-Nov-93	11	7.1	312	2120	1660	104	92	No WAS	83.4	413.3	176.2	30.8	29.5	0.0	0.0	0.0	1.3	0.0	32.5	38.5	44.4		5.57	6.94
10-Nov-93	12																							
11-Nov-93	13	7.0	304	1960	1530	102	86	No WAS	78.2	278.9	176.2	27.9	27.0	0.0	0.0	0.0	1.0	0.0	26.1	34.6	41.3		5.42	6.83
12-Nov-93	14																							
13-Nov-93	15	6.9	308	2010	1500	92	62	No WAS	86.9	373.8	215.7	70.1	45.6	19.0	1.4	2.0	2.1	0.0	31.4	37.3	37.8		5.57	6.82
14-Nov-93	16																							
15-Nov-93	17																							
16-Nov-93	18	7.2	304	1900	1430	138	90	No WAS	65.6	334.3	113.0	57.1	53.1	0.2	1.4	0.5	1.5	0.4	28.7	32.4	33.9		4.54	6.67
17-Nov-93	19																							
18-Nov-93	20	7.2	312	3070	2400	288	216	No WAS	68.2	626.6	215.7	62.7	58.3	0.3	1.6	0.2	2.1	0.3	38.2	43.3	60.3		10.40	11.37
19-Nov-93	21																							
20-Nov-93	22																							
21-Nov-93	23	7.1	336	4140	3260	188	140	No WAS	151.9	595.0	310.5	89.0	80.9	0.5	2.9	0.8	3.3	0.6	37.4	46.4	54.7		8.49	10.72
22-Nov-93	24																							
23-Nov-93	25	7.0	360	3960	3050	144	100	13	79.4	527.6	318.4	92.3	86.8	1.7	1.4	0.3	1.9	0.2	29.9	41.5	49.0		7.76	9.27
24-Nov-93	26																							
25-Nov-93	27	7.1	328	3680	2800	84	48	94	60.3	389.6	207.8	49.7	47.7	0.4	0.6	0.2	0.7	0.3	32.6	35.3	39.4		6.34	8.07
26-Nov-93	28																							
27-Nov-93	29																							
28-Nov-93	30	6.9	308	3530	2740	92	56	74	43.6	350.1	176.2	23.0	21.8	0.0	0.0	0.0	1.2	0.0	31.9	37.6	43.4		6.25	7.94
29-Nov-93	31																							
30-Nov-93	32	6.9	296	3670	2810	112	88	48	41.2	342.2	152.5	18.4	18.4	0.0	0.0	0.0	0.0	0.0	30.2	41.1	45.2		7.68	8.77
01-Dec-93	33																							
02-Dec-93	34	6.9	308	3200	2560	94	76	55	44.2	310.5	128.8	13.3	13.3	0.0	0.0	0.0	0.0	0.0	32.5	38.5	41.1		9.82	11.88
03-Dec-93	35																							
04-Dec-93	36																							
05-Dec-93	37																							
06-Dec-93	38	6.9	312	2480	2100	98	74	No WAS	46.3	343.2	209.2	20.9	18.4	0.0	1.1	0.0	1.4	0.0						
07-Dec-93	39																							
08-Dec-93	40	7.1	306	2450	2140	92	64	5	42.8	372.2	137.4	24.9	22.6	0.5	0.6	0.0	1.1	0.0	31.8	38.1	40.5		6.14	8.05
09-Dec-93	41																							
10-Dec-93	42	7.1	314	3100	2680	110	72	18	46.1	335.4	194.3	31.7	31.7	0.0	0.0	0.0	0.0	0.0	33.1	37.9	43.6		6.65	7.65
11-Dec-93	43																							
12-Dec-93	44																							
13-Dec-93	45	7.0	308	2920	2380	94	60	38	50.9	340.6	162.2	30.6	29.8	0.0	0.0	0.0	0.8	0.0	30.4	37.5	41.3		5.88	7.8
14-Dec-93	46																							
15-Dec-93	47	6.9	302	2900	2340	96	56	32	50.2	357.8	168.3	28.3	28.3	0.0	0.0	0.0	0.0	0.0	34.3	38.1	40.9		5.65	6.45
16-Dec-93	48																							
17-Dec-93	49	6.9	304	3505	2510	120	72	25	50.8	373.8	160.4	26.6	26.6	0.0	0.0	0.0	0.0	0.0	28.3	37.2	42.0		5.75	7.42

* Alkalinity as CaCO3

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
19-Dec-93	51																							
20-Dec-93	52	7.0	316	3650	2455	132	91	14	51.8	358.0	179.0	30.5	30.5	0.0	0.0	0.0	0.0	0.0	33.5	39.9	45.4		6.65	8.29
21-Dec-93	53																							
22-Dec-93	54	7.1	324	3420	2610	137	93	No WAS	47.2	358.0	144.6	24.3	24.3	0.0	0.0	0.0	0.0	0.0	31.5	36.4	44.2		4.81	6.59
23-Dec-93	55																							
24-Dec-93	56	7.0	308	2795	2215	96	70	25	44.2	326.3	215.7	24.6	24.6	0.0	0.0	0.0	0.0	0.0	30.6	36.6	42.6		5.33	6.74
25-Dec-93	57																							
26-Dec-93	58																							
27-Dec-93	59	6.8	316	3125	2530	110	92	20	50.8	440.3	228.2	38.7	37.1	0.2	0.0	0.0	1.3	0.0	30.0	35.5	42.8		5.11	6.35
28-Dec-93	60																							
29-Dec-93	61																							
30-Dec-93	62																							
31-Dec-93	63																							
01-Jan-94	64	7.1	320	3440	2230	132	76	No WAS	48.2	320.1	162.8	34.0	34.0	0.0	0.0	0.0	0.0	0.0	30.4	36.9	42.0		6.25	7.63
02-Jan-94	65																							
03-Jan-94	66	7.2	320	3370	2220	120	73	17	51.9	294.7	157.1	41.7	40.3	0.5	0.4	0.0	0.6	0.0	31.5	37.1	41.8		5.09	6.59
04-Jan-94	67																							
05-Jan-94	68			2850	2260	106	68	8	57.3			42.8	42.8	0.0	0.0	0.0	0.0	0.0						
06-Jan-94	69																							
07-Jan-94	70	6.9	332	3610	2870	109	88	50	56.2	373.8	152.5	42.0	39.9	0.0	0.0	0.0	2.1	0.0	37.2	43.5	51.5		5.40	7.22
08-Jan-94	71																							
09-Jan-94	72																							
10-Jan-94	73	7.0	304	3690	2760	119	102	37	40.8	350.1	144.6	18.3	18.3	0.0	0.0	0.0	0.0	0.0	32.1	38.4	47.5		4.94	6.58
11-Jan-94	74																							
12-Jan-94	75	7.0	308	3840	2710	97	67	79	45.3	310.3	114.2	28.4	28.4	0.0	0.0	0.0	0.0	0.0	30.6	37.5	42.1		5.12	7.01
13-Jan-94	76																							
14-Jan-94	77	7.0	292	2840	2290	103	72	13	47.6	322.8	148.7	28.1	28.1	0.0	0.0	0.0	0.0	0.0	31.3	38.3	42.6		5.92	7.32
15-Jan-94	78																							
16-Jan-94	79																							
17-Jan-94	80	7.2	292	2750	2510	99	96	15	52.9	355.7	210.1	39.7	36.5	1.3	0.0	0.0	1.9	0.0	32.2	40.6	43.5		5.84	7.4
18-Jan-94	81																							
19-Jan-94	82	7.0	300	3200	2560	91	74	60	53.8	320.2	185.3	41.9	41.9	0.0	0.0	0.0	0.0	0.0	32.6	36.1	41.8		6.12	7.97
20-Jan-94	83																							
21-Jan-94	84	7.0	280	2760	2070	86	70	44				41.8	40.0	1.8	0.0	0.0	0.0	0.0						
22-Jan-94	85																							
23-Jan-94	86																							
24-Jan-94	87	7.0	284	2850	2370	126	71	No WAS	56.6	317.5	200.8	47.1	44.5	1.2	0.0	0.0	1.3	0.0	28.1	33.1	39.2		5.8	7
25-Jan-94	88																							
26-Jan-94	89	6.8	280	2430	2040	88	70	13				51.6	46.9	2.8	0.0	0.0	1.9	0.0						
27-Jan-94	90																							
28-Jan-94	91	6.9	292	3850	2950	123	87	39	56.7	374.4	198.3	45.7	44.2	0.8	0.0	0.0	0.7	0.0	29.4	34.3	41.3		6.04	8.14
29-Jan-94	92																							
30-Jan-94	93																							
31-Jan-94	94																							
01-Feb-94	95	7.0	320	2950	2470	80	68	68	51.8	315.9	148.8	41.8	40.2	0.3	0.0	0.0	1.2	0.0	31.9	35.8	42.1		5.88	7.48
02-Feb-94	96	7.0	316	2750	2280	67	32	85																
03-Feb-94	97			2960	2680	96	80	36																
04-Feb-94	98	6.9	284	2780	2400	92	78	32	55.6	366.9	221.3	43.9	41.6	1.6	0.0	0.0	0.7	0.0	29.2	34.2	38.2		6.14	7.32
05-Feb-94	99																							
06-Feb-94	100																							
07-Feb-94	101	6.9	308	2900	2460	88	74	49	62.3	474.6	244.7	68.0	56.0	3.8	2.0	1.7	4.5	0.0	39.2	47.0	61.2		7.89	10.30

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
08-Feb-94	102																							
09-Feb-94	103			3660																				
10-Feb-94	104	6.7	286	3020	2440	74	62	84	64.0	369.6	225.6	59.8	51.4	4.1	1.3	0.0	3.0	0.0	33.5	39.0	44.3		5.69	6.87
11-Feb-94	105	6.9	276	2940	2600	82	74	63	55.2	349.6	197.8	44.5	41.4	0.0	1.0	0.0	2.0	0.0	32.5	36.6	43.1		5.35	7.02
12-Feb-94	106			2440		80		34																
13-Feb-94	107																							
14-Feb-94	108	6.8	256	2340	2180	76	66	36	48.7	334.0	182.2	41.3	39.7	0.0	0.0	0.0	1.6	0.0	26.9	32.1	39.1		5.83	7.47
15-Feb-94	109																							
16-Feb-94	110																							
17-Feb-94	111	6.9	290	2380	2140	82	70	24	52.6	342.8	205.6	45.7	44.2	0.0	0.0	0.0	1.5	0.0	32.9	37.0	43.9		6.05	8.08
18-Feb-94	112																							
19-Feb-94	113	6.9	288	2360	2120	80	70	27	53.2	330.3	201.5	43.8	42.5	0.0	0.0	0.0	1.3	0.0	31.6	35.7	43.2		5.63	7.28
20-Feb-94	114																							
21-Feb-94	115			2370	2040	72	64	48																
22-Feb-94	116	6.9	284	2380	2160	64	58	69	52.9	325.9	190.0	40.0	38.5	0.0	0.0	0.0	1.5	0.0	31.3	36.3	41.5		5.44	6.97
23-Feb-94	117																							
24-Feb-94	118	6.6	196	2140	1960	76	70	18				42.2	40.3	0.8	0.0	0.0	1.1	0.0						
25-Feb-94	119																							
26-Feb-94	120	6.4	188	2280	1960	66	46	57				37.6	36.4	0.6	0.0	0.0	0.6	0.0						
27-Feb-94	121																							
28-Feb-94	122																							
01-Mar-94	123	6.6	200	2300	1980	70	58	48	53.2	336.7	198.2	42.5	40.2	0.7	0.5	0.0	1.3	0.0	28.9	34.1	38.5		5.51	6.5
02-Mar-94	124																							
03-Mar-94	125																							
04-Mar-94	126	6.5	188	2380	2020	76	66	39	54.7	340.3	215.5	42.7	39.9	1.1	0.5	0.0	1.2	0.0	29.8	34.6	39.4		5.12	6.22
05-Mar-94	127																							
06-Mar-94	128																							
07-Mar-94	129	6.5	196	2360	1960	88	68	7	60.8	340.7	204.6	47.6	43.8	1.4	1.1	0.0	1.2	0.0	30.1	36.9	40.2		5.53	7.12
08-Mar-94	130																							
09-Mar-94	131	6.4	190			78	56		48.8			45.8	39.2	2.2	1.6	1.1	1.8	0.0						
10-Mar-94	132																							
11-Mar-94	133	6.6	196	2620	1960	92	64	20	49.3	450.7	224.6	43.4	39.1	1.3	1.4	0.0	1.6	0.0	28.8	33.8	36.7		5.73	7.49
12-Mar-94	134																							
13-Mar-94	135	6.5	200	2580	1920	94	74	12	60.8	406.7	209.6	45.4	42.3	0.0	1.6	0.0	1.6	0.0	33.4	39.7	42.8		5.61	7.04
14-Mar-94	136																							
15-Mar-94	137	6.4	156	2200	1640	84	46	No WAS	54.3	375.2	185.9	42.3	41.1	0.0	0.0	0.0	1.2	0.0	31.8	36.0	39.9		5.31	6.74
16-Mar-94	138																							
17-Mar-94	139																							
18-Mar-94	140	6.6	200	4140	2600	146	112	19	61.7	454.1	241.1	42.6	39.7	2.1	0.0	0.0	0.9	0.0	32.3	36.8	43.4		5.80	7.42
19-Mar-94	141																							
20-Mar-94	142																							
21-Mar-94	143	6.4	196	2960	2280	116	84	No WAS	64.3	461.9	233.2	47.0	42.9	1.9	1.2	0.0	1.1	0.0	33.0	34.9	47.2		6.43	7.76
22-Mar-94	144																							
23-Mar-94	145	6.3	178	2640	2120	108	72	No WAS	45.2	302.9	154.4	29.5	29.5	0.0	0.0	0.0	0.0	0.0	28.7	33.1	38.7		4.99	6.04
24-Mar-94	146																							
25-Mar-94	147	6.4	186	2440	1920	88	64	14	45.9			26.0	26.0	0.0	0.0	0.0	0.0	0.0						
26-Mar-94	148																							
27-Mar-94	149																							
28-Mar-94	150	6.8	204	2460	2140	68	58	65	45.7	328.6	185.9	24.2	24.2	0.0	0.0	0.0	0.0	0.0	29.7	35.1	37.3		5.09	6.04
29-Mar-94	151																							
30-Mar-94	152	6.6	156	2720	2080	102	64	6	46.0			36.7	28.6	1.2	0.8	0.3	1.2	4.6						

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
31-Mar-94	153																							
01-Apr-94	154	6.6	144	2840	2100	104	52	11	42.4	296.3	146.5	27.7	23.9	0.9	0.7	0.6	1.3	0.2	25.7	30.4	33.6		4.02	4.99
02-Apr-94	155																							
03-Apr-94	156																							
04-Apr-94	157	6.5	146	3080	2160	82	44	71	42.2	272.7	138.6	22.5	17.2	0.8	0.7	1.0	2.2	0.7	25.1	30.9	32.8		4.10	4.91
05-Apr-94	158																							
06-Apr-94	159	6.5	180	3040	2140	86	50	61	54.1	268.8	198.6	48.6	31.8	1.2	1.7	4.7	5.4	3.9	29.0	35.3	36.7		4.05	4.98
07-Apr-94	160																							
08-Apr-94	161	6.5	156	2560	2080	76	52	53	50.8	324.7	201.7	36.8	31.6	1.3	1.0	0.8	1.4	0.6	30.7	35.1	36.3		5.42	6.18
09-Apr-94	162																							
10-Apr-94	163	6.6	172	2540	1820	84	46	32	49.7	296.3	167.0	35.0	30.8	1.3	0.8	0.6	1.1	0.3	29.1	33.3	35.8		4.50	4.99
11-Apr-94	164																							
12-Apr-94	165	6.6	168	3640	2320	120	62	33	47.5	280.6	167.0	24.3	22.0	0.9	0.3	0.3	0.7	0.1	27.5	31.6	36.0		4.07	4.82
13-Apr-94	166																							
14-Apr-94	167	6.5	200	4440	2620	194	86	No WAS	51.2	327.9	154.4	35.0	29.9	1.3	1.1	0.8	1.3	0.6	26.9	31.9	37.6		4.42	5.38
15-Apr-94	168																							
16-Apr-94	169	6.4	216	3680	2520	96	64	74	116.2	469.8	359.4	152.1	115.7	27.5	1.8	4.2	1.4	1.6	28.6	31.2	34.0		3.88	4.57
17-Apr-94	170																							
18-Apr-94	171	6.5	260	3320	2100	74	46	97	139.4	343.6	275.7	191.0	144.1	35.0	2.6	4.9	2.0	2.4	27.2	33.4	39.1		4.05	4.92
19-Apr-94	172																							
20-Apr-94	173	6.5	188	4660	2640	126	84	69	52.5	343.6	168.6	32.3	28.0	0.8	1.3	0.7	1.4	0.1	31.2	35.2	41.4		5.40	6.39
21-Apr-94	174	6.5	210						52.4			32.1	27.7	0.7	1.3	0.4	1.3	0.6						
22-Apr-94	175																							
23-Apr-94	176	6.5	216	2960	2280	104	74	20	50.5	320.1	175.7	34.9	30.9	0.7	1.1	0.4	1.3	0.5	28.9	34.7	39.4		5.35	6.25
24-Apr-94	177																							
25-Apr-94	178	6.6	194	2780	2120	94	66	28	45.4	312.7	168.0	35.2	28.8	0.9	1.5	1.1	1.6	1.2	30.1	33.1	37.9		5.07	5.82
26-Apr-94	179																							
27-Apr-94	180	6.4	184	3000	2280	84	62	63	60.6	342.7	205.6	35.7	30.4	0.5	1.1	1.5	1.6	0.5	30.6	32.3	38.1		5.14	5.7
28-Apr-94	181																							
29-Apr-94	182											39.1	32.6	0.8	1.6	1.9	1.9	0.3						
30-Apr-94	183																							
01-May-94	184											38.9	32.3	0.9	1.4	1.6	1.7	0.9						
02-May-94	185	6.3	160	3580	2320	154	82	No WAS	62.9															
03-May-94	186																							
04-May-94	187	6.0	136	5040	2380	104	62	107	56.2															
05-May-94	188																							
06-May-94	189	6.1	136	3520	2500	94	64	71	48.0			22.9	19.1	0.5	0.9	0.9	1.3	0.3	31.1	35.3	40.3		5.5	6.77
07-May-94	190																							
08-May-94	191																							
09-May-94	192	6.2	126	3360	2340	70	62	106	46.9			19.0	16.2	0.2	0.8	0.2	0.8	0.7	29.1	33.0	38.2		4.75	5.89
10-May-94	193																							
11-May-94	194	6.2	144	2940	2120	74	56	80	56.6			36.2	32.8	0.8	1.1	0.5	1.1	0.0						
12-May-94	195																							
13-May-94	196	6.2	136	2880	2280	92	74	39	55.1			33.0	29.7	0.4	1.1	0.4	1.4	0.0	32.6	36.8	43.3		5.32	6.44
14-May-94	197																							
15-May-94	198																							
16-May-94	199	6.3	126	3340	2660	98	82	55	54.2			29.0	24.1	0.6	1.3	0.5	2.0	0.5	31.4	37.2	42.8		5.64	6.58
17-May-94	200																							
18-May-94	201	6.0	106						65.7			17.9	9.6	2.5	1.5	1.4	2.1	0.9						
19-May-94	202																							
20-May-94	203																							

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Jul-94	204																									
06-Jul-94	205	7.1	416								57.6			51.7	40.5	5.6	1.5	1.8	2.2	0.0						
07-Jul-94	206																									
08-Jul-94	207																									
09-Jul-94	208	7.4	456	2040	1560	64	52	912	236	50																
10-Jul-94	209																									
11-Jul-94	210	7.3	468	2360	1460	66	54	1108	256	28	28.4	203.1	94.4	12.0	8.0	0.8	0.0	2.6	0.6	0.0	18.3	20.3	21.3	2.63	3.15	4.28
12-Jul-94	211																									
13-Jul-94	212	7.3	440	2280	1800	44	42	648	184	110	31.9			15.0	12.0	0.4	0.8	0.9	0.9	0.1						
14-Jul-94	213																									
15-Jul-94	214	7.4	496	2140	1680	36	34	984	304	129	22.2			9.6	7.3	0.6	0.0	0.2	0.9	0.7						
16-Jul-94	215																									
17-Jul-94	216																									
18-Jul-94	217	7.5	428	2280	1720	106	80	1032	320	No WAS	33.0	182.1	83.3	12.6	11.1	0.8	0.0	0.8	0.0	0.0	13.6	17.3	20.4	2.12	2.74	3.25
19-Jul-94	218																									
20-Jul-94	219	7.2	388	2240	1640	108	74	928	312	No WAS	33.3			16.5	13.9	0.0	0.0	0.7	1.9	0.0						
21-Jul-94	220																									
22-Jul-94	221	7.2	410	2460	1740	152	102	952	332	No WAS	60.7			42.2	37.1	0.8	1.0	0.8	2.0	0.7						
23-Jul-94	222																									
24-Jul-94	223																									
25-Jul-94	224	7.4	482	2480	1880	140	98	828	328	No WAS	49.7	256.5	121.3	45.6	33.2	6.8	1.1	2.1	2.4	0.9						
26-Jul-94	225																									
27-Jul-94	226	7.3	464	2360	1840	86	58	744	280	61	40.4			43.6	32.2	6.9	0.7	1.1	1.1	1.6						
28-Jul-94	227																									
29-Jul-94	228	7.3	448	2400	1940	92	62	856	292	58	31.3			43.4	32.1	5.8	0.6	1.5	2.2	1.2						
30-Jul-94	229																									
31-Jul-94	230																									
01-Aug-94	231	7.2	456	2300	1800	116	90	892	296	No WAS	39.7															
02-Aug-94	232																									
03-Aug-94	233	7.2	366	2720	2240	110	84	920	200	25	54.5	243.1	140.7	43.0	33.1	6.4	0.5	1.2	1.5	0.4	22.5	28.2	32.0	3.52	4.03	4.61
04-Aug-94	234																									
05-Aug-94	235	7.0	368	2460	2100	134	124	692	280	No WAS	66.1			66.4	54.0	1.9	1.8	2.2	4.9	1.6						
06-Aug-94	236																									
07-Aug-94	237																									
08-Aug-94	238	6.9	332	2520	2020	50	46	844	252	113	54.9			50.7	34.0	8.7	0.9	1.8	4.4	0.9						
09-Aug-94	239																									
10-Aug-94	240	7.1	390	2720	2200	62	52	828	264	108	55.7	225.4	130.3	49.5	34.9	4.6	1.5	1.4	4.8	2.3	25.8	30.2	33.9	3.91	4.08	4.45
11-Aug-94	241																									
12-Aug-94	242	7.0	372	2720	2220	60	52	876	276	109	60.0			49.5	30.9	7.0	1.5	2.2	6.1	1.9						
13-Aug-94	243																									
14-Aug-94	244																									
15-Aug-94	245	7.2	378	3780	2960	86	74	752	336	100	51.6			39.1	25.8	7.2	1.1	1.7	2.8	0.5						
16-Aug-94	246																									
17-Aug-94	247	6.9	412	3140	2360	100	78	884	308	52	67.7	286.6	180.1	59.8	43.5	8.4	1.6	1.9	3.8	0.6	27.9	28.6	31.9	4.22	4.37	5.12
18-Aug-94	248																									
19-Aug-94	249	7.1	380	2840	2400	89	76	820	260	60	58.1			53.7	39.0	6.7	1.1	1.7	4.1	1.2						
20-Aug-94	250																									
21-Aug-94	251																									
22-Aug-94	252	7.1	372	3060	2500	82	78	752	264	63	52.8			49.3	39.8	3.9	1.0	1.2	2.8	0.5						
23-Aug-94	253																									

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
24-Aug-94	254	7.2	368	3140	2500	90	78	912	264	63	59.0			47.8	40.4	2.3	1.3	1.0	2.5	0.3						
25-Aug-94	255																									
26-Aug-94	256	7.1	380	3680	2700	72	56	852	244	126	62.5	274.5	147.0	48.6	42.6	2.1	1.3	0.0	2.4	0.3	29.8	29.4	32.6	4.02	5.16	5.28
27-Aug-94	257																									
28-Aug-94	258																									
29-Aug-94	259																									
30-Aug-94	260	7.0	372	3600	2640	106	78	808	276	73	57.2			44.2	34.5	4.9	1.3	1.1	2.5	0.0						
31-Aug-94	261																									
01-Sep-94	262	7.0	368	3840	2740	116	82	808	244	70	63.2	328.1	172.4	51.9	43.4	3.8	1.0	0.8	2.3	0.6	29.5	36.0	39.2	3.93	4.41	5.36
02-Sep-94	263																									
03-Sep-94	264																									
04-Sep-94	265																									
05-Sep-94	266	7.1	360	3720	2440	126	74	908	232	68	50.0			33.7	27.2	1.7	1.0	1.0	1.9	1.0						
06-Sep-94	267																									
07-Sep-94	268	7.0	364	4140	2980	92	80	872	284	89	60.2	354.8	163.3	44.9	36.2	2.8	1.0	1.1	2.8	1.0	25.2	29.3	33.2	3.3	3.75	4.94
08-Sep-94	269																									
09-Sep-94	270	7.1	408	4020	2740	86	58	820	284	123	51.2			33.9	28.1	2.5	0.8	0.7	1.4	0.5						
10-Sep-94	271																									
11-Sep-94	272																									
12-Sep-94	273	7.2	396	3680	2620	106	78	872	293	71	60.1			37.1	29.9	2.5	1.2	0.8	2.2	0.5						
13-Sep-94	274																									
14-Sep-94	275	7.2	400	3720	2580	84	68	896	304	84	47.5	271.2	160.8	36.7	32.1	0.0	2.6	0.0	2.0	0.0	24.1	28.0	31.3	3.27	3.43	4.28
15-Sep-94	276																									
16-Sep-94	277																									
17-Sep-94	278	7.1	428	3940	2820	90	68	887	278	108	51.1	281.9	212.0	32.9	27.2	1.7	0.9	0.9	1.7	0.5	19.6	24.2	26.7	3.17	3.26	4.12
18-Sep-94	279																									
19-Sep-94	280			3740	2620	48	40			118																
20-Sep-94	281	7.1	448	4140	2860	80	52	844	272	136	60.9			41.4	32.7	4.5	1.0	1.0	2.1	0.1						
21-Sep-94	282																									
22-Sep-94	283			4060	2780	74	72			93																
23-Sep-94	284	7.2	376	4100	2760	88	64	752	260	114	58.6	275.4	258.1	38.5	32.6	2.6	0.9	1.0	1.9	0.5	23.2	27.5	30.1	3.61	3.84	4.94
24-Sep-94	285																									
25-Sep-94	286																									
26-Sep-94	287			4340	2920	70	48			157																
27-Sep-94	288	7.1	402	4020	2850	86	62	800	280	120	71.7			65.6	54.2	4.4	1.3	2.9	2.2	0.6						
28-Sep-94	289																									
29-Sep-94	290			4255	2785	66	56			130																
30-Sep-94	291	7.1	356	4320	2900	86	72	660	224	103	58.2	280.2	141.5	43.6	35.8	2.9	1.2	1.4	2.1	0.3	28.7	32.6	35.9	4.83	5.03	5.92
01-Oct-94	292																									
02-Oct-94	293																									
03-Oct-94	294			4280	2930	82	52			143																
04-Oct-94	295																									
05-Oct-94	296																									
06-Oct-94	297	7.0	346	3581	2430	78	62	664	256	104	59.0	339.6	178.2	47.3	39.2	3.3	1.1	1.4	2.0	0.3	29.3	33.4	37.5	4.85	4.7	5.47
07-Oct-94	298																									
08-Oct-94	299																									
09-Oct-94	300																									
10-Oct-94	301	7.3	360	4020	2640	60	44	620	248	149	30.8			3.6	1.4	0.5	0.0	1.3	0.4	0.0						
11-Oct-94	302																									
12-Oct-94	303	7.3	420	3800	2480	76	56	768	268	118	52.1	245.3	145.2	36.6	30.0	2.3	0.8	1.1	1.9	0.6	24.1	27.4	31.2	3.68	3.81	4.51
13-Oct-94	304																									

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
14-Oct-94	305	7.1	438	4040	2720	84	62			112	57.2			42.4	34.2	3.2	0.7	1.5	2.2	0.6						
15-Oct-94	306																									
16-Oct-94	307																									
17-Oct-94	308	7.1	420	4080	2796	78	60	768	288	121	63.8			39.8	31.8	3.2	1.6	1.3	1.4	0.5						
18-Oct-94	309	7.1	392	3950	2658	82	68	740	276	97	60.4			45.1	36.9	3.8	0.9	1.0	1.7	0.9	27.2	30.9	35.2	3.98	4.21	5.13
19-Oct-94	310																									
20-Oct-94	311																									
21-Oct-94	312	7.2	440	4660	3100	80	58	736	284	140	47.6			32.0	25.0	4.2	0.8	0.8	1.2	0.1						
22-Oct-94	313																									
23-Oct-94	314																									
24-Oct-94	315	7.2	520	4780	3440	82	62	1020	360	141	45.5			28.1	23.3	2.6	0.5	0.6	1.0	0.2						
25-Oct-94	316																									
26-Oct-94	317																									
27-Oct-94	318	7.3	480	5240	3420	98	64	940	404	138	52.2	323.6	167.1	34.2	28.2	2.3	0.8	0.8	1.8	0.3	24.2	28.2	32.3	3.12	3.75	4.82
28-Oct-94	319			5040	3230	88	66			126																
29-Oct-94	320																									
30-Oct-94	321																									
31-Oct-94	322	7.0	420	4930	3410	96	76	844	332	117	66.5	350.2	206.6	64.3	53.9	5.3	1.1	1.3	2.3	0.5	28.2	29.3	35.3	4.11	4.43	5.59
01-Nov-94	323																									
02-Nov-94	324	6.9	416	4690	3190	92	72	800	304	118	73.2			64.0	52.7	5.4	1.1	1.1	3.3	0.4						
03-Nov-94	325																									
04-Nov-94	326	6.9	432	5450	3430	96	68	864	332	134	63.5			53.6	44.1	4.7	0.7	1.3	2.3	0.4						
05-Nov-94	327																									
06-Nov-94	328																									
07-Nov-94	329	7.0	416	5650	3630	92	76	832	320	128	68.3	382.5	205.4	56.0	45.6	5.3	0.9	1.2	2.7	0.4	29.9	34.9	38.6	4.1	4.41	5.46
08-Nov-94	330																									
09-Nov-94	331	7.0	376	5640	3590	108	66	732	292	144	50.8			62.6	49.1	7.7	1.0	1.4	3.1	0.5						
10-Nov-94	332																									
11-Nov-94	333	7.1	408	5370	3540	100	76	776	260	125	49.4			60.3	46.5	8.7	0.7	1.5	2.5	0.6						
12-Nov-94	334																									
13-Nov-94	335																									
14-Nov-94	336	7.0	412	5180	3460	88	64	824	328	144	52.7	363.2	189.2	61.0	50.0	6.5	0.9	1.2	2.4	0.0	32.1	36.6	40.8	4.47	4.6	5.81
15-Nov-94	337																									
16-Nov-94	338	7.0	424	4920	3300	62	40			177	44.3			53.1	44.3	4.5	0.8	1.2	2.0	0.3						
17-Nov-94	339																									
18-Nov-94	340			4720	3250	90	72	836	330	118				52.1	44.4	2.6	1.2	1.0	2.7	0.3						
19-Nov-94	341																									
20-Nov-94	342																									
21-Nov-94	343	7.2	474	4140	2860	78	64	772	296	119	46.0	318.7	160.1	44.2	35.8	4.5	0.7	1.0	2.0	0.3	25.2	29.3	33.5	3.45	3.9	4.68
22-Nov-94	344																									
23-Nov-94	345	7.2	470	4510	2885	96	66	996	332	116	54.1			49.6	41.3	4.1	0.9	1.1	2.0	0.3						
24-Nov-94	346																									
25-Nov-94	347	7.3	476	4750	2970	84	54	924	320	105	39.4			30.7	24.8	1.4	1.8	0.6	1.9	0.2						
26-Nov-94	348																									
27-Nov-94	349																									
28-Nov-94	350	6.7	428	5070	3260	82	58	856	300	106	57.8	349.3	172.3	52.9	43.2	3.9	2.1	1.1	2.4	0.2	28.7	32.5	38.3	4.24	4.67	5.39
29-Nov-94	351																									
30-Nov-94	352	7.1	448	5230	3400	88	62	856	336	102				52.8	40.7	7.5	1.1	1.1	2.0	0.4						
01-Dec-94	353																									
02-Dec-94	354	7.0	436	5320	3500	78	64	800	280	104	56.8			56.5	45.9	5.6	1.5	1.1	2.1	0.3						
03-Dec-94	355																									

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
04-Dec-94	356																									
05-Dec-94	357	7.0	420	5310	3496	98	68	864	316	95	49.3	310.2	162.2	48.1	39.1	4.6	1.1	0.8	2.2	0.3	27.4	33.9	38.7	4.36	4.64	5.34
06-Dec-94	358																									
07-Dec-94	359			5370	3620	86	58	792	284	122	45.7			46.1	37.4	5.3	0.5	0.9	1.8	0.2				4.28		
08-Dec-94	360																									
09-Dec-94	361	7.1	412	5335	3639	86	68	792	300	101	53.1			66.6	56.4	6.3	0.5	1.2	2.0	0.3				4.41		
10-Dec-94	362																									
11-Dec-94	363									50																
12-Dec-94	364	7.1	400	6620	4270	100	82	772	284	97	51.5	352.4	176.7	47.8	39.5	5.0	0.6	1.2	1.3	0.2	27.2	32.9	38.7	4.23	4.4	5.1
13-Dec-94	365																									
14-Dec-94	366			6170	3920	115	80	800	284	87	53.7			61.3	50.6	6.5	0.9	1.2	1.9	0.3				4.8	5.08	6.17
15-Dec-94	367																									
16-Dec-94	368	7.1	372	6310	4160	98	72	784	292	111	50.5			58.8	50.6	5.2	0.6	1.2	1.2	0.2						
17-Dec-94	369									55																
18-Dec-94	370																									
19-Dec-94	371	6.6	356	6350	4180	116	88	812	292	82	56.3	356.3	148.9	55.9	45.4	4.9	2.1	1.0	2.4	0.2	27.7	35.2	41.2	4.71	5.22	5.84
20-Dec-94	372																									
21-Dec-94	373			6020	3960	112	82	800	292	85	59.4	447.5	200.3	68.3	55.1	6.2	2.0	1.6	3.0	0.4	30.0	37.3	42.7	4.7	5.05	5.98
22-Dec-94	374																									
23-Dec-94	375	7.1	372	5780	3760	114	82	796	288	76	53.7			52.9	40.6	6.2	1.5	1.5	2.8	0.3						
24-Dec-94	376									65																
25-Dec-94	377																									
26-Dec-94	378	7.1	364	5410	3530	90	66	696	236	101	46.2	296.1	185.4	46.5	40.6	1.9	1.2	1.0	1.5	0.3	28.5	36.2	41.3	4.32	4.57	5.23
27-Dec-94	379																									
28-Dec-94	380	7.1	266	4950	3190	56	40	516	188	148	33.1			28.9	24.1	2.1	0.7	0.8	1.1	0.2				3.08	3.41	4.2
29-Dec-94	381										46.5			40.6	33.5	2.9	0.8	1.2	1.9	0.3				4.16		
30-Dec-94	382	7.2	360	4960	3270	70	52	680	208	121				40.9	35.3	1.8	0.4	1.1	2.0	0.3						
31-Dec-94	383									60																
01-Jan-95	384																									
02-Jan-95	385			5170	3490	92	62	820	224	109																
03-Jan-95	386																									
04-Jan-95	387	7.2	354	5020	3490	84	56	796	248	124	40.9	331.5	173.5	37.0	30.4	3.0	0.8	0.9	1.6	0.4	30.7	36.7	41.3	4.72	5.1	5.84
05-Jan-95	388																									
06-Jan-95	389	7.1	332	4750	3360	90	72	692	264	78	46.4	371.0	213.0	36.6	29.0	4.5	0.2	1.0	1.6	0.3	31.3	36.8	43.0	4.71	5.15	5.79
07-Jan-95	390																									
08-Jan-95	391									40																
09-Jan-95	392	7.1	336	5780	4250	110	94	724	256	74	50.7			47.5	35.6	7.6	1.0	1.3	1.6	0.3						
10-Jan-95	393																									
11-Jan-95	394	7.0	350	5800	4210	102	84	716	256	91	64.4	424.1	259.4	75.5	56.9	12.2	1.2	1.6	3.0	0.6	33.5	39.2	44.9	4.9	5.3	6.36
12-Jan-95	395																									
13-Jan-95	396	7.1	334	5400	3830	78	56			131	70.5			89.0	67.4	14.8	1.4	2.0	2.8	0.6						
14-Jan-95	397																									
15-Jan-95	398									65																
16-Jan-95	399	7.1	328	5420	3800	74	54	688	288	135	51.8	369.2	212.4	52.6	42.0	5.3	1.5	1.3	2.2	0.4	32.5	38.3	43.0	4.66	5.13	6.19
17-Jan-95	400																									
18-Jan-95	401	7.1	328	5570	3670	96	64	716	304	110	52.9	392.8	240.6	59.5	46.9	5.6	1.8	1.5	3.2	0.4	33.8	40.0	44.8	4.87	5.51	6.44
19-Jan-95	402																									
20-Jan-95	403			5480	3800	82	64	672	204	115																
21-Jan-95	404																									
22-Jan-95	405									60																
23-Jan-95	406	7.2	304	5370	3630	100	54	668	208	133	43.8			39.7	33.0	2.6	1.2	1.1	1.6	0.3						

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
24-Jan-95	407																									
25-Jan-95	408	7.1	336	5240	3640	88	62	676	224	115	50.9	377.9	226.0	52.2	42.3	4.7	1.4	1.2	2.2	0.4	33.8	40.6	45.8	4.66	5.55	6.68
26-Jan-95	409																									
27-Jan-95	410			5120	3700	80	66			109	50.0			53.2	42.6	5.5	1.3	1.2	2.3	0.4				4.55		
28-Jan-95	411																									
29-Jan-95	412									55																
30-Jan-95	413	7.0	310	5220	3700	72	50	636	228	145	54.3				49.6	9.1	1.3	1.6	2.1	0.5				4.62		
31-Jan-95	414																									
01-Feb-95	415	7.0	324	5420	3760	76	52	684	284	141	55.9	393.1	248.8		58.3	7.5	2.3	1.3	2.9	0.5	30.9	38.9	44.4	5.35	6.2	7.11
02-Feb-95	416																									
03-Feb-95	417	7.0	312	5350	3760	68	54	644	236	138	49.9				46.2	5.9	1.4	1.3	2.9	0.4				5.05		
04-Feb-95	418																									
05-Feb-95	419									70																
06-Feb-95	420			5820	4020	102	70			110	52.7				51.6	6.3	1.6	1.3	2.7	0.4				5.41		
07-Feb-95	421																									
08-Feb-95	422	7.2	308	5450	3840	92	72	644	260	100	49.6	408.3	241.2		46.5	5.7	1.6	1.3	2.4	0.4	32.2	37.9	43.1	4.95	5.53	6.66
09-Feb-95	423																									
10-Feb-95	424	7.2	304	5160	3620	90	58			122	58.9				49.3	6.2	1.3	1.6	2.5	0.3				4.84		
11-Feb-95	425																									
12-Feb-95	426									60																
13-Feb-95	427	7.1	308	5490	3670	112	78	680	308	80	55.5				48.0	7.2	1.2	1.7	2.4	0.4				4.9		
14-Feb-95	428																									
15-Feb-95	429	7.1	320	5660	3820	126	92	600	280	85	56.8	420.4	253.3		42.6	6.6	1.2	1.2	2.3	0.3	41.2	45.6	51.0	5.29	5.44	6.53
16-Feb-95	430																									
17-Feb-95	431	7.2	296	5430	3730	126	88	540	192	61	56.2				47.7	7.0	1.2	1.9	2.4	0.4				5.44		
18-Feb-95	432																									
19-Feb-95	433									30																
20-Feb-95	434	7.1	296	5700	3880	106	68	552	248	113	64.4				58.3	9.4	1.2	2.0	3.2	0.5				5.3		
21-Feb-95	435																									
22-Feb-95	436	7.0	308	6120	4110	76	60	604	280	134	77.1	438.6	324.7		84.4	16.7	1.7	2.3	4.1	0.6	35.4	43.0	46.8	4.8	5.09	5.61
23-Feb-95	437																									
24-Feb-95	438	7.0	296	5990	3970	118	90	552	264	69	60.3				48.8	9.0	1.3	1.9	3.4	0.5				4.87		
25-Feb-95	439																									
26-Feb-95	440									35																
27-Feb-95	441	7.1	284	6240	4100	100	72	536	220	110	60.2				55.9	7.9	1.5	1.6	2.7	0.2				5.45		
28-Feb-95	442																									
01-Mar-95	443			6070	3890	130	82			82																
02-Mar-95	444																									
03-Mar-95	445	7.0	288	5920	3790	134	94	536	240	52	60.4	453.8	265.8		59.2	6.0	1.8	1.9	3.2	0.5	34.8	41.1	47.6	5.52	5.7	6.91
04-Mar-95	446																									
05-Mar-95	447									30																
06-Mar-95	448	7.1	276	6040	3930	86	62	584	296	126	56.6				49.5	6.5	1.3	1.7	2.9	0.3				4.93		
07-Mar-95	449																									
08-Mar-95	450	7.0	284	5750	3750	120	80	584	308	80	71.9	476.6	309.5		56.5	7.1	1.5	2.1	2.9	0.5	35.2	41.2	49.6	5.01	6.25	7.85
09-Mar-95	451																									
10-Mar-95	452	7.0	282	6040	4040	132	90	504	288	72	66.3				52.6	3.5	1.6	0.9	3.0	0.4				5.04		
11-Mar-95	453																									
12-Mar-95	454									36																
13-Mar-95	455	7.0	280	5490	3750	98	78	536	236	84	63.8				47.7	6.5	1.5	1.4	2.7	0.3				5.15		
14-Mar-95	456																									
15-Mar-95	457	6.9	204	5140	3420	98	66	652	196	97	50.8	324.7	188.0		45.0	3.9	0.8	0.9	1.8	0.3	16.2	21.5	25.4	2.84	3.2	4.1

TABLE A2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
16-Mar-95	458																									
17-Mar-95	459			4930	3220	74	42	600	232	146	57.3				45.0	3.6	1.2	1.3	2.4	0.4				3.32		
18-Mar-95	460																									
19-Mar-95	461									72																
20-Mar-95	462	7.1	252	4390	2880	60	32	560	192	157	42.2				30.5	1.3	0.7	0.8	1.5	0.2				2.67		
21-Mar-95	463																									
22-Mar-95	464	7.1	304	4500	2980	52	40	556	234	145	48.2	278.2	181.0		38.8	2.7	1.0	1.0	2.2	0.3	24.6	30.8	33.5	2.78	3.95	4.76
23-Mar-95	465																									
24-Mar-95	466	7.1	308	4260	2830	58	52	516	168	103	45.0				31.3	2.8	0.9	0.9	1.8	0.2				3.13		
25-Mar-95	467																									
26-Mar-95	468									52																
27-Mar-95	469	7.1	304	4460	2790	62	34	560	184	159	39.7	290.8	133.9		28.7	3.2	0.7	0.8	1.3	0.4	21.6	26.5	29.7	3.04	3.71	4.26
28-Mar-95	470																									
29-Mar-95	471	7.1	310	3970	2520	54	34	580	192	149	32.9				25.4	2.0	0.8	1.0	1.6	1.0				1.67		
30-Mar-95	472																									
31-Mar-95	473	7.3	334	3850	2460	46	32	592	200	152	38.0	204.5	115.5		22.3	0.5	0.5	0.4	1.2	0.2	17.3	23.2	26.0	2.5	2.86	3.27
01-Apr-95	474																									
02-Apr-95	475																									
03-Apr-95	476	7.1	340	4240	2630	82	54	636	232	86	46.8	259.4	126.1		26.7	3.0	0.9	0.9	1.6	0.2	21.7	25.9	28.9	3.45	3.64	4.52
04-Apr-95	477																									
05-Apr-95	478			4430	2720	68	44			122	50.1				29.2	8.2	1.6	2.5	2.5	1.6				3.57		
06-Apr-95	479																									
07-Apr-95	480									140																
08-Apr-95	481																									
09-Apr-95	482									130																
10-Apr-95	483	7.2	340	4560	2810	90	60	652	212	79	46.8				31.2	4.4	1.2	1.3	2.2	0.4				4.2		
11-Apr-95	484																									
12-Apr-95	485	7.2	346	4480	2800	74	50	620	240	109	44.2	259.4	149.6		27.7	3.4	0.0	0.4	2.2	0.3	28.7	35.1	38.9	4.18	4.25	5.28

TABLE A3 - REACTOR AND EFFLUENT CHARACTERISTICS (FERMENTER-F2)

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
17-Dec-93	1			2940	2310																			
18-Dec-93	2																							
19-Dec-93	3																							
20-Dec-93	4	7.2	312	3120	2460	149	91	88	36.0	342.2	105.1	14.6	14.6	0.0	0.0	0.0	0.0	0.0	24.8	45.4	48.8		6.41	8.30
21-Dec-93	5																							
22-Dec-93	6	7.2	312	2950	2430	124	90	123	47.0	350.1	136.7	24.1	23.0	0.0	0.0	0.0	1.1	0.0	28.9	36.2	43.3		4.30	6.63
23-Dec-93	7																							
24-Dec-93	8	7.0	316	2910	2410	101	78	167	48.8	326.3	144.6	17.4	17.4	0.0	0.0	0.0	0.0	0.0	30.2	37.1	43.8		5.36	6.80
25-Dec-93	9																							
26-Dec-93	10																							
27-Dec-93	11	6.9	312	2410	1950	125	89	64	52.2	350.3	150.3	26.5	26.5	0.0	0.0	0.0	0.0	0.0	30.5	36.1	42.6		5.25	6.65
28-Dec-93	12																							
29-Dec-93	13																							
30-Dec-93	14																							
31-Dec-93	15																							
01-Jan-94	16	7.1	316	2530	2000	104	63	128	42.3	330.2	138.6	20.4	20.4	0.0	0.0	0.0	0.0	0.0	31.4	36.3	41.3		5.66	7.17
02-Jan-94	17																							
03-Jan-94	18	7.1	316	2460	1960	129	84	60	48.3	342.2	140.2	26.9	25.1	0.9	0.0	0.0	0.9	0.0	31.0	36.9	43.4		4.69	6.63
04-Jan-94	19																							
05-Jan-94	20			2830	2100	104	70	155	55.4			36.2	34.7	0.0	0.0	0.0	1.6	0.0						
06-Jan-94	21																							
07-Jan-94	22	6.9	320	3310	2590	148	118	107	53.6	389.6	160.4	30.0	28.1	0.0	0.0	0.0	1.9	0.0	37.2	43.6	52.1		5.31	6.98
08-Jan-94	23																							
09-Jan-94	24																							
10-Jan-94	25	7.0	304	2500	2140	106	88	121	44.6	342.2	152.5	18.9	18.9	0.0	0.0	0.0	0.0	0.0	32.2	38.3	44.9		4.94	6.39
11-Jan-94	26																							
12-Jan-94	27	6.9	304	2460	1970	106	64	116	40.6	312.1	126.3	26.1	26.1	0.0	0.0	0.0	0.0	0.0	30.1	37.8	43.3		5.3	6.97
13-Jan-94	28																							
14-Jan-94	29	6.9	296	2440	1860	102	72	124	43.6	325.8	138.6	27.9	27.9	0.0	0.0	0.0	0.0	0.0	33.7	38.8	43.4		6.15	7.25
15-Jan-94	30																							
16-Jan-94	31																							
17-Jan-94	32	7.2	300	2060	1810	107	102	63	53.3	373.4	170.9	36.5	36.5	0.0	0.0	0.0	0.0	0.0	32.2	40.1	44.7		6.33	7.23
18-Jan-94	33																							
19-Jan-94	34	6.9	296	2320	1820	92	79	137	47.4	340.2	162.1	33.3	33.3	0.0	0.0	0.0	0.0	0.0	32.9	35.4	42.8		5.87	7.36
20-Jan-94	35																							
21-Jan-94	36	7.0	288	2240	1710	115	51	67				40.2	39.0	0.0	0.0	0.0	1.2	0.0						
22-Jan-94	37																							
23-Jan-94	38																							
24-Jan-94	39	6.9	278	2060	1780	88	72	119	52.3	376.2	188.5	41.9	40.5	0.0	0.0	0.0	1.5	0.0	28.8	32.8	41.0		6.03	7.7
25-Jan-94	40																							
26-Jan-94	41	6.8	280	2160	1670	149	120	No WAS				47.5	41.3	0.0	4.1	0.0	2.1	0.0						
27-Jan-94	42																							
28-Jan-94	43	6.8	288	2950	2340	144	99	82	51.2	388.6	183.3	44.0	42.8	0.0	0.0	0.0	1.2	0.0	30.6	35.4	44.9		6.4	8.42
29-Jan-94	44																							
30-Jan-94	45																							
31-Jan-94	46																							
01-Feb-94	47	6.8	314	2460	2070	103	85	124	49.6	343.7	143.8	39.1	39.1	0.0	0.0	0.0	0.0	0.0	31.0	36.6	42.1		6.12	7.45
02-Feb-94	48	7.0	308	2300	1860	95	56	127																
03-Feb-94	49			2180	1900	128	112	23																
04-Feb-94	50	6.8	288	1960	1720	102	86	63	55.9	360.3	202.2	43.8	43.8	0.0	0.0	0.0	0.0	0.0	28.3	33.4	43.9		5.60	7.19

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
06-Feb-94	52																							
07-Feb-94	53	6.9	304	2340	1840	80	72	170	58.3	439.0	236.9	56.9	48.0	2.7	1.7	1.4	3.2	0.0	36.0	43.3	64.5		8.10	10.46
08-Feb-94	54																							
09-Feb-94	55			2720		84		190																
10-Feb-94	56	6.7	292	2660	2140	82	70	190	57.6	354.2	228.5	55.8	50.2	2.3	1.2	0.0	2.1	0.0	34.6	40.3	45.7		5.95	7.67
11-Feb-94	57	6.8	280	2380	2120	96	78	133	54.8	356.5	199.8	43.0	41.2	0.0	0.0	0.0	1.9	0.0	32.7	37.8	47.1		5.70	7.80
12-Feb-94	58			2150		118		46																
13-Feb-94	59																							
14-Feb-94	60	6.7	256	2070	1820	102	84	79	52.7	330.5	195.9	34.5	33.1	0.0	0.0	0.0	1.4	0.0	26.2	31.6	39.1		5.44	6.97
15-Feb-94	61																							
16-Feb-94	62																							
17-Feb-94	63	6.8	284	2280	1940	94	82	128	52.6	347.5	197.9	40.5	40.5	0.0	0.0	0.0	0.0	0.0	32.6	37.0	42.5		6.03	7.52
18-Feb-94	64																							
19-Feb-94	65	6.8	290	2160	1900	98	80	103	50.1	358.3	184.5	40.1	38.8	0.0	0.0	0.0	1.3	0.0	32.3	37.2	42.8		5.83	7.67
20-Feb-94	66																							
21-Feb-94	67			2080	1860	102	88	81																
22-Feb-94	68	6.9	284	2120	1840	104	84	81	52.8	369.6	205.6	35.1	33.2	0.0	0.0	0.0	1.9	0.0	32.9	36.3	42.2		5.86	7.04
23-Feb-94	69																							
24-Feb-94	70	6.7	210	2140	1780	116	102	50				40.8	39.1	0.0	0.0	0.0	1.7	0.0						
25-Feb-94	71																							
26-Feb-94	72	6.5	196	2180	1740	110	88	72				35.6	34.0	0.0	0.3	0.0	1.2	0.0						
27-Feb-94	73																							
28-Feb-94	74																							
01-Mar-94	75	6.7	206	2200	1820	106	92	86	50.9	356.8	187.2	34.3	32.7	0.0	0.7	0.0	0.9	0.0	29.3	33.5	40.6		5.49	6.54
02-Mar-94	76																							
03-Mar-94	77																							
04-Mar-94	78	6.5	190	2130	1800	112	104	60	52.8	366.5	208.2	33.8	32.5	0.0	1.3	0.0	0.0	0.0	30.1	34.1	39.5		5.06	6.26
05-Mar-94	79																							
06-Mar-94	80																							
07-Mar-94	81	6.7	208	2110	1780	122	98	28	62.5	352.2	210.2	35.5	33.3	1.1	0.0	0.0	1.2	0.0	30.8	36.4	41.1		5.92	6.86
08-Mar-94	82																							
09-Mar-94	83	6.5	196			174	116		51.7			34.6	31.7	0.0	1.7	1.3	0.0	0.0						
10-Mar-94	84																							
11-Mar-94	85	6.7	202	2400	1680	136	90	35	53.2	392.1	226.7	40.2	37.6	0.0	1.2	0.0	1.4	0.0	28.2	33.1	39.3		5.84	6.55
12-Mar-94	86																							
13-Mar-94	87	6.4	172	2350	1780	116	88	79	54.4	406.7	193.8	38.0	35.3	0.0	1.4	0.0	1.3	0.0	33.3	37.8	42.0		5.67	7.06
14-Mar-94	88																							
15-Mar-94	89	6.5	160	2660	1740	126	76	91	53.3	391.0	209.6	26.9	25.7	0.0	0.0	0.0	1.1	0.0	32.0	36.6	42.3		6.57	7.10
16-Mar-94	90																							
17-Mar-94	91																							
18-Mar-94	92	6.7	204	2420	1880	110	84	102	61.8	477.7	233.2	31.2	31.2	0.0	0.0	0.0	0.0	0.0	33.2	36.0	44.1		5.97	7.21
19-Mar-94	93																							
20-Mar-94	94																							
21-Mar-94	95	6.5	196	2540	1940	116	84	101	64.8	441.4	225.4	33.1	31.8	0.0	0.0	0.0	1.3	0.0	32.9	33.7	43.7		6.24	7.61
22-Mar-94	96																							
23-Mar-94	97	6.3	176	2450	1980	78	56	184	42.2	327.9	140.6	25.5	25.5	0.0	0.0	0.0	0.0	0.0	28.5	32.5	40.3		4.86	6.04
24-Mar-94	98																							
25-Mar-94	99	6.4	188	2380	2000	86	74	158	44.9			24.3	24.3	0.0	0.0	0.0	0.0	0.0						
28-Mar-94	102	6.7	204	2360	2040	72	60	192	40.4	312.1	154.4		20.2	0.0	0.0	0.0	0.0	0.0	29.8	34.0	38.1		4.99	5.83
29-Mar-94	103																							
30-Mar-94	104	6.5	160	2640	1900	108	64	130	40.0			20.2	18.4	0.7	0.7	0.0	0.9	0.0						

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
31-Mar-94	105																							
01-Apr-94	106	6.6	144	2880	2120	104	46	158	41.4	288.4	154.4	21.4	17.2	0.8	0.6	0.5	1.4	0.9	26.1	29.9	33.0		4.07	4.83
02-Apr-94	107																							
03-Apr-94	108																							
04-Apr-94	109	6.5	148	2720	2180	80	40	199	46.3	267.9	138.6	20.0	17.9	0.4	0.7	0.0	0.9	0.0	26.6	29.9	31.4		4.15	4.82
05-Apr-94	110																							
06-Apr-94	111	6.6	182	2780	2140	82	54	198	57.2	267.2	188.3	35.1	30.2	1.0	1.1	1.1	1.7	0.1	30.3	35.9	38.1		4.17	4.92
07-Apr-94	112																							
08-Apr-94	113	6.5	158	2470	1960	76	54	190	52.3	343.6	182.8	34.5	30.2	1.2	1.0	0.7	1.3	0.1	31.2	35.8	37.8		5.36	6.17
09-Apr-94	114																							
10-Apr-94	115	6.6	176	2640	1880	78	42	198	50.4	280.6	154.4	33.0	29.8	0.9	0.8	0.5	1.0	0.1	29.6	33.3	34.0		4.29	4.88
11-Apr-94	116																							
12-Apr-94	117	6.5	168	2810	1980	108	52	144	46.8	272.7	138.6	23.2	20.9	0.8	0.6	0.2	0.6	0.2	27.9	32.3	35.5		4.07	4.65
13-Apr-94	118																							
14-Apr-94	119	6.5	204	3020	2200	136	74	105	53.1	324.7	140.2	34.9	30.4	0.8	0.9	0.7	1.4	0.7	27.6	31.8	36.9		4.50	5.26
15-Apr-94	120																							
16-Apr-94	121	6.4	214	2840	2100	130	80	100	114.3	509.3	335.8	155.0	120.3	26.8	1.5	3.8	1.0	1.7	29.1	32.8	39.3		3.96	4.62
17-Apr-94	122																							
18-Apr-94	123	6.5	258	2650	1960	42	26	280	133.8	470.3	265.2	174.8	135.4	29.4	2.0	4.2	1.7	2.1	28.3	34.1	40.2		4.05	4.92
19-Apr-94	124																							
20-Apr-94	125	6.6	192	2620	2140	116	76	109	47.8	326.3	154.4	27.0	23.2	0.4	1.2	0.6	1.2	0.5	31.4	35.9	40.7		5.28	6.09
21-Apr-94	126	6.4	206						46.5			25.7	22.8	0.2	1.1	0.0	1.2	0.4						
22-Apr-94	127																							
23-Apr-94	128	6.5	188	2760	2160	102	80	153	46.2	310.4	157.5	32.0	28.9	0.4	1.3	0.3	1.1	0.0	30.0	35.3	39.1		5.2	6.15
24-Apr-94	129																							
25-Apr-94	130	6.6	194	2550	1980	98	72	144	47.4	312.6	152.3	29.0	24.4	0.6	1.0	0.9	1.3	0.7	29.6	33.4	38.3		4.93	5.8
26-Apr-94	131																							
27-Apr-94	132	6.4	186	2720	2180	80	64	199	56.5	340.1	180.4	30.1	26.6	1.3	0.0	1.1	1.1	0.0	31.3	32.1	38.4		5.11	5.62
28-Apr-94	133																							
29-Apr-94	134											36.7	32.3	0.5	1.1	0.9	2.0	0.0						
30-Apr-94	135																							
01-May-94	136											39.9	33.9	1.0	1.3	1.3	1.7	0.7						
02-May-94	137	6.2	164	2520	1840	118	72	94	60.4															
03-May-94	138																							
04-May-94	139	6.1	112	2410	1810	102	64	121	58.7															
05-May-94	140																							
06-May-94	141	6.1	132	2230	1760	74	60	176	43.0			21.2	19.0	0.2	0.9	0.0	1.1	0.0	30.7	34.9	39.0		5.38	6.43
07-May-94	142																							
08-May-94	143																							
09-May-94	144	6.1	124	2120	1860	68	58	183	42.1			17.2	14.8	0.4	0.8	0.2	0.9	0.0	29.7	33.5	37.8		4.82	5.82
10-May-94	145																							
11-May-94	146	6.1	148	2080	1640	80	66	144	52.9			32.7	28.0	0.5	1.0	1.1	1.5	0.8						
12-May-94	147																							
13-May-94	148	6.2	136	1990	1700	96	78	86	52.5			35.5	31.4	0.1	0.5	1.1	1.8	0.5	32.3	36.4	42.9		5.18	6.6
14-May-94	149																							
15-May-94	150																							
16-May-94	151	6.2	132	2020	1660	90	76	108	47.8			22.6	18.1	0.9	1.2	0.7	1.7	0.0	31.7	37.7	41.3		5.75	6.42
17-May-94	152																							
18-May-94	153	6.1	136						57.4			33.3	27.9	1.6	1.7	0.6	1.5	0.0						
19-May-94	154																							
20-May-94	155																							

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Jul-94	156			2100																						
06-Jul-94	157	7.0	404								45.8			36.5	23.4	7.3	0.8	3.1	1.5	0.4						
07-Jul-94	158																									
08-Jul-94	159																									
09-Jul-94	160	7.3	350	2060	1600	78	58	904	208	33																
10-Jul-94	161																									
11-Jul-94	162	7.4	440	2200	1420	98	56	1180	308	13	25.9	183.1	88.3	12.4	8.4	0.4	0.0	0.0	2.7	0.8	19.0	21.0	22.6	2.82	3.45	4.52
12-Jul-94	163																									
13-Jul-94	164	7.3	412	2080	1960	64	62	680	220	60	31.9			16.0	12.9	0.4	0.8	0.9	0.9	0.2						
14-Jul-94	165																									
15-Jul-94	166	7.4	444	1880	1600	62	60	1020	332	25	26.6			11.6	7.4	0.3	0.0	0.9	0.9	0.0						
16-Jul-94	167																									
17-Jul-94	168																									
18-Jul-94	169	7.1	406	2380	1980	60	46	1008	332	111	40.4	207.8	109.3	28.0	17.1	7.4	0.5	1.0	1.7	0.3	16.2	21.0	24.3	2.56	3.07	4.14
19-Jul-94	170																									
20-Jul-94	171	7.1	356	2120	1920	40	30	912	304	156	41.7			22.7	15.9	5.2	0.0	0.5	1.1	0.0						
21-Jul-94	172																									
22-Jul-94	173	7.1	368	2380	1820	58	46	860	264	98	64.3			46.4	31.7	8.4	1.1	1.8	2.8	0.7						
23-Jul-94	174																									
24-Jul-94	175																									
25-Jul-94	176	7.1	364	2800	2140	98	62	828	300	76	69.9	278.8	138.1	53.4	37.2	8.3	1.3	2.3	3.5	0.8	25.5	31.1	35.6	4.49	5.1	6.37
26-Jul-94	177																									
27-Jul-94	178	7.0	364	2800	2120	80	62	724	244	75	69.2			48.7	34.6	8.5	0.8	1.2	2.0	1.7						
28-Jul-94	179																									
29-Jul-94	180	7.0	358	2960	2140	84	58	868	300	87	54.0			47.4	31.8	6.2	0.8	3.1	4.5	1.1						
30-Jul-94	181																									
31-Jul-94	182																									
01-Aug-94	183	6.9	344	3260	2400	92	68	968	272	80	66.9			45.1	32.9	6.5	0.6	1.7	2.9	0.6						
02-Aug-94	184																									
03-Aug-94	185	7.1	326	3400	2440	88	72	884	236	73	59.6	257.0	138.5	47.0	35.0	6.4	0.8	1.4	2.8	0.5	23.4	29.7	34.1	3.97	4.4	5.34
04-Aug-94	186																									
05-Aug-94	187	6.9	296	3600	2880	86	80	628	220	83	64.0			52.5	35.5	6.5	1.9	2.5	4.7	1.4						
06-Aug-94	188																									
07-Aug-94	189																									
08-Aug-94	190	6.9	336	3820	2960	62	58	852	264	132	56.8			52.1	35.0	7.9	1.3	2.4	5.0	0.6						
09-Aug-94	191																									
10-Aug-94	192	7.1	384	3300	2500	66	54	832	284	120	58.8	215.2	138.5	49.3	34.5	3.3	1.7	1.6	5.6	2.6	25.7	29.4	34.0	3.84	3.9	4.56
11-Aug-94	193																									
12-Aug-94	194	7.1	376	3520	2820	68	62	884	300	118	63.5			57.6	41.2	5.6	1.8	1.8	6.6	0.7						
13-Aug-94	195																									
14-Aug-94	196									60																
15-Aug-94	197	7.1	378	3140	2480	72	64	732	304	95	53.9			37.7	29.5	4.6	0.9	0.0	2.4	0.2						
16-Aug-94	198																									
17-Aug-94	199	7.0	412	3620	2720	72	50	832	296	140	68.2	280.7	187.3	61.0	47.4	6.0	1.7	1.9	3.7	0.5	28.7	29.1	33.0	4.47	4.79	5.75
18-Aug-94	200																									
19-Aug-94	201	7.0	364	3340	2820	82	72	844	280	97	64.9			56.7	42.1	6.1	1.6	1.7	4.5	0.6						
20-Aug-94	202																									
21-Aug-94	203									50																
22-Aug-94	204	7.0	362	4100	3200	68	66	736	244	126	58.8			52.5	42.8	3.6	1.1	1.6	2.8	0.6						
23-Aug-94	205																									
24-Aug-94	206	7.1	362	3700	2900	78	68	916	252	109	65.6			52.4	44.0	2.6	1.4	1.5	2.7	0.3						

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
25-Aug-94	207																									
26-Aug-94	208	7.1	372	3800	2700	84	56	864	224	126	78.7	291.5	169.3	51.1	44.3	2.8	1.3	0.0	2.5	0.2	28.1	30.9	33.7	4.29	5.56	5.61
27-Aug-94	209																									
28-Aug-94	210									126																
29-Aug-94	211																									
30-Aug-94	212	7.0	368	3780	2840	70	52	768	264	140	60.1			47.6	39.3	3.3	1.2	1.4	2.1	0.4						
31-Aug-94	213																									
01-Sep-94	214	7.0	362	4020	2980	120	92	764	216	65	70.6	356.7	185.5	54.2	46.2	3.1	1.2	1.1	2.5	0.1	30.3	36.6	40.4	4.26	4.83	6.02
02-Sep-94	215																									
03-Sep-94	216									65																
04-Sep-94	217																									
05-Sep-94	218	6.9	348	4400	2960	114	66	924	244	116	56.9			37.8	29.9	2.2	1.0	1.2	2.3	1.2						
06-Sep-94	219																									
07-Sep-94	220	7.1	364	4220	2940	84	76	812	268	95	62.0	340.7	154.5	48.3	37.8	3.0	1.2	1.7	3.2	1.5	26.3	30.8	34.8	3.65	4.12	5.38
08-Sep-94	221																									
09-Sep-94	222	7.1	408	4140	2920	74	52	800	284	146	53.3			36.9	29.5	3.0	0.9	0.8	1.9	0.8						
10-Sep-94	223																									
11-Sep-94	224									70																
12-Sep-94	225	7.1	388	3840	2780	86	66	860	296	108	60.8			39.2	31.3	2.9	1.2	0.9	2.6	0.2						
13-Sep-94	226																									
14-Sep-94	227	7.2	396	3780	2680	70	52	888	276	136	48.2	260.0	155.1	39.4	31.1	2.9	1.2	1.1	2.2	0.8	24.5	28.2	31.4	3.42	3.67	4.6
15-Sep-94	228																									
16-Sep-94	229									70																
17-Sep-94	230	7.0	436	3700	2720	66	58	876	276	124	48.9	267.5	224.1	32.0	24.1	3.7	0.8	1.0	2.1	0.3	19.7	24.2	26.8	3.15	3.28	4.15
18-Sep-94	231																									
19-Sep-94	232			3320	2440	48	36			108																
20-Sep-94	233	7.0	454	3460	2540	72	48	824	256	139	60.6			42.5	35.0	2.2	0.9	1.4	2.6	0.4						
21-Sep-94	234																									
22-Sep-94	235			3480	2520	76	72			79																
23-Sep-94	236	7.1	392	3960	2720	108	78	772	280	78	62.4	312.5	275.0	42.6	34.5	2.5	0.9	1.4	2.1	1.2	24.1	28.3	31.8	3.72	4	5.06
24-Sep-94	237																									
25-Sep-94	238																									
26-Sep-94	239			3980	2920	64	46			155																
27-Sep-94	240	7.1	394	3860	2760	76	58	812	296	124	67.5			63.3	51.7	3.9	1.0	4.0	2.3	0.5						
28-Sep-94	241																									
29-Sep-94	242			4020	2700	52	50			142																
30-Sep-94	243	7.1	356	4220	2940	80	70	672	232	101	63.8	260.0	147.6	49.7	41.7	2.8	1.2	1.6	2.3	0.2	29.5	33.3	36.8	5	5.17	6.29
01-Oct-94	244																									
02-Oct-94	245									50																
03-Oct-94	246			4010	2900	114	68			111																
04-Oct-94	247																									
05-Oct-94	248									50																
06-Oct-94	249	7.0	344	4250	3010	104	78	696	260	95	60.5	327.5	170.1	44.5	37.1	2.7	0.8	1.7	1.9	0.4	28.7	32.9	37.4	4.35	4.55	5.51
07-Oct-94	250																									
08-Oct-94	251									95																
09-Oct-94	252																									
10-Oct-94	253	7.2	360	3780	2580	76	50	636	244	134	29.0			8.3	3.9	0.8	0.0	1.3	2.3	0.0				2.64		
11-Oct-94	254																									
12-Oct-94	255	7.2	420	3600	2440	76	56	760	272	114	54.8	230.1	140.2	39.5	33.1	2.4	1.0	1.0	1.8	0.2	23.8	27.1	30.9	3.6	3.73	4.47
13-Oct-94	256																									
14-Oct-94	257	7.0	436	3920	2700	84	66	800	296	104	55.2			45.7	36.8	3.2	0.7	1.9	2.7	0.5						

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
15-Oct-94	258																									
16-Oct-94	259																									
17-Oct-94	260	7.0	400	3800	2620	74	60	772	296	114	61.3			40.2	32.5	4.1	1.0	1.0	1.3	0.4						
18-Oct-94	261	7.0	388	3800	2640	88	68	752	276	96	60.8			44.3	37.1	3.2	0.9	0.9	1.7	0.5	27.6	31.3	35.7	4.08	4.41	5.41
19-Oct-94	262																									
20-Oct-94	263																									
21-Oct-94	264	7.2	442	4500	3140	94	70	850	310	118	47.0			34.3	26.6	4.3	0.8	1.2	1.3	0.3						
22-Oct-94	265																									
23-Oct-94	266																									
24-Oct-94	267	7.1	508	4340	3220	80	58	1004	340	142	42.8			25.6	20.7	2.7	0.4	0.7	0.8	0.2						
25-Oct-94	268																									
26-Oct-94	269									140																
27-Oct-94	270	7.2	458	4700	3020	108	64	940	404	127	57.6	355.0	183.0	47.8	38.2	3.9	1.2	1.3	2.5	0.7	25.8	29.6	34.3	3.52	4.14	5.3
28-Oct-94	271			4650	2994	102	64			124																
29-Oct-94	272																									
30-Oct-94	273																									
31-Oct-94	274	7.0	440	4580	3200	86	60	808	316	140	65.8	340.0	210.3	66.3	55.3	5.4	0.7	1.5	2.6	0.8	28.6	29.8	35.6	4.22	4.56	5.76
01-Nov-94	275																									
02-Nov-94	276	6.9	432	4510	3200	88	72	816	336	117	73.0			69.5	57.0	6.1	1.5	1.4	3.1	0.4						
03-Nov-94	277																									
04-Nov-94	278	6.9	420	4910	3150	82	54	840	308	151	68.7			63.5	50.3	7.5	0.9	1.4	2.9	0.5						
05-Nov-94	279																									
06-Nov-94	280									70																
07-Nov-94	281	7.1	428	5420	3570	88	74	832	308	129	66.7	371.0	210.0	57.2	45.4	5.9	0.9	1.6	2.8	0.7	30.0	35.2	38.8	4.18	4.47	5.68
08-Nov-94	282																									
09-Nov-94	283	7.0	380	5200	3380	102	54	756	312	158	53.7			59.1	45.0	8.2	1.0	1.6	2.7	0.6						
10-Nov-94	284																									
11-Nov-94	285	7.0	406	5000	3380	100	76	788	268	118	49.0			59.1	47.3	6.7	0.7	1.3	2.7	0.4						
12-Nov-94	286																									
13-Nov-94	287									60																
14-Nov-94	288	7.0	414	4860	3260	92	68	812	316	128	54.1	348.0	199.0	60.4	47.9	7.8	0.7	1.3	2.2	0.5	32.2	36.7	41.2	4.53	4.74	5.89
15-Nov-94	289																									
16-Nov-94	290	7.0	412	4460	3030	64	48			161	43.9			51.4	41.8	5.7	0.6	1.2	1.7	0.4						
17-Nov-94	291																									
18-Nov-94	292			4285	2980	76	56	824	320	140				50.2	42.0	2.7	1.4	1.1	2.7	0.3						
19-Nov-94	293																									
20-Nov-94	294									70																
21-Nov-94	295	7.2	454	4260	2950	90	70	814	308	110	42.4	293.0	172.0	42.6	34.0	4.6	0.8	1.0	1.9	0.3	25.1	29.2	33.6	3.38	3.95	4.79
22-Nov-94	296																									
23-Nov-94	297	7.2	464	4570	2900	98	70	1008	336	108	51.4			46.9	37.7	4.6	0.9	1.1	2.1	0.5						
24-Nov-94	298																									
25-Nov-94	299	7.2	468	4560	2810	100	58	912	328	128	42.3			42.3	34.3	3.3	2.1	0.8	1.6	0.2						
26-Nov-94	300																									
27-Nov-94	301									60																
28-Nov-94	302	6.7	420	4780	3060	102	70	884	308	115	58.2	364.0	175.0	49.9	40.0	4.4	2.2	1.0	2.1	0.3	29.1	32.9	38.7	4.45	4.48	5.39
29-Nov-94	303																									
30-Nov-94	304	7.1	440	4640	2980	102	64	836	324	123				51.8	40.0	6.6	1.4	1.1	2.3	0.4						
01-Dec-94	305																									
02-Dec-94	306	7.0	424	4730	3140	92	74	824	292	110	54.6			55.6	44.4	6.2	1.1	1.3	2.2	0.4						
03-Dec-94	307																									
04-Dec-94	308																									

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Dec-94	309	7.1	404	4700	3080	92	58	856	272	140	44.9	292.0	150.0	45.5	37.1	3.8	1.2	1.0	2.1	0.3	27.2	33.5	38.4	4.26	4.5	5.3
06-Dec-94	310																									
07-Dec-94	311			4839	3230	104	76	808	296	110	45.5			41.6	34.5	4.0	0.4	1.0	1.6	0.2						
08-Dec-94	312										50.0			56.3	47.9	4.8	0.1	1.2	1.9	0.4				4.39		
09-Dec-94	313	7.1	404	5006	3325	102	76	808	300	113	54.8			65.8	55.2	6.2	0.8	1.3	1.9	0.4				4.52		
10-Dec-94	314																									
11-Dec-94	315									55																
12-Dec-94	316	7.1	392	5188	3390	106	80	760	284	109	46.7	339.4	165.7	46.4	39.4	4.0	0.6	1.0	1.2	0.2	27.6	33.1	39.1	4.37	4.54	5.14
13-Dec-94	317																									
14-Dec-94	318			5080	3310	112	78	752	252	109	49.7			56.8	47.5	5.7	0.4	1.2	1.8	0.3						
15-Dec-94	319										52.6			55.4	45.6	5.4	0.9	1.3	1.9	0.3				4.81	5.14	6.37
16-Dec-94	320	7.0	376	4840	3160	82	56	800	320	149	52.7			60.0	50.1	6.5	0.8	1.2	1.1	0.2						
17-Dec-94	321									75																
18-Dec-94	322																									
19-Dec-94	323	6.7	360	4860	3300	98	74	792	280	117	55.8	344.3	140.3	54.1	44.1	4.9	1.6	1.0	2.2	0.3	27.5	34.9	40.3	4.66	5.12	5.79
20-Dec-94	324																									
21-Dec-94	325			5064	3420	106	78	800	296	114	60.4	438.4	191.1	69.9	54.4	8.4	1.9	1.8	3.0	0.6	30.6	37.0	41.8	4.88	5.25	6.3
22-Dec-94	326																									
23-Dec-94	327	7.1	366	4828	3240	90	66	716	236	128	54.6			52.9	41.0	5.8	1.2	1.7	2.7	0.5						
24-Dec-94	328									65																
25-Dec-94	329																									
26-Dec-94	330	7.2	360	4210	2760	76	56	704	260	129	49.4	285.6	174.8	50.6	42.2	3.4	1.4	1.4	1.9	0.4	29.1	36.4	40.9	4.64	4.89	5.58
27-Dec-94	331																									
28-Dec-94	332	7.0	264	3600	2380	50	38	504	184	160	32.2			29.4	24.1	2.5	0.7	0.9	1.0	0.2				3.08	3.21	3.98
29-Dec-94	333										47.7			35.8	28.4	3.3	0.9	1.2	1.7	0.3				4.65		
30-Dec-94	334	7.2	360	3610	2440	60	44	680	204	144				38.5	32.5	1.6	1.1	1.1	1.8	0.3						
31-Dec-94	335									70																
01-Jan-95	336																									
02-Jan-95	337			3440	2370	80	52	808	228	120																
03-Jan-95	338																									
04-Jan-95	339	7.2	356	3480	2420	76	54	812	272	118	43.3	347.3	181.5	41.7	32.0	5.9	1.1	1.0	1.5	0.3	31.4	37.1	42.5	4.95	5.28	6.46
05-Jan-95	340																									
06-Jan-95	341	7.0	334	3620	2560	88	72	672	252	82	49.0	355.2	197.3	43.6	32.6	7.4	0.2	1.4	1.7	0.4	31.3	37.2	43.0	4.71	5.02	6.29
07-Jan-95	342																									
08-Jan-95	343									40																
09-Jan-95	344	7.1	332	3970	2940	76	70	688	240	95	50.0			48.4	34.7	9.0	1.2	1.4	1.7	0.3						
10-Jan-95	345																									
11-Jan-95	346	7.0	340	4010	2940	84	68	696	280	112	59.6	400.6	251.6	70.8	52.8	11.6	1.1	1.8	2.8	0.7	33.9	39.6	44.5	4.95	5.6	6.58
12-Jan-95	347																									
13-Jan-95	348	7.1	344	3600	2580	62	50			135	64.0			86.7	66.0	12.9	1.7	2.0	3.5	0.7						
14-Jan-95	349																									
15-Jan-95	350									65																
16-Jan-95	351	7.2	328	3860	2720	74	50	664	264	143	53.2	353.5	202.9	54.4	41.7	6.7	1.2	1.6	2.8	0.5	32.4	37.8	43.1	4.59	5.13	6.15
17-Jan-95	352																									
18-Jan-95	353	7.0	334	4040	2650	70	46	672	256	146	53.5	384.9	224.9	62.4	49.9	5.7	1.6	1.9	2.8	0.5	34.4	40.3	44.6	5.06	5.62	6.47
19-Jan-95	354																									
20-Jan-95	355			4110	2820	82	68	668	196	60																
21-Jan-95	356																									
22-Jan-95	357									30																
23-Jan-95	358	7.2	304	4350	2920	104	60	684	212	86	44.2			39.9	31.7	3.7	1.3	1.3	1.6	0.5						
24-Jan-95	359																									

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
25-Jan-95	360	7.2	332	4180	2940	84	60	680	216	87	48.7	377.9	210.8	48.1	37.5	5.7	1.3	1.3	2.0	0.4	32.5	40.1	45.5	4.75	5.48	6.55
26-Jan-95	361																									
27-Jan-95	362			4120	3020	88	78			42	45.5			45.7	35.1	6.0	1.2	1.2	1.7	0.5				4.4		
28-Jan-95	363																									
29-Jan-95	364									20																
30-Jan-95	365	7.0	308	4490	3280	80	60	632	224	104	54.6			63.9	51.4	7.2	1.3	1.4	2.2	0.4				4.72		
31-Jan-95	366																									
01-Feb-95	367	7.0	320	4350	3040	88	60	664	280	93	52.8	377.9	210.8	68.6	52.9	8.9	1.6	1.7	2.9	0.6	30.9	37.9	44.5	5.35	5.96	7.08
02-Feb-95	368																									
03-Feb-95	369	7.1	308	4430	3180	102	80	708	240	46	46.9			53.0	41.2	6.3	1.4	1.5	2.2	0.4				4.89		
04-Feb-95	370																									
05-Feb-95	371									20																
06-Feb-95	372			4720	3400	110	64			24	51.4			58.6	46.1	7.0	1.3	1.4	2.3	0.5				5.16		
07-Feb-95	373																									
08-Feb-95	374	7.2	306	4820	3520	106	80	632	248	No WAS	50.5	415.9	241.2	60.7	47.6	7.2	1.5	1.5	2.4	0.5	31.7	37.5	44.5	5.08	5.44	6.92
09-Feb-95	375																									
10-Feb-95	376	7.2	308	4900	3560	102	72			8	51.7			59.6	46.5	7.5	1.1	1.7	2.4	0.4				4.74		
11-Feb-95	377																									
12-Feb-95	378																									
13-Feb-95	379	7.1	308	5300	3640	136	76	660	284	8	51.2			57.4	46.4	5.9	1.1	1.6	2.0	0.4				4.82		
14-Feb-95	380																									
15-Feb-95	381	7.1	312	5410	3760	140	102	616	276	No WAS	54.0	438.6	241.2	47.0	36.4	5.6	0.8	1.4	2.4	0.4	36.6	44.2	51.2	5.13	5.44	6.45
16-Feb-95	382																									
17-Feb-95	383	7.2	284	5170	3570	134	88	556	204	No WAS	46.2			35.3	29.1	2.5	0.7	1.1	1.6	0.3				5.13		
18-Feb-95	384																									
19-Feb-95	385																									
20-Feb-95	386	7.1	284	5730	4010	114	74	540	232	25	55.4			51.4	42.5	4.0	0.9	1.4	2.3	0.3				4.98		
21-Feb-95	387																									
22-Feb-95	388	7.1	306	6450	4430	132	94	640	328	No WAS	63.8	461.4	286.8	67.7	55.9	6.4	1.0	1.4	2.7	0.3	34.6	42.4	49.3	4.53	4.94	6.25
23-Feb-95	389																									
24-Feb-95	390	7.1	288	7100	4900	126	92	552	264	22	52.1			45.7	35.9	4.9	0.9	1.0	2.6	0.4				4.65		
25-Feb-95	391																									
26-Feb-95	392																									
27-Feb-95	393	7.1	288	7990	5430	116	82	564	228	68	54.2			53.5	44.8	4.0	1.2	1.3	2.0	0.3				5.21		
28-Feb-95	394																									
01-Mar-95	395			7690	5160	104	68			93																
02-Mar-95	396																									
03-Mar-95	397	7.1	282	7830	5250	110	74	532	232	82	54.8	415.9	259.0	50.9	41.2	4.2	1.4	1.3	2.4	0.4	33.7	40.2	46.3	4.97	5.43	6.69
04-Mar-95	398																									
05-Mar-95	399																									
06-Mar-95	400	7.0	278	7910	5340	108	62	562	244	112	55.6			56.3	44.3	6.7	1.7	0.9	2.4	0.3				4.88		
07-Mar-95	401																									
08-Mar-95	402	7.0	284	8410	5810	92	66	580	284	113	68.1	469.0	294.3	61.6	48.2	7.2	1.6	1.4	3.0	0.2	35.2	42.1	49.4	4.72	6.33	7.5
09-Mar-95	403																									
10-Mar-95	404	7.0	278	8310	5720	142	102	548	248	36	61.8			62.0	48.1	7.3	1.7	1.3	3.1	0.5				4.98		
11-Mar-95	405																									
12-Mar-95	406																									
13-Mar-95	407	7.0	280	8220	5780	82	72	512	228	101	59.8			53.2	43.7	4.2	1.3	1.1	2.5	0.5				4.63		
14-Mar-95	408																									
15-Mar-95	409	6.9	206	7670	5290	94	62	656	188	111	42.7	294.3	195.6	43.9	38.4	2.6	0.7	0.5	1.5	0.2	15.7	21.5	24.3	2.46	3.08	3.87
16-Mar-95	410																									

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
17-Mar-95	411			6940	4780	92	58	600	216	104	45.8			53.8	45.0	3.6	1.2	1.3	2.4	0.4				2.84		
18-Mar-95	412																									
19-Mar-95	413																									
20-Mar-95	414	7.1	246	6320	4320	70	46	560	184	125	37.9			29.0	26.0	0.7	0.5	0.4	1.1	0.2				2.67		
21-Mar-95	415																									
22-Mar-95	416	7.1	296	6720	4670	72	54	576	248	111	47.6	290.8	149.6	43.4	37.9	1.7	1.0	0.7	2.0	0.2	24.4	31.0	33.5	2.67	3.83	4.7
23-Mar-95	417																									
24-Mar-95	418	7.0	296	6160	4300	64	54	500	156	99	37.4			32.9	29.1	1.0	0.7	0.5	1.5	0.2				3.02		
25-Mar-95	419																									
26-Mar-95	420																									
27-Mar-95	421	7.1	298	6420	4280	82	44	588	196	127	39.7	243.7	102.5	33.4	29.8	1.6	0.5	0.5	1.0	0.2	20.2	27.3	30.0	2.9	3.48	4.32
28-Mar-95	422																									
29-Mar-95	423	7.1	284	5700	3760	60	38	584	188	129	32.9			27.0	24.3	0.5	0.3	0.4	0.9	0.6				1.67		
30-Mar-95	424																									
31-Mar-95	425	7.3	326	5370	3590	64	44	612	212	102	32.2	197.0	110.2	22.8	22.2	0.0	0.0	0.0	0.6	0.0	16.8	23.1	25.9	2.56	2.74	3.33
01-Apr-95	426																									
02-Apr-95	427									125																
03-Apr-95	428	7.2	322	5940	3930	92	66	656	240	50	41.5	259.4	120.4	30.6	27.1	1.3	0.6	0.5	1.0	0.2	21.6	24.9	29.3	3.33	3.57	4.4
04-Apr-95	429																									
05-Apr-95	430			6220	3930	96	60			67	46.8			42.0	31.9	4.8	1.1	1.5	1.9	0.9				3.45		
06-Apr-95	431																									
07-Apr-95	432									65																
08-Apr-95	433																									
09-Apr-95	434									60																
10-Apr-95	435	7.1	326	6180	4100	102	62	652	212	68	42.6			39.2	30.5	4.2	1.1	1.2	2.0	0.3				4.32		
11-Apr-95	436																									
12-Apr-95	437	7.2	332	6360	4310	96	66	664	254	130	44.2	306.5	149.6	32.8	27.4	3.0	0.0	0.4	1.7	0.3	27.9	35.9	39.9	4.11	4.3	5.16
13-Apr-95	438																									
14-Apr-95	439			5930	4120	68	54			93																
15-Apr-95	440																									
16-Apr-95	441									45																
17-Apr-95	442			5500	3700	86	60			118	47.7			37.8	29.2	4.4	1.0	1.0	1.8	0.4				4.26		
18-Apr-95	443																									
19-Apr-95	444	7.1	328	5240	3600	80	48			142	51.4	330.0	173.1	50.0	38.7	5.3	1.4	1.2	3.0	0.5	30.0	33.6	38.2	4.23	4.54	5.59
20-Apr-95	445																									
21-Apr-95	446			4850	3410	74	62			104				61.0	45.9	7.3	1.8	1.8	3.6	0.5				4.54		
22-Apr-95	447																									
23-Apr-95	448									52																
24-Apr-95	449	7.2	336	5060	3620	74	50	704	292	140	85.0			101.4	67.6	9.1	2.4	17.5	3.6	1.2				3.76		
25-Apr-95	450																									
26-Apr-95	451									140																
27-Apr-95	452	7.0	368	9670	5940	94	68	724	284	162	74.8	447.7	298.6	94.9	69.2	5.6	2.3	13.7	3.5	0.6	29.1	34.3	38.5	3.24	4.57	5.84
28-Apr-95	453																									
29-Apr-95	454			8840	5420	86	54			172																
30-Apr-95	455																									
01-May-95	456	7.1	360	8360	5160	66	42	676	272	185	82.0			83.9	62.9	4.2	2.0	10.7	3.5	0.6				4		
02-May-95	457																									
03-May-95	458	7.1	352	8070	4970	64	46	676	244	179	56.0	293.9	157.4	42.3	37.3	1.0	0.7	1.2	1.9	0.3	27.2	34.0	37.9	4.44	4.95	5.9
04-May-95	459																									
05-May-95	460			7030	4380	64	48			170																
06-May-95	461																									

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
07-May-95	462									85																
08-May-95	463			6830	4360	78	62			136																
09-May-95	464																									
10-May-95	465	7.1	368	7050	4600	62	50			166	74.5			54.8	46.3	3.2	1.0	1.5	2.4	0.5				3.83		
11-May-95	466																									
12-May-95	467	7.0	356	6710	4410	66	50	660	236	161	74.5	314.3	212.3	57.7	47.7	4.0	1.2	1.7	2.5	0.5	29.0	33.3	36.8	4.06	5.43	6.61
13-May-95	468																									
14-May-95	469									80																
15-May-95	470			6900	4510	56	38			188																
16-May-95	471																									
17-May-95	472									160																
18-May-95	473																									
19-May-95	474			6470	4400	54	46			170																
20-May-95	475																									
21-May-95	476									85																
22-May-95	477			6230	4160	60	42			172																
23-May-95	478																									
24-May-95	479	7.2	428	5910	3930	52	34	772	272	188	30.8	235.9	110.4	38.4	33.8	0.5	1.2	0.5	2.2	0.3	24.3	27.9	30.7	3.16	3.36	3.96
25-May-95	480																									
26-May-95	481			5590	3780	56	48			149																
27-May-95	482																									
28-May-95	483									75																
29-May-95	484	7.1	444	5750	3880	60	48			151	36.9			40.7	37.9	0.4	0.7	0.5	1.2	0.1						
30-May-95	485																									
31-May-95	486			5360	3650	56	44			157																
01-Jun-95	487																									
02-Jun-95	488									150																
03-Jun-95	489																									
04-Jun-95	490									75																
05-Jun-95	491	7.2	394	6300	4330	72	56			150	39.2			45.8	42.1	0.5	1.0	0.5	0.5	1.3	26.1	31.2	35.4	3.84	4.29	5.21
06-Jun-95	492																									
07-Jun-95	493			6364	4310	80	58			143				44.8	39.4	0.3	1.3	0.7	2.9	0.3						
08-Jun-95	494																									
09-Jun-95	495	7.1	380	6340	4300	74	52	698	240	158	36.5	345.7	196.7	35.2	32.5	0.0	0.8	0.3	1.4	0.3	26.2	31.6	38.1	3.94	4	5.16
10-Jun-95	496																									
11-Jun-95	497									80																
12-Jun-95	498			6550	4500	64	48			169																
13-Jun-95	499																									
14-Jun-95	500			7510	5130	106	76			134																
15-Jun-95	501																									
16-Jun-95	502	7.1	374	6970	4710	78	54	692	276	162	63.0	376.2	221.2	66.3	53.6	0.7	3.2	4.4	3.4	1.1	29.3	33.1	38.6	3.89	4.19	5.14
17-Jun-95	503																									
18-Jun-95	504									80																
19-Jun-95	505			7000	4590	70	50			167																
20-Jun-95	506																									
21-Jun-95	507			7090	4620	76	58			153																
22-Jun-95	508																									
23-Jun-95	509	7.1	342	6780	4380	70	48	640	254	170	38.4	298.7	190.2	35.4	33.2	0.0	0.7	0.0	1.5	0.0	25.6	29.2	34.8	4.22	4.33	5.3
24-Jun-95	510																									
25-Jun-95	511									85																
26-Jun-95	512			7260	4780	74	50			166																

TABLE A3 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	Eff. TS (mg/L)	Eff. TVS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
27-Jun-95	513																									
28-Jun-95	514	7.0	374	7180	4570	88	70			130	59.1	384.0	213.5	47.3	42.2	1.0	1.5	0.6	1.7	0.3	31.0	35.4	41.0	3.52	4.21	5.41
29-Jun-95	515																									
30-Jun-95	516			7040	4580	92	72			124																
01-Jul-95	517																									
02-Jul-95	518									65																
03-Jul-95	519			6930	4550	68	54			106																
04-Jul-95	520																									
05-Jul-95	521																									
06-Jul-95	522	7.1	332	7130	4750	78	56			155	51.8			43.4	39.3	1.2	1.0	0.0	1.6	0.2	27.6	31.5	36.4	3.82	4.23	5.12

TABLE A4 - REACTOR AND EFFLUENT CHARACTERISTICS (FERMENTER-F4)

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
14-Jan-94	1			2980	2410																			
15-Jan-94	2																							
16-Jan-94	3																							
17-Jan-94	4			2470	2140	230	176	191	64.1	333.0	170.8	16.3	16.3	0.0	0.0	0.0	0.0	0.0	31.5	42.4	47.6		6.39	7.56
18-Jan-94	5																							
19-Jan-94	6	6.9	256	2280	1960	170	140	303	48.3	315.3	156.1	18.1	18.1	0.0	0.0	0.0	0.0	0.0						
20-Jan-94	7																							
21-Jan-94	8	7.0	268	2100	1780	110	94	436				24.2	24.2	0.0	0.0	0.0	0.0	0.0						
22-Jan-94	9																							
23-Jan-94	10																							
24-Jan-94	11	6.8	266	2100	1840	100	74	464	52.7	320.9	175.4	16.3	15.2	0.0	0.0	0.0	1.1	0.0	27.5	32.2	38.7		5.52	6.84
25-Jan-94	12																							
26-Jan-94	13	6.8	252	1920	1660	96	84	450				20.2	20.2	0.0	0.0	0.0	0.0	0.0	30.7	34.6	40.1		6.31	7.36
27-Jan-94	14																							
28-Jan-94	15	6.9	262	1980	1650	100.00	80.00	412	50.8	348.2	180.9	28.8	27.3	0.0	0.0	0.0	1.5	0.0	30.1	36.6	38.9		6.28	7.53
29-Jan-94	16																							
30-Jan-94	17																							
31-Jan-94	18																							
01-Feb-94	19	6.8	266	2010	1560	96	83	463	48.3	325.8	150.4	28.5	28.5	0.0	0.0	0.0	0.0	0.0	28.8	33.4	38.2		5.73	7.12
02-Feb-94	20	6.8	256	1940	1470	83	44	483																
03-Feb-94	21			1880	1660	80	78	463																
04-Feb-94	22	6.8	266	1900	1430	96	80	380	48.4	361.8	184.5	30.9	30.9	0.0	0.0	0.0	0.0	0.0	30.3	33.7	40.8		5.82	7.31
05-Feb-94	23																							
06-Feb-94	24																							
07-Feb-94	25	6.8	264	1840	1360	110	96	328	54.3	438.4	188.0	50.5	48.3	0.0	0.0	0.0	2.2	0.0	37.2	48.2	54.8		7.58	8.41
08-Feb-94	26																							
09-Feb-94	27			1800		114		370																
10-Feb-94	28	6.8	272	1440	1180	110	82	292	57.1	388.6	220.3	48.7	46.6	0.0	0.0	0.0	2.1	0.0	34.5	38.4	43.8		5.75	7.01
11-Feb-94	29	6.9	266	1260	1100	92	80	312	52.3	364.0	197.8	35.9	34.3	0.0	0.0	0.0	1.7	0.0	32.6	37.0	42.3		5.44	6.75
12-Feb-94	30			1080		84		283																
13-Feb-94	31																							
14-Feb-94	32	6.4	244	980	840	74	62	298	48.1	322.8	199.7	33.0	31.5	0.0	0.0	0.0	1.5	0.0	28.7	32.0	37.5		5.83	7.21
15-Feb-94	33																							
16-Feb-94	34																							
17-Feb-94	35	6.8	266	1100	980	80	70	314	48.1	307.2	174.4	34.9	33.8	0.0	0.0	0.0	1.4	0.0	33.1	36.8	41.9		5.90	7.36
18-Feb-94	36																							
19-Feb-94	37	6.7	262	1120	980	78	66	332	45.7	318.4	170.5	34.1	32.9	0.0	0.0	0.0	1.3	0.0	31.5	35.3	40.1		5.64	6.98
20-Feb-94	38																							
21-Feb-94	39	6.9	256	1080		104		172																
22-Feb-94	40	6.9	268	1100	980	90	82	378	46.1	325.0	175.8	33.3	31.9	0.0	0.0	0.0	1.4	0.0	32.3	36.1	39.6		5.50	6.75
23-Feb-94	41																							
24-Feb-94	42	6.7	196	1040	900	66	56	368																
25-Feb-94	43																							
26-Feb-94	44	6.6	188	1100	840	60	40	423																
27-Feb-94	45																							
28-Feb-94	46																							
01-Mar-94	47	6.4	170	1220	980	74	62	388	45.6	298.9	154.9	28.0	25.2	0.0	0.0	0.0	0.8	0.0	28.7	32.4	36.9		5.48	6.44
02-Mar-94	48																							
03-Mar-94	49																							
04-Mar-94	50	6.5	156	1140	940	82	74	318	48.4	326.2	160.2	32.4	31.2	0.0	0.0	0.0	1.2	0.0	30.8	34.4	37.1		5.14	6.90

TABLE A4 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Mar-94	51																							
06-Mar-94	52																							
07-Mar-94	53	6.7	180	1280	1040	80	66	375	55.3	335.5	172.8	43.0	41.5	0.0	0.0	0.0	1.5	0.0	31.4	36.9	38.8		5.76	6.58
08-Mar-94	54																							
09-Mar-94	55	6.5	166			84	70		47.8			38.8	36.0	0.0	1.2	0.0	1.4	0.0						
10-Mar-94	56																							
11-Mar-94	57	6.7	184	1680	1240	80	66	464	52.6	350.8	181.6	35.0	32.6	0.0	1.1	0.0	1.3	0.0	28.6	35.7	40.3		6.02	6.84
12-Mar-94	58																							
13-Mar-94	59	6.7	186	1560	1180	78	64	456	56.7	327.9	172.5	31.0	29.0	0.0	1.4	0.0	1.5	0.0	33.0	36.7	41.1		6.09	7.04
14-Mar-94	60																							
15-Mar-94	61	6.5	156	1340	1120	70	54	437	48.6	320.0	180.1	17.5	16.4	0.0	0.0	0.0	1.1	0.0	32.1	36.8	40.6		5.39	6.44
16-Mar-94	62																							
17-Mar-94	63																							
18-Mar-94	64	6.7	200	1220	1080	100	94	256	64.8	486.8	215.9	25.0	25.0	0.0	0.0	0.0	0.0	0.0	31.7	36.9	43.1		6.18	7.25
19-Mar-94	65																							
20-Mar-94	66																							
21-Mar-94	67	6.6	182	1180	1020	100	70	342	62.8	408.7	232.5	27.4	27.4	0.0	0.0	0.0	0.0	0.0	31.8	37.1	40.1		6.14	7.08
22-Mar-94	68																							
23-Mar-94	69	6.3	148	1220	1080	72	48	366	41.4	284.8	140.7	15.8	15.8	0.0	0.0	0.0	0.0	0.0	28.5	32.3	36.7		4.73	5.78
24-Mar-94	70																							
25-Mar-94	71	6.3	156	1140	980	86	60	297	42.3			12.3	12.3	0.0	0.0	0.0	0.0	0.0						
26-Mar-94	72																							
27-Mar-94	73																							
28-Mar-94	74	6.6	184	1260	980	80	78	321	36.6	320.0	141.8	7.7	7.7	0.0	0.0	0.0	0.0	0.0	29.2	33.4	36.4		4.79	5.75
29-Mar-94	75																							
30-Mar-94	76	6.5	132	1040	1140	82	50	413	36.9			15.9	8.3	0.4	0.8	5.2	0.0	0.2						
31-Mar-94	77																							
01-Apr-94	78	6.5	136	1980	1220	78	40	507	43.1	256.8	122.8	7.8	4.2	0.1	0.5	0.3	1.9	0.8	25.8	30.1	32.7		4.32	4.87
02-Apr-94	79																							
03-Apr-94	80																							
04-Apr-94	81	6.4	114	1720	1100	102	56	384	36.3	252.2	126.0	3.0	2.3	0.0	0.2	0.0	0.5	0.0	24.5	28.5	33.3		3.95	5.01
05-Apr-94	82																							
06-Apr-94	83	6.4	170	1980	1080	88	66	403	49.7	284.2	162.1	15.1	12.2	0.1	0.7	0.4	1.6	0.2	28.8	35.2	37.4		3.98	5.26
07-Apr-94	84																							
08-Apr-94	85	6.5	146	1480	1020	84	64	408	45.1	280.6	143.6	3.8	1.0	1.0	0.0	0.7	0.8	0.0	30.4	34.4	38.1		5.08	6.04
09-Apr-94	86																							
10-Apr-94	87	6.6	184	1780	1080	88	36	450	42.5	248.0	108.1	1.4	0.0	0.6	0.0	0.1	0.6	0.0	28.8	33.1	33.8		4.33	5.12
11-Apr-94	88																							
12-Apr-94	89	6.8	184	2210	1280	108	54	457	43.8	233.2	74.7	4.7	3.2	0.3	0.4	0.2	0.6	0.0	27.5	31.5	36.1		4.04	4.75
13-Apr-94	90																							
14-Apr-94	91	6.8	192	2020	1340	188	82	324	43.8	288.4	80.2	4.2	2.1	0.2	0.4	0.1	0.8	0.5	28.8	30.8	36.2		4.23	5.32
15-Apr-94	92																							
16-Apr-94	93	6.4	240	2440	1280	128	84	435	116.8	438.3	240.8	102.3	80.2	7.4	1.7	1.1	1.1	0.7	31.3	34.8	43.8		5.01	6.12
17-Apr-94	94																							
18-Apr-94	95	6.8	208	2200	1220	144	82	357	116.8	380.3	231.8	122.5	101.5	12.9	2.2	2.8	2.2	1.2	28.9	33.8	42.7		5.11	6.38
19-Apr-94	96																							
20-Apr-94	97	6.5	182	1780	1140	124	82	327	38.2	312.1	88.2	2.3	0.7	0.0	0.3	0.4	0.9	0.0	29.2	34.2	44.8		5.00	6.20
21-Apr-94	98	6.5	170						40.3			5.4	18.8	2.0	1.4	0.8	1.4	1.2						
22-Apr-94	99																							
23-Apr-94	100	6.4	158	1700	1140	108	88	369	40.2	284.4	113.3	7.8	5.3	0.2	0.8	0.3	0.8	0.5	27.3	30.4	34.9		5.21	6.08
24-Apr-94	101																							

TABLE A4 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	VFA-Tot. (mg/L)	Acetic (mg/L)	Propionic (mg/L)	Iso-butyric (mg/L)	Nano-butyric (mg/L)	Iso-valeric (mg/L)	Nano-valeric (mg/L)	NH4-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
25-Apr-94	102	6.5	162	1340	1020	80	66	362	38.4	248.2	108.7	5.4	1.8	0.8	0.3	0.8	0.8	0.8	28.4	29.5	35.4		4.70	5.98
26-Apr-94	103																							
27-Apr-94	104	6.6	174	1160	940	90	66	336	50.4	220.5	164.8	5.4	2.7	1.1	0.0	0.8	0.7	0.0	29.1	30.9	33.6		4.66	5.66
28-Apr-94	105																							
29-Apr-94	106											4.8	1.7	0.0	0.6	0.7	1.4	0.4						
30-Apr-94	107																							
01-May-94	108											6.1	1.3	0.5	1.1	1.0	1.2	1.1						
02-May-94	109	6.1	126	2020	1200	124	80	382	50.8															
03-May-94	110																							
04-May-94	111	6.0	124	1600	1040	102	76	367	42.9															
05-May-94	112																							
06-May-94	113	6.0	98	1700	1360	82	70	425	32.9			5.8	4.9	0.0	0.0	0.0	0.5	0.3	29.7	33.3	38.5		4.88	5.72
07-May-94	114																							
08-May-94	115																							
09-May-94	116	6.8	74	1500	1260	78	78	448	36.2			2.1	1.7	0.0	0.0	0.0	0.4	0.0	27.3	31.7	38.0		4.14	5.60
10-May-94	117																							
11-May-94	118	6.0	104	1480	1180	88	80	353	44.6			8.7	7.2	0.0	0.5	0.4	0.8	0.0						
12-May-94	119																							
13-May-94	120	6.0	86	1580	1400	108	84	347	55.1			18.3	13.8	0.4	1.1	1.4	1.8	0.0	30.8	38.0	43.5		4.72	5.84
14-May-94	121																							
15-May-94	122																							
16-May-94	123	6.0	80	1460	1240	104	94	323	43.3			8.0	4.2	0.4	0.5	0.3	0.7	0.0	28.4	33.8	41.6		5.01	5.82
17-May-94	124																							
18-May-94	125	6.0	94			110	88		52.4			15.9	9.6	0.0	1.1	2.9	2.3	0.0						

APPENDIX B

Page

Table B1 - Reactor and Effluent Characteristics (Reactor B1; PAF-SBR System) 301

Table B2 - Reactor and Effluent Characteristics (Reactor B2; Conventional-SBR) 309

TABLE B1 - REACTOR AND EFFLUENT CHARACTERISTICS (REACTOR B1; PAF-SBR SYSTEM)

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Jul-94	1			1350															
06-Jul-94	2			1320	980	24	10	239		22.9									
07-Jul-94	3																		
08-Jul-94	4																		
09-Jul-94	5	8.3	304	820	720	34	10	217											
10-Jul-94	6																		
11-Jul-94	7	8.4	352	1240	720	50	14	183		21.4	72.5	25.1	14.1	1.5	15.6	17.0	3.08	3.40	3.77
12-Jul-94	8																		
13-Jul-94	9	8.5	348	960	880	40	36	55		25.4									
14-Jul-94	10																		
15-Jul-94	11	8.6	396	840	820	52	42	No WAS		23.2									
16-Jul-94	12																		
17-Jul-94	13																		
18-Jul-94	14	8.5	350	800	700	58	48	No WAS		26.2	105.2	34.1	10.5	1.3	14.2	16.4	2.76	3.16	3.71
19-Jul-94	15																		
20-Jul-94	16	8.2	272	620	460	36	22	13		24.6									
21-Jul-94	17																		
22-Jul-94	18	7.9	228	920	680	44	28	53		33.0									
23-Jul-94	19																		
24-Jul-94	20																		
25-Jul-94	21	8.0	214	1120	860	34	16	188		24.8	110.5	41.6	0.1	13.2	3.8	5.8	3.31	3.41	3.82
26-Jul-94	22																		
27-Jul-94	23	7.9	204	1540	1180	30	24	178		23.9									
28-Jul-94	24																		
29-Jul-94	25	8.2	220	1560	1180	26	22	188		23.4									
30-Jul-94	26																		
31-Jul-94	27																		
01-Aug-94	28	7.5	198	1620	1160	12	10	248		21.0									
02-Aug-94	29																		
03-Aug-94	30	7.8	182	1820	1380	12	10	257		21.9	36.8	13.1	0.0	11.4	1.7	2.6	0.61	0.82	1.20
04-Aug-94	31																		
05-Aug-94	32	7.6	162	2300	1820	4	2	293		20.9									
06-Aug-94	33																		
07-Aug-94	34							150											
08-Aug-94	35	7.6	194	2560	1900	6	4	287		19.8									
09-Aug-94	36																		
10-Aug-94	37	7.4	234	2280	1600	8	6	278		22.1	40.5	13.1	0.4	12.6	2.2	3.9	0.00	0.31	0.80
11-Aug-94	38																		
12-Aug-94	39	7.6	224	2560	1920	4	2	294		21.5									
13-Aug-94	40																		
14-Aug-94	41							145											
15-Aug-94	42	7.5	242	2700	2000	12	7	279	63	22.3									
16-Aug-94	43																		
17-Aug-94	44	7.1	234	2540	1780	10	4	287		20.0	13.1	6.1	0.4	11.8	0.4	0.5	0.20	0.30	0.41
18-Aug-94	45																		
19-Aug-94	46	7.6	210	2480	2060	10	5	285	73	20.2									
20-Aug-94	47																		
21-Aug-94	48							140											
22-Aug-94	49	7.6	196	2670	2030	4	2	294		20.4									
23-Aug-94	50																		

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
24-Aug-94	51	7.9	194	2780	2045	8	3	291		21.7									
25-Aug-94	52																		
26-Aug-94	53	7.7	220	2640	1860	10	3	290	62	18.6	9.7	5.5	0.3	12.2	0.3	0.4	0.17	0.18	0.34
27-Aug-94	54																		
28-Aug-94	55							290											
29-Aug-94	56																		
30-Aug-94	57	7.7	188	1960	1340	4	1.5	293		21.5									
31-Aug-94	58																		
01-Sep-94	59	7.7	184	2800	2060	5	2	294	56	20.5	9.7	5.5	0.0	13.7	1.6	1.8	0.00	0.11	0.20
02-Sep-94	60																		
03-Sep-94	61							290											
04-Sep-94	62																		
05-Sep-94	63	7.6	166	2640	1740	10	6	279		21.7									
06-Sep-94	64																		
07-Sep-94	65	7.4	206	2620	1940	8	4	288	54	22.0			0.2	14.5	1.4	1.8	0.00	0.20	0.32
08-Sep-94	66																		
09-Sep-94	67	6.1	244	2680	1920	11	6	276		20.7									
10-Sep-94	68																		
11-Sep-94	69							135											
12-Sep-94	70	7.9	212	2720	1880	16	11	265		21.5									
13-Sep-94	71																		
14-Sep-94	72	8.0	244	2900	2160	11	6	284	52	18.3			0.0	16.1	1.2	1.5	0.46	0.72	0.89
15-Sep-94	73																		
16-Sep-94	74							135											
17-Sep-94	75	7.9	286	2780	2040	8	4	295		20.3			0.0	15.5	1.3	1.3	0.53	0.64	0.77
18-Sep-94	76																		
19-Sep-94	77			2460	1820	12	8	273											
20-Sep-94	78	8.1	314	2300	1580	15	8	274		21.2									
21-Sep-94	79																		
22-Sep-94	80			2420	1920	14	9	272											
23-Sep-94	81	7.8	240	2400	1780	14	10	288	46	19.0			0.1	12.5	1.8	1.8	0.05	0.14	0.20
24-Sep-94	82																		
25-Sep-94	83							140											
26-Sep-94	84			2280	1600	10	7	274											
27-Sep-94	85	8.0	220	2640	1900	12	9	272		21.2									
28-Sep-94	86																		
29-Sep-94	87			2660	1900	10	7	277											
30-Sep-94	88	7.4	200	2560	1820	9	6	279	51	22.8			0.2	14.2	1.3	1.8	0.00	0.14	0.42
01-Oct-94	89																		
02-Oct-94	90							140											
03-Oct-94	91			2790	1930	12	9	272											
04-Oct-94	92																		
05-Oct-94	93							200											
06-Oct-94	94	7.3	182	2750	1950	11	8	276	44	22.2			0.2	16.4	1.9	2.0	0.06	0.09	0.21
07-Oct-94	95																		
08-Oct-94	96			2680	1890	12	10	269											
09-Oct-94	97																		
10-Oct-94	98			2880	1960	16	10	270		17.6							4.03	4.24	4.34
11-Oct-94	99																		
12-Oct-94	100	8.0	272	2740	1870	11	8	275	46	17.4			0.0	13.9	1.0	1.6	0.20	0.27	0.36
13-Oct-94	101																		

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
14-Oct-94	102	8.0	252	2780	2020	16	13	261		21.3									
15-Oct-94	103																		
16-Oct-94	104							130											
17-Oct-94	105	8.0	234	2800	1960	10	6	283		21.1									
18-Oct-94	106	8.0	226	2740	1920	16	11	264	44	21.1			0.0	13.2	1.4	2.3	0.18	0.34	0.85
19-Oct-94	107																		
20-Oct-94	108							130											
21-Oct-94	109	8.2	308	2480	1780	15	9	270		17.9									
22-Oct-94	110																		
23-Oct-94	111							135											
24-Oct-94	112	8.2	372	2780	2140	18	15	258		19.2									
25-Oct-94	113																		
26-Oct-94	114							140											
27-Oct-94	115	8.0	306	3120	2100	18	11	277	32	21.4			0.5	16.4	1.4	3.0	1.15	1.28	1.56
28-Oct-94	116			3160	2140	14	10	280											
29-Oct-94	117																		
30-Oct-94	118							100											
31-Oct-94	119	7.8	274	3260	2240	10	5	293		19.8			0.4	13.4	1.6	1.9	0.05	0.17	0.31
01-Nov-94	120																		
02-Nov-94	121	7.8	238	3230	2290	13	9	278											
03-Nov-94	122																		
04-Nov-94	123	7.8	262	3198	2187	12	8	280	36	22.7									
05-Nov-94	124																		
06-Nov-94	125							140											
07-Nov-94	126	7.9	248	3100	2170	10	6	283	39	18.5			0.0	16.5	2.3	2.4	0.23	0.34	0.47
08-Nov-94	127																		
09-Nov-94	128	7.5	222	3090	2030	11	4	298		16.0									
10-Nov-94	129																		
11-Nov-94	130	7.9	234	2860	2010	11	9	286		17.5									
12-Nov-94	131																		
13-Nov-94	132							140											
14-Nov-94	133	7.9	230	3630	2470	18	14	271	33	17.2			0.2	16.9	2.3	3.0	0.00	0.01	0.51
15-Nov-94	134																		
16-Nov-94	135	7.9	264	3360	2300	13	6	292		14.0									
17-Nov-94	136																		
18-Nov-94	137			3070	2100	14	12	272											
19-Nov-94	138							140											
20-Nov-94	139																		
21-Nov-94	140	8.1	304	2970	2070	9	8	286	36	14.0	30.0	20.0	0.6	16.0	2.2	2.5	2.40	2.68	3.10
22-Nov-94	141																		
23-Nov-94	142	8.1	288	2660	1850	11	9	289		17.7									
24-Nov-94	143																		
25-Nov-94	144	8.2	292	2780	1890	11	10	274		16.5									
26-Nov-94	145																		
27-Nov-94	146							135											
28-Nov-94	147	7.5	252	3020	2070	16	10	278	37	16.8	30.0	20.0	0.3	17.7	2.2	2.5	0.25	0.32	0.59
29-Nov-94	148																		
30-Nov-94	149	8.0	246	3000	1980	10	8	285											
01-Dec-94	150																		
02-Dec-94	151	8.0	258	3000	2100	6	5	294		17.2									
03-Dec-94	152																		

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
04-Dec-94	153							145											
05-Dec-94	154	7.9	242	2980	1970	15	7	286	35	13.7	41.2	36.0	0.5	17.0	1.8	2.1	0.90	0.93	1.06
06-Dec-94	155																		
07-Dec-94	156			2980	1970	8	3	290		14.8									
08-Dec-94	157									14.0							0.13		
09-Dec-94	158	8.0	216	4470	2990	17	12	264		14.5							0.13		
10-Dec-94	159																		
11-Dec-94	160							135											
12-Dec-94	161	7.9	218	4180	2800	7	6	284	36	18.5	41.2	36.0	1.0	17.5	3.2	3.7	0.60	0.64	0.83
13-Dec-94	162																		
14-Dec-94	163			4160	2750	6	4	299		14.9									
15-Dec-94	164			3910	2560												0.00	0.14	
16-Dec-94	165	7.8	194	3870	2550	5	2	306		15.3									
17-Dec-94	166																		
18-Dec-94	167							150											
19-Dec-94	168	7.1	188	3600	2375	11	10	282	36	14.8	42.6	34.6	0.6	16.5	3.0	3.4	0.00	0.14	0.37
20-Dec-94	169																		
21-Dec-94	170			3600	2430	5	4	295		17.8							0.00	0.12	
22-Dec-94	171																		
23-Dec-94	172	7.8	164	3290	2240	7	5	298		14.4									
24-Dec-94	173																		
25-Dec-94	174							150											
26-Dec-94	175	7.6	184	3380	2280	3	1	298		14.5	40.2	36.7	0.5	18.1	2.1	3.0	0.06	0.14	0.43
27-Dec-94	176																		
28-Dec-94	177	7.4	136	4110	2740	2	1	305	39	12.8							0.13	0.23	
29-Dec-94	178			3800	2640					15.3							1.99		
30-Dec-94	179	7.7	140	4100	2750	12	8	283											
31-Dec-94	180																		
01-Jan-95	181							140											
02-Jan-95	182			3810	2580	5	3	296											
03-Jan-95	183																		
04-Jan-95	184	7.9	172	3610	2420	11	3	302	39	15.5	41.2	36.0	0.4	18.4	2.1	2.3	1.32	1.48	1.50
05-Jan-95	185																		
06-Jan-95	186	7.8	148	3960	2710	8	4	300		16.4	42.2	36.0							
07-Jan-95	187																		
08-Jan-95	188							150											
09-Jan-95	189	7.7	148	4230	2930	10	6	268		15.6									
10-Jan-95	190																		
11-Jan-95	191	7.3	150	3550	2470	13	8	281	42	15.1	53.7	42.6	0.9	16.6	2.0	2.6	0.11	0.11	0.15
12-Jan-95	192																		
13-Jan-95	193	7.4	180	4760	3310	11	8	290		16.8									
14-Jan-95	194																		
15-Jan-95	195							150											
16-Jan-95	196	7.5	124	4630	3180	11	8	280		16.0				19.6			0.00	0.08	0.21
17-Jan-95	197																		
18-Jan-95	198	7.7	128	5020	3430	18	10	274	42	14.6	37.0	31.5	0.4	19.7	1.8	2.5	0.04	0.06	0.19
19-Jan-95	199																		
20-Jan-95	200			4740	3310	10	6	281											
21-Jan-95	201																		
22-Jan-95	202							140											
23-Jan-95	203	7.7	104	4610	3130	8	5	294		15.2									

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
24-Jan-95	204																		
25-Jan-95	205	7.7	118	4550	3100	18	11	272	40	16.3	37.0	31.5	0.0	19.9	2.8	2.9	0.10	0.20	0.40
26-Jan-95	206																		
27-Jan-95	207			4580	3220	11	8	278		15.2							0.10		
28-Jan-95	208																		
29-Jan-95	209							140											
30-Jan-95	210	7.5	116	4060	2800	18	10	287		16.4							0.36		
31-Jan-95	211																		
01-Feb-95	212	7.6	122	4100	2770	12	7	280	39	15.0	42.6	37.0	0.0	18.6	2.6	2.7	0.15	0.18	0.36
02-Feb-95	213																		
03-Feb-95	214	7.6	110	4890	3380	12	8	281		14.7							0.10		
04-Feb-95	215																		
05-Feb-95	216							140											
06-Feb-95	217			5380	3700	11	8	270		14.2							0.32		
07-Feb-95	218																		
08-Feb-95	219	7.6	118	5140	3540	10	8	282	35	15.6	53.7	37.0	0.3	17.6	2.8	2.8	0.24	0.35	0.48
09-Feb-95	220																		
10-Feb-95	221	7.4	120	4970	3390	10	7	284		15.0							0.10		
11-Feb-95	222																		
12-Feb-95	223							182											
13-Feb-95	224	7.4	184	5090	3400	10	6	285		14.5							0.36		
14-Feb-95	225																		
15-Feb-95	226	7.4	118	4740	3290	16	12	265	24	14.6	53.7	48.2	0.4	18.1	3.4	4.3	0.42	0.53	0.62
16-Feb-95	227																		
17-Feb-95	228	7.5	128	4750	3270	10	8	280		16.3							0.19		
18-Feb-95	229																		
19-Feb-95	230							140											
20-Feb-95	231	7.6	116	5580	3770	10	8	283		17.5							0.15		
21-Feb-95	232																		
22-Feb-95	233	7.3	140	5820	4020	8	6	280	36	16.7	53.7	42.6	0.0	13.2	3.3	4.2	0.00	0.10	0.22
23-Feb-95	234																		
24-Feb-95	235	7.3	112	5260	3640	8	6	286		16.7							0.07		
25-Feb-95	236																		
26-Feb-95	237							143											
27-Feb-95	238	7.4	108	5770	3960	10	8	284		16.8							0.24		
28-Feb-95	239																		
01-Mar-95	240			6500	4390	7	4	292	43										
02-Mar-95	241																		
03-Mar-95	242	7.3	100	6550	4500	7	4	284		16.0	31.5	20.4	0.8	18.2	3.1	4.1	0.18	0.27	0.38
04-Mar-95	243																		
05-Mar-95	244							142											
06-Mar-95	245	7.2	96	6020	4110	12	8	284		15.8							0.20		
07-Mar-95	246																		
08-Mar-95	247	7.3	104	6020	4020	10	8	289	50	16.6	53.7	48.2	0.5	16.8	1.9	3.4	0.12	0.35	0.47
09-Mar-95	248																		
10-Mar-95	249	7.2	108	6390	4360	8	6	285		18.3							0.12		
11-Mar-95	250																		
12-Mar-95	251							142											
13-Mar-95	252	7.1	108	5730	3910	8	6	294		18.4							0.12		
14-Mar-95	253																		

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
15-Mar-95	254	7.4	128	4690	3100	10	8	285	55	15.4	37.0	31.5	0.6	6.6	1.7	3.1	0.42	0.54	0.68
16-Mar-95	255																		
17-Mar-95	256			4510	2940	10	6	284		17.3							0.47		
18-Mar-95	257																		
19-Mar-95	258							142											
20-Mar-95	259	7.3	144	3980	2580	10	6	299		15.0				8.2			0.17		
21-Mar-95	260																		
22-Mar-95	261	7.4	198	3980	2600	10	7	284	55	17.6	52.1	45.8	0.7	8.1	2.1	3.4	0.23	0.42	0.59
23-Mar-95	262																		
24-Mar-95	263	7.4	200	4510	2960	10	8	277		15.9							0.14		
25-Mar-95	264																		
26-Mar-95	265							138											
27-Mar-95	266	7.6	204	4460	2900	8	6	288		15.2	39.6	33.3	0.4	4.2	2.2	3.1	0.06	0.17	0.41
28-Mar-95	267																		
29-Mar-95	268	7.6	214	4150	2690	10	7	280	53	12.8							0.30		
30-Mar-95	269																		
31-Mar-95	270	7.8	234	4260	2840	6	4	296		14.8	33.3	30.8	0.4	7.9	2.1	2.8	0.84	0.96	1.18
01-Apr-95	271																		
02-Apr-95	272							148											
03-Apr-95	273	7.4	224	4380	2880	15	10	260		16.1	45.8	35.1	0.2	6.9	2.0	2.2	0.40	0.53	0.89
04-Apr-95	274																		
05-Apr-95	275			4410	2890	10	6	290	50	18.6							0.24		
06-Apr-95	276																		
07-Apr-95	277							286											
08-Apr-95	278																		
09-Apr-95	279							142											
10-Apr-95	280	7.7	198	4180	2720	12	8	276		15.5							0.16		
11-Apr-95	281																		
12-Apr-95	282	7.6	206	3890	2530	10	6	295	54	16.4	39.6	27.1	0.3	8.8	3.6	4.4	0.14	0.28	0.46
13-Apr-95	283																		
14-Apr-95	284			4190	2780	12	8	277											
15-Apr-95	285																		
16-Apr-95	286							135											
17-Apr-95	287			4740	3130	14	8	270		18.3							0.10		
18-Apr-95	288																		
19-Apr-95	289	7.7	188	5050	3350	12	8	272	51	18.0	45.8	39.6	0.0	7.1	3.5	3.6	0.15	0.26	0.52
20-Apr-95	290																		
21-Apr-95	291			4680	3150	12	10	268		17.2							0.27		
22-Apr-95	292																		
23-Apr-95	293							134											
24-Apr-95	294	7.4	228	4910	3540	8	6	279		18.3							0.00		
25-Apr-95	295																		
26-Apr-95	296																		
27-Apr-95	297	7.6	234	5240	3990	10	8	280	77	18.7	52.1	37.1	2.1	8.1	3.4	3.9	0.06	0.13	0.76
28-Apr-95	298																		
29-Apr-95	299							280											
30-Apr-95	300																		
01-May-95	301	7.6	284	4860	3660	70	58	170		18.5							0.00		
02-May-95	302																		
03-May-95	303	7.6	238	4600	3440	17	14	274	87	19.2	52.1	45.8	8.3	8.3	12.6	14.0	0.00	0.19	0.63
04-May-95	304																		
05-May-95	305			4530	3320	16	12	266											

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
06-May-95	306																		
07-May-95	307							135											
08-May-95	308			4580	3350	18	14	267					7.5						
09-May-95	309																		
10-May-95	310	7.5	224	4580	3310	12	10	276		20.0			1.5				0.00		
11-May-95	311																		
12-May-95	312	7.7	226	4880	3550	8	6	280	80	20.0	42.1	38.6	1.4	7.6	2.8	3.2	0.07	0.20	0.41
13-May-95	313																		
14-May-95	314							140											
15-May-95	315			4400	3250	16	12	267					0.0						
16-May-95	316																		
17-May-95	317							260					0.0						
18-May-95	318																		
19-May-95	319			4250	3120	14	10	270											
20-May-95	320																		
21-May-95	321							135											
22-May-95	322			4250	3090	10	6	280											
23-May-95	323																		
24-May-95	324	8.0	310	3960	2860	8	6	284	58	10.9	39.6	27.1	0.4	6.3	2.1	2.8	0.46	0.62	0.74
25-May-95	325																		
26-May-95	326			3620	2680	10	6	273											
27-May-95	327																		
28-May-95	328							135											
29-May-95	329	8.0	322	3510	2630	14	8	274		14.0									
30-May-95	330																		
31-May-95	331			3680	2620	10	8	276											
01-Jun-95	332																		
02-Jun-95	333			3740	2760	16	12	265											
03-Jun-95	334																		
04-Jun-95	335							130											
05-Jun-95	336	7.8	270	3860	2840	16	10	272		11.1			0.3	6.2	2.3	2.7	0.16	0.24	0.47
06-Jun-95	337																		
07-Jun-95	338			5030	3640	16	10	278	58										
08-Jun-95	339																		
09-Jun-95	340	7.9	260	4930	3600	12	8	282		13.7	45.8	27.1	0.4	6.6	2.7	3.0	0.19	0.27	0.77
10-Jun-95	341																		
11-Jun-95	342							140											
12-Jun-95	343			4840	3580	10	8	282											
13-Jun-95	344																		
14-Jun-95	345			4640	3440	8	4	290											
15-Jun-95	346																		
16-Jun-95	347	7.8	246	4550	3400	10	6	286	54	13.6	53.1	39.8	0.6	7.7	1.8	2.2	0.11	0.28	0.54
17-Jun-95	348																		
18-Jun-95	349							142											
19-Jun-95	350			4660	3420	10	6	288											
20-Jun-95	351																		
21-Jun-95	352			4710	3530	14	8	286						5.3					
22-Jun-95	353																		
23-Jun-95	354	8.0	224	4730	3520	12	10	281		14.7	59.8	46.4	0.3	6.1	1.9	2.3	0.32	0.45	0.56
24-Jun-95	355																		
25-Jun-95	356							140											

TABLE B1 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
26-Jun-95	357			4580	3440	16	12	272											
27-Jun-95	358																		
28-Jun-95	359	7.9	236	4670	3530	14	10	275	50	19.3	53.1	39.8	0.5	6.2	2.2	2.7	0.38	0.45	0.70
29-Jun-95	360																		
30-Jun-95	361			4810	3680	12	8	283											
01-Jul-95	362																		
02-Jul-95	363							140											
03-Jul-95	364			4850	3660	10	8	278											
04-Jul-95	365																		
05-Jul-95	366																		
06-Jul-95	367	7.8	200	4970	3730	14	8	282		13.8			0.0	6.2	1.4	1.9	0.29	0.38	0.51
07-Jul-95	368																		
08-Jul-95	369																		

TABLE B2 - REACTOR AND EFFLUENT CHARACTERISTICS (REACTOR B2; CONVENTIONAL-SBR)

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
05-Jul-94	1			1350															
06-Jul-94	2	7.9	244	1460	1140	32	12	237		21.9									
07-Jul-94	3																		
08-Jul-94	4																		
09-Jul-94	5	7.6	266	1700	1420	8	4	283											
10-Jul-94	6																		
11-Jul-94	7	8.3	254	2400	1760	14	6	280		21.8	40.9	18.2	0.2	11.4	1.4	3.9	2.59	2.86	3.65
12-Jul-94	8																		
13-Jul-94	9	8.4	284	1820	1620	28	26	204		19.8									
14-Jul-94	10																		
15-Jul-94	11	8.3	312	1820	1600	38	36	165		21.0									
16-Jul-94	12																		
17-Jul-94	13																		
18-Jul-94	14	8.4	250	1800	1500	30	28	188		21.3	38.3	20.4	0.0	12.2	2.2	3.5	2.56	2.87	3.45
19-Jul-94	15																		
20-Jul-94	16	8.3	232	1400	1080	42	28	144		22.4									
21-Jul-94	17																		
22-Jul-94	18	8.1	212	1540	1240	52	34	135		31.9									
23-Jul-94	19																		
24-Jul-94	20																		
25-Jul-94	21	8.1	196	2040	1540	20	10	261		27.4	41.6	27.8	0.0	14.0	3.8	4.3	2.04	2.25	2.68
26-Jul-94	22																		
27-Jul-94	23	7.7	194	2820	2160	22	18	250		23.1									
28-Jul-94	24																		
29-Jul-94	25	8.0	200	3300	2460	22	16	261		21.3									
30-Jul-94	26																		
31-Jul-94	27							130											
01-Aug-94	28	7.5	172	2880	2200	18	16	256		20.8									
02-Aug-94	29																		
03-Aug-94	30	7.7	170	3120	2360	10	8	280		21.7	27.0	13.1	0.0	14.0	2.0	2.4	2.15	2.56	2.65
04-Aug-94	31																		
05-Aug-94	32	7.4	154	2300	1820	8	4	287		21.8									
06-Aug-94	33																		
07-Aug-94	34							140											
08-Aug-94	35	7.5	176	3720	2700	5	2	296		20.5									
09-Aug-94	36																		
10-Aug-94	37	7.5	200	3300	2500	10	6	286		20.3	27.8	10.1	0.5	13.9	1.7	3.4	1.88	2.21	2.29
11-Aug-94	38																		
12-Aug-94	39	7.5	204	4090	3121	5	2	296		20.9									
13-Aug-94	40																		
14-Aug-94	41							150											
15-Aug-94	42	7.5	228	3960	2920	6	2	296	134	19.8									
16-Aug-94	43																		
17-Aug-94	44	7.2	192	3660	2680	14	8	282		18.8	22.4	5.1	0.3	8.8	0.3	0.4	0.36	0.67	0.75
18-Aug-94	45																		
19-Aug-94	46	7.5	176	4460	3540	8	4	293	104	18.3									
20-Aug-94	47																		
21-Aug-94	48							145											
22-Aug-94	49	7.6	176	3960	3060	6	2	296		19.5									
23-Aug-94	50																		

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
24-Aug-94	51	7.7	160	4360	3360	28	20	264		19.5									
25-Aug-94	52																		
26-Aug-94	53	7.6	174	4400	3180	8	2	296	104	19.5	37.5	16.7	0.4	10.6	0.5	0.5	0.17	0.19	0.44
27-Aug-94	54																		
28-Aug-94	55							295											
29-Aug-94	56																		
30-Aug-94	57	7.6	170	4220	3100	10	4	292		19.4									
31-Aug-94	58																		
01-Sep-94	59	7.5	160	4380	3240	6	3	294	148	18.1	30.5	16.7	0.0	15.2	1.6	2.1	0.18	0.28	0.62
02-Sep-94	60																		
03-Sep-94	61							290											
04-Sep-94	62																		
05-Sep-94	63	7.4	150	4120	2760	11	2	296		22.2									
06-Sep-94	64																		
07-Sep-94	65	7.4	196	4270	3120	8	3	294	130	22.5			0.5	13.7	1.9	2.8	1.76	2.28	2.37
08-Sep-94	66																		
09-Sep-94	67	7.7	238	4020	2960	11	8	284		21.6									
10-Sep-94	68																		
11-Sep-94	69							140											
12-Sep-94	70	7.7	176	4040	2900	16	11	278		21.9									
13-Sep-94	71																		
14-Sep-94	72	7.8	210	3740	2700	11	7	285	96	17.4			0.0	15.9	1.0	1.3	2.89	3.06	3.22
15-Sep-94	73																		
16-Sep-94	74							135											
17-Sep-94	75	7.8	252	3340	2480	9	7	301		17.7			0.0	13.8	0.7	1.6	3.45	3.62	3.69
18-Sep-94	76																		
19-Sep-94	77			3560	2680	20	14	269											
20-Sep-94	78	7.8	274	3240	2240	19	10	274											
21-Sep-94	79																		
22-Sep-94	80			3150	2346	24	12	278											
23-Sep-94	81	7.6	192	3160	2340	29	20	256	42	21.5			0.0	14.5	1.0	2.7	1.85	2.22	2.76
24-Sep-94	82																		
25-Sep-94	83							130											
26-Sep-94	84			3620	2500	35	20	254											
27-Sep-94	85	7.7	188	3600	2500	50	34	227		24.7									
28-Sep-94	86																		
29-Sep-94	87			3260	2260	31	20	246											
30-Sep-94	88	7.4	160	3340	2420	37	31	232	33	25.5			0.2	14.6	2.0	3.7	1.89	2.40	3.88
01-Oct-94	89																		
02-Oct-94	90							120											
03-Oct-94	91			3750	2720	38	25	245											
04-Oct-94	92																		
05-Oct-94	93							135											
06-Oct-94	94	7.3	164	4080	2980	28	18	264	32	25.8			0.2	12.7	2.1	3.7	0.99	1.44	2.35
07-Oct-94	95																		
08-Oct-94	96			4130	2890	39	27	244											
09-Oct-94	97																		
10-Oct-94	98	8.2	262	4040	2720	43	31	229									3.42	3.94	4.62
11-Oct-94	99																		
12-Oct-94	100	8.0	238	4050	2730	51	28	239	26	21.4			0.0	17.7	2.9	3.8	3.35	3.96	4.56
13-Oct-94	101																		

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
14-Oct-94	102	8.1	236	4070	2840	49	36	224		24.9									
15-Oct-94	103																		
16-Oct-94	104							110											
17-Oct-94	105	7.8	192	4020	2940	43	28	248		26.1									
18-Oct-94	106	7.9	188	4010	2830	40	27	243	31	24.2			0.0	14.0	1.9	3.7	2.61	2.83	3.35
19-Oct-94	107																		
20-Oct-94	108							120											
21-Oct-94	109	8.1	294	4820	3380	35	21	263		25.1									
22-Oct-94	110																		
23-Oct-94	111							130											
24-Oct-94	112	8.2	344	4420	3340	45	36	239		22.7									
25-Oct-94	113																		
26-Oct-94	114							160											
27-Oct-94	115	7.9	274	4860	3440	37	22	270	29	18.5			0.3	16.6	1.8	3.6	2.68	2.77	3.06
28-Oct-94	116			4650	3420	37	22	277											
29-Oct-94	117																		
30-Oct-94	118							100											
31-Oct-94	119	7.7	224	4550	3310	32	22	265		22.5			0.3	16.3	2.0	4.2	1.07	1.58	2.48
01-Nov-94	120																		
02-Nov-94	121	7.7	208	4410	3280	30	20	270		25.3									
03-Nov-94	122																		
04-Nov-94	123	7.7	220	4450	3060	20	11	285	36	24.4									
05-Nov-94	124																		
06-Nov-94	125							140											
07-Nov-94	126	7.9	208	5500	3940	25	20	270	33	24.2			0.0	18.2	2.3	3.0	1.62	1.81	2.00
08-Nov-94	127																		
09-Nov-94	128	7.8	180	5060	3460	13	6	299		18.0									
10-Nov-94	129																		
11-Nov-94	130	8.0	204	4780	3420	15	13	284		16.6									
12-Nov-94	131																		
13-Nov-94	132							140											
14-Nov-94	133	7.8	192	5580	3980	15	12	291	38	18.3			0.1	19.7	2.0	3.0	1.67	1.92	2.05
15-Nov-94	134																		
16-Nov-94	135	7.7	246	4730	3340	5	3	296		16.8									
17-Nov-94	136																		
18-Nov-94	137			4230	3090	13	8	290											
19-Nov-94	138							150											
20-Nov-94	139																		
21-Nov-94	140	7.9	272	4390	3280	18	11	281	41	16.3	40.0	20.0	0.1	16.5	1.9	2.4	2.68	3.10	3.38
22-Nov-94	141																		
23-Nov-94	142	8.1	268	4460	3050	23	16	275		18.2									
24-Nov-94	143																		
25-Nov-94	144	8.1	284	4190	2830	20	15	273		17.1									
26-Nov-94	145																		
27-Nov-94	146							135											
28-Nov-94	147	7.4	236	4430	3090	18	11	276	43	17.3	44.0	34.3	0.1	18.9	1.4	1.8	1.58	1.90	2.82
29-Nov-94	148																		
30-Nov-94	149	7.9	236	4470	3200	14	8	293											
01-Dec-94	150																		
02-Dec-94	151	7.8	226	4960	3430	8	7	288		18.0									
03-Dec-94	152																		

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
04-Dec-94	153							145											
05-Dec-94	154	7.7	202	5530	3780	12	8	288	44	13.7	51.8	38.0	0.0	17.8	1.6	1.8	2.51	2.64	2.91
06-Dec-94	155																		
07-Dec-94	156			4750	3360	11	6	290		15.2									
08-Dec-94	157									14.6							2.38		
09-Dec-94	158	7.8	194	5870	3948	13	12	284		15.6							2.23		
10-Dec-94	159																		
11-Dec-94	160							150											
12-Dec-94	161	7.7	184	6520	4320	5	4	291	45	14.7	40.2	35.5	0.0	18.5	2.9	3.5	2.19	2.38	2.45
13-Dec-94	162																		
14-Dec-94	163			6630	4320	8	5	294		15.2									
15-Dec-94	164			6370	4240												2.37	2.55	
16-Dec-94	165	7.7	154	6140	4060	5	2	293		14.6									
17-Dec-94	166							150											
18-Dec-94	167																		
19-Dec-94	168	7.0	142	6410	4370	9	8	289	53	15.6	44.6	38.3	0.5	17.8	3.2	4.0	3.69	3.90	4.08
20-Dec-94	169																		
21-Dec-94	170			6490	4350	5	4	295		15.7							1.12	1.28	
22-Dec-94	171																		
23-Dec-94	172	7.7	144	6090	4070	7	5	298		16.2									
24-Dec-94	173							145											
25-Dec-94	174																		
26-Dec-94	175	7.7	164	5780	3830	7	4	305		16.7	43.5	39.9	0.6	18.9	2.9	3.4	4.14	4.26	4.46
27-Dec-94	176																		
28-Dec-94	177	7.5	120	5880	3860	7	6	305	44	12.7							6.04	6.37	
29-Dec-94	178									15.5							2.44		
30-Dec-94	179	7.5	128	5850	3950	11	8	284											
31-Dec-94	180																		
01-Jan-95	181							140											
02-Jan-95	182			5710	3930	14	7	282											
03-Jan-95	183																		
04-Jan-95	184	7.8	142	5590	3970	14	8	288	45	15.6	41.2	39.1	0.2	19.5	1.8	2.7	3.79	3.91	4.16
05-Jan-95	185																		
06-Jan-95	186	7.6	116	5530	3980	31	27	255		15.5	51.8	38.0							
07-Jan-95	187																		
08-Jan-95	188							130											
09-Jan-95	189	7.6	122	4700	3500	14	10	336		15.5									
10-Jan-95	190																		
11-Jan-95	191	7.6	126	5140	3890	18	15	284	49	15.3	46.4	40.2	0.2	18.4	1.9	3.0	2.15	2.34	2.51
12-Jan-95	192																		
13-Jan-95	193	7.4	170	6070	4410	5	4	302		15.7									
14-Jan-95	194																		
15-Jan-95	195							150											
16-Jan-95	196	7.3	116	5780	4180	11	8	285		15.0				19.3			1.01		
17-Jan-95	197																		
18-Jan-95	198	7.5	104	5790	4000	14	9	282	43	14.7	42.6	37.0	0.2	21.6	1.5	2.1	2.05	2.24	2.37
19-Jan-95	199																		
20-Jan-95	200			6230	4490	12	8	282											
21-Jan-95	201																		
22-Jan-95	202							140											
23-Jan-95	203	7.6	94	6510	4740	15	8	282		16.4									

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
24-Jan-95	204																		
25-Jan-95	205	7.5	100	6270	4600	14	8	300	48	15.9	42.6	37.0	0.0	21.7	2.7	3.0	2.77	2.96	3.21
26-Jan-95	206																		
27-Jan-95	207			6440	4880	17	12	284		15.0							2.41		
28-Jan-95	208																		
29-Jan-95	209							142											
30-Jan-95	210	7.4	108	6480	4920	12	8	287		14.9							0.61		
31-Jan-95	211																		
01-Feb-95	212	7.4	116	6180	4570	10	6	294	50	13.9	42.6	37.0	0.0	17.5	2.1	2.4	3.62	3.79	3.95
02-Feb-95	213																		
03-Feb-95	214	7.3	104	7270	5320	14	12	278		15.1							4.62		
04-Feb-95	215																		
05-Feb-95	216							139											
06-Feb-95	217			7840	5660	14	10	282		15.1							3.52		
07-Feb-95	218																		
08-Feb-95	219	7.6	104	7580	5600	15	12	286	54	17.0	55.9	53.7	0.4	18.5	3.6	4.6	4.07	4.21	4.75
09-Feb-95	220																		
10-Feb-95	221	7.2	118	6780	5020	50	37	247		16.3							2.14		
11-Feb-95	222																		
12-Feb-95	223							124											
13-Feb-95	224	7.4	120	7790	5520	86	62	218		15.6							2.49		
14-Feb-95	225																		
15-Feb-95	226	7.6	90	7650	5480	80	60	214	63	15.9	180.6	42.6	0.6	18.3	4.2	6.3	2.72	2.80	3.60
16-Feb-95	227																		
17-Feb-95	228	7.4	120	7570	5440	122	88	176		16.3							1.79		
18-Feb-95	229																		
19-Feb-95	230							88											
20-Feb-95	231	7.3	96	7470	5300	104	66	203		17.5							1.02		
21-Feb-95	232																		
22-Feb-95	233	7.4	102	7750	5540	70	51	230	63	17.9	172.8	59.3	0.0	19.7	3.2	5.6	0.15	0.22	2.45
23-Feb-95	234																		
24-Feb-95	235	7.6	108	7840	5630	78	62	215		16.1							3.08		
25-Feb-95	236																		
26-Feb-95	237							108											
27-Feb-95	238	7.2	104	7820	5610	110	82	183		16.0							1.21		
28-Feb-95	239																		
01-Mar-95	240			7880	5630	194	134	110	75										
02-Mar-95	241																		
03-Mar-95	242	7.1	84	7710	5580	177	125	120		15.3	256.4	53.7	0.5	19.5	3.4	15.5	1.58	1.64	6.03
04-Mar-95	243																		
05-Mar-95	244							60											
06-Mar-95	245	7.0	70	7280	5210	150	108	138		14.4							0.67		
07-Mar-95	246																		
08-Mar-95	247	7.2	86	6710	4710	278	188	-27	66	15.6	377.9	37.0	0.3	18.8	4.7	20.0	1.40	1.68	9.02
09-Mar-95	248																		
10-Mar-95	249	7.0	90	6840	4830	180	124	95		16.1							0.41		
11-Mar-95	250																		
12-Mar-95	251							45											
13-Mar-95	252	7.1	86	7310	4990	198	148	61		16.5							2.46		
14-Mar-95	253																		
15-Mar-95	254	7.3	110	7820	5270	18	10	263	58	14.4	42.6	37.0	0.4	8.3	3.7	5.4	2.75	3.15	3.90

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
16-Mar-95	255																		
17-Mar-95	256			7520	5020	14	8	289		15.1							1.73		
18-Mar-95	257																		
19-Mar-95	258							145											
20-Mar-95	259	7.4	122	6750	4690	12	8	300		13.5				12.7					
21-Mar-95	260																2.83		
22-Mar-95	261	7.4	178	6960	4860	10	6	285	56	15.6	42.1	34.8	0.4	8.1	4.5	4.8	2.73	2.90	3.42
23-Mar-95	262																		
24-Mar-95	263	7.4	224	6410	4490	12	8	290		16.6									
25-Mar-95	264																0.74		
26-Mar-95	265							145											
27-Mar-95	266	7.6	188	6510	4390	10	8	295		15.4	44.6	33.3	0.2	5.0	5.0	5.7	1.16	1.39	2.57
28-Mar-95	267																		
29-Mar-95	268	7.7	206	6520	4320	10	6	285	55	14.0									
30-Mar-95	269																2.12		
31-Mar-95	270	7.7	228	6820	4480	12	10	275		13.2	42.8	29.6	0.1	6.0	5.3	6.0	2.74	2.86	3.18
01-Apr-95	271																		
02-Apr-95	272							135											
03-Apr-95	273	7.3	212	6940	4540	26	20	273		17.1	52.9	38.9	0.0	5.6	2.0	6.5	1.19	1.25	2.10
04-Apr-95	274																		
05-Apr-95	275			6580	4260	20	12	282	55	16.9									
06-Apr-95	276																0.36		
07-Apr-95	277							275											
08-Apr-95	278																		
09-Apr-95	279							140											
10-Apr-95	280	7.5	180	6880	4520	14	8	295		15.7									
11-Apr-95	281																0.55		
12-Apr-95	282	7.5	198	7120	4810	12	6	299	60	17.5	39.6	33.3	0.4	6.4	5.2	5.6	0.59	0.68	2.15
13-Apr-95	283																		
14-Apr-95	284			7390	4950	38	26	258											
15-Apr-95	285																		
16-Apr-95	286							125											
17-Apr-95	287			7710	5090	98	57	205		17.3									
18-Apr-95	288																0.88		
19-Apr-95	289	7.7	176	7680	5060	200	130	95	80	17.6	297.1	39.6	0.0	6.6	4.7	12.6	1.69	1.72	5.94
20-Apr-95	290																		
21-Apr-95	291			7620	5020	250	172	30		17.4									
22-Apr-95	292																0.64		
23-Apr-95	293							No WAS											
24-Apr-95	294	7.4	210	7700	5180	220	154	64		18.8									
25-Apr-95	295																0.23		
26-Apr-95	296							No WAS											
27-Apr-95	297	7.8	220	7480	5050	266	184	9	92	15.7	269.3	34.6	0.1	5.0	2.8	14.1	0.48	0.57	7.24
28-Apr-95	298																		
29-Apr-95	299							60											
30-Apr-95	300																		
01-May-95	301	7.7	212	6530	4550	146	100	128		19.9									
02-May-95	302																0.20		
03-May-95	303	7.7	200	6230	4340	177	122	74	91	19.7	190.9	49.6	0.0	6.5	5.7	13.0	0.77	1.08	5.33
04-May-95	304																		
05-May-95	305			6110	4260	137	93	128											

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
06-May-95	306																		
07-May-95	307							65											
08-May-95	308			6000	4360	192	136	48											
09-May-95	309																		
10-May-95	310	7.7	206	6040	4410	170	125	74		21.0									
11-May-95	311																1.86		
12-May-95	312	7.6	204	5470	4120	166	124	60	99	19.5	206.4	39.6	0.3	7.2	2.5	9.6	2.03	2.28	5.49
13-May-95	313																		
14-May-95	314							25											
15-May-95	315			5250	3830	132	95	102											
16-May-95	316																		
17-May-95	317							70											
18-May-95	318																		
19-May-95	319			4710	3440	115	88	95											
20-May-95	320																		
21-May-95	321							42											
22-May-95	322			4980	3730	88	66	158											
23-May-95	323																		
24-May-95	324	8.0	296	5560	4110	48	35	232	70	12.1	65.4	27.1	0.3	5.1	1.9	3.7	1.92	2.24	2.77
25-May-95	325																		
26-May-95	326			5170	3870	28	18	263											
27-May-95	327																		
28-May-95	328							130											
29-May-95	329	8.0	292	5140	3920	36	26	256		13.2									
30-May-95	330																		
31-May-95	331			5220	3960	56	42	220											
01-Jun-95	332																		
02-Jun-95	333			5720	4286	86	54	200											
03-Jun-95	334																		
04-Jun-95	335							100											
05-Jun-95	336	7.9	256	6150	4670	177	130	76		12.3									
06-Jun-95	337																		
07-Jun-95	338			7160	5180	190	135	92	92				0.2	5.9	2.4	9.7	1.02	1.34	4.82
08-Jun-95	339																		
09-Jun-95	340	7.9	228	6860	4960	52	36	245		12.0	88.8	33.3	0.4	5.6	2.7	6.7	0.84	1.08	2.84
10-Jun-95	341																		
11-Jun-95	342							125											
12-Jun-95	343			6550	4500	64	48	252											
13-Jun-95	344																		
14-Jun-95	345			6680	4570	36	22	262											
15-Jun-95	346																		
16-Jun-95	347	7.7	232	6460	4720	24	14	294	87	14.9	66.4	39.8	0.3	6.1	2.6	3.1	0.46	0.61	1.11
17-Jun-95	348																		
18-Jun-95	349							145											
19-Jun-95	350			6450	4620	86	63	200											
20-Jun-95	351																		
21-Jun-95	352			6520	4740	114	94	140											
22-Jun-95	353													4.1					
23-Jun-95	354	7.8	208	6480	4680	155	110	112		11.4	236.7	39.8	0.4	5.4	3.7	8.2	1.98	2.04	5.07
24-Jun-95	355																		
25-Jun-95	356							55											

TABLE B2 - Continued .....

Date	Day	pH	Alkalinity (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	Eff. SS (mg/L)	Eff. VSS (mg/L)	WAS (mL)	SVI (mL/g)	SOC (mg/L)	COD-Tot. (mg/L)	COD-Sol. (mg/L)	NH4-N (mg/L)	NOx-N (mg/L)	TKN-Sol. (mg/L)	TKN-Tot. (mg/L)	Ortho-P (mg/L)	P-Sol. (mg/L)	P-Tot. (mg/L)
26-Jun-95	357			6360	4660	170	124	88											
27-Jun-95	358																		
28-Jun-95	359	7.8	216	6240	4780	242	196	No WAS	96	15.7	386.2	46.4	2.5	4.3	4.0	17.9	1.07	1.13	7.66
29-Jun-95	360																		
30-Jun-95	361			5980	4540	254	188	No WAS											
01-Jul-95	362																		

APPENDIX C

Page

Table C1 (a) - Profiles of Ortho-P, SOC & NOx-N in Reactor B1
During 8 h Operational Cycle (High VFA Conditions)..... 318

Table C1 (b) - Profiles of Ortho-P, SOC & NOx-N in Reactor B2
During 8 h Operational Cycle (High VFA Conditions)..... 318

Table C2 - Profiles of Ortho-P & SOC in BNR-SBRs
During 8 h Operational Cycle (Low VFA Conditions)..... 319

Table C3 (a) - Profiles of Ortho-P, SOC & NOx-N in Reactor B1
During 6 h Operational Cycle (Stage 2; Continuous Aeration)..... 320

Table C3 (b) - Profiles of Ortho-P, SOC & NOx-N in Reactor B2
During 6 h Operational Cycle (Stage 2; Continuous Aeration)..... 320

Table C4 (a) - Profiles of Ortho-P, SOC & NOx-N in Reactor B1
During 6 h Operational Cycle (Stage 3; Intermittent Aeration)..... 321

Table C4 (b) - Profiles of Ortho-P, SOC & NOx-N in Reactor B2
During 6 h Operational Cycle (Stage 3; Intermittent Aeration)..... 322

Table C5 - Profiles of SOC & NOx-N in Reactor B1
During 6 h Operational Cycle (Step 4; Step Feeding)..... 323

Table C6 - Profiles of P-Release in BNR-SBRs
During Initial Anoxic/Anaerobic Portion of 8 h Operational Cycle..... 324

Table C7 - VFA and Acetic Acid Uptake in Reactor B1
During Initial Anoxic/Anaerobic Portion of 8 h Operational Cycle..... 324

Table C8 - Change in ORP of the BNR Reactors
During 6 h Operational Cycle (Stage 3; Intermittent Aeration)..... 325

Table C9 - Sludge Settleability in BNR Reactors..... 326

TABLE C1 (a) - PROFILES OF ORTHO-P, SOC & NOx-N IN REACTOR B1 DURING 8 h OPERATIONAL CYCLE (HIGH VFA CONDITIONS *)

Time (min)	Ortho-P (mg/L)				SOC (mg/L)				NOx-N (mg/L)			
	Run 1	Run 2	Run 3	Mean	Run 1	Run 2	Run 3	Mean	Run 1	Run 2	Run 3	Mean
0												
20	6.54	5.15	5.95	5.88	43.6	44.7	52.0	46.8	0.26	0.00	0.00	0.09
80	36.06	33.84	31.20	33.70	30.3	26.8	27.6	28.2	0.22	0.00	0.00	0.07
140	37.68	35.52	34.50	35.90	28.3	23.5	26.7	26.1	0.00	0.00	0.00	0.00
200	14.82	17.32	18.00	16.71	22.9	22.3	23.2	22.8	1.24	8.14	6.00	5.13
260	1.80	10.24	11.10	7.71	21.6	18.9	20.7	20.4	12.02	12.78	12.57	12.46
320	0.04	3.21	4.07	2.44	21.4	19.5	20.5	20.5	13.22	13.92	14.00	13.71
380	0.04	0.28	0.00	0.11	18.9	19.8	20.0	19.5	14.02	13.83	14.29	14.05
440	0.20	0.17	0.00	0.12	19.7	18.2	18.0	18.6	13.90	13.39	13.86	13.72
460	0.20	0.17	0.00	0.12	20.0	18.6	20.5	19.7	10.82	8.66	13.72	11.07
480												

TABLE C1 (b) - PROFILES OF ORTHO-P, SOC & NOx-N IN REACTOR B2 (CONVENTIONAL-SBR) DURING 8 h OPERATIONAL CYCLE (HIGH VFA CONDITIONS)

Time (min)	Ortho-P (mg/L)				SOC (mg/L)				NOx-N (mg/L)			
	Run 1	Run 2	Run 3	Mean	Run 1	Run 2	Run 3	Mean	Run 1	Run 2	Run 3	Mean
0												
20	7.77	4.43	4.89	5.70	35.8	31.4	39.8	35.7	0.17	0.00	0.00	0.06
80	17.82	14.40	14.76	15.66	32.6	28.2	39.0	33.2	0.09	0.00	0.00	0.03
140	22.62	19.50	19.92	20.68	29.4	25.7	30.8	28.6	0.00	0.00	0.00	0.00
200	5.32	7.41	9.08	7.27	21.2	19.1	27.2	22.5	1.75	9.10	4.72	5.19
260	0.20	2.04	4.39	2.21	21.4	18.5	24.2	21.4	9.29	14.30	15.58	13.06
320	0.09	0.26	1.45	0.60	18.6	18.8	21.5	19.6	11.43	14.35	16.43	14.07
380	0.05	0.24	0.24	0.18	18.8	19.1	22.3	20.1	11.17	14.09	17.00	14.09
440	0.38	0.17	0.53	0.36	19.8	17.5	23.0	20.1	10.83	13.04	16.29	13.39
460	0.36	0.17	0.18	0.24	18.8	19.5	18.1	18.8	8.78	10.59	15.15	11.51
480												

* Mean SOC (Raw wastewater) = 58 mg/L, Mean VFA (Raw wastewater) = 15.5 mg/L
Mean SOC (Fermented wastewater) = 72.5 mg/L, Mean VFA (Fermented wastewater) = 55.5 mg/L

TABLE C2 - PROFILES OF ORTHO-P & SOC IN BNR-SBRs DURING 8 h OPERATIONAL CYCLE (LOW VFA CONDITIONS *)

	Reactor B1						Reactor B2					
Time	Ortho-P (mg/L)			SOC (mg/L)			Ortho-P (mg/L)			SOC (mg/L)		
(min)	Run 1	Run 2	Mean	Run 1	Run 2	Mean	Run 1	Run 2	Mean	Run 1	Run 2	Mean
0												
20	3.57	3.62	3.60	45.6	43.2	44.4	2.95	3.24	3.10	34.4	29.6	32.0
80	19.86	22.85	21.36	38.5	28.7	33.6	4.50	6.77	5.64	26.6	26.1	26.3
140	22.23	24.48	23.36	31.4	27.1	29.3	7.51	11.98	9.75	26.6	25.9	26.2
200	11.38	9.38	10.38	23.6	24.6	24.1	4.12	4.98	4.55	24.7	21.6	23.1
260	6.20	0.42	3.31	22.5	23.8	23.1	2.98	2.86	2.92	20.9	22.1	21.5
320	3.33	0.31	1.82	22.6	22.7	22.6	2.39	2.01	2.20	20.9	23.1	22.0
380	1.12	0.00	0.56	20.8	18.8	19.8	2.09	1.73	1.91	22.6	22.4	22.5
440	0.64	0.00	0.32	21.3	21.7	21.5	2.19	1.83	2.01	20.7	20.4	20.5
460	0.61	0	0.31	21.9	22.1	22.0	2.15	1.88	2.02	21.7	20.3	21.0
480												

* Mean SOC (Raw wastewater) = 40 mg/L, Mean VFA (Raw wastewater) = 2.90 mg/L

Mean SOC (Fermented wastewater) = 59.2 mg/L, Mean VFA (Fermented wastewater) = 48.2 mg/L

TABLE C3 (a) - PROFILES OF ORTHO-P, SOC & NOx-N IN REACTOR B1 DURING 6 h OPERATIONAL CYCLE (STAGE 2; CONTINUOUS AERATION)

Time	Ortho-P (mg/L)				SOC (mg/L)				NOx-N (mg/L)			
(min)	Run1	Run 2	Run 3	Mean	Run1	Run 2	Run 3	Mean	Run1	Run 2	Run 3	Mean
0												
20	4.39	4.39	5.17	4.65	39.9	36.6	41.6	39.4	0.00	1.67	0.41	0.69
45	17.84	18.15	17.99	17.99	28.1	23.6	31.0	27.6	0.00	0.00	0.00	0.00
105	6.03	7.45	6.78	6.75	21.8	19.0	24.2	21.7	8.32	3.21	5.15	5.56
165	2.52	3.04	0.49	2.02	19.5	19.3	19.2	19.3	14.32	9.55	11.69	11.85
225	0.24	0.18	0.00	0.14	18.7	18.4	18.4	18.5	15.86	12.55	12.80	13.74
265	0.10	0.00	0.00	0.03	18.2	18.7	18.3	18.4	16.55	12.83	13.08	14.15
340	0.07	0.00	0.00	0.02	17.9	19.9	17.9	18.6	16.25	12.90	12.80	13.98
360												

TABLE C3 (b) - PROFILES OF ORTHO-P, SOC & NOx-N IN REACTOR B2 DURING 6 h OPERATIONAL CYCLE (STAGE 2; CONTINUOUS AERATION)

Time	Ortho-P (mg/L)				SOC (mg/L)				NOx-N (mg/L)			
(min)	Run1	Run 2	Run 3	Mean	Run1	Run 2	Run 3	Mean	Run1	Run 2	Run 3	Mean
0												
20	4.06	5.58	4.31	4.65	24.9	22.3	27.3	24.8	1.33	3.00	2.59	2.31
45	4.76	5.62	4.47	4.95	21.1	21.1	26.5	22.9	0.00	0.31	1.49	0.60
105	2.71	3.57	2.77	3.02	17.7	20.6	24.9	21.0	8.44	8.16	7.05	7.88
165	2.10	3.05	1.79	2.31	17.7	20.2	20.2	19.4	15.82	13.53	13.50	14.28
225	2.10	2.86	1.36	2.11	17.5	21.4	20.1	19.6	16.25	14.36	16.12	15.58
265	2.10	2.84	1.32	2.09	17.5	19.9	19.2	18.8	17.01	14.85	16.34	16.07
340	2.10	2.93	1.33	2.12	17.4	18.7	21.3	19.1	16.50	14.36	14.29	15.05
360												

TABLE C4 (a) - PROFILES OF ORTHO-P, SOC & NOx-N IN REACTOR B1 DURING 6 h OPERATIONAL CYCLE (STAGE 3; INTERMITTENT AERATION)

Time	Ortho-P (mg/L)						SOC (mg/L)						NOx-N (mg/L)					
(min)	Run 1	Run 2	Run 3	Run 4	Run 5	Mean	Run 1	Run 2	Run 3	Run 4	Run 5	Mean	Run 1	Run 2	Run 3	Run 4	Run 5	Mean
0																		
20	6.52	7.86	5.82	7.32	4.52	6.41	38.7	56.2	28.0	43.6	29.5	39.2	0.00	0.00	0.00	0.00	0.00	0.00
45	22.62	27.89	18.78	24.51	19.15	22.59	27.7	36.7	20.9	25.8	20.2	26.3	0.00	0.00	0.00	0.00	0.00	0.00
60	16.82	21.39	12.57	19.56	12.84	16.64							1.54	0.92	1.86	1.23	1.48	1.41
75	13.56	14.87	8.00	14.04	9.47	11.99	19.1	28.0	15.4	18.4	15.3	19.2	2.94	2.15	5.67	2.34	3.94	3.41
90	9.45	11.24	5.29	12.65	6.70	9.07							6.05	4.76	9.22	4.81	8.37	6.64
105	6.92	7.67	3.42	9.68	4.25	6.39	18.5	23.6	13.6	17.1	14.1	17.4	9.74	7.48	14.55	7.95	12.75	10.49
120	5.30	5.17	2.68	6.98	3.13	4.65							7.93	5.60	12.88	6.07	11.42	8.78
135	4.83	3.56	1.94	5.14	2.29	3.55	17.1	22.4	13.6	16.7	13.5	16.7	6.44	4.43	11.16	4.53	9.76	7.26
150	3.44	2.12	1.23	3.29	1.52	2.32							5.10	3.04	9.07	3.12	8.29	5.72
165	2.12	1.56	0.90	2.83	1.07	1.70	16.7	21.3	14.3	15.4	14.6	16.5	3.76	1.95	7.32	2.16	6.73	4.38
180	0.95	1.17	0.65	2.24	0.72	1.15							2.59	1.00	5.86	1.34	5.38	3.23
195	0.78	2.14	0.58	2.22	0.66	1.28	17.3	22.1	13.9	16.7	14.7	17.0	1.58	0.00	4.52	0.72	3.93	2.15
210	0.53	3.93	0.45	3.18	0.58	1.73	17.9	22.2	14.2	16.3	14.8	17.1	0.36	0.00	3.38	0.00	2.54	1.26
225																		
240	0.46	0.22	0.32	0.33	0.46	0.36	17.5	21.2	13.8	15.3	14.5	16.4	5.37	6.61	7.45	5.96	6.53	6.38
255																		
270	0.15	0.12	0.19	0.13	0.37	0.19	17.2	21.3	13.0	14.7	14.2	16.1	7.86	8.38	7.91	8.58	7.64	8.07
285																		
300																		
315																		
330																		
340	0.15	0.07	0.19	0.11	0.32	0.17	18.0	21.0	13.7	13.6	14.7	16.2	7.10	7.64	6.62	7.73	6.10	7.04
360																		
MLVSS (mg/L)	3079	3274	3463	3230	3385	3286												

TABLE C4 (b) - PROFILES OF ORTHO-P, SOC & NOx-N IN REACTOR B2 DURING 6 h OPERATIONAL CYCLE (STAGE 3; INTERMITTENT AERATION)

Time	Ortho-P (mg/L)					SOC (mg/L)					NOx-N (mg/L)				
(min)	Run 1	Run 2	Run 3	Run 4	Mean	Run 1	Run 2	Run 3	Run 4	Mean	Run 1	Run 2	Run 3	Run 4	Mean
0															
20	9.65	8.81	5.32	6.64	7.61	27.5	34.9	20.0	21.2	20.7	0.00	0.00	0.00	0.00	0.00
45	14.83	16.93	9.30	9.89	12.74	23.3	29.8	18.3	18.6	18.0	0.00	0.00	0.00	0.00	0.00
60											2.15	1.67	2.90	2.42	2.29
75	9.97	8.30	6.94	7.85	8.27	19.1	24.0	17.9	16.3	15.4	5.26	4.15	6.62	5.68	5.43
90											9.86	7.15	11.17	10.32	9.63
105	7.13	4.06	4.55	5.21	5.24	15.8	20.0	14.0	13.1	12.6	12.49	12.00	14.76	13.87	13.28
120											10.12	9.23	13.66	13.04	11.51
135	6.36	3.12	3.73	5.07	4.57	15.2	19.5	14.1	13.4	12.4	8.15	6.92	11.79	11.53	9.60
150											5.47	3.69	9.10	10.10	7.09
165	5.84	2.51	3.28	4.48	4.03	16.8	18.2	15.6	14.5	13.0	4.08	0.92	7.66	7.85	5.13
180	5.17	4.10	2.87	4.10	4.06						3.33	0.00	5.79	5.66	3.70
195	4.71	6.37	2.51	3.79	4.35						2.45	0.00	5.17	4.52	3.04
210	4.39	8.60	2.33	3.10	4.61	18.5	21.0	16.4	15.3	14.2	1.96	0.00	4.14	2.93	2.26
225															
240	2.69	3.39	1.12	2.44	2.41						6.65	8.07	5.79	5.32	6.46
255															
270	1.84	2.30	0.85	2.12	1.78	17.5	19.8	14.6	12.7	12.9	7.12	8.77	6.00	5.82	6.93
285															
300															
315															
330															
340	1.69	2.03	0.84	1.98	1.64	17.6	20.3	14.0	11.4	12.7	6.60	7.15	5.59	5.40	6.19
360															
MLVSS (mg/L)	4728	4058	4844	4430	4515										

TABLE C5 - PROFILES OF SOC & NOx-N IN REACTOR B1 DURING 6 h OPERATIONAL CYCLE (STAGE 4; STEP FEEDING)

Time	SOC (mg/L)			NOx-N (mg/L)		
(min)	Run 1	Run 2	Mean	Run 1	Run 2	Mean
0						
20	41.7	24.0	32.9	0.00	0.00	0.00
45	35.6	22.3	29.0	0.00	0.00	0.00
60				1.60	0.80	1.20
75	24.4	15.6	20.0	4.06	3.00	3.53
90				7.00	5.27	6.14
105	20.0	13.3	16.6	9.03	7.53	8.28
120				8.35	6.65	7.50
135	19.1	13.8	16.4	7.45	5.15	6.30
150				6.54	4.65	5.60
165	20.4	14.2	17.3	5.87	4.00	4.94
180				7.56	5.98	6.77
195	20.2	13.5	16.9	7.45	7.41	7.43
210	22.8	15.2	19.0	6.21	5.53	5.87
225	21.8	14.1	18.0	5.64	4.77	5.21
240	20.3	13.5	16.9	5.00	4.27	4.64
255	18.7			6.43	6.03	6.23
270	17.7	13.1	15.4	6.55	6.32	6.44
285						
300						
315						
330						
340	16.9	12.2	14.5	6.31	6.24	6.28
360						

TABLE C6 - PROFILES OF P-RELEASE IN BNR-SBRs DURING INITIAL ANOXIC/ANAEROBIC PORTION OF 8 h OPERATIONAL CYCLE

	Reactor B1 (PAF-SBR)					Reactor B2 (Conventional-SBR)				
Time (min)	Run 1 15-Dec-95	Run 2 19-Dec-95	Run 3 21-Dec-95	Run 4 26-Dec-95	Run 5 29-Dec-95	Run 1 15-Dec-95	Run 2 19-Dec-95	Run 3 21-Dec-95	Run 4 26-Dec-95	Run 5 29-Dec-95
0										
20	4.2	5.0	7.0	4.8	5.1	4.9	5.6	4.8	5.0	5.1
35	11.7	15.8	19.9	16.3	16.2					
50	24.0	28.6	31.9	27.1	25.6	5.2	6.5	7.7	5.8	5.3
65	30.6	31.9	36.8	28.7	25.5					
80	31.1	33.5	38.2	30.3	28.0	6.9	7.8	10.8	7.1	6.0
95	33.2	35.0	40.0	31.2	28.7					
110	33.2	35.6	41.8	31.5	29.5	8.6	10.4	14.5	9.0	6.8
125	35.1	36.8	41.8	32.1	29.5					
140	37.9	37.5	42.0	32.1	30.3	10.5	12.5	17.5	11.0	7.8

TABLE C7 - VFA & ACETIC ACID UPTAKE IN U1 DURING INITIAL ANOXIC/ANAEROBIC PORTION OF 8 h OPERATIONAL CYCLE

Time	VFA (mg/L)					Acetic Acid (mg/L)				
(min)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5
0										
20	27.6	27.0	26.2	29.4	33.2	22.0	22.9	20.5	23.9	26.5
25		17.9	19.5		24.3		15.5	14.8		20.5
30	8.2	9.9	15.2	15.7	15.7	6.9	8.1	12.1	13.2	14.1
35		3.6	4.5		10.5		2.6	3.0		9.5
40	1.8	1.6	1.8	5.9	6.8	1.0	0.9	0.9	5.3	5.8
45	0.8	0.6	0.6	1.4	2.1	0.0	0.0	0.0	0.7	1.1
50	0.7	0.5	0.6	0.6	0.9	0.0	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE C8 - CHANGE IN ORP OF THE BNR REACTORS DURING 6 h OPERATIONAL CYCLE (STAGE 3; NTERMITTENT AERATION)

Time (min)	REACTOR B1 Run1 (mV)	Run 2 (mV)	Run 3 (mV)	Run 4 (mV)	Mean (mV)	REACTOR B2 Run 1 (mV)	Run 2 (mV)	Run 3 (mV)	Run 4 (mV)	Mean (mV)
0										
5										
10										
15										
20	-186	-178	-182	-205	-188	-138	-168	-146	-121	-143
25	-174	-148	-159	-201	-171	-112	-130	-114	-101	-114
30	-164	-154	-149	-181	-162	-110	-112	-115	-100	-109
35	-162	-150	-149	-172	-158	-110	-113	-116	-99	-110
40	-162	-150	-151	-170	-158	-112	-114	-118	-98	-111
45	-162	-152	-151	-173	-160	-116	-116	-119	-107	-115
50	-132	-119	-128	-116	-124	58	41	-82	-54	-9
55	-120	-100	-110	-105	-109	38	6	-44	-25	-6
60	-110	-88	-95	-88	-95	48	36	35	14	33
65	-104	-78	-89	-82	-88	53	65	50	27	49
70	-99	-73	-86	-77	-84	58	77	58	38	58
75	-95	-67	-79	-72	-78	65	82	67	48	66
80	-88	-62	-75	-67	-73	73	89	70	60	73
85	-84	-54	-70	-62	-68	78	94	77	69	80
90	-78	-46	-66	-57	-62	83	100	82	72	84
95	-73	-42	-61	-53	-57	88	103	84	75	88
100	-66	-36	-56	-48	-52	93	110	90	78	93
105	-60	-35	-53	-43	-48	96	112	93	83	96
110	-54	-33	-49	-40	-44	102	114	98	86	100
115	-56	-38	-53	-52	-50	105	102	80	64	88
120	-60	-53	-66	-71	-63	109	44	45	32	58
125	-73	-68	-77	-79	-74	110	19	26	17	43
130	-81	-76	-85	-85	-82	110	6	12	5	33
135	-87	-82	-91	-89	-87	111	-4	0	-4	26
140	-92	-87	-96	-93	-92	109	-14	-12	-13	18
145	-96	-89	-99	-96	-95	109	-20	-20	-20	12
150	-98	-95	-102	-98	-98	107	-29	-26	-24	7
155	-101	-98	-105	-101	-101	105	-35	-33	-28	2
160	-103	-101	-107	-102	-103	103	-38	-37	-33	-1
165	-105	-103	-108	-104	-105	101	-46	-42	-38	-6
170	-105	-105	-108	-105	-106	99	-48	-46	-41	-9
175	-107	-106	-108	-105	-107	98	-53	-51	-43	-12
180	-107	-107	-108	-105	-107	96	-57	-55	-47	-16
185	-106	-108	-107	-105	-107	94	-59	-57	-48	-18
190	-83	-65	-107	-105	-106	96	42	-60	-50	-55
195	-63	-48	-108	-105	-107	97	62	-62	-52	-57
200	-44	-29	-107	-105	-106	98	79	-65	-57	-61
205	-31	-20	-107	-105	-106	98	83	-66	-64	-65
210	-20	-12	-107	-106	-107	100	88	-69	-73	-71
215	-15	-4	-107	-106	-107	106	92	-72	-78	-75
220	-7	-1	-64	-55	-60	111	94	18	5	12
225	-2	5	-48	-32	-40	112	97	50	43	47
230	0	9	-36	-24	-30	114	100	77	56	67
235	1	14	-25	-17	-21	119	107	85	66	76
240	3	17	-14	-12	-13	126	110	95	76	86
245	5	19	-10	-6	-8	129	117	101	82	92
250	7	21	-4	-2	-3	131	125	105	86	96
255	9	23	7	2	5	133	134	110	90	100
260	10	25	13	8	11	135	136	115	94	105
265	12	27	17	15	16	135	150	117	102	110
270			20	19	20			123	105	114
275	14	29	24	22	23	140	166	125	109	117
280			27	24	26			127	112	120
290			30	25	28			139	115	127
300			32	28	30			142	120	131
310			35	31	33			144	127	136
320			37	33	35			148	136	142
330			40	36	38			152	144	148
340			41	38	40			153	150	152
350			43	40	42			154	155	155
360			45	41	43			155	159	157

TABLE C9 - SLUDGE SETTLEABILITY IN BNR REACTORS

	REACTOR B1							REACTOR B2						
	Settling Time (min)							Settling Time (min)						
	0	5	10	15	20	25	30	0	5	10	15	20	25	30
Date	Settled Sludge Volume at the End of Each Time Interval (mL)							Settled Sludge Volume at the End of Each Time Interval (mL)						
15-Aug-94	100	24	20	19	18	17	17	100	93	85	77	70	63	58
19-Aug-94	100	25	22	20	19	18	18	100	91	78	66	59	51	46
26-Aug-94	100	28	22	19	17	16	16	100	93	81	71	58	51	46
01-Sep-94	100	28	20	17	16	16	15	100	90	68	57	49	40	34
07-Sep-94	100	23	18	16	16	15	14	100	70	58	48	41	37	32
14-Sep-94	100	19	17	15	14	14	14	100	38	27	22	21	21	20
23-Sep-94	100	17	13	12	12	12	12	100	23	17	15	14	13	13
30-Sep-94	100	20	16	14	13	13	13	100	16	13	12	11	11	11
06-Oct-94	100	27	20	19	18	12	12	100	22	17	15	14	13	13
12-Oct-94	100	20	15	14	14	12	12	100	15	12	11	10	10	10
18-Oct-94	100	15	13	12	12	12	12	100	15	13	12	12	12	12
27-Oct-94	100	15	12	11	11	10	10	100	19	16	15	14	14	14
04-Nov-94	100	15	13	12	12	11	11	100	24	20	17	16	16	16
07-Nov-94	100	15	13	12	12	12	12	100	26	21	19	18	18	18
14-Nov-94	100	15	13	13	13	12	12	100	32	26	23	22	21	21
21-Nov-94	100	12	11	11	11	11	10	100	24	20	19	18	18	18
28-Nov-94	100	12	12	12	11	11	11	100	27	22	21	20	20	19
05-Dec-94	100	12	11	11	11	10	10	100	38	30	26	25	24	24
12-Dec-94	100	20	17	16	15	15	15	100	60	43	37	33	30	29
19-Dec-94	100	15	14	13	13	13	13	100	82	59	48	42	38	34
28-Dec-94	100	20	17	17	16	16	16	100	46	35	31	28	27	26
04-Jan-95	100	19	16	15	15	14	14	100	43	33	29	27	26	25
11-Jan-95	100	23	18	17	16	16	15	100	43	34	30	27	26	25
18-Jan-95	100	34	26	23	22	22	21	100	45	34	29	27	26	25
25-Jan-95	100	31	20	19	19	18	18	100	59	43	38	34	31	30
01-Feb-95	100	21	18	17	17	16	16	100	69	51	41	36	33	31
08-Feb-95	100	24	20	19	18	18	18	100	90	73	59	50	45	41
15-Feb-95	100	21	18	13	12	11	11	100	93	82	70	62	54	48
22-Feb-95	100	31	24	23	22	22	21	100	91	81	72	63	55	49
01-Mar-95	100	47	35	30	29	29	28	100	95	88	80	73	66	58
08-Mar-95	100	58	41	35	32	30	30	100	88	73	62	53	48	44
15-Mar-95	100	36	29	27	27	26	26	100	89	78	66	57	48	46
22-Mar-95	100	35	27	24	23	23	22	100	83	65	55	48	43	39
29-Mar-95	100	38	27	24	23	22	22	100	82	63	49	42	38	36
05-Apr-95	100	35	26	24	23	22	22	100	81	62	50	42	39	36
12-Apr-95	100	38	29	24	22	21	21	100	88	73	60	52	46	43
19-Apr-95	100	48	37	33	29	27	26	100	95	88	83	75	68	62
27-Apr-95	100	90	73	60	51	45	40	100	96	90	84	78	74	69
03-May-95	100	89	65	56	50	44	40	100	95	85	77	69	62	57
12-May-95	100	88	71	59	50	44	39	100	91	80	70	63	59	54
24-May-95	100	42	32	27	25	24	23	100	78	58	49	44	41	39
07-Jun-95	100	59	43	37	33	30	29	100	95	90	83	76	71	66
16-Jun-95	100	89	74	63	52	45	38	100	94	84	75	69	62	56
28-Jun-95	100	40	28	25	24	23	23	100	95	88	85	74	66	60