

**INVESTIGATION OF THE EFFECTS OF SEQUENTIAL ANAEROBIC, ANOXIC
AND AEROBIC ZONES ON DISSOLVED OXYGEN TRANSFER
PARAMETERS IN A BIOLOGICAL NUTRIENT REMOVAL PILOT PLANT**

by

Arthur William Nair

Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial
fulfillment of the requirements for the degree of

MASTERS OF SCIENCE

IN

ENVIRONMENTAL ENGINEERING

APPROVED:

Clifford W. Randall, Chair

Nancy G. Love

John C. Little

December 1, 1998
Blacksburg, Virginia

Keywords: Alpha, $K_L a$, dissolved oxygen transport, biological nutrient removal

INVESTIGATION OF THE EFFECTS OF SEQUENTIAL ANAEROBIC, ANOXIC AND AEROBIC ZONES ON THE DISSOLVED OXYGEN TRANSFER PARAMETERS IN A BIOLOGICAL NUTRIENT REMOVAL PILOT PLANT

by

Arthur William Nair

C. W. Randall, Chairman

Environmental Engineering

(ABSTRACT)

Bench and pilot scale determinations of the volumetric oxygen transfer coefficient, K_La , were performed on an improved A^2/O biological nutrient removal (BNR) pilot plant. Effluent from a full scale primary clarifier, used as pilot plant influent, was found to have an alpha (ratio of process to clean water K_La) of 0.71 as determined in a 21 liter bench scale reactor and an alpha of 0.332 as determined in a 0.45 m^3 aeration basin of the 2.4 m^3 pilot plant. Alpha of a 1:1 mixture of primary clarifier effluent with pilot plant return activated sludge was determined to be 0.94 at bench scale and 0.71 at pilot scale. An assay of alphas through the initial non aerated treatment zones of the pilot plant using the bench scale reactor indicated that alphas peaked in the effluent of the first anaerobic zone (alpha equal to 1.01) and were lower in the second anaerobic zone and first anoxic zone. An assay of alphas in the three pilot plant series sideline aeration basins indicated that alpha was maximum in the first aeration basin (alpha equal to 0.905) and were lower in the second and third aeration basins (0.716 and 0.661 respectively). A consistent increase in average surface tension was noted from the first to second to third aeration basins, however the differences were not statistically significant. A comparison of pilot plant alphas determined in the first aeration basin following anaerobic nominal hydraulic retention times of 0.0, 0.21, 0.43, and 0.64 hours yielded alpha values of 0.71, 0.94, 0.64, and 0.74 respectively. Like the assay using the bench scale reactor, the alpha values at pilot scale peaked following treatment in only one anaerobic zone (nominal HRT of 0.21 hours). The study concludes that short exposures in an initial anaerobic reactor as required for biological phosphorus removal may benefit oxygen transfer efficiency through increased alphas, however the benefits of long periods of anaerobic reaction time (over 0.43 hours) are uncertain.

Keywords: Volumetric oxygen mass transfer coefficient, K_La , alpha, BNR, anaerobic reactor

ACKNOWLEDGMENTS

The author acknowledges his gratitude for the opportunity, guidance and assistance provided by his committee chairman, Dr. Clifford Randall. The author also expresses appreciation for the comments and suggestions offered by committee members, Dr. Nancy Love and Dr. John Little.

The pilot plant and associated mechanical and electrical equipment used in this study was previously used by the State of Connecticut, City of Norwalk and Malcolm Pirnie, Inc. for a demonstration project for the City of Norwalk, Connecticut. After completion of that study, the plant was donated to Virginia Tech by the State of Connecticut. Dr. Peter Kos, of Malcolm Pirnie, Inc. developed the improved A²O process performed by the pilot plant and consented to its use in this study. Kruger, Inc. supported the reconstruction of the pilot plant at Virginia Tech with a grant of \$5000.00.

The pilot plant was constructed on the grounds of the Blacksburg-VPI Sanitation Authority Lower Stroubles Creek Waste Water Treatment Plant. The author wishes to acknowledge the assistance and cooperation of Plant Superintendent, Michael Vaught Chief Operator, Bobby Epperly and the plant personnel.

The assembly of the pilot plant and construction of its housing structure was a team project. Builders also included fellow graduate students John Ennis and Bill Thacker.

Laboratory work and sampling was also a joint effort including John Ennis and undergraduate student Karen Stall.

The author was assisted with stipends provided by the Sussman fund.

Julie Petruska, the environmental laboratory director, provided abundant assistance, vast knowledge of laboratory procedures, and many kind words of encouragement.

Special thanks and gratitude are expressed to the author's dear friend, Suzanne Irwin, for her patient moral support and to her mother Anne Gorsline for extending to the author her legendary hospitality.

TABLE OF CONTENTS

I. Introduction	1
II. Literature Review	3
Wastewater treatment and reduced oxygen requirements.....	3
Oxygen transfer parameters in wastewater systems.....	5
Alpha.	5
Factors affecting alpha.....	5
Factors affecting beta	9
Oxygen transfer theory.....	9
Dissolved oxygen transfer parameter determinations	10
Steady state continuous testing.....	10
Non steady state continuous testing.....	12
III. Materials and Methods	14
Experimental approach.....	14
Pilot plant analytical baseline.	15
Dissolved oxygen probe response coefficient	15
Bench scale reactor clean water K_La	16
Pilot Plant reactor clean water K_La	16
Determination of K_La , OUR and alpha and comparison of steady state and non steady state techniques	17
Bench scale reactor influent alpha.	17
Bench scale reactor BNR alphas	18
Pilot plant alpha of influent without non aerated contact.	18
Pilot plant alphas under BNR conditions	18
Pilot plant surface tensions under BNR conditions.	19
Alpha and non aerated HRT	20
Experimental Equipment	21
Pilot Plant	21
Pilot plant monitoring and collection of samples	29
Analytical Procedures	31
Dissolved oxygen	31
Dissolved oxygen probe response	32
Temperature.....	34
Chemical oxygen demand	34
Total Kjeldahl nitrogen.....	35
Total and soluble ammonia	35
Soluble nitrite	35

Soluble nitrate and soluble orthophosphate	35
Total phosphorus.....	36
Mixed liquor suspended solids and total suspended solids	36
Mixed liquor and effluent volatile suspended solids.....	36
Oxygen uptake rate	36
Surface tension.....	37
Determination of oxygen transfer parameters	38
Testing of clean and non respiring water.....	38
Testing of respiring liquids.....	39
Determination of alpha	41
Statistical methods	42
IV. Results	44
Pilot plant operating conditions	44
Pilot plant analytical results	45
Clean water K_La calibrations	56
Bench scale reactor clean water calibration	56
Pilot plant clean water calibration	59
Evaluation of K_La determination method	63
Bench reactor influent alpha.....	66
Bench reactor BNR alpha.....	66
Pilot plant influent alpha	71
Pilot plant BNR alpha	72
Pilot plant surface tension, progressive aerobic treatment	72
Pilot plant alpha and anaerobic HRT	74
V. Discussion	81
Discussion of results	81
Clean water results	81
K_La determination method	81
Primary effluent results.....	83
Effects of initial anaerobic zones on alpha and surface tension.....	84
VI. Conclusions.....	87
VII. Symbols and Nomenclature	89
VIII. References	91
Appendices.....	95
Appendix A: Plant analytical data	96
Appendix B: Transfer parameter data	104
Vita.....	114

LIST OF FIGURES

Figure 1. Pilot plant schematic flow diagram.....	22
Figure 2. Flow schematic of pilot plant receiving influent directly into the first aeration basin.	25
Figure 3. Flow schematic of pilot plant configured with a nominal anaerobic HRT of 0.21 hours.	27
Figure 4. Flow schematic of pilot plant configured with a nominal anaerobic HRT of 0.43 hours.	29
Figure 5. Flow schematic of pilot plant configured with a nominal anaerobic HRT of 0.64 hours and with supplemental sodium acetate carbon source feed.	30
Figure 6. Dissolved oxygen probe response curve and regression model.	33
Figure 7. Average influent total COD and average soluble	48
Figure 8. Average total suspended solids concentration (MLSS).....	49
Figure 9. Average influent TKN and effluent TKN and free ammonia.....	50
Figure 10. Average TCOD/TP and TCOD/TKN	52
Figure 11. Average total nitrogen and total phosphorus	53
Figure 12. Average denitrification phosphorus removal efficiency and estimated phosphorus content of waste.....	54
Figure 13. Average soluble nitrate profile	55
Figure 14. Estimated total excess phosphorus removal.....	57
Figure 15. Pilot plant influent total phosphorus and soluble phosphorus.	58
Figure 16. Bench scale reactor $K_L a_f$ and temperature	60
Figure 17. Box plot of the pilot plant clean water data.	62
Figure 18. Bottle OUR versus calculated OUR determined by the non steady state step method.....	68
Figure 19. Steady state versus non steady state alpha determinations	68
Figure 20. Pilot plant alphas in aeration basins.	73
Figure 21. Top: Surface tension measured in pilot plant concurrent with alpha measurements.....	75
Figure 22. Alphas in pilot plant for Anaerobic HRTs	78

LIST OF TABLES

Table 1. Summary of basin volumes and nominal anaerobic hydraulic residence times for pilot plant configurations.....	25
Table 2. Pilot plant operating conditions.	44
Table 3. Summary of pilot plant analytical data.	46
Table 4. Summary of pilot plant clean water oxygen transfer parameters.	61
Table 5. Dual non steady state $K_L a$ analysis results and summary table..	67
Table 6. Summary of results of bench scale reactor alpha and $K_L a_{(20)}$ determinations on effluent from different pilot plant pre-aeration basins.	70
Table 7. Alpha in pilot plant aeration basin 1 measured by steady state methods.....	77
Table 8. Alpha in pilot plant aeration basin 1 measured by non steady state methods.	79

I. INTRODUCTION

The use of biological nutrient removal (BNR) systems as a waste water treatment method has been shown to require less energy input for aeration than conventional methods. The amount of energy input for aeration required by either the BNR or conventional process is dependent on both the total oxygen demand loading and the efficiency of oxygen transfer. The decrease in energy input for aeration may be gained by three sources: reduced oxygen demand loadings in the aerated zone of the process, the use of nitrate and nitrite as electron acceptors in lieu of oxygen, and by increased rates of oxygen transfer in the aerobic zone of the process. All three of these mechanisms reduce the energy input required to maintain the BNR process as compared to a conventional activated sludge process. The first two reduce the total amount of oxygen needed to maintain the process. The third source of energy savings is a result of increases to the energy efficiency by which oxygen is transferred from the atmosphere to the aerated zone of the treatment process.

Municipal wastewater typically contains organic constituents which impede the diffusion of oxygen from the atmosphere to the bulk liquid medium. The rate of transfer of oxygen from a gaseous medium to a liquid medium is described by the dual resistance model proposed by Lewis. The rate of transfer can be quantitatively evaluated and compared through the computation of the bulk liquid side diffusion rate coefficient (K_La). The value of K_La in the subject medium relative to K_La determined for clean water in the same reactor under the same conditions is described by the term alpha (α).

It has been reported that alpha ranges from 0.1 to 0.7 averaging 0.4 for fine pore aeration systems in municipal wastewater (Joint Task Force 1992). The value of alpha following treatment depends on the degree of treatment undergone.

The BNR process requires the use of non aerated unit processes prior to aerated unit processes. Within these anaerobic and anoxic unit processes, organic constituents of the waste water are sorbed and metabolized. Although other organics are released, overall, the concentration of organic constituents in the liquid medium are progressively reduced through a series of non aerated unit processes prior to aeration.

The object of this thesis is to determine if oxygen transfer in a single activated sludge BNR process can be expected to be more efficient than in a conventional activated sludge process due to more favorable intrinsic dissolved oxygen transfer characteristics. In support of this thesis, the following objectives were established:

1. Construct and maintain a pilot scale BNR wastewater treatment plant.
2. Measure and document treatment parameters to establish pilot plant function, degree of treatment and nutrient removal.
3. Investigate the methods used to measure K_La values and determine which method produces the most consistent and accurate results.
4. Measure and document alpha in pilot plant aeration basins and in the influent to the pilot plant.
5. Compare measured values of alpha to those determined and recommended by other researchers for conventional treatment and design.
6. Measure and document surface tension throughout the treatment process to quantify changes in surfactant concentration.

II. Literature Review

Wastewater treatment and reduced oxygen requirements

The presence of surfactants and other wastewater constituents which affect alpha may be related to the degree of treatment of the waste. Several researchers have noted a increase in alpha directly related to aerobic treatment time.

Boyle et al. (1990) presents extensive data on the progressive increase of alpha through the length of plug flow aeration basins. In a study of fine pore aeration systems in Whittier Narrows CA, they measured alpha increases from 0.16 to 0.24 for ceramic dome aerators and from 0.25 to 0.31 for ceramic disc aerators from the first third to the last third of a plug flow aeration basin. Boyle et al. (1990) present alpha data from 10 plants using fine pore aerators operating in a plug flow mode. On average the mean alpha increased from the first third to the last third of the plug flow aeration basin. Boyle et al. (1990) also present data which document an increase of oxygen transfer efficiency with increasing mean cell residence time (SRT), an increase in transfer efficiency with nitrifying as opposed to non nitrifying conditions, and an increase in transfer efficiency with an increase in mixed liquor suspended solids. They propose that the concentration of surfactants, which are constituents in the substrate, are lowered as substrate is biologically consumed, resulting in increases in alpha.

Boyle et al. (1990) noted that metabolism of organic matter in anoxic zones in biological denitrification plants has the ability of increasing alpha in subsequent aeration. They also conjecture that a similar effect may be attributable to anaerobic zones in biological phosphorus removal plants, although the effect had not been confirmed.

In Groves et al. (1992), the authors have reviewed a data base of 21 plants in addition to and including the EPA data base of 17 plants ((Boyle et al. (1990) and other

studies). They reported an increase in alpha with increasing SRT and increase in alpha with nitrifying conditions. Groves et al. (1992) concluded that the increase in alpha and the accompanying increase in transfer efficiency and associated cost savings may in some cases offset the cost of additional oxygen demand required by nitrification. The article indicates alpha for nitrifying conditions averages 0.48 ranging from 0.24 to 0.73 and alpha for non nitrifying conditions averages 0.35 ranging from 0.24 through 0.51.

Doyle et al. (1983) evaluated the effects of various operational parameters affecting SOTE and alpha. Their data include alpha measurements with time, SOTE versus submergence, SOTE versus depth, and alpha versus treatment and dilution. They determined alpha in a pilot plant fed from a full scale plant for clarifier effluent, mixed liquor effluent and mixed liquor influent. Their data indicate changes of alpha from no change (a value of 0.53) to a significant increase (0.45 to 0.58) from aeration tank inlet to clarifier effluent. Batch tests of aeration tank influent indicated an increasing alpha with aeration time in an aerated mixed liquor basin. This indicated an increasing alpha as an effect of treatment. No treatment data were presented (or description of the treatment process) so it could not be determined from the article if the plant was nitrifying. They also indicated that α decreases with submergence. Alphas were greater than 0.9 at 2 feet depth versus approximately 0.75 at 10 feet depth.

Hwang and Stenstrom (1985) measured increases in alpha with increasing level of treatment in mixed liquor. The increasing level of treatment was assessed by a declining OUR as aerated treatment proceeded towards an endogenous phase. A decline in the mixed liquor OUR was also related to the process aeration time and an increase in surface tension.

Reith et al. (1995) operated side by side pilot plants in which they varied sludge age, volumetric organic loading, and adding anoxic and aerobic selectors. They reported that higher sludge ages, 8 days as compared to 2 days promoted nitrifying conditions and had higher alpha values under nitrifying conditions. The alpha coefficient increased to the

extent that total energy costs should be lower for the nitrifying operation. Differences in organic loading did not show an effect.

Reith et al. (1995) also reported that the addition of either an upstream anoxic or aerobic reactor improved alpha by 10%, in the case of the anoxic reactor, and 25% for the aerobic reactor. The anoxic selector had a 0.22 hour hydraulic retention time and was added to the system resulting in an overall sludge age of 10 days.

Suescun et al. (1998) operated a 175 L pilot plant featuring three anoxic-oxic steps in series with step influent feed split among the three anoxic basins. They reported that the 0.4 meter deep pilot plant had $K_L a$'s ranging from approximately 0.2 to 0.3 /min (12 to 18 /h).

Oxygen transfer parameters in wastewater systems

Alpha. Alpha is defined (ASCE 1992) as the ratio of the volumetric mass transfer coefficients of a system as evaluated in process water to the volumetric mass transfer coefficient as evaluated in clean water, both transformed to standard temperature conditions. In the notation of this study,

$$\alpha = \frac{K_L a_{f(20)}}{K_L a_{(20)}} \dots \dots \dots \text{Equation 1}$$

Factors affecting alpha. It has been shown that the type of aeration device has a marked effect on alpha. In a review of alpha factors for various devises, Bachman (1987) noted ranges of alpha as tested with tap water with low concentrations of surfactant. Alphas for low speed surface aerators ranged from 0.7 to 2.0. Alphas for coarse bubble diffusers ranged from 0.6 to 0.8. Alphas for fine bubble diffusers ranged from 0.2 to 0.9

at bench scale and 0.7 to 0.9 at pilot scale. Alphas for jet aerators ranged from 0.9 to 1.3 at pilot scale.

The addition of surfactants reduces surface tension resulting in reduced bubble diameter, increased surface area, decreased rise velocity and decreased bubble coalescence. These factors tend to increase alpha. On the other hand, the accumulation of surfactants at the liquid gas interface tends to reduce the film transfer coefficient and the surface renewal rate. The net effect in municipal wastewaters is usually a reduction in alpha EPA(1983).

The effects of surfactants on K_La are specific to the surfactant constituent. Individual surfactants may affect the oxygen transfer coefficient, K_L and specific interfacial area, "a" differently and to varying degrees. In general, addition of surfactants will have both positive and negative effects on the chemical and hydrodynamic parameters affecting oxygen transfer. The overall effect may be either beneficial or detrimental. According to Wagner (1996), the rate of oxygen transfer is influenced by K_La , K_L , interfacial area, molecular diffusion coefficient, slip velocity, bubble diameter, air content, and the oxygen saturation concentration. Some organic compounds other than surfactants have been shown to have a beneficial effect on oxygen transfer, (Ganczarczyk (1972), Gurol and Nekouinainni (1985) and Backman (1987)). Addition of phenolics, acetic acid, ethanol and other alcohols enhanced oxygen transfer in wastewater. The effect was attributed to the hindrance of coalescence (Gurol and Nekouinainni, 1985).

When alpha is plotted against surfactant concentration the curve usually shows an initial rapid decline in alpha followed by a full or partial recovery as surfactant concentrations increase (Gurol and Nekouinainni, (1965), Eckenfelder(1995), Leu (1998), and Backman (1987)). The final alpha may plateau at a value greater or less than one depending on the surfactant and experimental conditions. The initial decrease in K_La is thought to be due to the reduction of K_L and reduced surface renewal rates. The recovery is thought to be due to the beneficial effects caused by decreasing bubble size (increasing interfacial area) at higher concentrations and inhibition of bubble coalescence. In typical

municipal wastewater conditions the concentrations of surfactants are insufficient to be within the recovery portion of the curve, hence influent alphas tend to be low (below 0.5)

Gurol and Nekouinainni (1985) found significant differences between the effects of organics and a commercial surfactant (SDS). They investigated ten phenolic compounds, tetrabutyl alcohol (TBA) and acetic acid. All the phenolic compounds which had both hydrophilic and hydrophobic regions, similar to surfactants, improved $K_L a$. The most symmetrical phenolic tested, hydroquinone, had the smallest impact on $K_L a$. In general, for solutions of the phenolic compounds, alpha increased in proportion to the water octanol partition coefficient. Alphas ranged from 1 to 3.0. When TBA or acetic acid was added to water, alphas also dramatically improved to a maximum of approximately 2.5. Gurol and Nekouinainni (1985) found that the organic compounds did not affect K_L , surface tension or the size of bubble formation. Enhancement of alpha tends to increase with ionic strength. They concluded that the effective mechanism for the increase in alpha was hindrance to coalescence. Unlike the commercial surfactants, increased concentrations of the organics increased alpha without an initial suppression of K_L or alpha. Gurol and Nekouinainni (1985) conjectured that simultaneous concentrations of organics and surfactants would result in an additive effect on $K_L a$ by increasing the interfacial area by coalescence inhibition, more than offsetting the reduction of K_L caused by the surfactants.

Literature indicates that some wastewaters have greatly enhanced alphas. (Backman (1987) measured pharmaceutical waste alphas in excess of 20.0 with jet aerators.) Eckenfelder and O'Conner (1961) has a table of frequently cited alpha values. In this table the authors cite alpha values in pharmaceutical wastes ranging from 1.65 to 2.15 for raw waste and ranging from 0.73 to 0.83 for effluent. These values are notable in that they indicate an alpha much greater than 1.0 in the raw waste and a declining alpha upon treatment.

The effects of scale cannot be neglected. Under conditions with high mixing

energy densities (bench scale reactors, jet aerators, surface aerators), high surface renewal rates dominate and shearing prevents coalescence. Under these conditions, alphas tend to increase with higher concentrations of surfactants (and at lower surface tensions) since high surface renewal rates are maintained even with smaller bubble size while coalescence is prevented. At lower energy densities (full scale plants, fine pore grid aerators) increasingly small bubble size is less effective for oxygen transfer due to low surface renewal rates and increased coalescence. Thus increasing surfactants at low mixing energies tend to reduce oxygen transfer.

Bachman's (1987) research on the effects of surfactants on fine pore diffuse aerators and jet aerators points out how the effects of surfactants in the wastewater create differing responses in alpha depending on the aeration device. Jet aerators, producing high surface renewal rates, generate higher alphas than fine pore dome aerators in the same wastewater and surfactant concentrations. In both pilot plant and bench scale systems, alpha in tap water with surfactant added generally increases as more surfactant is added. Alpha values near 3.0 were obtained with fine bubble dome aerators and up to 0.5 mM of acetic acid added as a surfactant.

Newbry (1997), in a derivation of the relationship between energy intensity and specific oxygen transfer rate, derived a direct linear relationship between oxygen transfer rate and airflow in a bubble column. This derivation however neglected the effects of coalescence and turbulent complete mixing. Newbry's data however suggest that a second degree equation best describes the relationship between specific oxygen transfer rate and energy intensity (a function of the ratio of air flow rate to reactor volume).

Hwang and Stenstrom's (1985) experimental data show a linear increase in K_La with air flow rate for clean water with aerator depths from 1.5 to 4.3 m. In process water testing, Hwang and Stenstrom (1985) found a decrease in alpha with increasing air flow rate.

Hwang and Stenstrom (1985) experimentally found that K_La decreases with depth in clean water experiments and that alpha also decreases with depth in experiments with

mixed liquor. The decrease in alpha versus depth was steeper with increasing mixed liquor OUR. The surface tension of the mixed liquor was shown to decrease with higher OUR, an indication of increasing surfactant concentrations as OURs increased in waste water mixed liquor.

Coalescence is also a factor in comparing alpha from one aeration system to another. It has been proposed (EPA,1983) that increased coalescence in deeply submerged fine bubble systems explains why alphas for deeply submerged systems tend to be lower than alphas for identical but shallower systems.

Factors affecting beta. Some of the factors affecting the saturation value of oxygen include: barometric pressure, temperature, solids, organic constituents and dissolved salts. EPA(1983) contends that the equilibrated dissolved oxygen concentration cannot be reliably measured due to interference with the Winkler method. They also note that the standard dissolved oxygen probe cannot reliably measure the dissolved oxygen concentration if the activity of the solution is not known. ASCE (1995) recommends that when a Winkler determination cannot be used, beta be determined by measurement of total dissolved solids.

Oxygen transfer theory

Current models of the kinetics of gas absorption originate with the work of Lewis and Whitman (Lewis 1924). In this paper they presented the concept that a gas diffusing from a gas phase to a solute phase must pass through two quiescent films at the boundary. The rate of absorption of a solute from a gas is limited by the process of diffusion and the two films through which the solute must pass may be considered as two diffusional resistances in series. They indicated that the concentration difference across either of the boundaries is the driving force impelling the diffusion across the boundary.

According to their concept, the two films do not offer the same diffusional resistance. Because of the greater density of the liquid, the “diffusional resistance encountered in the liquid film is much greater than that in the gas”. For a gas of low solubility, such as oxygen in water, the rate of absorption is dependent upon the bulk interface area, the liquid side diffusivity constant, the driving force, and the difference between the solute concentration in the gas and the solute concentration in the bulk liquid.

In modern notation the basic mass transfer model describing the concentration of dissolved oxygen in clean water as a function of time becomes (quoted from ASCE1992):

$$C = C_{\infty}^* - (C_{\infty}^* - C_0) \exp(-K_L a t) \dots \dots \dots \text{Equation 2}$$

This model is applicable to systems wherein a gas of low solubility is bubbled into a completely mixed vessel of bulk liquid. It is the recommended model which is used for the evaluation of clean water dissolved oxygen parameters.

This model tends to underestimate $K_L a$ when used for submerged aerators (Brown and Balloild, 1982). During a non steady state test, C^* varies with time whereas the recommended model makes the assumption that C^* remains constant at the final concentration attained over infinite time. Because the model assumes a higher C^* than that actually realized, values for $K_L a$ tend to be underestimated. A correction can be made to convert the apparent $K_L a$ to the true $K_L a$. For tests performed for an aerator submergence of less than ten feet in depth however, the correction is not significant.

Dissolved oxygen transfer parameter determinations

Steady state continuous testing. Under waste water treatment process conditions aeration tanks are often operated with continuous flow through the basins.

Under steady state conditions (uniform flow, organic loading, and solids loading) the basin will achieve a dissolved oxygen balance where the transfer of oxygen by diffusion into the bulk liquid is balanced by the respiration of oxygen and the uptake of oxygen due to the difference in the dissolved oxygen content in the influent and effluent flows. The rate of oxygen transfer by diffusion is governed by $K_L a$, the driving force, and the difference between the steady state concentration and the maximum steady state dissolved oxygen concentration under test conditions.

EPA (EPA1983) notes that at steady state, the oxygen transfer rate equation becomes:

$$K_L a_f = \frac{R - \frac{Q}{V}(C_i - C_R)}{C^*_{\infty} - C_R} \dots\dots\dots \text{Equation 3}$$

In a review of oxygen transfer determination procedures, Muller and Boyle (1988) noted that for an accurate measurement C_R should be no lower than 2 mg/L and a maximum of 75% of C^*_{∞} . They cautioned that spatial variations of dissolved oxygen concentration and oxygen uptake rate may exist in the basin. They also cautioned that temporal variations may occur over the duration of the test. Variable influent wastewater during the duration of the test may also vary the $K_L a$ values both temporally and spatially while the test is being conducted.

The steady state test is also dependent on the measurement of the oxygen uptake rate (OUR), R . Under some circumstances the value for R may be either overestimated or underestimated. For this reason, Mueller and Boyle (1988) do not recommend this procedure.

Mueller and Stensel (1990) indicate that potentially severe errors may result in determining oxygen transfer coefficients by the steady state/bottle OUR techniques. Their

use of off gas techniques indicates that severe errors may occur under low dissolved oxygen/high OUR conditions, in which case bottle OUR can be expected to be well above in situ OUR. Under high dissolved oxygen and high OUR, bottle OUR values were found to be below actual OUR values. Bottle OUR compared favorably to in situ measurements under endogenous conditions. They recommend that off-gas and/or non steady -state techniques be used for testing of equipment in activated sludge systems.

Non steady state continuous testing

Under process conditions with continuous flow of respiring liquid through a completely mixed basin, the model for dissolved oxygen transfer becomes (Mueller(1988)):

$$C = C_R - (C_R - C_0)e^{-(K_La_f + Q/V)t} \dots\dots\dots \text{Equation 4}$$

Using the non steady state method, K_La_f can be determined without the direct measurement of OUR, as long as OUR remains constant throughout the test period. The test may be conducted by a step increase of the aerator airflow at time zero and recording the rise in concentration C with time.

Mueller (1986) showed that an estimate of the in situ value of R may be made by the dual step non steady state test. Mueller proposed that a determination of K_La can be made at two different air flow rates (or aerator power levels). The oxygen uptake rate can then be directly computed from the results of the two test.

$$R = \frac{C_{R2} - C_{R1} + \left(\frac{Q}{V}\right) \left(\frac{C_i - C_{R1}}{K_L a_{f1}} - \frac{C_i - C_{R2}}{K_L a_{f2}} \right)}{\frac{1}{K_L a_{f1}} - \frac{1}{K_L a_{f2}}} \dots\dots\dots \text{Equation 5}$$

And knowing R allows for the computation of the steady state maximum dissolved oxygen concentration:

$$C_{\infty f}^* = C_R + \frac{R}{K_L a_f} - \frac{C_i - C_R}{K_L a_f \left(\frac{V}{Q} \right)} \dots\dots\dots \text{Equation 6}$$

Even though this test eliminates the need to obtain instantaneous oxygen uptake rates using a bottle test, it has a major disadvantage in that the in situ oxygen uptake rate must remain constant over the duration of at least two non steady state tests, a time period of up to several hours. For a pilot plant receiving non equilibrated influent from a full scale waste water system and subject to diurnal variations in flow and strength, it may be impossible to assure steady state in situ oxygen uptake rates.

Since the calculated steady state maximum dissolved oxygen concentration is dependent on oxygen probe measurements of C_i and C_R , the step method is not suitable for the evaluation of beta as the activity of the media would still influence the dissolved oxygen probe measurements. This method may be used to determine if bottle OUR measurements are consistent with OURs determined by the step method. Knowledge of the consistency of OUR measurements may be used to infer the accuracy of steady state $K_L a$ measurements.

III. Materials and Methods

Experimental approach

An experimental approach was developed to test the validity of the thesis: *The volumetric oxygen mass transfer rate (K_La) in the aerated portions of a BNR wastewater treatment system is enhanced by treatment effects in the non aerated treatment stages.*

A pilot plant operated in a BNR mode was maintained and a series of experiments were performed to evaluate hypotheses deduced as consequential to the validity of the thesis.

The following experiments were performed:

- Development of an analytical baseline for pilot plant performance
- Determination of dissolved oxygen probe coefficient
- Determination of clean water K_La for pilot plant and bench scale reactors
- Determination of K_La in pilot plant with varying non aerated hydraulic residence times in the initial stages of treatment
- Determination of influent K_La in bench scale reactor
- Determination of K_La in bench scale reactor of effluent from non aerated pilot plant reactors
- Determination of influent K_La in pilot plant reactor
- Determination in K_La in pilot plant aeration zones
- Determination of surface tension in influent and in pilot plant aeration zones

- Determination of K_{La} , OUR and alpha by the step method and comparison of steady state and non steady state techniques

The experimental approach for each of the experiments is described below:

Pilot plant analytical baseline. A BNR pilot plant was constructed, operated and used to test the effects of an initial anaerobic zone on oxygen transfer. The plant, described in more detail below in Experimental Equipment was operated with three different hydraulic residence times in the anaerobic VFA uptake/phosphorus release phase of the treatment plant. One additional mode included the feed of a supplemental VFA carbon source. Operational data were collected to establish that the pilot plant was properly operated in an attempt to achieve biological nitrogen and phosphorus removals. Key operational parameters were tabulated to provide a baseline of operational results for the four BNR modes evaluated. Comparisons of the degree of treatment or success or failure of nutrient removal among the different operational modes was beyond the scope of this study. Baseline analytical data evaluated and presented in this study include parameter and constituent averages over the selected operational periods during which oxygen mass transfer measurements were performed.

Dissolved oxygen probe response coefficient. The accuracy of K_{La} measurements may be adversely influenced by the use of a dissolved oxygen probe with too long of a response time. The dissolved oxygen probe response coefficient was determined for the probe used in the pilot plant and bench scale reactor K_{La} determinations. A nonlinear regression was used to fit the probe response data to a first order model. The probe response coefficient was compared to values from the literature to validate or reject the appropriateness of the probe used to perform the K_{La} determinations.

Bench scale reactor clean water K_La . The clean water volumetric mass transfer coefficient for a 21 liter bench scale reactor used in this study was determined over 15 trials at one air flow rate and over a range of temperatures from approximately 10 to 20 °C. The K_La at standard conditions and theta for the reactor/aerator system were determined by evaluating the data through a non linear regression model for theta, the geometric temperature conversion coefficient. The value of K_La at standard conditions determined by the non linear regression was used as the basis of alpha determinations for measurements made in the bench scale reactor. Theta determined through the model was compared to the value 1.024, as recommended by ASCE(1995). The comparison was made by constructing 95% confidence intervals about the mean value of theta as determined by the non linear regression analysis. If the confidence interval bracketed the recommended value of 1.024, the value of 1.024 would be used for all K_La determinations made with the bench scale reactor.

Pilot Plant reactor clean water K_La . The clean water volumetric mass transfer coefficient for the pilot plant aeration basins used in this study was determined over 45 trials at three air flow rates, in three identical basins and over a range of temperatures from approximately 10 to 25 °C. Theta and a second degree expression for K_La at standard conditions as a function of airflow for the reactor/aerator system were determined by evaluating the data through non linear regression models. The values of K_La at standard conditions for each airflow determined by non linear regression was used as the basis of alpha determinations for measurements made in the pilot plant reactors. Theta determined through the model was compared to the value 1.024, as recommended by ASCE(1995). The comparison was made by constructing 95% confidence intervals about the mean value of theta as determined by the non linear regression analysis. If the confidence interval bracketed the recommended value of 1.024, the value of 1.024 would be used for all K_La determinations made with the pilot plant reactors. If the confidence interval did not

bracket 1.024, the determined value of theta would be used for all K_La determinations in the pilot plant reactors.

Determination of K_La , OUR and alpha and comparison of steady state and non steady state techniques. The mass transfer coefficient was determined using the step continuous non steady state method at two airflow rates. The average OUR was computed from the results of the two K_La determinations by the step method described by Mueller (1982), Equation 4. Bottle OURs were determined before and after each K_La determination and independent continuous steady state K_La determinations were made. A total of nine dual K_La determinations were performed. Values of OUR and alphas determined by steady state and non steady state techniques were compared.

The step K_La studies were performed to assess the validity of the steady state techniques performed in this study. According to Mueller(1982), substantial inaccuracies in alpha may result from determining K_La by the steady state technique while measuring OUR by the bottle method. Inaccuracies may be caused by inadequate mixing, limited oxygen conditions, or limited substrate conditions. Depending on the specific limiting condition, the bottle OUR may overestimate or underestimate the actual OUR.

Bench scale reactor influent alpha. The value of alpha was determined using the 21 liter bench scale reactor containing effluent from the primary clarifiers located ahead of the pilot plant. Multiple non steady state K_La determinations were made on random grab samples. Mean values for K_La and alpha were determined. These values of alpha would be compared to values of alpha for treated samples to assess the effects of treatment in the initial non aerated stages of BNR treatment.

Bench scale reactor BNR alphas. The 21 liter bench scale reactor was used to determine alpha of contents from the initial stages of the pilot plant: influent to the first anaerobic zone, effluent from the first anaerobic zone, effluent from the second anaerobic zone, and effluent from the first anoxic zone.

The thesis that treatment in the initial stages of BNR treatment results in higher alpha values than if no initial treatment is provided leads to the hypothesis that the alpha values from the effluent of the initial non aerated stages of the BNR system should exhibit progressively higher alpha values when evaluated in an aerated reactor. This hypothesis was tested by applying an ANOVA to the alpha data from the initial stages of treatment.

The means of the alphas from the influent to the anaerobic zone, the effluent from the first anaerobic zone and the effluent from the second anaerobic zone were evaluated with a single factor ANOVA to determine if the means were the same. The means were evaluated at a 95% significance level and with a null hypothesis that the differences in the means were zero.

Pilot plant alpha of influent without non aerated contact. The alpha of pilot plant influent mixed with return activated sludge in the first aeration basin was determined in order to simulate the alpha of a system without initial non aerated basins. Multiple non steady state volumetric mass transfer determinations were made. Mean values for K_La and alpha were determined.

Pilot plant aeration alphas under BNR conditions. Previous studies show that alpha tends to increase directly in relation to aeration residence time as aerobic treatment progresses in a conventional treatment process. The hypothesis that alpha increases in a BNR system directly in relation to aeration time was tested.

To test whether alphas increased in a BNR system, sequential alpha determinations were made in three aeration basins, each representing an increased level of treatment.

Multiple samples were taken from each basin and the average for each basin was compared using a single factor ANOVA. The means were evaluated to determine if there was a difference at a 95% significance level. If the ANOVA indicated that the hypothesis that the means were equal could be rejected, further comparisons between means were made. Comparisons of the means were made using Duncan's Multiple comparison test, Fishers's LSD Multiple comparison test and the Tukey-Kramer multiple comparison test.

Pilot plant surface tensions under BNR conditions. The measurement of surface tension is an indication of the concentration of surfactants in the wastewater. Previous studies indicate an increase in the surface tension as conventional aerated treatment progresses. The hypothesis that surface tension increases with treatment in the aerated portions of a BNR system was tested.

The removal of surfactants through the progressive treatment of the waste should result in an increase in surface tension of the activated sludge. Surface tension was measured on primary effluent (pilot plant influent) and on the filtered supernatant from each of the three aeration basins. Statistical analyses were conducted to determine if an increase of surface tension occurred with increasing treatment.

It was hypothesized that the measured surface tension in primary influent is less than that measured in the first, second and third aeration basins and that the measured surface tension in the first aeration basin is less than that measured in the third aeration basin.

The hypothesis was tested using a paired single tailed t-test. Paired observations of surface tension were measured in the primary effluent and the first, second and third aeration basins. A null hypothesis was established that the surface tensions of the compared samples were equal and was tested against the alternate hypothesis that the more treated sample had a lower surface tension than the less treated sample. The hypothesis was tested at a 95% significance level.

Alpha and non aerated hydraulic retention time (HRT). The central thesis of this study states that treatment in the initial non aerated stages of BNR treatment results in lower alpha values in the aerated stages. This statement implies that alpha in the aerated stages increases with increased anaerobic hydraulic retention time. This implication was tested by evaluating alpha following treatment by four distinct anaerobic detention times, including zero, and comparing them to each other and to the no anaerobic treatment case.

A single factor ANOVA was performed to determine if the differing levels of anaerobic treatment had an effect on alpha of the first aeration basin. Random alpha measurements were performed on the first aeration basin and under each of four anaerobic HRT conditions. The alternate hypothesis that the means of the alpha for all conditions were not equal was tested by single factor ANOVA against the null hypothesis that all means were equal. The decision was made at a 95% significance level. If the means were unequal, a Tukey-Kramer Multiple comparison test would be performed to evaluate the differences.

A second evaluation of the data tested whether anaerobic treatment in the initial stages of treatment increased alpha. Randomly selected first aeration basin alphas without an initial anaerobic state was compared to alphas with an anaerobic stage. A variant of the two sample Student's T test was used. The Aspin-Welch Unequal Variance Test was used to test the alternate hypothesis that the mean alpha with anaerobic treatment was greater than alpha without anaerobic treatment against the null hypothesis that the mean alphas were the same. The evaluation was made at a 95% level of significance.

Experimental Equipment

Pilot plant. A 2.4 m³ pilot scale wastewater treatment plant was constructed and operated at the site of the Blacksburg - Virginia Polytechnic Institute Sanitation Authority Wastewater Treatment Plant near Blacksburg, Virginia. The treatment process used was a modified A²/O process termed the improved A2/O by inventor Dr. Peter Kos. The plant consists of anaerobic, anoxic, aerobic and deoxygenation basins configured for removal of both phosphorus and nitrates from the influent wastewater. The basic flow diagram for the system is shown in Figure 1.

Four variations on a common flow scheme were set up and operated. All variations received municipal wastewater which had been screened and settled in a primary clarifier. The primary clarifier effluent entered the pilot plant in a stirred basin and was mixed with return activated sludge from the pilot plant clarifier. This first stage of treatment is the anaerobic (AN) stage. The anaerobic designation was nominal however since dissolved oxygen from the influent and nitrates from the clarifier return activated sludge (RAS) sometimes prevented true anaerobic conditions from occurring in the initial treatment stage. As will be described, the number of anaerobic basins following the initial anaerobic basin were varied during the execution of this study. Each anaerobic basin measured 0.30 m by 0.30 m at the surface and was 1.20 m deep and had a volume of 0.10 m³. Each anaerobic basin was mixed with a propeller mixer. Flow entered each basin at the bottom and was discharged at the top to promote thorough mixing.

From the last anaerobic basin, flow entered the first anoxic (AX 1) basin. The first anoxic basin received flow from both the last anaerobic basin and from the first internal recycle. Flow leaving the first anoxic basin was split between the first aerobic basin (OX 1) and the second anoxic basin (AX 2). Each anoxic basin measured 0.30 m by 0.30 m at the surface and was 1.2 m deep and had a volume of 0.10 m³ each.. The basins were continuously mixed with a propeller mixer.

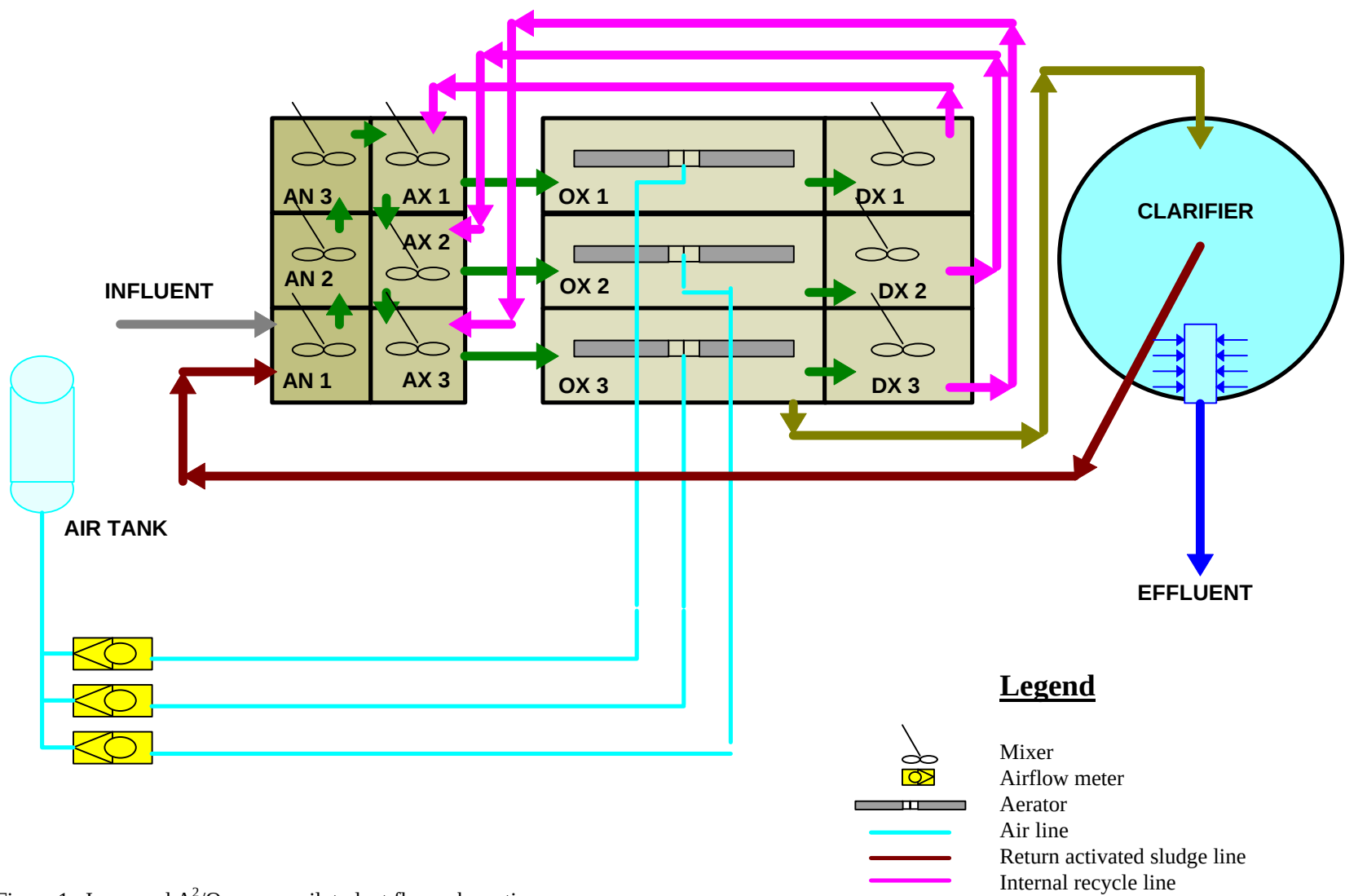


Figure 1. Improved A²/O process pilot plant flow schematic.

The first aeration basin (OX 1) received flow from the first anoxic basin and discharged into the first deoxygenation basin (DX 1). Each aeration basin was 0.31 m by 1.37 m at the surface and 1.16 m deep for a total volume of 0.45 m³. Each aeration basin was aerated and mixed with two fine pore tube diffusers. Each tube diffuser was approximately 0.46m long, with an 0.08m diameter and was covered with a perforated non ridged plastic membrane. The two diffusers were fed from a tee fitting located between them. Air was delivered to the diffusers through 0.02m galvanized piping equipped with inline flow meters. The diffusers were operated at an airflow range of between 0.57 and 1.70 m³/h (20 to 60 scfh).

The first deoxygenation basin received flow from the first aeration basin. The deoxygenation basins measured 0.31 m by 0.77 m at the surface and were 1.20 m deep for a total volume of 0.15 m³. The basins were stirred with propeller mixers. The deoxygenation basin discharged to the suction of the first internal recycle pump. The first internal recycle pump discharged to the first anoxic basin. The internal recycle pump was one half horsepower and of the centrifugal close couple constant speed type. The rate of flow in the internal recycle was controlled by a manually set ball valve and checked once per day.

The second anoxic basin (AX 2) received flow from the first anoxic basin and the second internal recycle line. The second anoxic basin discharged a split flow to the second aeration basin (OX 2) and to the third anoxic basin (AX 3). The second aeration basin discharged flow to the second deoxygenation basin which in turn discharged to the second internal recycle pump which returned flow to the second anoxic basin. The basin dimensions and volumes for the second stage anoxic, aeration and deoxygenation basins are the same as for the corresponding first stage basins.

The third anoxic basin (AX 3) received flow from the second anoxic basin and the third internal recycle line. The third anoxic basin discharged all its flow to the third aeration basin (OX 3). The third aeration basin discharged a split flow to the third deoxygenation basin and to the final clarifier. The third deoxygenation basin discharged to

the third internal recycle pump which returned flow to the third anoxic basin. The basin dimensions and volume for the third stage anoxic, aeration and deoxygenation basins are the same for the corresponding first stage basins.

The final clarifier was a cylindrical tank with a conical settling zone. The upper portion of the clarifier had a diameter of 0.76 m and a side water depth of 0.30 m. The lower conical section of the tank had a minimum diameter of 0.1 m at the apex of the cone and a depth of 0.56 m making the overall depth of the clarifier 0.86 m. The clarifier was equipped with a mechanical rotating scraper to prevent bridging of the settled sludge. The unit discharged through an effluent weir consisting of a horizontal capped three inch PVC pipe with eighteen 0.015 m holes drilled along the spring line of the pipe. The effluent was pumped back to the B-VPI WWTP. The settled sludge was pumped back to the first anaerobic basin through a progressive cavity pump.

The plant was operated in four different flow configurations. These consisted of varying the number of anaerobic basins from one to two to three, adding an external carbon source to the plant, and operating the plant with an influent feed directly into the first aeration basin. These four configurations are summarized below. They are listed in order of their nominal anaerobic HRT. The nominal HRT was calculated by dividing basin volume by the nominal plant influent flow rate (454 L/h). The actual HRT was approximately half the nominal HRT values since the return activated sludge rate was approximately equal to the influent flow rate.

The various plant configurations are summarized in Table 1. In general, the pilot plant was operated with an influent flow of approximately 454 L/h, a RAS flow of 454 L/h and internal recycle flows of 454 L/h.

Table 1. Summary of basin volumes and nominal anaerobic hydraulic residence times for pilot plant configurations.

Anaerobic HRT (h)	Anaerobic Volume (m³)	Anoxic Volume (m³)	Aerobic Volume (m³)	Deoxy- genation Volume (m³)	Total Volume (m³)
0.00	0.0	0.3	1.35	0.75	2.40
0.21	0.1	0.3	1.35	0.65	2.40
0.43	0.2	0.3	1.35	0.55	2.40
0.64	0.3	0.3	1.35	0.45	2.40

Direct aeration treatment of influent. From April 18, 1997 to June 4, 1998 the plant was temporarily (eight hours at a time) configured so that influent and RAS was discharged directly into the first aerobic basin. A schematic flow diagram for this configuration is shown in Figure 2. All anaerobic basins were eliminated. The first aerobic basin was piped to discharge to the first anoxic basin. The second deoxygenation basin was expanded to include the former first deoxygenation basin and one former anaerobic basin. The second deoxygenation basin was recycled to the first anoxic basin.

Anaerobic nominal HRT of 0.21 hours. Between December 21, 1996 and January 10, 1997, the plant was configured to include one anaerobic basin between the influent and the first anoxic basin (Figure 3). In this configuration, the anaerobic volume was 4% of the total pilot plant volume (exclusive of clarifier volume). The analytical data collected during this period were used to establish the baseline conditions for description of plant performance while oxygen transfer coefficients were determined for this plant configuration. The mean cell residence time during this period was 10 days.

Anaerobic nominal HRT of 0.43 hours. Between February 5, 1997 and April 18, 1997 the plant was configured to include two anaerobic basins between the influent and first anoxic

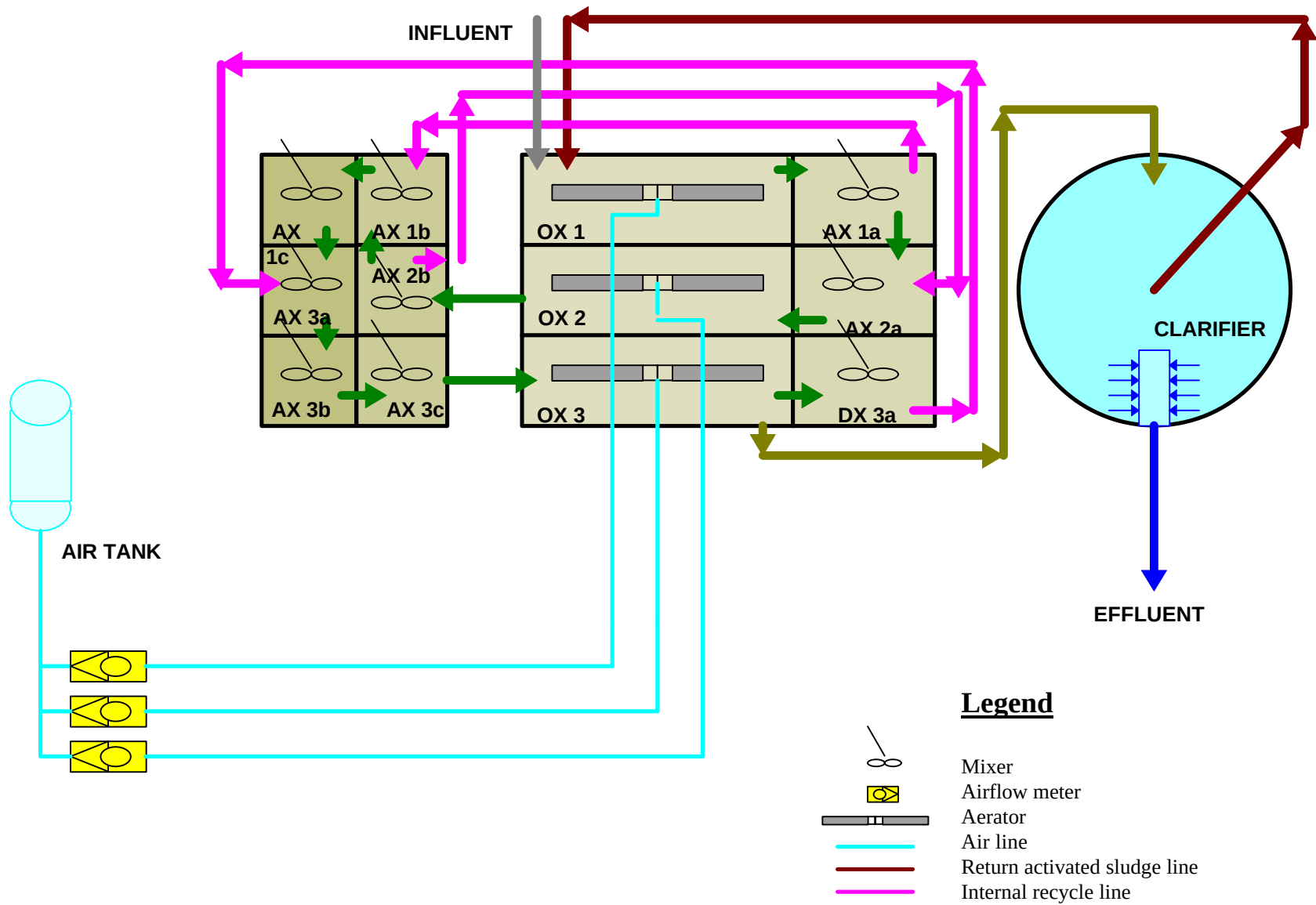


Figure 2. Flow schematic of pilot plant receiving influent directly into first aeration basin.

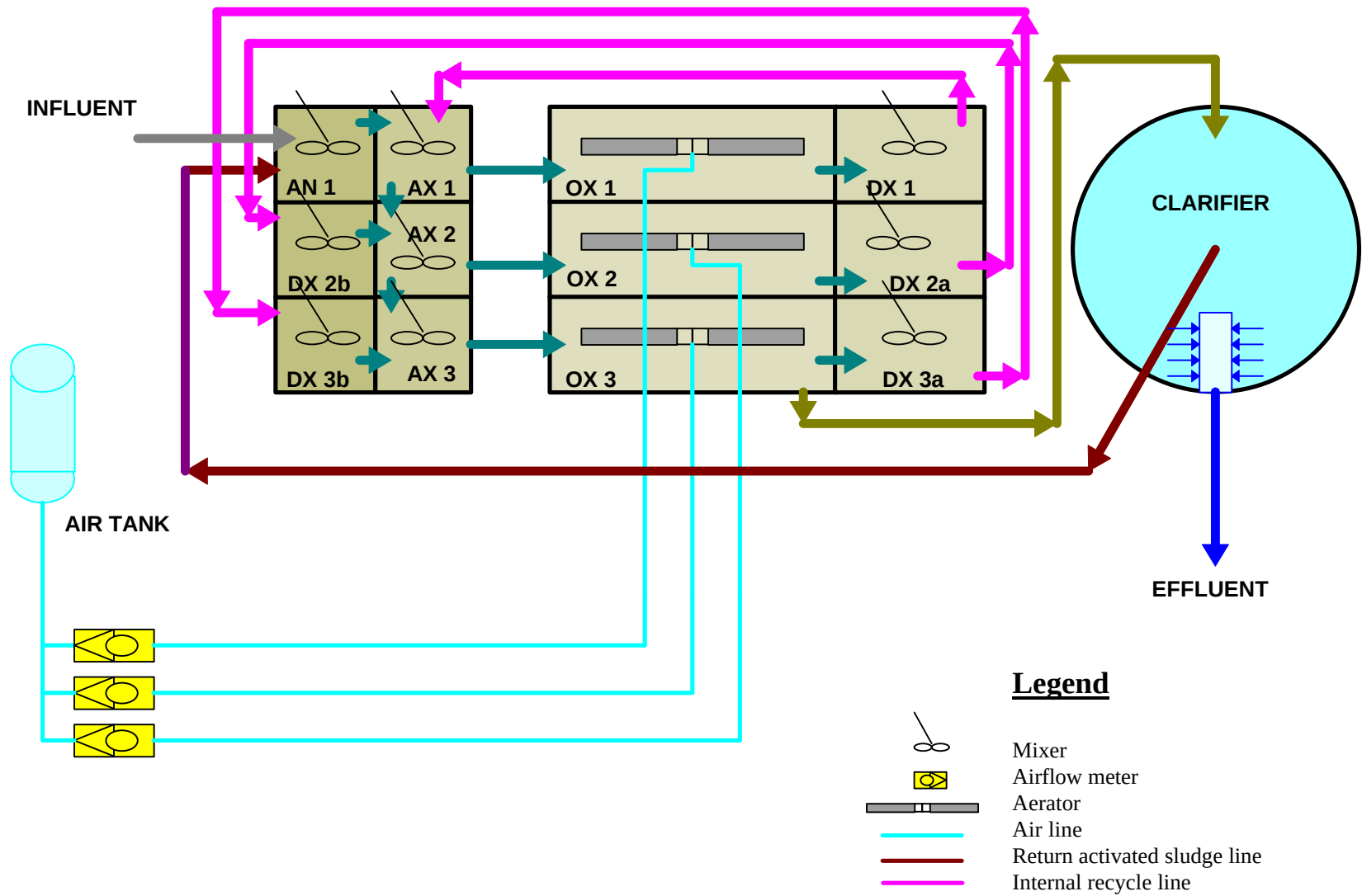


Figure 3. Flow schematic of pilot plant configured with a nominal anaerobic HRT of 0.21 hours.

basin (Figure 4). In this configuration, the anaerobic volume was 8 % of the total pilot plant volume (exclusive of clarifier volume). The analytical data collected from March 3, 1997 to April 18, 1997 were used to establish the baseline conditions for description of plant performance while oxygen transfer coefficients were determined for this plant configuration. Analytical data collected between February 5 and March 3 1997 were not used due to interruptions in the plant operation and upsets due to mechanical failures. The mean cell residence time during this period was 20 days.

Anaerobic nominal HRT of 0.64 hours. From September 10 1996 to December 9 1996 the plant was operated in a configuration having three anaerobic basins between the influent and the first anoxic basin (Figure 1). In this configuration, the anaerobic volume was 12% of the total pilot plant volume (exclusive of clarifier volume). The analytical data during this period were used to establish the baseline conditions for description of plant performance while oxygen transfer coefficients were determined for this plant configuration. The mean cell residence time during this period was 10 days.

Anaerobic nominal HRT of 0.64 hours with acetate feed. The plant basin and flow configuration was the same as the previous configuration. A peristaltic pump was installed to pump a solution of sodium acetate from a solution tank to anoxic basin 2 (Figure 5). Sodium acetate was added at a feed rate of 250 g/d from December 11 to December 19, 1996

The plant was allowed to stabilize from December 11 to December 13. Data used to evaluate the performance of the pilot plant during acetate addition were collected during the period from December 13 through December 19, 1996. The mean cell residence time during this period was also 10 days

Pilot plant monitoring and collection of samples. During the operation of the pilot plant, the plant was monitored and samples were collected on a regular basis. On a daily basis, the influent temperature, influent flow rate, and sludge settling rate for sludge

Thumbnail of figure 4

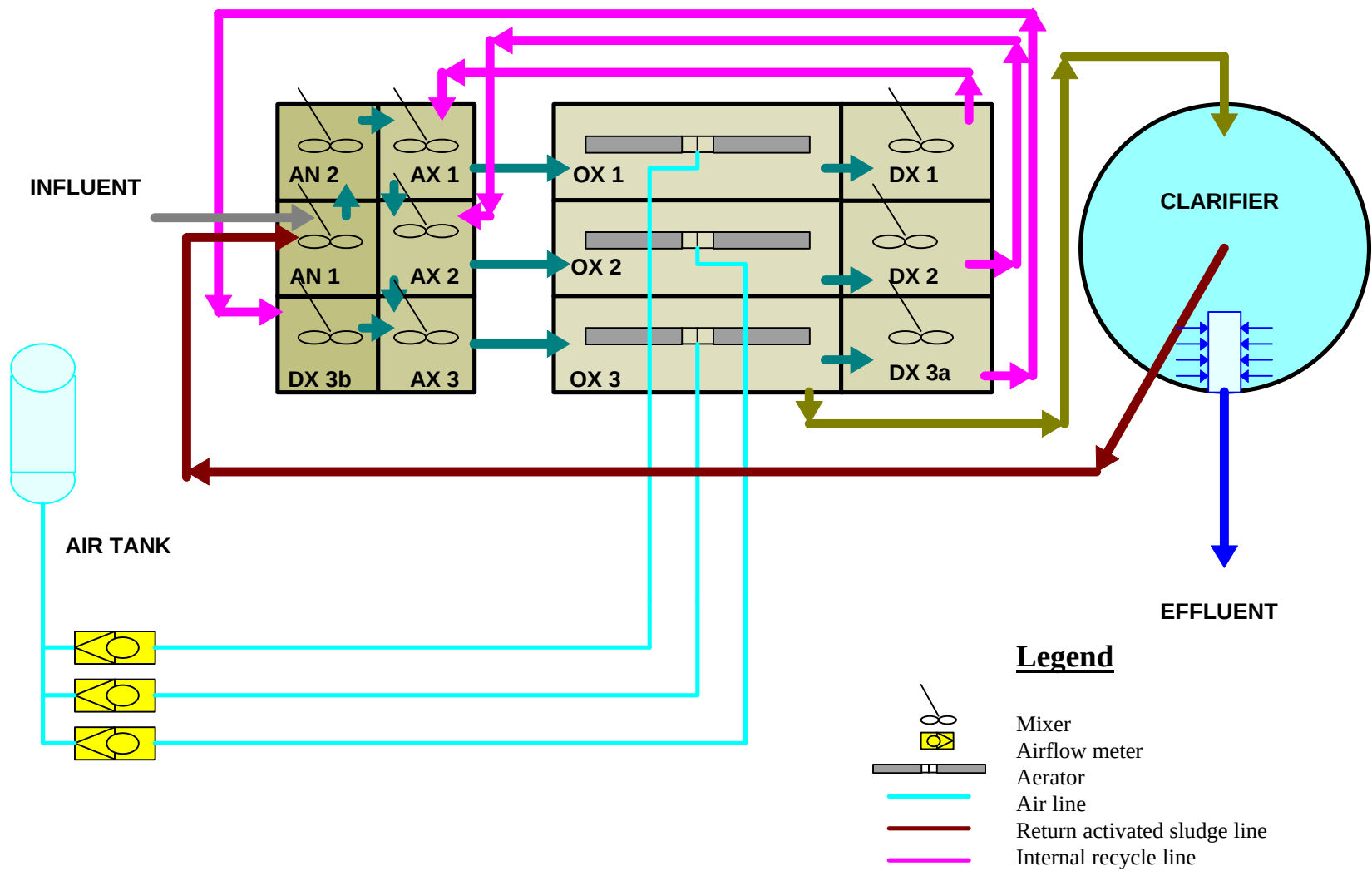


Figure 4. Flow schematic of pilot plant configured nominal with anaerobic HRT of 0.43 hours.

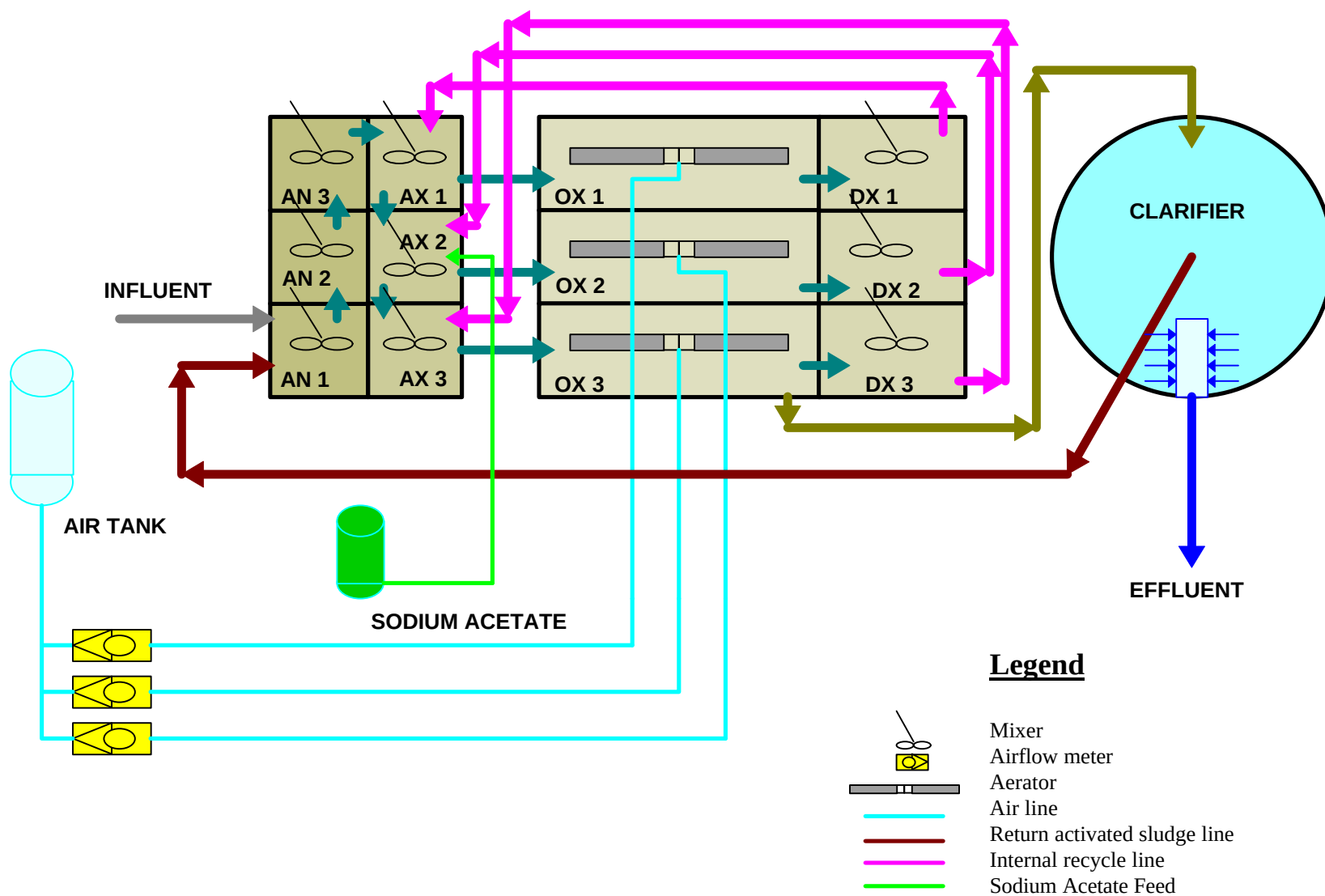


Figure 5. Flow schematic of pilot plant configured with a nominal anaerobic HRT of 0.64 hours and with supplemental sodium acetate feed.

volume index were measured. The airflow rates, RAS and internal recycle rates were checked. On a schedule of approximately three days per week, the following samples were collected: soluble chemical oxygen demand, soluble phosphorus, soluble nitrate, and soluble nitrite for the influent, first and last anaerobic basins, first and last anoxic basins, first and last aerobic basins, clarifier and effluent; total chemical oxygen demand, total phosphorus, total Kjeldahl nitrogen for the influent, and effluent; and total ammonia for the effluent; and, total suspended solids in the mixed liquor and the effluent. Samples were filtered and fixed in the field as appropriate and as described below. The prepared samples were then transported to the laboratory at Virginia Tech and stored and/or analyzed as described for the individual analysis.

Analytical Procedures

Dissolved oxygen. The concentration of dissolved oxygen was measured in accordance with Standard Method 4500-O G (AWWA 1995 p.4-102-104), membrane electrode method. Two models of dissolved oxygen meter were used. The YSI Incorporated (Yellow Springs, Ohio) Model 57 with Model 5739 probe was used in pilot plant basin and bench reactor applications. The YSI Model 51B instrument with bottle probe model 5150 was used for measurements performed in BOD bottles. Both probes were fitted with a manufacturer supplied “standard” Teflon membrane. Both instrument were calibrated in air at 100 % relative humidity prior to each time series of measurements or each single measurement. The calibration of the instrumentation was checked by a repeated air calibration following each time series of measurements for $K_L a$ determination.

The air calibration of the membrane probes was verified periodically by analysis of an aerated sample of potable water by a modification of Standard Method 4500-O C. Oxygen dissolved/azide modification (also referred to as the Winkler method). The standard method was modified by the elimination of sodium azide from the standard alkali-

iodide-azide reagent. Method 4500-O C was used for the determination of dissolved oxygen in only potable tap water. Azide was eliminated from the standard reagent since nitrites, ferrous iron and other oxidants and reductants were assumed to be in insignificant concentrations in the potable water tested.

Dissolved oxygen probe response. The dissolved oxygen meter probe response coefficient was recorded by plunging a dissolved oxygen probe into a solution stripped of dissolved oxygen. The YSI model 57 DO meter and probe were equilibrated in the head space of a BOD bottle half full with distilled water. The Probe was calibrated in accordance with Standard Method 4500 - G and manufacturers recommendations. The probe was then plunged into distilled water that had been stripped of dissolved oxygen by nitrogen gas stripping.. The response of the probe was recorded on a strip chart recorder. The probe response data were scaled manually from the strip chart recording and the data were fitted using non linear regression techniques to the following equation (from Philichi 1989):

$$\frac{(C - C_f)}{(C_0 - C_f)} = e^{-\frac{t}{\tau}} \dots\dots\dots \text{Equation 7}$$

A dissolved oxygen probe response curve was recorded for the field probe and YSI Model 52 meter used in this study. The probe was moved from saturated humid air to a solution of water stripped of oxygen. The probe response was recorded on a strip chart recorder. The probe was stabilized at an initial dissolved oxygen concentration of 8.38 mgL⁻¹ and stabilized at a final dissolved oxygen concentration of 0.28 mgL⁻¹. The response curve was fitted to Equation 7 by non linear regression.

The regression curve (Figure 6) indicated that the probe has a probe constant of 11.6 seconds. With this probe constant the responding probe and meter will stabilize to

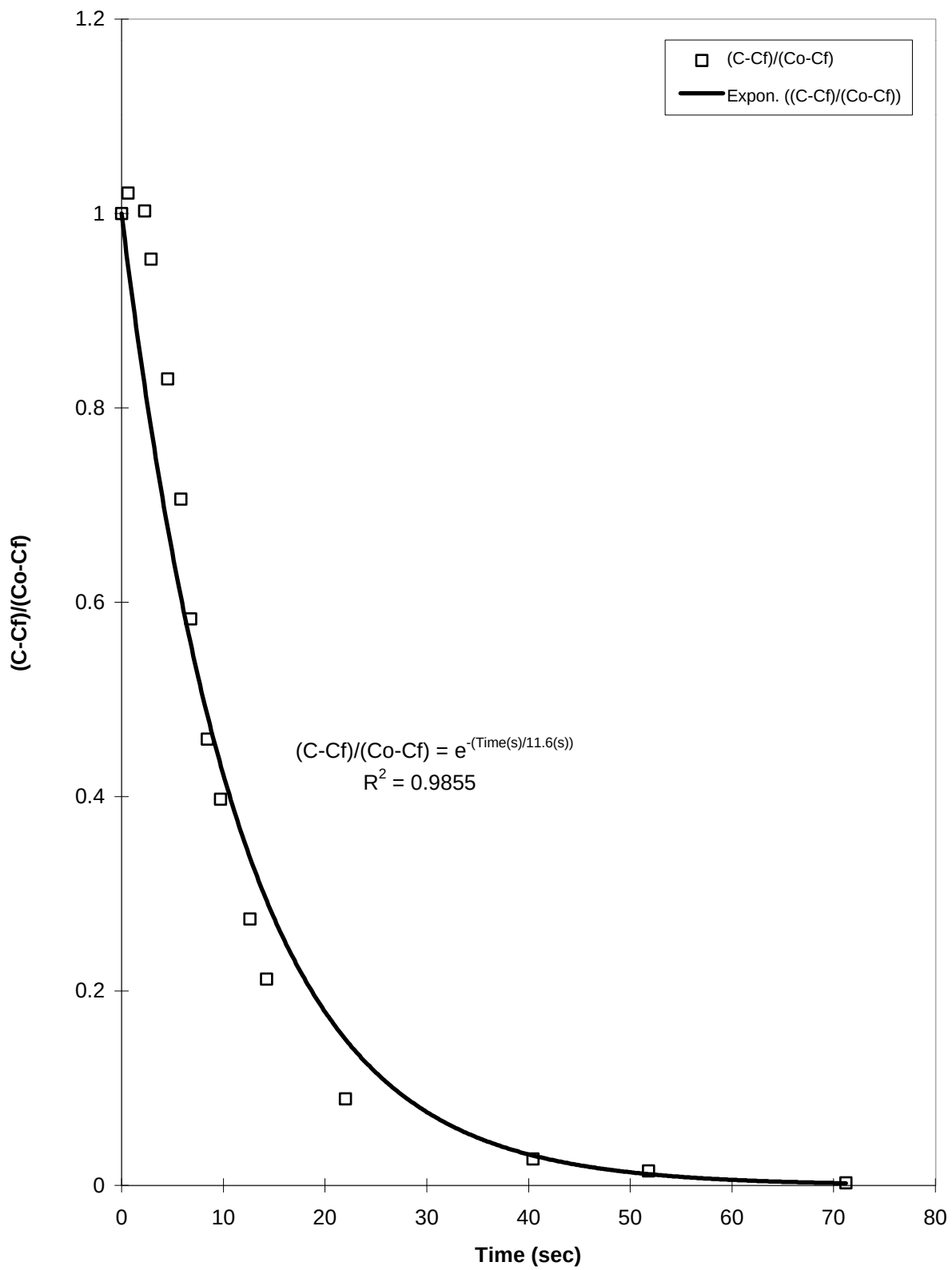


Figure 6. Dissolved oxygen probe response curve and regression model

within 95% of the remaining span in approximately 35 seconds. The fitted curve had a regression coefficient, R^2 , of 0.9855.

Philichi(1989) recommends that the product of K_La and the probe time constant be less than 0.02 to limit errors in K_La to less than 1%. It is recommended that this product can be increased to 0.05 if 20% of the initial K_La data are truncated. Truncation of up to 20 % was used in this study. The maximum values of K_La allowed under these recommended limits for a probe time constant of 11.6 seconds using non truncated and truncated data are 6.2 and 15.5 h^{-1} respectively. Since data truncation was used in this study the K_La determined for clean water fall within the limitations of the response of the dissolved oxygen probes. Philichi (1989) also presents a residual plot from a non steady state K_La analysis showing bias caused by inadequate probe response. A review of K_La Probe Response curve residual plots was made for each alpha determination to insure that adequate truncation was performed.

Temperature. The pilot plant basin temperatures were read daily from a glass thermometer graduated in 1.0 degree Celsius divisions. Temperatures required for the calibration of the dissolved oxygen meters and for the conversion of dissolved oxygen readings were read from the electronic temperature element integrated into the YSI dissolved oxygen probe and meters.

Chemical oxygen demand. Analyses for chemical oxygen demand (COD) were performed in accordance with Standard Method 5220-C, Closed Reflux , Titrimetric Method (AWWA1995 p. 5-14,15). Sample volumes of 5 ml were analyzed. Samples for Total COD were collected as grab samples and were immediately fixed by the addition of sufficient concentrated sulfuric acid to lower the pH to less than 2 standard pH units.

Samples for soluble COD were collected as grab samples, filtered through a 0.45 micron filter, and immediately fixed through the addition of concentrated sulfuric acid. The acid persevered samples for COD analysis were stored at temperatures less than 4 degree C prior to analysis.

Total Kjeldahl nitrogen. Analyses for the determination of Total Kjeldahl Nitrogen (TKN) were conducted using Standard Method 4500-N_{org} B Macro -Kjeldhal Method (AWWA 1995 p.4-94-94). Samples were distilled in accordance with Standard Method 4500-NH₃-B. Preliminary Distillation Step (AWWA 1995 p. 4-76,77) and analyzed for ammonia by use of Standard Method 4500-NH₃-C Titrimetric Method. (AWWA 1995 p. 4-77-78). Samples were acidified to a pH of 1.5 to 2.0 with concentrated H₂SO₄ upon collection and stored at 4°C.

Total and soluble ammonia. Samples that were analyzed for soluble ammonia were collected and immediately filtered through a 0.45 micron membrane filter (Gelman model Metrical GN-6) prior to preservation and storage. Both total (unfiltered) and soluble ammonia samples were acidified to a pH of less than 2 and stored at a temperature of 4°C. Samples were distilled in accordance with Standard Method 4500-NH₃-B. Preliminary Distillation Step (AWWA 1995 p. 4-76,77) and analyzed for total and soluble ammonia by use of Standard Method 4500-NH₃-C Titrimetric Method. (AWWA 1995 p. 4-77-78).

Soluble Nitrite. Samples collected for soluble nitrite analyses were filtered through a 0.45 micron membrane filter (Gelman model Metrical GN-6) and stored at 4° C. Soluble nitrite concentrations were determined using the Colormetric Method, Standard Method 4500-NO₂- B. (AWWA 95 p. 4-83, 84). A Beckman Model DU 640 Spectrometer with 1 cm light path and a Bausch and Lomb Model Spectronic 20 with 1 cm light path were variously used for the colormetric analysis.

Soluble nitrate and soluble orthophosphate. Samples collected for the analysis of soluble nitrate and phosphorus were filtered through a 0.45 micron membrane filter (Gelman model Metrical GN-6) at the time of collection. Prior to analysis, the samples were stored at 4°C. Soluble nitrate and soluble phosphorus concentrations were determined through the use of Standard Methods 4500-NO₃-C (Nitrate by Ion Chromatographic Method) (AWWA 95 p. 4-86), and Standard Method 4110 B. Ion Chromatography with Chemical Suppression of Eluent Conductivity(AWWA 95 p. 4-83,

84). A Dionex chromatograph with a Dionex model P/N 3741 column was used for the analyses.

Total phosphorus. Samples collected for the analysis of total phosphorus were collected and stored in acid washed containers at 4° C until analysis. After collection, samples were acidified to a pH less than 2 standard units with concentrated sulfuric acid. The analysis of total phosphorus was performed using Standard Method 4500-P E. Ascorbic Acid Method (AWWA 95, pp.4-113,114). A spectrophotometer with a one cm light path was used for the photometric analysis. A Beckman Model DU 640 or a Bausch and Lomb Model Spectronic 20 was variously used for the analyses.

Mixed liquor suspended solids and total suspended solids. Samples of pilot plant influent, effluent and mixed liquor were collected for the analysis of total suspended solids. Samples of the bulk liquid were collected and stored up to three hours at 4° C. Samples were analyzed in accordance with Standard Method 2540 D. Total Suspended Solids Dried at 130 - 105°C. (AWWA 95, p. 2-56). Samples were filtered onto prepared 150 micron, 55mm diameter glass fiber disks (Whatman G6 or Fisher G6). Sample volumes of 10 mL were used for mixed liquor samples while volumes of 100 mL were analyzed for effluent samples. Dried filters and residues were weighed using a Mettler model H12 analytical balance.

Mixed liquor and effluent volatile suspended solids. The determination of volatile solids was made from the residues of the total suspended solids analysis in accordance with Standard Method 2540 E. Fixed and Volatile Solids Ignited at 550° C. (AWWA 95, p52-57). Prior to filtering suspended solids, the filters were prepared by washing with distilled water and igniting at 550°C for 20 min. Final residues were obtained by igniting the suspended solids residues at 550°C for 20 min, cooling and weighing on a Mettler Model H12 analytical balance.

Oxygen uptake rate. Oxygen uptake rates were measured by timing oxygen depletion of a grab sample in a closed container. A dissolved oxygen bottle probe was air

calibrated at the approximate sample temperature and idled in a beaker of oxygen depleted mixed liquor supernatant. A 500ml plastic beaker containing an aeration stone was used to contain and simultaneously aerate a grab sample of well suspended mixed liquor. A timer was activated at the moment the mixed liquor sample was taken. Immediately after a sample was taken, it was poured to fill a 300 ml BOD bottle containing a magnetic stir bar. A dissolved oxygen membrane probe was inserted into the BOD bottle and the bottle was visually inspected to assure that it was full and contained no air bubbles. The BOD bottle was then placed on a 1/8 inch Styrofoam sheet covering the plate of a magnetic stirring apparatus. The temperature of the stirred sample was measured with a YSI Model 51B Dissolved Oxygen Meter. The meter was then adjusted for temperature compensation. The dissolved oxygen concentration and time to the nearest tenth of a second were then recorded at equal dissolved oxygen intervals so that measurements were made at intervals of fifteen to forty-five seconds. The oxygen uptake rate was determined by plotting dissolved oxygen concentration versus time. A visual inspection of the curve was made to eliminate data affected by probe response (rising or non-linear dissolved oxygen response). Linear regression software was then used to determine the rate of the dissolved oxygen depletion in the initial apparent linear portion of the curve. The Oxygen Uptake Rate (OUR), is the measured rate of dissolved oxygen depletion as expressed in mg/L-h.

Surface tension. The surface tension of samples of pilot plant influent, effluent and activated sludge supernatant were measured using procedures defined in ASTM D 1331 - 89 Surface and Interfacial Tension of Solutions of Surface-Active Agents. Samples for surface tension analysis were filtered immediately after collection by allowing solids to settle and filtering the supernatant through a 150 micron glass filter (Fisher Model G6 or Whatman 934/AH). The samples were allowed to stabilize at 20 °C in a temperature controlled room and were then placed in a 100 mL beaker and analyzed with a Fisher Manual Model 20 Tensiometer in accordance with ASTM 1331-89 (Reapproved

1995) Standard Test Methods for Surface and Interfacial Tension of Solutions of Surface-Active Agents, and the equipment manufacturer's instructions for use.

Determination of oxygen transfer parameters

Testing of clean and non respiring water. The determination of α requires that the oxygen bulk mass transfer coefficient be determined for tap water in each reactor where an alpha is to be determined. For this study, the oxygen bulk transfer coefficients were determined in substantial conformance to the standard published by the American Society of Civil Engineers, Measurement of Oxygen Transfer in Clean Water (ANSI/ASCE 2-91).

Although the procedures of ANSI/ASCE 2-91 were followed as closely as practical, some deviations from the recommended standard were made. The standard recommends testing at a temperature as close to 20°C as possible. K_La values were measured in the pilot plant and bench reactors over a range of temperatures from 9.5 to 24.9 °C reflecting the range of temperatures over which the pilot plant was operated. Specific temperature correction factors were determined for both the pilot plant and bench reactor basins.

The following procedure was used to perform clean water tests on the pilot plant: The aeration basin to be tested was drained, and the basin and aerators were hosed down and brushed off with a scrub brush. The basin and aerators were then rinsed with treatment plant non potable wash water (plant effluent). The basins were then filled with clean non potable wash water or tap water depending on tap water availability.

For each series of tests, cobaltous chloride was added to the filled basin for a concentration of 0.5 mg/L as cobalt and mixed with the aerators for approximately five minutes. A single air calibrated dissolved oxygen membrane probe was dropped into the

middle of the basin at approximately mid depth. The probe was raised and lowered by hand in accordance with manufacturers directions to prevent stagnation of the membrane. With the aerators on, sodium sulfite was added to the basin to a concentration of 10 mg/L as sodium sulfite per mg/L of oxygen. The aerators were set to the desired airflow as measured with a Dwyer Model Visi-Float VFB, 20 to 200 scfh, 4" scale air flow meter. The air was left on to mix the basin. When it became apparent that the concentration of dissolved oxygen was rising, a timer was started and dissolved oxygen concentrations were noted at even intervals (typically 0.2 mg/L). The data were recorded for a minimum of 20 minutes or until the measured dissolved oxygen concentration reach 98% of the equilibrium concentration. The temperature of the clean water was recorded before and after each determination.

Data from the clean water test were evaluated using a non linear regression modeling program from a statistical software package, NCSS 6.0.22 or NCSS 97. The data were plotted and initial points censored by visual inspection. The initial dissolved oxygen readings may be influenced by residual sodium sulfite. The ASCE(1992) testing standard allows removal of up to 20% of the initial data to minimize error due to probe response and residual sodium sulfite effects. No more than 20 % of the data were omitted in the statistical analysis. Equation 2 was used as the non linear regression model.

Values of $K_L a$, C^* and C_o were estimated from the nonlinear regression analyses with known inputs of dissolved oxygen versus time data. For a sequence of $K_L a$ measurements, additional sodium sulfite was added for each trial, however, at no time was more than 1500 mg/L of dissolved solids added before the batch of water was replaced.

Testing of respiring liquids. Mass transfer parameters and alpha were determined on three types of respiring liquids in the pilot plant. As the plant was operated under each of the flow configurations, mass transfer parameters were determined on the in situ contents of the aeration basin. Both continuous steady state and continuous non steady state methods as described in EPA 1983 were used. Another set of experiments involved making changes to the flow scheme of the plant and directly introducing RAS and primary

clarifier effluent into the first aeration basin (eliminating initial anaerobic and anoxic stages). Mass transfer coefficients and alpha of the aeration basin directly receiving primary effluent and influent were measured using continuous steady state and continuous non steady state methods. Finally, on occasion, the first aeration basin of the pilot plant was blocked off, drained, cleaned and filled with only primary clarifier effluent. K_La and alpha values for the aeration basin filled with primary effluent were determined using non continuous, non steady state methods.

Both batch (non continuous) and continuous non steady state methods of K_La determination were performed on respiring liquids in a 21 liter bench scale reactor.

Non steady state conditions. Testing of respiring media in the pilot plant under continuous flow conditions was conducted as recommended by EPA (EPA1983). The airflow to the basin aerators was set at the desired flow rate using a needle valve and Dwyer model Visi-Float VFB 20 to 200 scfh, 4" scale air flow meter. The air was then shut off or substantially throttled with a ball valve. A paddle was used to mix the basin while the air was shut off. A single DO probe was suspended in the basin near the midpoint of the basin. The probe was moved up and down to provide a fluid flow across the membrane. When the dissolved oxygen concentration fell below 2.0 mg/L, the air was turned on and the timer was started. Time and dissolved oxygen concentrations were recorded at equal concentration intervals.

Oxygen mass transfer parameters were determined by applying a nonlinear regression to the collected time and dissolved oxygen concentration data. Equation 4 was used as the non linear regression model. With dissolved oxygen concentration and time as input data, and measured flow and volume from the experimental setup, the nonlinear regression was used to estimate values of C_R , C_{O_s} , and K_La_f . Flows through the basins were determined by diverting the flow to a bucket and measuring the rate of fill to a measured volume with a stopwatch.

The temperature and oxygen uptake rate of the contents of the basin was measured before and after the testing for mass transfer rate.

Continuous flow conditions were also established in the bench scale reactor for some mass transfer parameter determinations in respiring liquids. In these cases, flow was pumped into the bench scale reactor at a constant rate with a peristaltic pump and allowed to exit through an overflow port. Mass transfer parameters were determined from the time and dissolved oxygen concentration data using non linear regression techniques applied to Equation 4.

Methods and procedures used to determine oxygen mass transfer data for non continuous, non steady state conditions in the pilot plant were similar to those for continuous conditions except that in the model used for non continuous flow, the transport term in Equation 4 was set to zero. The same model was applied to bench scale reactor data for respiring liquid data collected under batch or non continuous conditions.

Steady State Conditions. Mass transfer parameters were determined on the operating pilot plant under steady state conditions by measurements of oxygen uptake rate (OUR), dissolved oxygen concentrations, flow through the basin and the dissolved oxygen concentration of the influent taken as near together in time as possible. OUR was measured in a single grab sample after the determination of the steady state dissolved oxygen concentration in the basin and influent flow stream by use of a DO probe. Procedures for the measurement of dissolved oxygen and OUR were described previously.

The mass transfer coefficient was determined by solution of Equation 2. The values R , Q , V , C_i , and C_R were all directly measured. The value of C^*_{yf} , the steady state dissolved oxygen concentration at field conditions when the rate of respiration is zero, was not directly measured. A beta value of 0.98 was assumed for all trials. The value of C^*_{yf} was taken to be the product of beta and the book value for the clean water dissolved oxygen saturation concentration at the experimental temperature and elevation.

Determination of alpha. Alpha is the expression of the ratio of the mass transfer coefficient of the wastewater aeration system tested to the mass transfer coefficient of clean water in the same system. Both mass transfer coefficients in the ratio must be

representative of the same field conditions or of standard conditions. If not, the computed alpha must be transformed to represent standard conditions.

For the purposes of this study, mass transfer coefficients for clean and process waters were transformed to standard temperature conditions. Other pertinent variables such as aerator depth and the test elevation of 530 m MSL were the same for both clean water and process water conditions. Values of $K_L a$ presented in this study were not transformed to standard pressure conditions prior to determining alpha. However, since the factors used to transform non standard pressure conditions to standard sea level conditions would cancel in the determination of alpha, the use of non transformed $K_L a$ values should not affect the values of alpha reported.

Statistical methods

Several statistical methods were performed in the course of this study. A description of those methods are presented below.

Box plots presented in this study were developed using NCSS 97(1998). The box plots are of the standard type showing the interquartial range within the box and a line drawn at the medium value. The upper T shaped outer fence, indicating the upper adjacent value, indicate the largest observation that is less than or equal to the 75th percentile plus 1.5 times the interquartial range. Similarly, the lower adjacent value is the smallest observation that is larger than the 25th percentile less 1.5 times the interquartial range.

Line and bar graphs were performed on Microsoft Excel for Windows 95, version 7.0 (1995). Error bars shown on bar graphs are 95% confidence intervals about the mean as determined using the z statistic.

Linear regressions, including all those for determination of oxygen uptake rates, were performed using Excel for Windows 95, version 7.0 by Microsoft (1995).

Nonlinear regressions, including those for determination of $K_L a$ and θ , were performed using NCSS 97 (1998). The parameters of the nonlinear models were estimated by NCSS 97 (1998) using the Levenberg-Marquardt nonlinear least-squares algorithm. Confidence intervals for the parameter estimates are appropriate for large samples (n greater than 25).

Analysis of variance (ANOVA) was performed using NCSS 97 (1998). The data were screened to assure that they were randomly distributed, that the variances were equal, and that the individual values were independent. Normality was evaluated using Shapiro-Wilks.

Multiple comparisons were made when it was determined through the ANOVA that means were not equal. Techniques used to evaluate multiple comparisons included Tukey-Kramer, Fisher LSD, and Duncan.

RESULTS

Pilot plant operating conditions

As a pilot plant receiving primary clarifier effluent from a municipal wastewater system, some operating conditions were controlled whereas others were not. The pilot plant anaerobic HRT was controlled and was varied with different plant configurations in accordance with the experimental plan. Influent COD concentrations entering the pilot plant was not controlled and showed considerable temporal variation. The operating MCRT was adjusted in order to maintain a well functioning system in response to variations in temperature and COD loading. The resulting operating conditions are summarized in Table 2 showing the combined effects of varying anaerobic zone sizing and influent COD loading.

Table 2. Pilot plant operating conditions.

Anaerobic HRT	COD Loading	Anaerobic		Operating MCRT	MLSS	MLVSS	
		COD Loading	Anaerobic Floc				
			Loading				
(h)	(g/d)	(mg/L/d)	TSS (/d)	VSS (/d)	(d)	(mg/L)	(mg/L)
0.00	0	0	0	0	20 ⁽¹⁾	1905 ⁽¹⁾	1620 ⁽¹⁾
0.21	959	9588	8.86	10.48	10	1082	915
0.43	1231	6156	3.23	3.80	20	1905	1620
0.64	1907	6356	3.32	3.90	10	1916	1630
0.64 w/ acetate	1079 ⁽²⁾	3596 ⁽²⁾	2.92 ⁽²⁾	3.50 ⁽²⁾	10	1231	1028

Note:

1. Operations for anaerobic HRT of 0.00 h were set up intermittently and temporarily while pilot plant was operated nearly continuously with an anaerobic HRT of 0.43 h.
2. COD values are for primary influent COD only. A supplemental feed of 250 g/d of sodium acetate was added to the second anoxic basin resulting in an additional COD loading of 195 g/d (as COD) for a total average plant COD loading of 1274 g/d. The supplemental feed did not directly affect the anaerobic COD loading.

Pilot Plant Analytical Results

Chemical analysis were performed on the pilot plant in order to operate and monitor plant performance and to collect data for research beyond the scope of this present discussion. The pilot plant operation data are presented here to describe the plant performance during the same period that oxygen transfer coefficients were being determined. The influent to the pilot plant was effluent from a primary clarifier at a municipal waste water treatment plant. This primary effluent was subject to daily and seasonal variations during the period in which experiments were performed for this thesis. The quality of the influent to the pilot plant was uncontrolled. The nature of the variation in the performance of the plant during the various plant configurations are presented.

Data are presented for four plant configurations. The four configuration include three different anaerobic HRT's and one configuration with a supplemental carbon source. The pilot plant analytical data are summarized in Table 3.

As the plant influent strength varied seasonally, the measured total COD of the pilot plant influent varied during the different configurations. Average influent TCOD during periods when the anaerobic nominal HRT's were 0.21, 0.43, and 0.64 hours were 88, 113, and 175 mg/L respectively. The average influent TCOD concurrent with the 0.64 hr nominal HRT and acetate feed was 99 mg/L. A supplemental sodium acetate feed of 17.9 mg/L (as COD based on influent flow rate) was added to the second anoxic basin. The total plant TCOD loading including the supplemental acetate feed was 117 mg/L. The average influent total COD varied by approximately 100% between the shortest and longest HRT evaluation period.

A much smaller variation was noted in the influent soluble COD. The measured influent soluble COD for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 45, 47, 57, and 46 mg/L, respectively.

Table 3. Summary of pilot analytical data

	Average			
	Anaerobic Nominal HRT of 0.21 h	Anaerobic Nominal HRT of 0.43 h	Anaerobic Nominal HRT of 0.64 h	Anaerobic Nominal HRT of 0.64 h, Acetate Feed
Solids (mg/L)				
Aeration TSS (mg/L)	1082	1905	1916	1231
RAS TSS	1786	3157	3842	2695
Eff TSS	7	15	11	7
COD (mg/L)				
Total influent COD (mg/L)	88	113	178	99
Soluble Influent	45	47	55	46
First Anaerobic	27	27	44	33
Last Anaerobic	27	27	32	30
First Anoxic	25	27	31	27
Last Anoxic	21	32	29	28
Last Aerobic	21	24	31	25
Effluent Soluble	23	23	30	22
Effluent Total	34	36	39	30
TCOD/TP Ratio	43	55	44	44
TCOD/TKN Ratio	10	10	12	8
TKN (mg/L as N)				
Influent TKN	9.4	14.5	16.5	11.9
Effluent TKN	2.7	1.8	1.6	2.6
Effluent ammonia	2.3	1.8	0.5	2.2
Ions (mg/L)				
<i>Nitrate (as N)</i>				
Influent	1.4	1.5	0.6	1.0
An sol 1	2.9	3.9		
Last Anaerobic Basin	2.9	3.4	3.2	0.9
Last Anoxic Basin	3.8	5.6	3.0	1.7
Last Aerobic Basin	4.0	6.5	5.8	2.4
Effluent	3.1	6.7	5.7	2.3
<i>Nitrite (as N)</i>				
Influent	0.0	0.2	0.1	0.1
An sol 1	0.6	0.3		
An sol 3	0.6	0.3	0.4	0.1
Ax sol 3	0.8	0.3	0.3	0.2
Aer sol 3	0.9	0.2	0.3	0.3
Eff sol	0.9	0.2	0.4	0.4
<i>Phosphate (as P), mg/L</i>				
Influent	0.8	1.1	0.8	1.2
An sol 1	0.9	1.0		
Last Anaerobic Basin	0.9	1.0	1.2	0.8
Last Anoxic Basin	0.9	1.2	1.1	0.8
Last Aerobic basin	0.9	1.1	1.0	0.7
Effluent	0.8	1.1	1.1	0.7
<i>Phosphate (as P) g/d</i>				
Influent	8.7	11.8	8.4	13.6
An sol 1	20.6	22.6	0.0	0.0
Last Anaerobic Basin	20.6	22.1	26.4	18.0
Last Anoxic Basin	20.6	25.5	24.3	16.8
Last Aerobic basin	19.2	23.2	22.5	15.3
Effluent	8.8	11.6	12.4	7.5
TP (mg/L as P)				
Total Phosphorus Influent (mg/L as P)	2.1	2.4	4.0	2.5
Total Phosphorus Influent (g/d as P)	22.8	25.8	43.7	26.9
Total Phosphorus Effluent (mg/L as P)	1.7	1.8	1.6	0.9
Total Phosphorus Effluent (g/d as P)	18.9	19.2	17.2	9.6
Phosphorus Removal (%)	54%	55%	72%	71%
P Wasted g/d as P	5.19	4.55	9.18	5.91
P available, g/d as P	17.7	21.3	34.7	21.1
P removed, g/d as P	3.9	6.6	26.6	17.4
Excess P removal, g/d as P	-1.3	2.1	17.5	11.5
Calculated TP in Waste Sludge (%)	2.01%	3.97%	7.44%	7.35%
Nitrogen Balance				
Total Nitrogen Inf (mg/L as N)	10.8	15.4	16.7	12.9
Total Nitrogen Eff (mg/L as N)	6.7	8.5	7.7	5.4
Total Nitrogen Wasted (g as N)	10.5	17.7	36.8	23.6
Total Nitrogen Available (g as N)	103.2	153.3	133.2	113.6
Total Denitrification (g as N)	34.9	57.6	61.5	59.0
Denitrification Efficiency (%)	32%	35%	41%	52%

Here there was only an increase in influent soluble COD of 27% from the shortest to the longest HRT period, and three of the four were approximately the same.

The COD removal performance of the plant was consistent throughout the four experimental configurations. The average effluent soluble COD for the periods with nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 23, 23, 31, and 22 mg/L, respectively. Profiles of COD removal are presented in Figure 7.

The aeration basin mix liquor suspended solids also varied over the four plant configurations. The aeration basin average total suspended solids for the configurations providing nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 1082, 1905, 1916, and 1231 mg/L, respectively. The average total suspended solids are presented in Figure 8. The MLSS data reflect both variation in influent TCOD and sludge age. The increase in MLSS concentration from 1082 to 1916 mg/L for HRT configurations of 0.21 to 0.64 hours was probably the result of an increase in influent TCOD from 88 to 175 mg/L. The increase in MLSS concentration from 1082 to 1905 for anaerobic HRT's of 0.21 to 0.43 hours was primarily due to the increase in operating sludge retention time from 10 to 20 days for these two plant configurations.

Similar to the influent COD, the influent TKN also varied over the four plant configuration periods. The measured influent TKN for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 9.4, 14.5, 16.5, and 11.9 mg/L as N respectively. There was an increase in influent TKN of 75% from the shortest to the longest HRT period. Influent average TKN concentrations are shown in Figure 9.

The COD and TKN both varied with the fluctuating strength of the wastewater during the four plant configurations. The influent total COD to influent TKN ratio remained comparatively constant. The measured influent TCOD to TKN ratio for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 10, 10, 12, and 8 (mg/L)/(mg/L as N) respectively. There was an

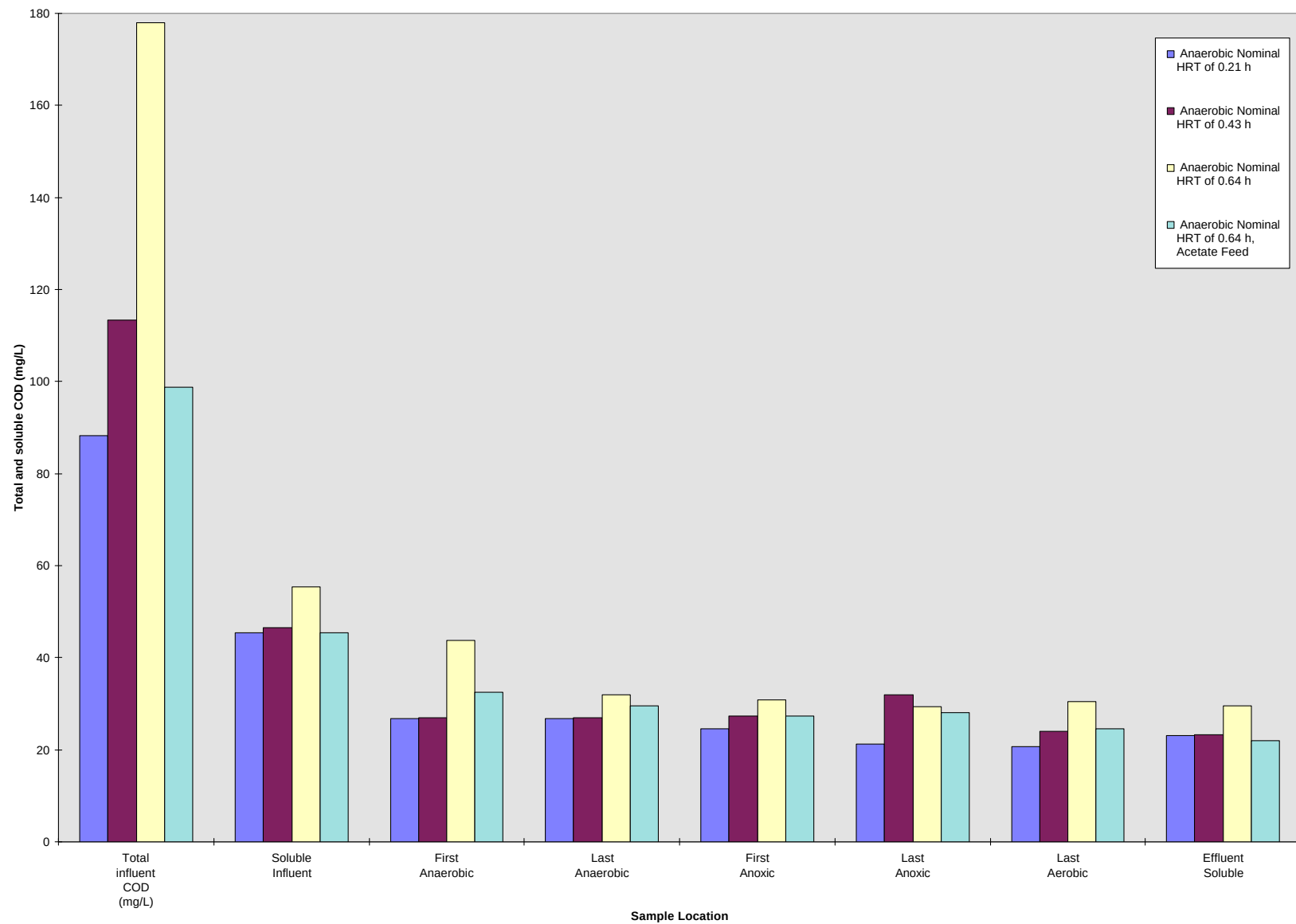


Figure 7. Average influent total COD and average soluble COD profile for the four operational configurations.

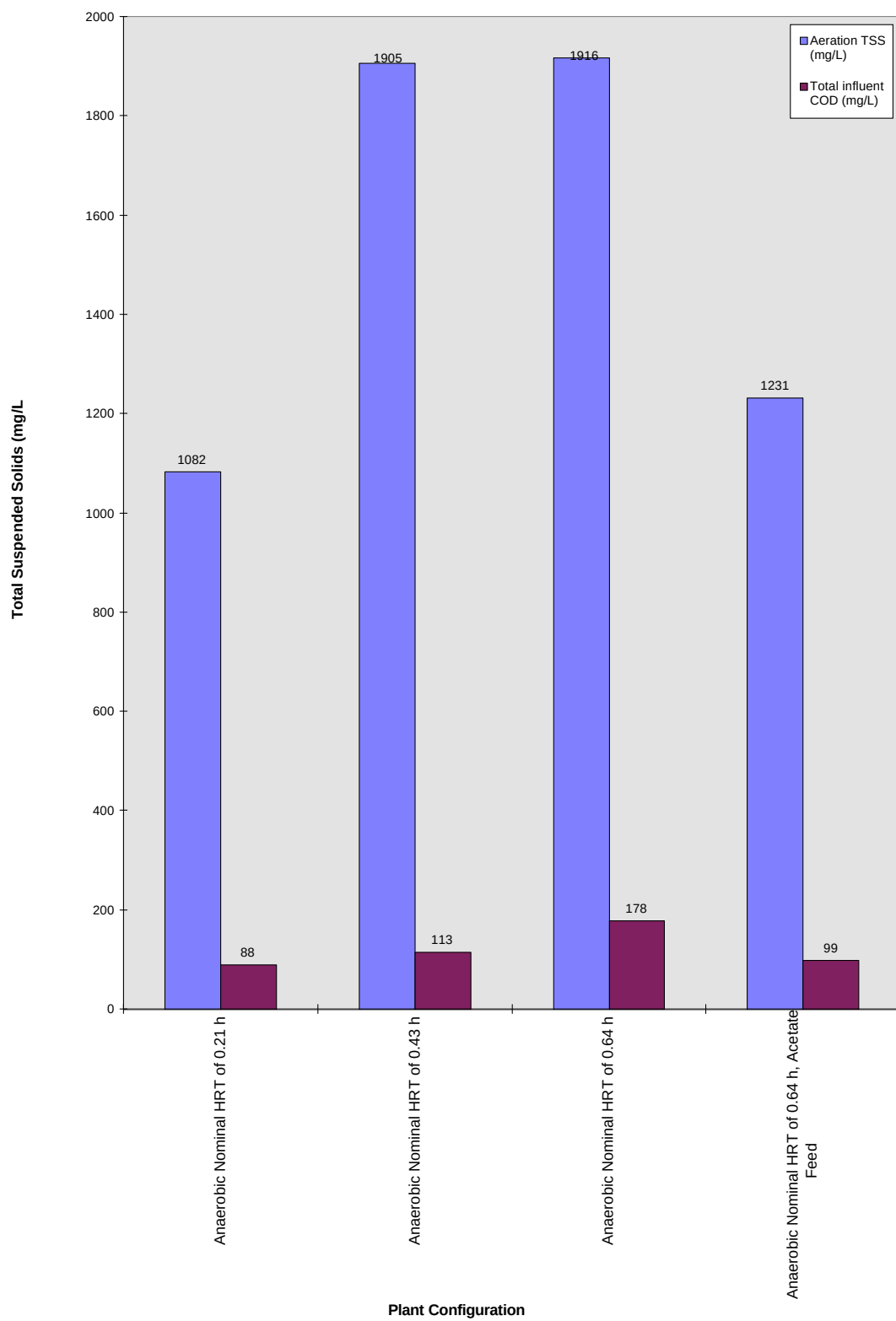


Figure 8. Average total suspended solids concentration (MLSS) in the pilot plant aeration basins for the four operational configurations.

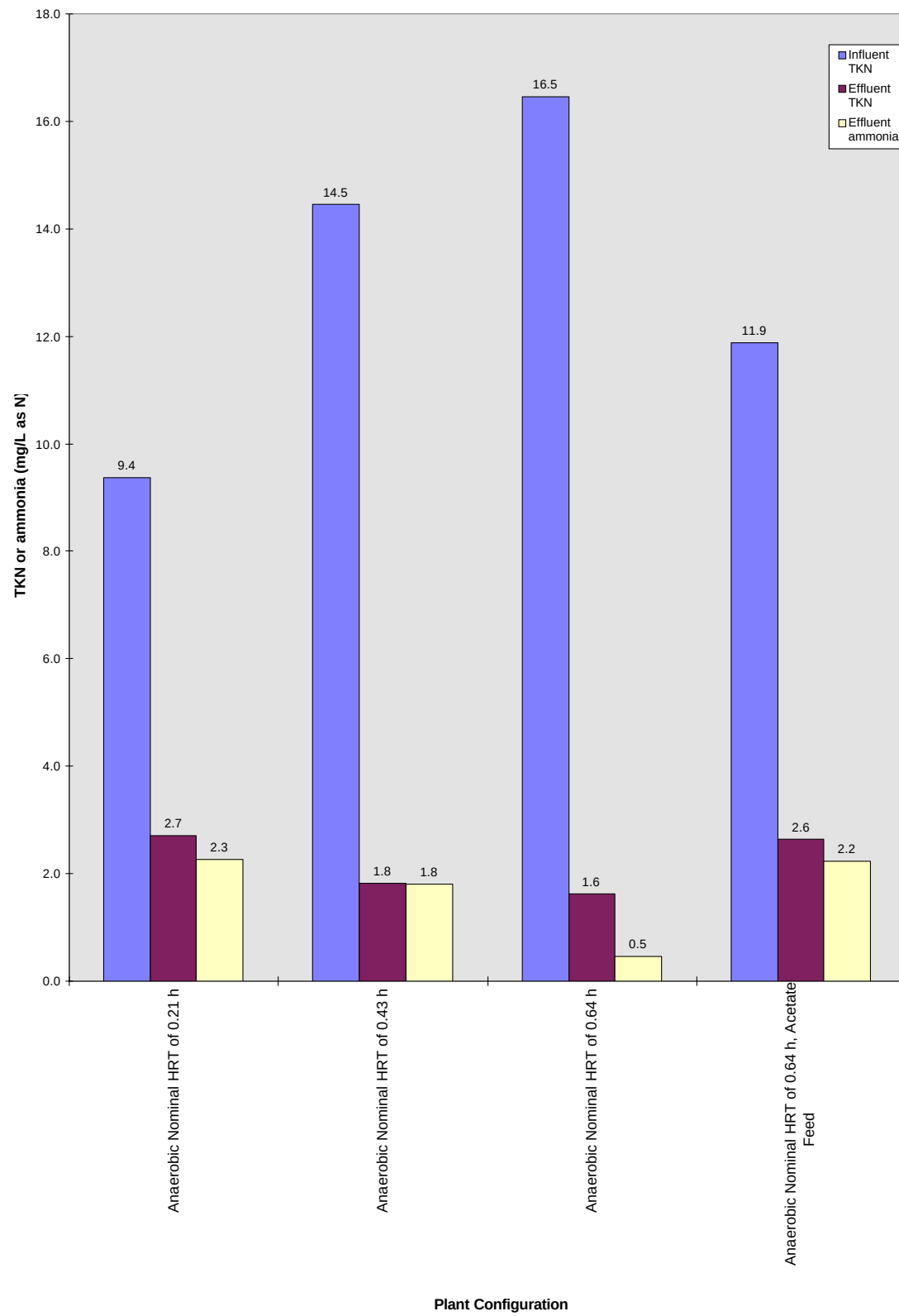


Figure 9. Average influent kTKN and effluent ammonia for the four operational configurations.

increase in influent TCOD to TKN ratio of 20% from the shortest to the longest HRT period. The TCOD to TKN ratios for each plant configuration are shown in Figure 10.

There was even less variability in the influent TCOD to TP ratio (Figure 9). The influent TCOD to influent TP ratio also remained comparatively constant. The measured influent TCOD to TP ratio for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 43, 55, 44, and 44 (mg/L)/(mg/L as P) respectively. As shown in Figure 11, the influent TP for the same HRT periods were 2.1, 2.4, 4.0, and 2.5 mg/L.

The plant was configured with the intention of providing complete nitrification, biological denitrification and biologically enhanced phosphorus removal. The ability of the plant to oxidize ammonia varied with the plant configuration. The measured effluent ammonia for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 2.3, 1.8, 0.5, and 2.2 mg/L as N respectively (Figure 9).

In general the denitrification efficiency increased with anaerobic HRT. As shown in Figure 12, the measured denitrification efficiency for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 32, 35, 41, and 52%, respectively. More significantly, the highest efficiency occurred along with the supplemental acetate feed indicating that, at the lowest TCOD to TKN ratio, denitrification efficiency was limited by the readily available carbon source. Without the supplemental acetate feed, the denitrification efficiency increased with influent total COD. Profiles of average nitrate (Figure 13) indicate a gradual increase in nitrate from influent through effluent.

The phosphorus removal and removal efficiency increased with both increasing HRT and anaerobic zone COD floc loading. The measured total phosphorus removal efficiency for the periods evaluating nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 14, 23, 59, and 61%, respectively. The dependence

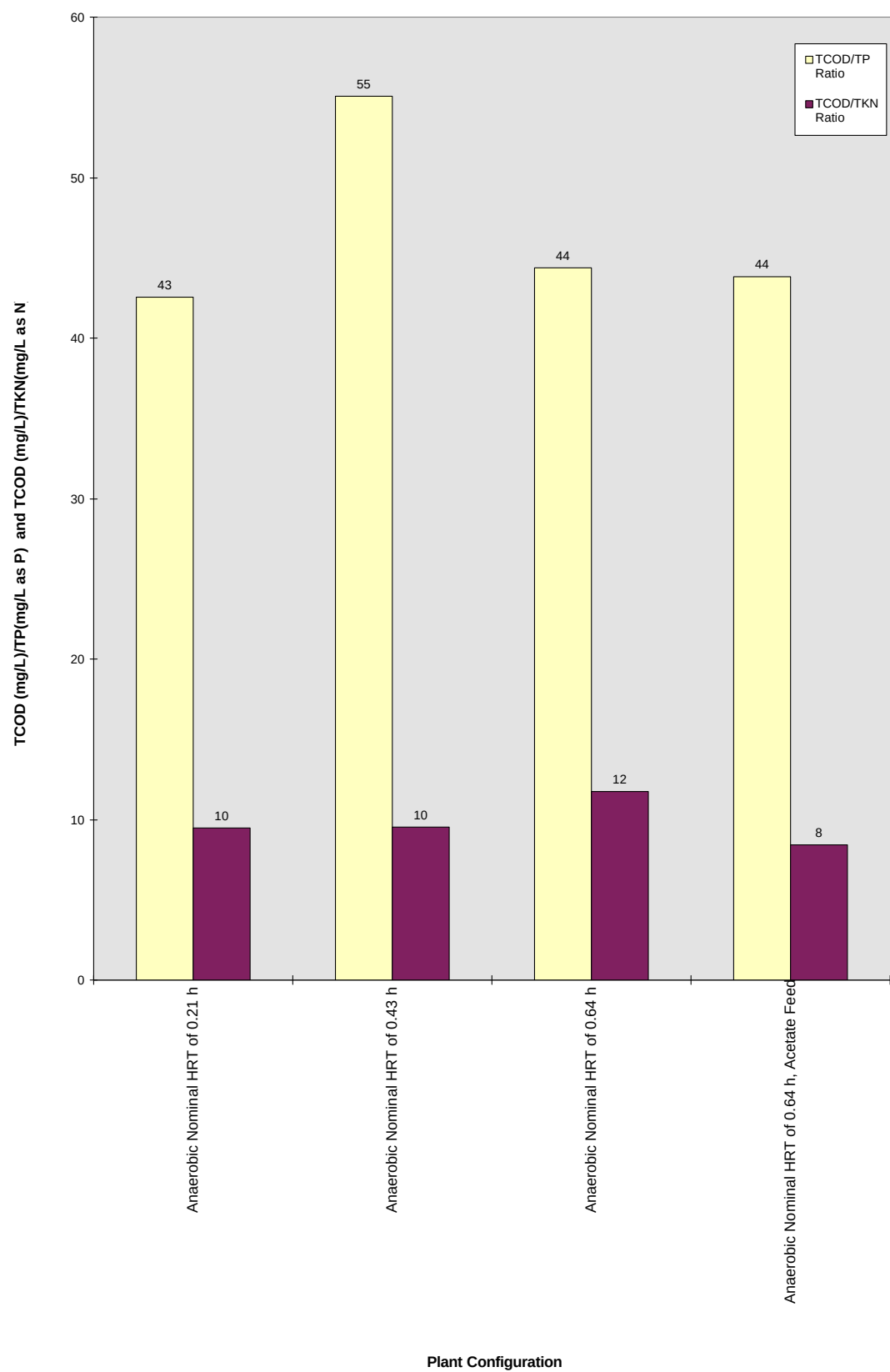


Figure 10. TCOD/TP and TCOD/TKN ratios for the four pilot plant operational configurations.

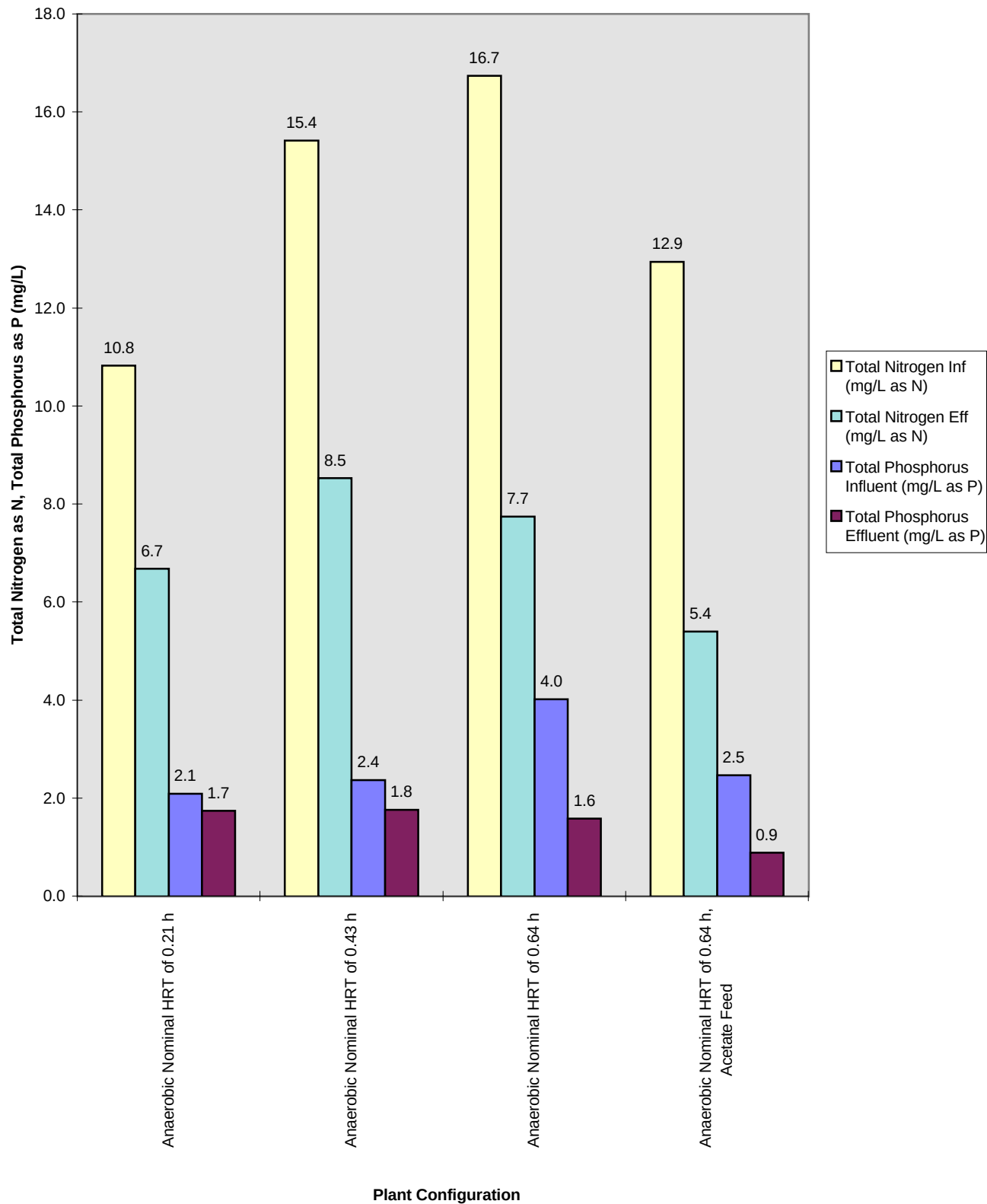


Figure 11. Average total nitrogen (TKN, nitrate and nitrite) and total phosphorus in the pilot plant influent and effluent during the four operational configurations evaluation periods.

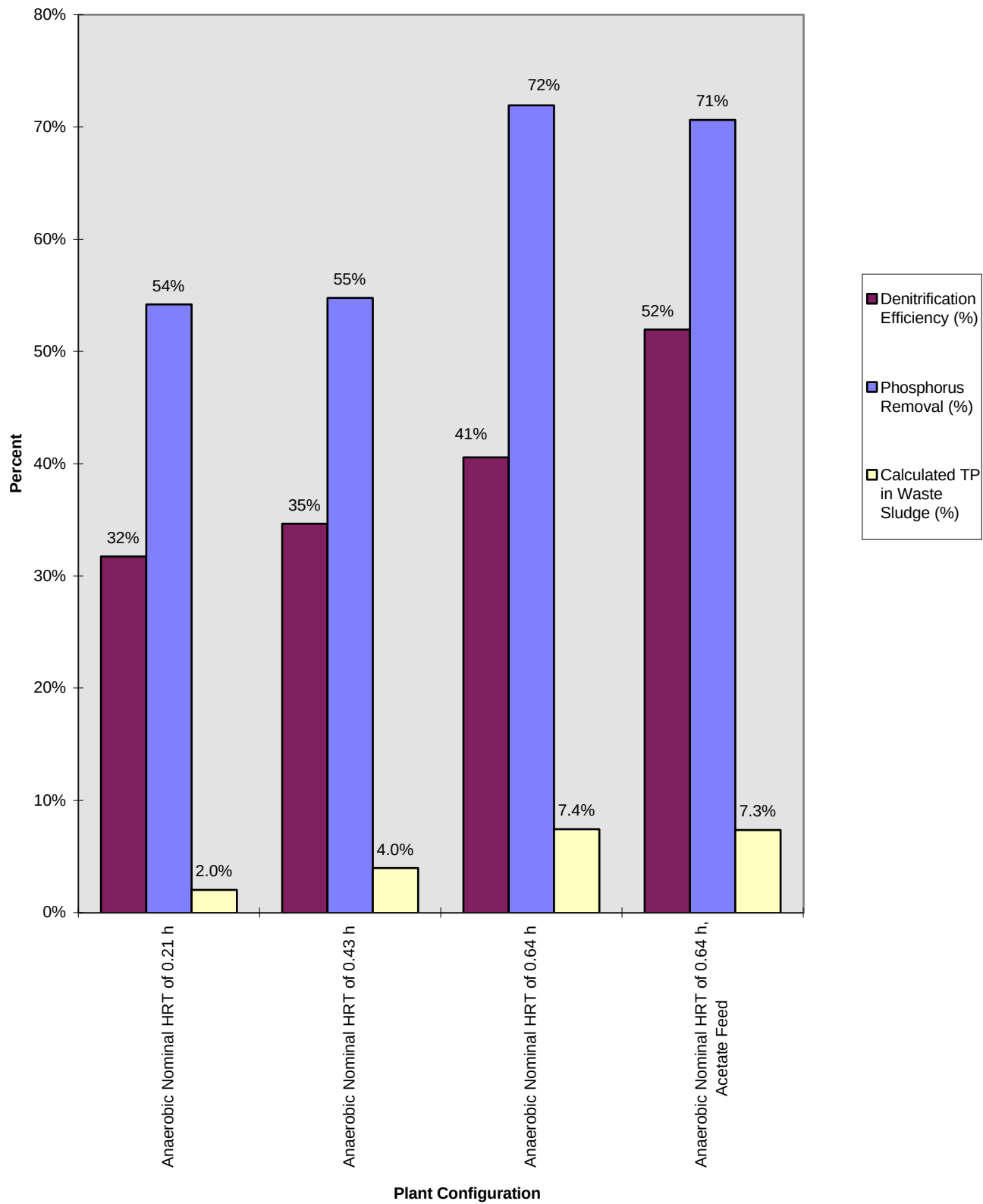


Figure 12. Average denitrification, phosphorus removal efficiency and estimated total phosphorus content of waste sludge.

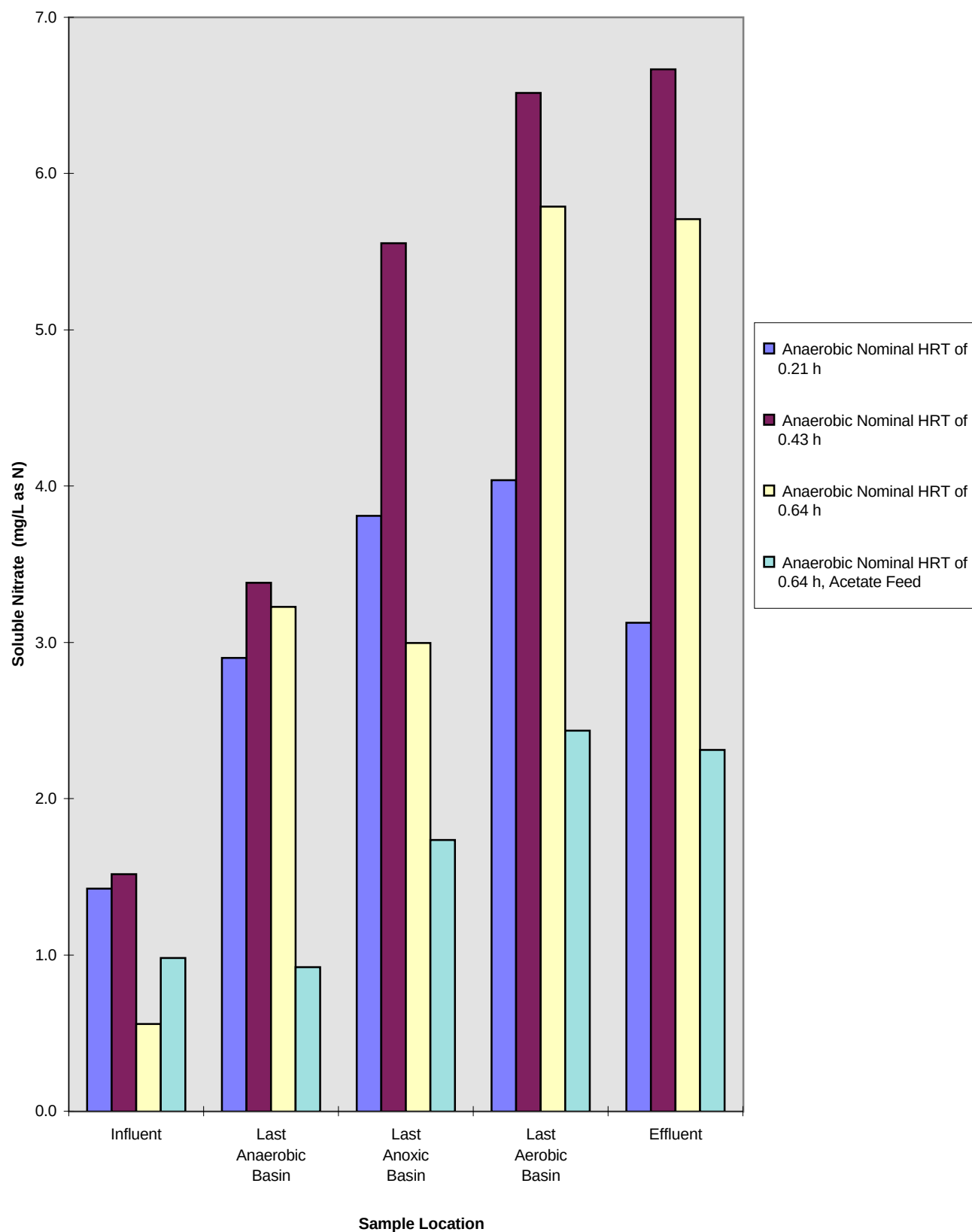


Figure 13. Average soluble nitrate profile for the four operational configurations.

of removal efficiency on HRT indicates that the rate of fermentation of influent COD to volatile fatty acid products was a limiting factor. With the anaerobic HRT held constant, the mass of phosphorus removed was directly dependent on the COD loading to the anaerobic zone. A phosphorus mass balance was calculated to estimate the phosphorus content in the wasted sludge. The estimated phosphorus content of the waste sludge varied with total phosphorus removal efficiency. The estimated phosphorus content in the waste sludge for anaerobic HRT periods of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed were 2.01, 3.97, 7.44, and 7.34% respectively. Phosphorus fractions in waste sludge greater than 2.5 % of volatile solids by weight indicate enhanced uptake and removal. As shown in Figure 14, the mass of phosphorus removed in excess of 2.5% by weight of the waste sludge VSS was -1.7, 1.8, 16.9, and 11.1 g/d for nominal anaerobic HRTs of 0.21, 0.43, 0.64 hours and 0.64 hours with acetate feed, respectively. The nutrient removal efficiencies as well as the estimated waste sludge total phosphorus content as are shown graphically in Figure 12. A profile of average soluble phosphate (Figure 15) daily effluent mass through individual pilot plant basins generally indicates steadily declining phosphate loadings as the process progresses from anaerobic to aerobic units.

Clean water K_La calibrations

Bench scale reactor clean water calibration Oxygen mass transfer coefficients measured for clean water under field conditions (K_{La_f}) were determined for the 21 liter bench scale reactor. Fifteen observations were made, all at the same constant air flow rate, at temperatures varying from 2.2 °C to 28 °C. The observed values of K_{La_f} ranged from 5.3 /h to 12.49 /h.

A geometric temperature correction factor, θ , was determined from the same clean water K_{La} data. A nonlinear regression was used to model the temperature dependence of the data. The following model was used:

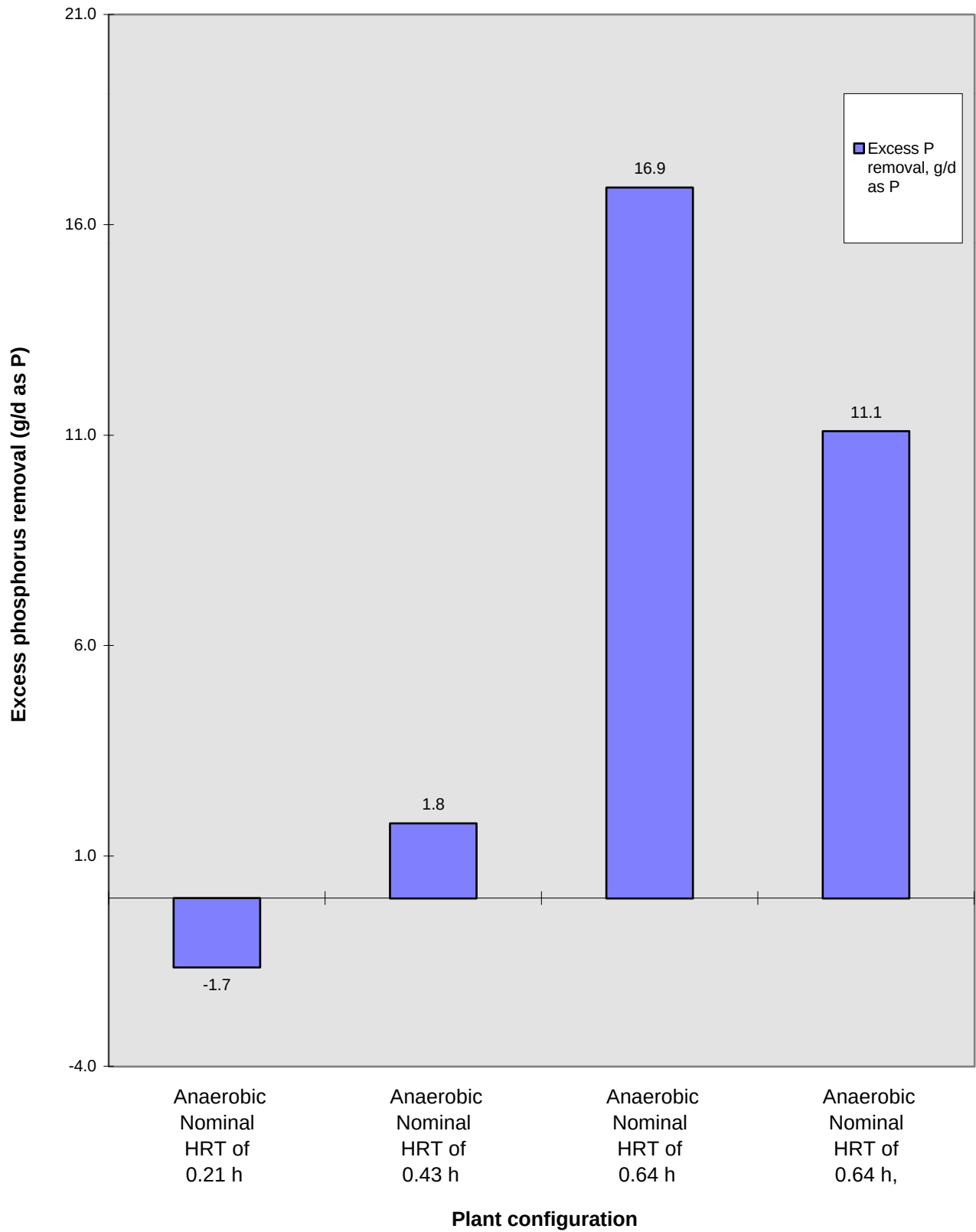


Figure 14. Estimated total excess phosphorus removal for the four evaluated pilot plant operational conditions.

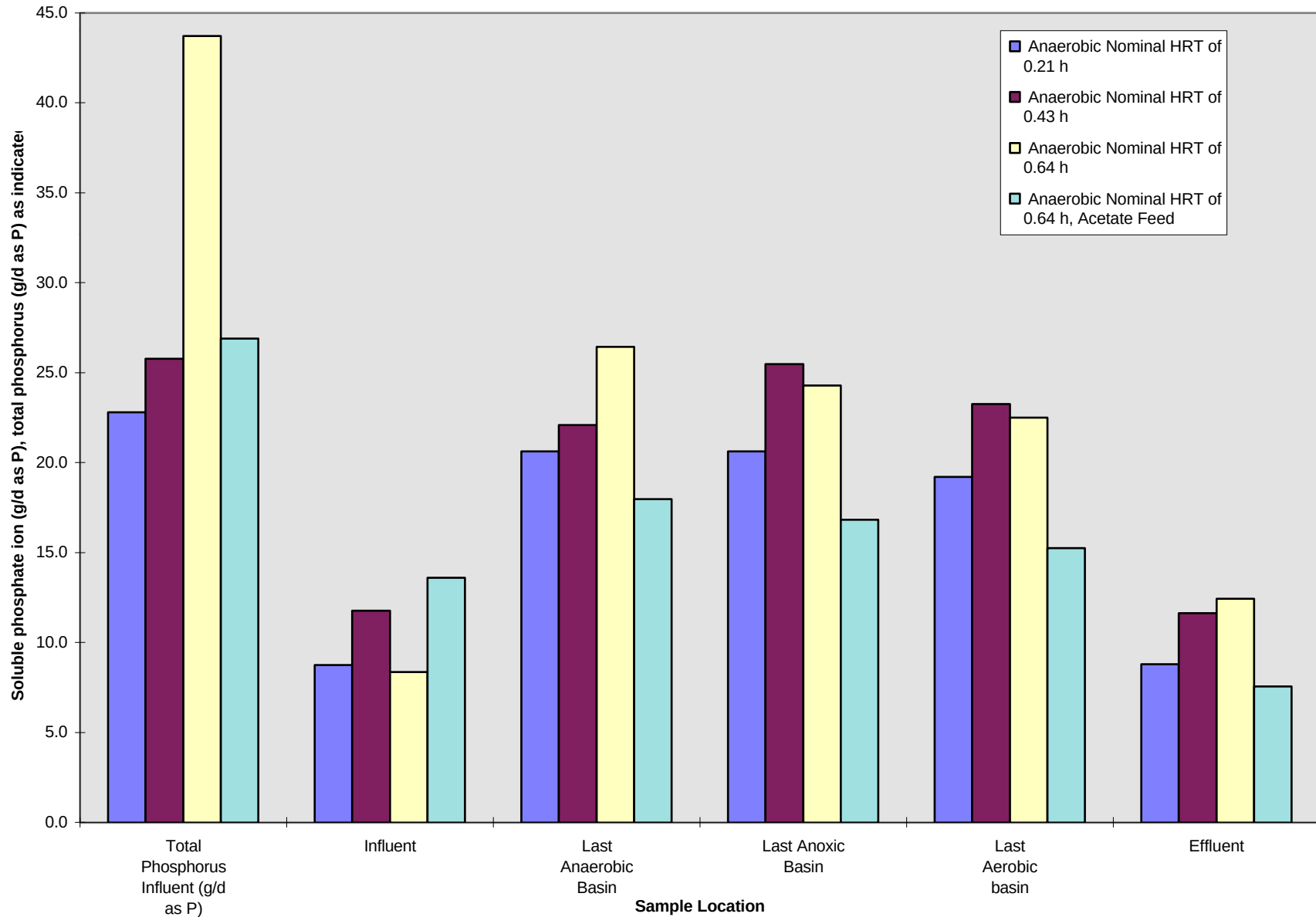


Figure 15. Pilot plant influent total phosphorus and soluble phosphorus at various points in treatment for differing plant configurations.

$$K_L a_f = K_L a_{(20)} q^{(T-20)} \dots \dots \dots \text{Equation 8}$$

With measured values of $K_L a_f$ and temperature, a non linear regression was used to estimate values of $K_L a_{(20)}$ and θ . Estimated values of $K_L a_{(20)}$ and θ of 9.82 h^{-1} and 1.026 respectively were determined. The nonlinear regression had a regression coefficient, R^2 , of 0.830 . A graph of the data and fitted regression model is shown in Figure 16.

Pilot plant clean water calibration. Oxygen mass transfer coefficients for clean water at three airflow rates, and a temperature correction factor were determined for the three aeration zones of the pilot plant. Each basin was evaluated at the airflow rates of 20, 40, and 60 standard ft^3/h . A total of 47 $K_L a$ determinations for clean water in the pilot plant basins were made. Four $K_L a$ determinations were made for each of the three airflow rates in each of the three basins for a total of 36 trials. An additional 11 determinations were made in basin #1 at an airflow of 40 scfh over an extended temperature range. Two $K_L a$ trials were rejected because the dissolved oxygen probe failed to stabilize within five percent of the calibrated value at the end of the test. The tests were conducted over temperatures ranging from 8.7°C to 19.6°C .

A non linear regression was used to estimate the parameters $K_L a_{(20)}$ and θ . A second-degree expression was incorporated into the model to estimate the relationship between $K_L a$ and airflow. Three airflow rates were used in the experimental setup. By using a second-degree expression, which is fully defined by three points, the overall fit of the model to $K_L a_{(20)}$ and θ parameters was maximized and the fit was not constrained by the assumed airflow model. The second degree relationship is also consistent with findings by Newby(1998). The non linear regression model that was used is as follows:

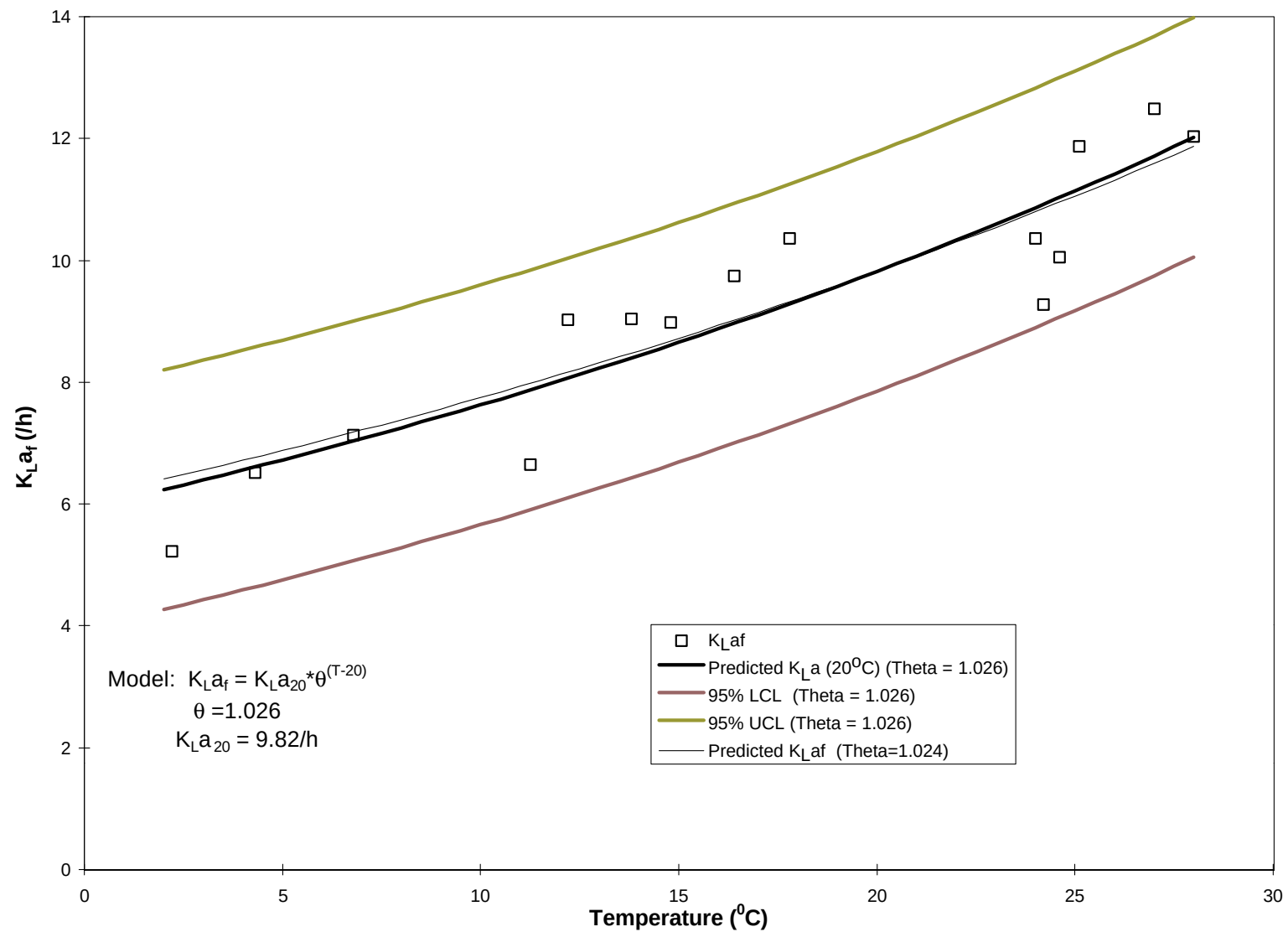


Figure 16. Bench scale reactor $K_L a_f$ and temperature coefficient determination and data for clean water.

$$K_L a_f = K_L a_{(20)} q^{(T-20)} \dots\dots\dots \text{Equation 9}$$

and:

$$K_L a_{(20)} = (A Q_s^2 + B Q_s + C) \dots\dots\dots \text{Equation 10}$$

The parameters $K_L a_{(20)}$ for each of three airflow rates and θ were estimated by the non linear regression analysis. Upper and lower 95% confidence levels for θ were determined directly from this model using the 45 data points. Upper and lower 95% confidence levels for $K_L a_{(20)}$ at each of the three airflow rates were determined by repeating the regression analysis three times using only data with equal airflow rates and the predetermined theta while solving for a specific $K_L a_{(20)}$ at the given airflow rate. Therefore upper and lower confidence levels for $K_L a_{(20)}$ at 20, 40, and 60 scfh are based on 11, 22 and 12 data points respectively. Table 4 presents the clean water oxygen transfer parameter estimates for the pilot plant. A box plot of the pilot plant $K_L a$ data transformed to 20 °C is presented in Figure 17. As the box plots and the value near zero of the second degree coefficient, A, indicates, $K_L a$ was found to have a nearly linear dependence on airflow.

Table 4. Summary of pilot plant clean water oxygen transfer parameters.

Parameter Name	Parameter Estimate	Number of Trials	Lower 95% Confidence Level	Upper 95% Confidence Level
Temperature correction coefficient, θ	1.037	45	1.029	1.045
$K_L a_{(20)}$ at 20 scfh, h^{-1}	5.56	11	5.07	6.05
$K_L a_{(20)}$ at 40 scfh, h^{-1}	10.06	22	9.72	10.39
$K_L a_{(20)}$ at 60 scfh, h^{-1}	14.13	12	13.7	14.5
A	-0.000538	45	-0.00170	0.000622
B	0.257	45	0.166	0.349
C	0.634	45	-1.14	2.41

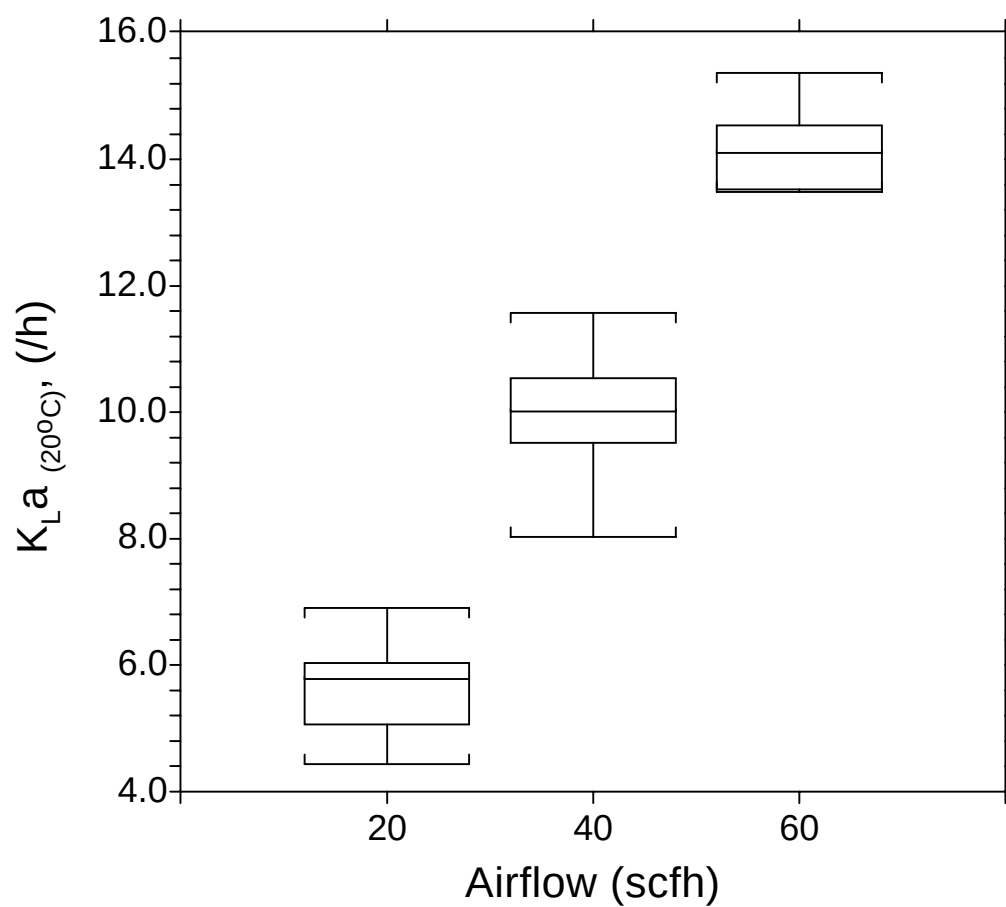


Figure 17. Box plot of the pilot plant clean water data transformed to 20 °C using theta of 1.037. The number of data points represented are 11, 22, and 12 for 20, 40 and 60 scfh air flow, respectively.

Evaluation of K_La determination method.

The dual step method described by Mueller (1983) was used to determine the K_La , alpha and OUR by in situ non steady state methods in the first aeration basin of the pilot plant. Prior to and following each non steady state test, bottle OURs were performed and steady state determination of K_La and alpha were made. Comparisons were then made between OUR, beta, and alpha determined by bottle and steady state methods as opposed to results determined by the non steady state in situ dual step method.

Two of the dual step tests were conducted with a pilot plant anaerobic HRT of 0.21 h. The remaining seven dual step tests were conducted with a pilot plant anaerobic HRT of 0.43 h. Non steady state alpha ranged from 0.55 to 1.10 with a mean of 0.80 and median of 0.76. Alpha determined by steady state method and bottle OUR ranged from 0.21 to 1.17 with a mean of 0.60 and median of 0.63. Oxygen uptake rates determined by the dual step method ranged from 12.7 to 116 mg/L-h with a mean of 50.1 and a median of 38.5. Oxygen uptake rates as determined by bottle OUR ranged from 10.1 to 32.9 mg/L-h with mean of 21.4 and median of 25.2 mg/L-h. A summary of the dual step method data is presented in Table 5.

Performing the dual step K_La analysis allowed an estimation of in situ OUR independent of bottle OUR techniques. The data are summarized in Table 5. The ratio of bottle OUR to in situ OUR was computed. The ratio ranges from 0.22 to 0.93 a strong indication that the bottle OUR data used in this research may have been biased. Ratios near unity would indicate no bias. As the OUR computed by the dual step method increased, the ratio of bottle OUR to computed OUR decreased, deviating further from unity (see Figure18). The higher OURs indicated a more rapid depletion of the available substrate. The higher the OURs, the more the system deviated from an endogenous condition. As indicated in Figure 18 the nearest agreement between bottle OUR and computed OUR occurred when the OURs were the lowest. This agrees with Mueller's (1990) assessment that bottle OURs are most accurate during endogenous conditions.

Further analysis was made to determine the accuracy and applicability of the use of the dual step method for this application. Mueller and Rysinger (1981) indicated that the dual step method accurately predicted the field saturation value, $C_{\infty f}^*$, when the ratio of the dual values of $K_L a$ determined in the analysis was greater than 5. As the ratio of the dual values of $K_L a$ approaches 1.0, small inaccuracies in either or both of the values of $K_L a$ result in large inaccuracies of the predicted $C_{\infty f}^*$ and R . There must be sufficient difference between the dual $K_L a$ measurements to insure accuracy.

Beta, the ratio between the field saturation value and the clean water saturation value ($C_{\infty f}^* / C_{\infty}^*$), may be approximated by the ratio of the field saturation value to the theoretical solubility, or book saturation value (C_{sat}), if the clean water field saturation value equals the book saturation value. In conditions where aerator depth and the system energy intensity does not induce a difference between C_{∞}^* and C_{sat} , C_{sat} may be used as a substitute value for C_{∞}^* without further adjustment for aerator depth. For the pilot plant basins operating under clean water conditions, the measured average value of the ratio of C_{∞}^* to C_{sat} was near unity ($C_{\infty}^* / C_{sat} = 1.01$, $n = 48$). This experience with the clean water testing indicates that the ratio $C_{\infty f}^* / C_{sat}$ can be accurate predictor of beta for this set of basins and aerators.

The simultaneous steady state and dual non steady state $K_L a$ determinations allow for three separate judgments of the value for beta. For the steady state analysis, beta was assumed to equal 0.98 based on a review of total dissolved solids data. For each $K_L a$ determination of the dual non steady state analysis a simultaneous bottle determination of OUR was made, so that $C_{\infty f}^*$ and beta could be determined by Equation 6 with the value of the bottle OUR substituted for R . Finally, a third measurement of $C_{\infty f}^*$ (and beta) may be obtained by the dual step non steady state method and the direct application of Equations 5 and 6. Evaluation of the values for beta determined by these three methods is a valid means to compare these three methods their accuracy.

The assumed beta for non steady state analysis was 0.98. As indicated in Table 5, the average computed beta for the dual non steady state method was 1.29 with a range

from 0.67 to 2.05 and a standard deviation of 0.394 ($n = 18$). The average beta based on non steady state $K_L a$ and simultaneous bottle OUR is 0.85, with a range from 0.59 to 1.20 and a standard deviation of 0.16 ($n = 18$). There was a much better agreement between the assumed value of beta and the value of beta determined using the non steady state $K_L a$ and bottle OUR than there was between the assumed value of beta and the value of beta determined by the dual step non steady state method. Furthermore, the finding of a value of beta greater than 1.0 using the dual step non steady state method casts serious doubt on the method's reliability.

The average ratio between dual $K_L a$ values used in the dual step non steady state method was 1.52, with a range from 1.1 to 2.2. The poor agreement between bottle OUR and OUR determined by dual step method, the poor agreement between the assumed value for beta and the value of beta determined by the dual step method and the determined value of beta significantly greater than one, may be attributed to inaccuracies in OUR computed by equation 5 due to the small difference between the measured dual values of $K_L a$.

The average value of alpha determined by steady state analysis and the average value of alpha determined by non steady state analysis were set equal to each other by using an assumed value of 0.9225 for beta in the steady state analyses. The resulting steady state determinations had a average alpha of 0.80, a median alpha of 0.72, a range of alpha from 0.24 to 3.20, and a standard deviation of 0.65 ($n = 18$). Although revising the assumed beta resulted in the same average alpha using steady state and non steady state determinations, the resulting steady state alpha determinations were not more accurate. The revised steady state alphas had a standard deviation over three times as large as the non steady state alpha standard deviation, and had outlying values up to a value of 3.2. The results indicate that the initial assumption of beta for steady state analysis cannot be rejected in favor of a lower value needed to align alpha results from steady state and non steady state methods. The results also indicated that the source of differences between

alphas determined by steady state and non steady state techniques may be inaccuracies in OUR measurement rather than caused by an inaccurate assumption of beta.

OURs determined by the bottle method were used to compute K_La under steady state conditions which were in turn used to compute alphas. Alphas also were determined by non steady state methods simultaneously with the steady state methods. The results of this experiment indicated that the alphas measured by non steady state techniques were significantly lower than the alphas measured by steady state techniques for the same conditions (Figure 19). The under estimation of OUR under substrate limited conditions with the possible over estimation of beta led to an under estimation of steady state K_La and alpha.

Bench reactor influent alpha

The calibrated 21 liter bench scale reactor was used to measure the value of K_La in pilot plant influent samples. A total of 14 non continuous, non steady state oxygen mass transfer determinations were made in the bench scale reactor over a temperature range from 14.9 to 24.7. It was determined that K_La adjusted to 20 degrees centigrade for primary effluent ranged from 5.36 to 8.90 resulting in alphas ranging from 0.546 to 0.907. The mean alpha was 0.710 with a standard deviation of 0.119. The mean of the fourteen sampled alphas has lower and upper 95 % confidence limits of 0.679 and 0.743 respectively.

Bench reactor BNR alpha

The 21 liter bench scale reactor was used to measure K_La and alphas from the contents of the initial stages of the pilot plant. The bench scale reactor measured K_La and alpha for four reactor contents: equal parts influent and return activated sludge from the pilot plant; effluent from the first pilot plant anaerobic zone; effluent from the second

Table 5. Dual non steady state K_La analysis results and summary table.

										Ratio of			Beta	Beta		
										Dual Step	Bottle OUR			Computed	Computed	
										Method	to			by Dual	by Bottle	
										Computed	Computed	NSS	SS Alpha	Step	OUR and	SS Alpha
										OUR	Alpha	(β= 0.98)	Method	NSS K _L a	(β=.9225)	
Trial	Date	Anaerobic	Air flow		K _L a	Temp		Bottle OUR	Computed OUR							
		HRT (h)	rate	Q(gph)	(/h)	(C)	C _R (mg/L)	(mg/L-h)	(mg/L-h)	OUR	Alpha					
1	1/2/97	0.64	20	80	3.49	14.2	5.30	11.4	27.1	0.42	0.98	0.62	1.444	1.079	0.718	
1	1/2/97	0.64	40	80	5.16	14.2	7.76	10.1	27.1	0.37	1.10	0.87	1.353	0.957	1.297	
2	1/7/97	0.64	20	0	4.29	13.1	6.66	14.8	16.8	0.88	1.02	0.88	1.106	1.198	1.091	
2	1/7/97	0.64	60	0	9.41	13	8.79	14.8	16.8	0.88	1.05	1.17	1.122	1.044	3.198	
3	3/4/97	0.43	40	126.6	4.45	14.20	3.53	10.7	12.7	0.84	0.55	0.24	0.762	0.630	0.265	
3	3/4/97	0.43	60	126.6	6.29	14.2	4.44	10.5	12.7	0.82	0.55	0.21	0.695	0.593	0.239	
4	3/8/97	0.43	40	126.6	5.68	14.2	2.94	25.4	57.5	0.44	0.70	0.43	1.421	0.744	0.474	
4	3/8/97	0.43	60	126.6	6.56	14.2	4.17	25.4	57.5	0.44	0.57	0.40	1.344	0.651	0.445	
5	3/17/97	0.43	40	67.2	6.58	14.50	4.61	25.5	38.5	0.66	0.80	0.59	1.100	0.836	0.663	
5	3/17/97	0.43	60	67.2	7.69	15.2	5.45	25.1	38.5	0.65	0.65	0.53	1.087	0.773	0.615	
6	3/18/97	0.43	40	65.4	6.07	15.2	5.05	14.3	17.0	0.84	0.72	0.40	0.862	0.808	0.464	
6	3/18/97	0.43	60	65.4	7.88	15.5	5.75	17.3	17.0	1.02	0.66	0.42	0.839	0.764	0.492	
7	3/18/97	0.43	40	160.2	7.83	15.2	3.72	30.8	68.7	0.45	0.93	0.64	1.393	0.932	0.715	
7	3/18/97	0.43	60	160.2	9.11	15.5	4.88	32.9	68.7	0.48	0.76	0.64	1.319	0.813	0.729	
8	3/20/97	0.43	40	160.2	7.98	15.8	3.71	31.8	95.9	0.33	0.92	0.66	1.750	0.940	0.736	
8	3/20/97	0.43	60	160.2	8.95	15.8	4.89	32.9	95.9	0.34	0.74	0.65	1.685	0.823	0.744	
9	3/25/97	0.43	40	317.4	8.11	14.5	3.98	25.8	116.3	0.22	0.99	0.67	2.036	0.936	0.744	
9	3/25/97	0.43	60	317.4	8.91	14.9	5.06	26.5	116.3	0.23	0.76	0.70	1.834	0.797	0.806	
Mean								21.4	50.1	0.57	0.80	0.60	1.29	0.85	0.80	
Median								25.3	38.5	0.46	0.76	0.63	1.33	0.82	0.72	
Standard Deviation								8.4	36.2	0.25	0.18	0.23	0.38	0.16	0.65	

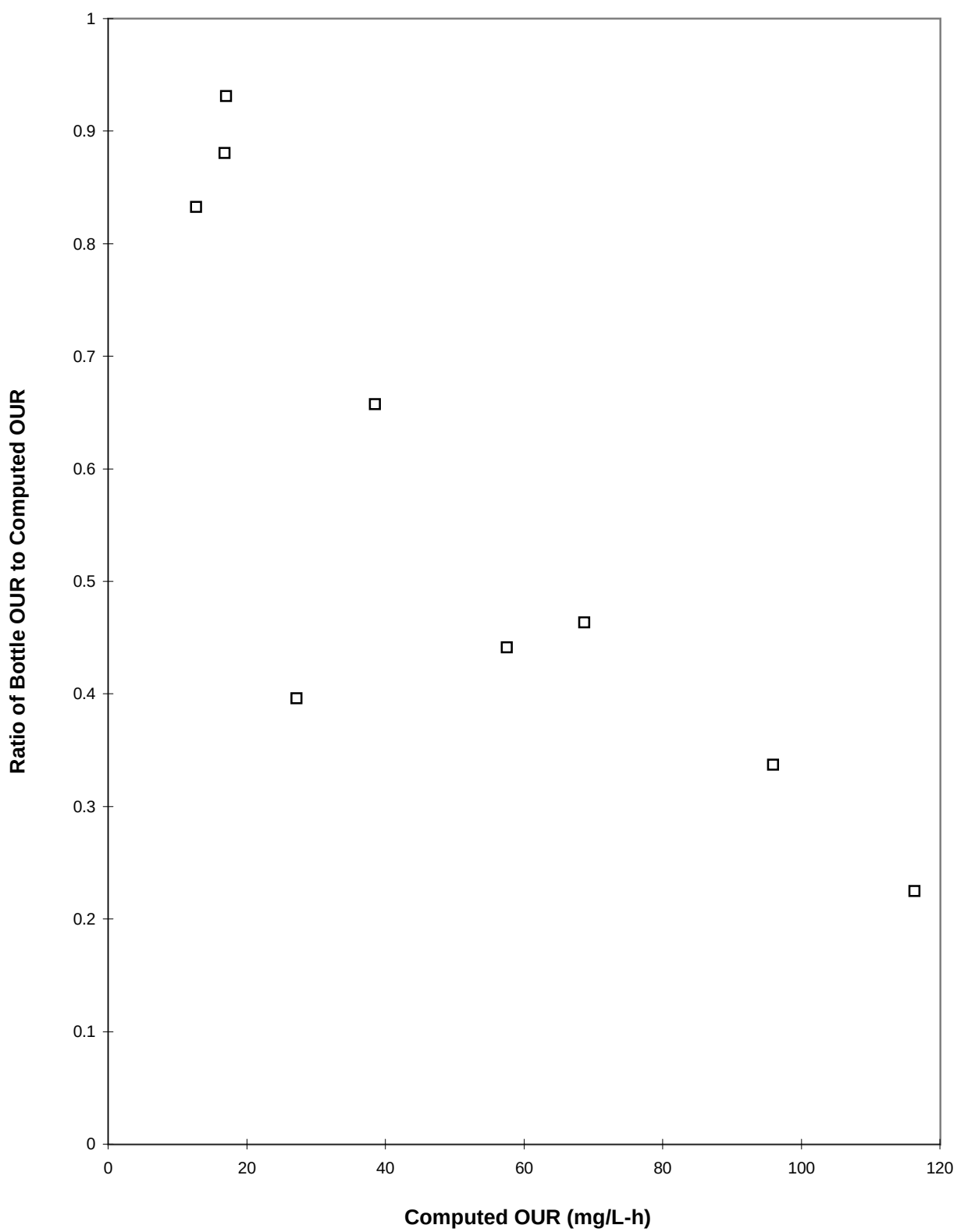


Figure 18. Ratio of Bottle OUR to calculated OUR versus calculated OUR determined by the non steady state step method.

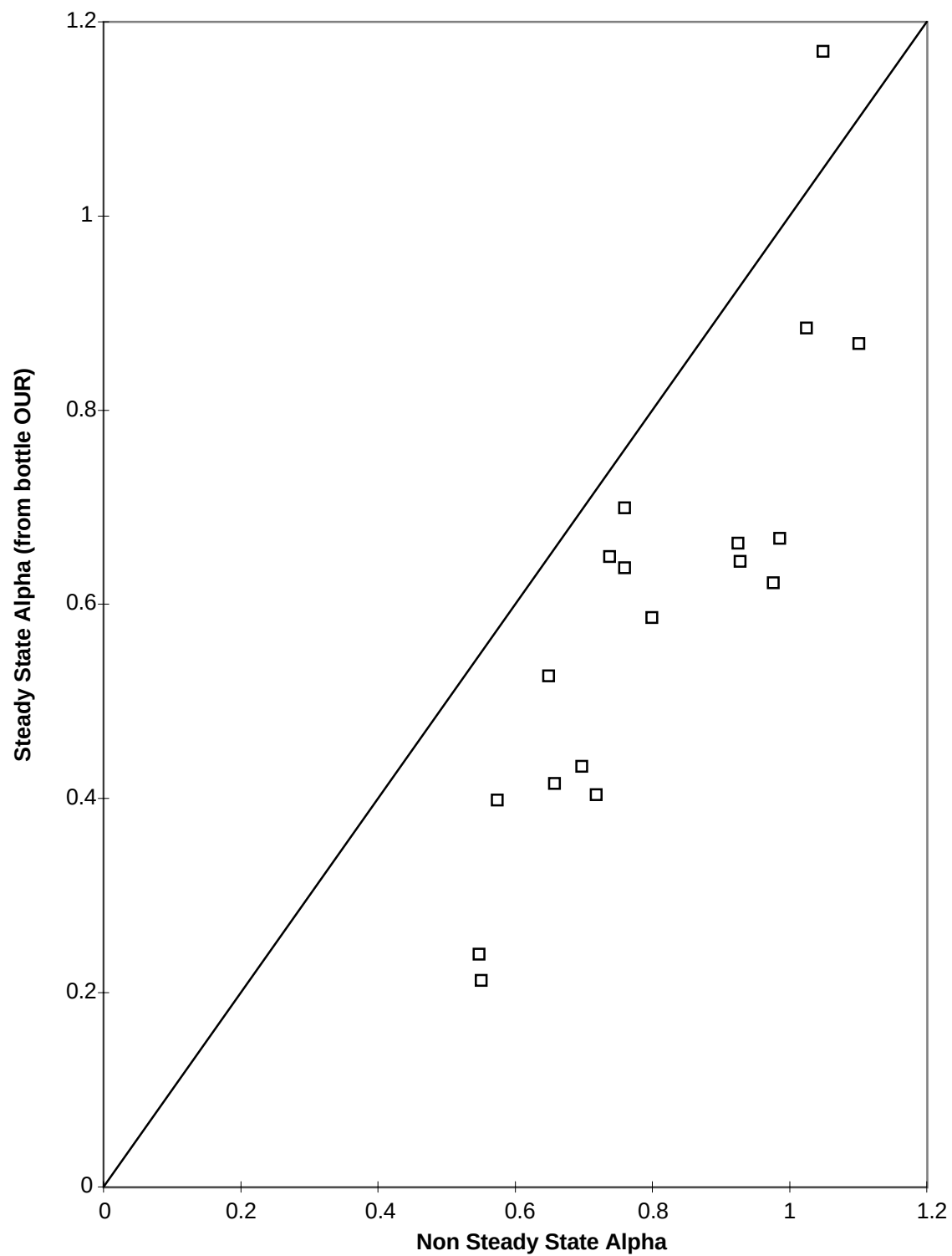


Figure 19. Steady state versus non steady state alpha. Steady state alpha as determined by bottle OUR plotted against alpha determined by non steady state techniques.

pilot plant anaerobic zone; and effluent from the first pilot plant anoxic zone. The values of K_La were determined in triplicate by the continuous non steady state method. The flow through the bench scale reactor was set at 42 L/h for an estimated mean hydraulic residence time 0.5 h. The anaerobic basins each had an estimated mean hydraulic retention time of 0.215 hours. In addition to influent and RAS flow, each 454L/h, the anoxic basin received an internal recycle flow of 454 L/h. The estimated actual mean hydraulic retention time for the anoxic basin was 0.17 h. The results of the oxygen mass transfer determinations are presented in Table 6.

Table 6. Summary of results of bench scale reactor alpha and $K_La_{(20)}$ determinations on effluent from different pilot plant pre-aeration basins.

Basin	Average $K_La_{(20)}$, hr^{-1}	Average Alpha	Average OUR, $mg\ L^{-1}\ hr^{-1}$
Influent and RAS	9.20	0.94	30.66
Anaerobic #1	9.85	1.00	34.27
Anaerobic #2	9.09	0.93	37.75
Anoxic #1	4.89	0.50	36.22

The results indicate that alpha values for direct aeration of influent with RAS before treatment, after treatment in one anaerobic zone, and after treatment in two anaerobic zones varied from 0.94 to 1.01 to 0.93 respectively. An analysis of variance (ANOVA) was performed on the bench reactor alpha data to test whether the measured values for alpha were significantly different as the number of anaerobic zones varied. Although the means for alpha as a response to the three treatments were not equal, the results of the ANOVA indicated that the alphas were not significantly different at a 0.05 level of significance. (The measured probability level was 0.76)

Alpha measured in the anoxic basin was sharply lower than the alphas for the anaerobic basins or the influent plus RAS. An average alpha of 0.50 was determined

based on two measurements (results of the third trial was not completed due to mechanical failure).

Pilot plant influent alpha

The Pilot Plant was used to determine the K_La and alpha of aeration basin 1 when it was receiving RAS and primary clarifier effluent without prior treatment in anoxic or anaerobic zones. A return activated sludge flow of approximately 454 L/h and a primary clarifier effluent plant influent flow of approximately 454 L/h were maintained to simulate the same influent and RAS flows received by the pilot plant. A total of 32 K_La and alpha determinations were made. Eight of those determinations were made using non steady state methods while 24 determinations were made using steady state methods. Non steady state determinations were made at a range of temperatures from 14.8 to 17.1 °C, including three trials at an airflow of 40 scfh and five trials at an airflow of 60 scfh. Steady state determinations were made over a temperature range of 14.8 to 17.1 °C and included eleven trials at 20 scfh, six trials at 40 scfh, and seven trials at 60 scfh. The mean alpha for all the trials, determined with both steady state and non steady state methods, was 0.714 with a standard deviation of 0.155. The mean for the eight non steady state and twenty-four steady state determinations of alpha were 0.749 (with 0.155 standard deviation) and 0.703 (with 0.084 standard deviation), respectively. A two value unequal variance t test was used to determine that the difference between the non steady state mean alpha and steady state mean alpha was not greater or less than zero at the 95% confidence level ($p = 0.35$).

The value of K_La was twice measured for primary influent (not mixed with RAS) in the pilot plant aeration basin 1 at an air flow of 60 scfh. The two measurements for K_La (20) were 3.96 and 4.73 /h. The alpha for the same two measurements were 0.280 and 0.384. A measurement of K_La in the bench scale reactor yielded an alpha of 0.684 concurrent with the 0.384 value determined in the pilot plant.

Pilot plant BNR alpha

While operating under single cell anaerobic zone and three anaerobic zones with acetate feed, each aeration basin in the pilot plant was subjected to nearly simultaneous determinations of K_La and α by the continuous steady state method. These trials were repeated eleven times so that there were eleven joint determinations of K_La in each of the three aeration basins. The K_La determinations were carried out at different internal recycle rates and at three different air flow rates. When all thirty three trials over all three basins are considered, the mean α was 0.760, with a standard deviation of 0.196.

When the results of the α determinations are considered in each basin separately, differences in the three α s are apparent. The mean α s for aeration basins 1, 2, and 3 are 0.905, 0.716, and 0.661 respectively. The mean values of α are shown in Figure 20. The mean oxygen uptake rate in aeration basins 1, 2, and 3 was 18.0, 17.1, and 18.2 mg/L-h respectively. The mean hydraulic flows through aeration basins 1, 2, and 3 were 545, 575, and 1580 L/h

An ANOVA performed on the same data indicated that the mean α in each aerobic basin was not equal for all basins ($F=6.17$, $p=0.006$). Further comparison by the Duncan's Multiple Comparison Test, Fisher's LSD Multiple Comparison Test, and Tukey-Kramer Multiple Comparison Test all indicated that the mean α of aeration basin 1 was different from the mean α of both aeration basins 2 and 3. The additional comparisons also indicated no difference in the mean α between aeration basins 2 and 3.

Pilot plant surface tension, progressive aerobic treatment

A total of fourteen paired samples were collected in each of the three pilot plant aeration basins for surface tension analysis. The mean surface tensions determined in five replicates for all fourteen samples each in aeration basins #1, #2, and #3 were 65.7, 66.8, and 66.7 dynes/cm respectively. An additional seven samples of primary effluent were

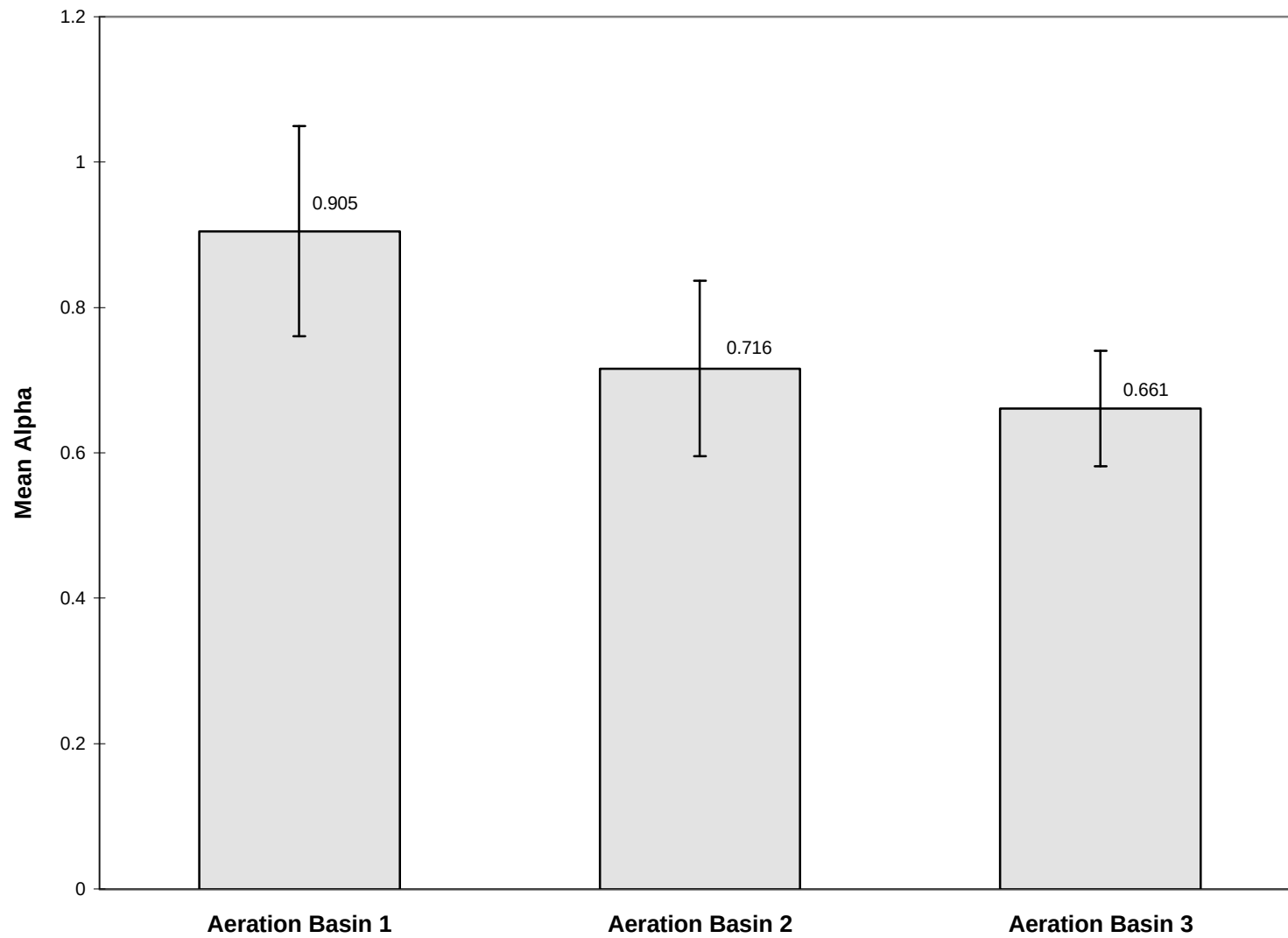


Figure 20. Pilot plant alpha in aeration basins while operating with an anaerobic HRT of 0.21 hours.

collected along with seven of the thirteen paired samples. The mean surface tension of the six influent samples was 62.2 dynes/cm.

The measured surface tensions in each aeration basin was compared with influent surface tension and the surface tension of contents or the other aeration basins. The comparisons were made with single sided paired t-test to determine if the more treated samples had higher surface tension values than the less treated samples at a 95% level of significance. Each comparison between aeration basins compared 70 pairs (fourteen samples by five replicates). Each comparison between aeration basin and influent compared 35 pairs of measurements (seven samples by five replicates). The results of the t-tests indicated that the influent surface tension was significantly lower than the first aeration basin surface tension ($t = 5.27$, $p = 0.0000$, $P = 0.9998$). The results further indicated that the first aeration basin surface tension was significantly lower than the second aeration basin surface tension ($t = 2.58$, $p = 0.0061$, $P = 0.817$), and significantly lower than the surface tension of the third aeration basin ($t = 2.19$, $p = 0.0161$, $P = 0.699$). The t-test results also indicated that there is no significant difference between the mean values of the surface tension in the second and third aeration basin ($t = 0.196$, $p = 0.423$, $P = 0.0734$). The data indicates a significant increase in surface tension from the first to last aeration basin.

The surface tension of a filtered sample of the contents in each aeration basin was measured along with six out of the eleven paired determinations of K_La . The average surface tensions for aeration basins #1, #2, and #3 were 66.9, 67.5, and 67.9 dynes/cm respectively, as illustrated by Figure 21.

Pilot plant alpha and anaerobic HRT.

The pilot plant was configured in four different flow schemes each with a different anaerobic zone HRT. Nominal HRTs in the anaerobic zone of 0.0, 0.21, 0.43, and 0.64 hours were used. K_La measurements were made while the pilot plant was in each

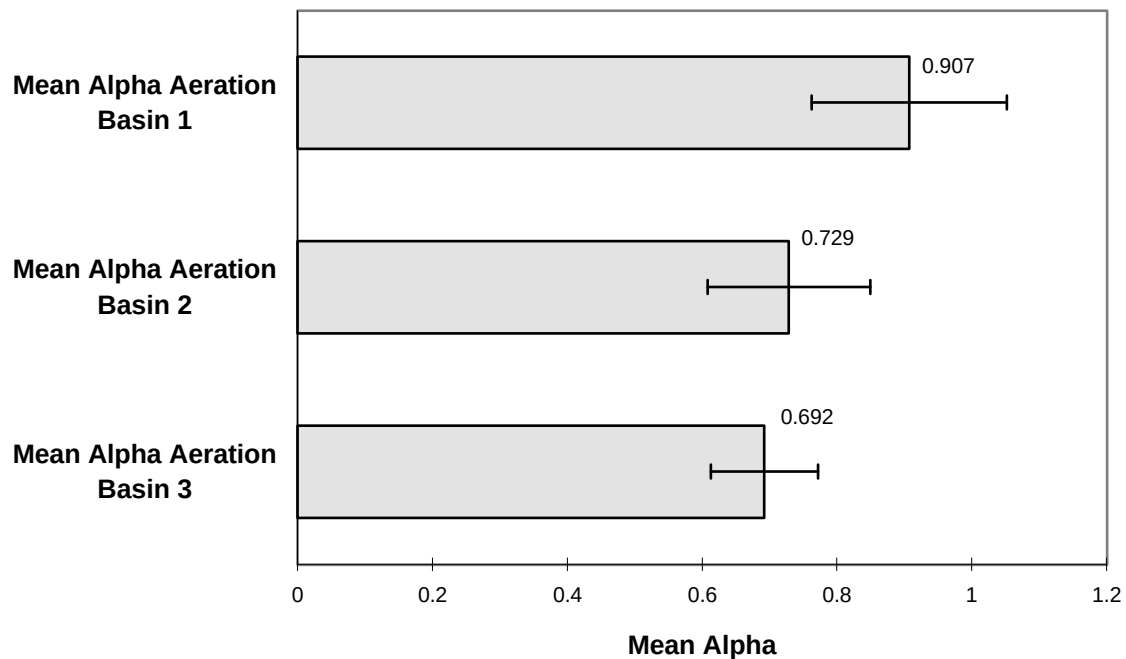
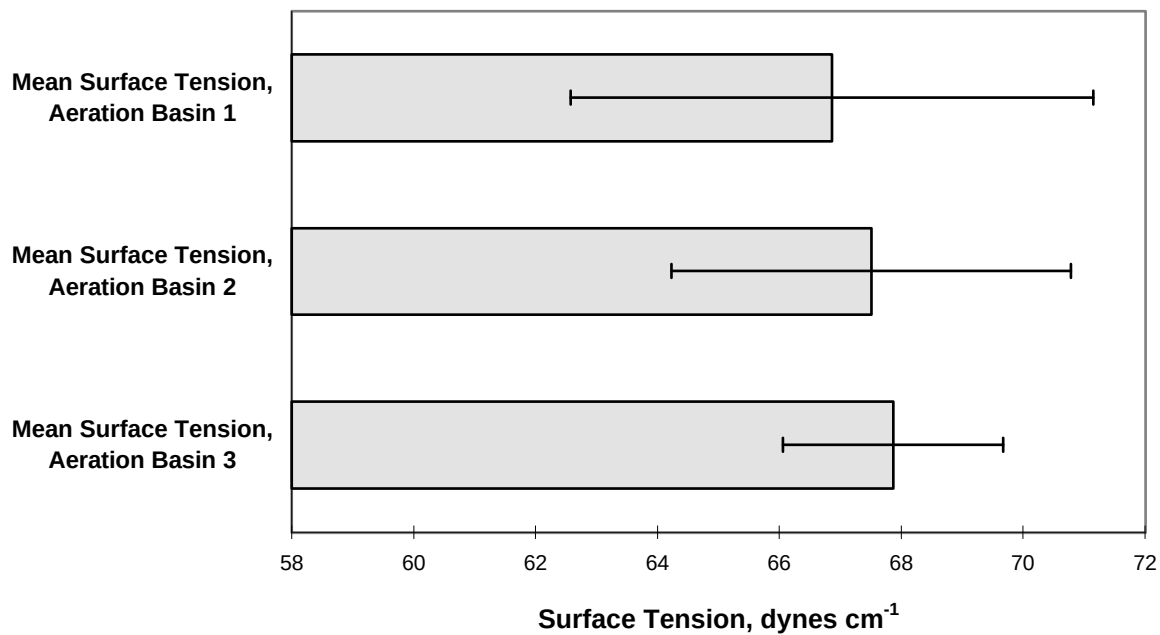


Figure 21. Top: Surface tension measured in pilot plant concurrent with alpha measurements. **Bottom:** Mean alpha of pilot plant aeration basins taken simultaneously with the surface tension measurements presented above.

configuration and the values of K_La were converted to alphas under standard conditions.

A total of 32 alpha determinations were made in the first aeration basin while the plant received influent directly into the first aeration basin. Under this flow scheme the anaerobic zone HRT was 0 hours. The alpha was determined by continuous flow non steady state measurements eight times and by continuous flow steady state measurements a total of 24 times. The thirty two measurements of alpha had a mean of 0.714 and median of 0.740, a variance of 0.0242. The 95% confidence interval about the mean variance ranged from 0.0155 to 0.0427. The alpha data were distributed normally as determined by the Shapiro-Wilk W test.

A total of 12 alpha determinations were made in the first aeration basin while the plant was operated with one anaerobic zone having a nominal HRT of 0.21 hours. Alpha was determined by continuous flow non steady state measurements five times and by continuous flow steady state measurements a total of seven times. The measurements of alpha had a mean of 0.942 a median of 0.953, and a variance of 0.0210. The 95% confidence interval about the mean variance ranged from 0.0105 to 0.0606. The data were distributed normally as determined by the Shapiro-Wilk W test.

A total of 36 alpha determinations were made in the first aeration basin while the plant was operated with one anaerobic zone having a nominal HRT of 0.43 hours. The alpha was determined by continuous flow non steady state measurements 22 times and by continuous flow steady state measurements a total of fourteen times. The 36 measurements of alpha had a mean of 0.638, a median of 0.649, and a variance of 0.0322. The 95% confidence interval about the mean variance ranged from 0.0212 to 0.0548. The data were distributed as determined normally by the Shapiro-Wilk W test.

A total of 8 alpha determinations were made in the first aeration basin while the plant was operated with three anaerobic zones having a total nominal HRT of 0.64 hours without acetate feed added. The alpha was determined by continuous flow steady state measurements. The eight measurements of alpha had a mean of 0.735 and median of 0.715, a variance of 0.205. The 95% confidence interval about the mean variance ranged

from 0.00895 to 0.0848. The data were distributed normally as determined by the Shapiro-Wilk W test.

The alpha data indicated that each group tested was normally distributed, had a continuous response and had equal variances. However, since differing numbers of steady state and non steady state tests were made to determine alphas, a direct comparison of all the data is not made. Instead, steady state data and non steady state data are reviewed separately.

The data indicate that the alphas determined by steady state methods ranged from 0.507 to 1.014 with the peak alpha occurring at an anaerobic HRT of 0.21 hours. The data for each HRT evaluated had approximately equal variances. Each data group was also distributed normally as evaluated by the Shapiro-Wilk W normality test at the 95% significance level. Table 6 presents a summary of the steady state alpha data for the varying anaerobic HRT. The data is also shown in Figure 22 .

Table 7. Alpha in pilot plant aeration basin 1 measured by steady state methods.

Anaerobic				Variance	Variance
HRT (h)	Mean	Count	Variance	95% UCL	95% LCL
	Alpha				
0.00.	0.703	24	.0299	.0181	.0589
0.21	1.014	7	.01039	.00432	.0504
0.43	0.507	14	.0247	.0130	.0641
0.64	.0735	8	.0205	.00895	.0848

Given these characteristics, a single factor, balanced cell ANOVA was used to determine if the means differed between groups. A random sample of seven alpha measurements were selected from each group.

The four groups of seven random samples selected for each anaerobic HRT group had mean alphas of 0.671, 1.014, 0.498, and 0.739 for anaerobic HRTs of 0.0, 0.21, 0.43, and 0.64 hours respectively. The overall mean alpha for all 28 samples was 0.731. The

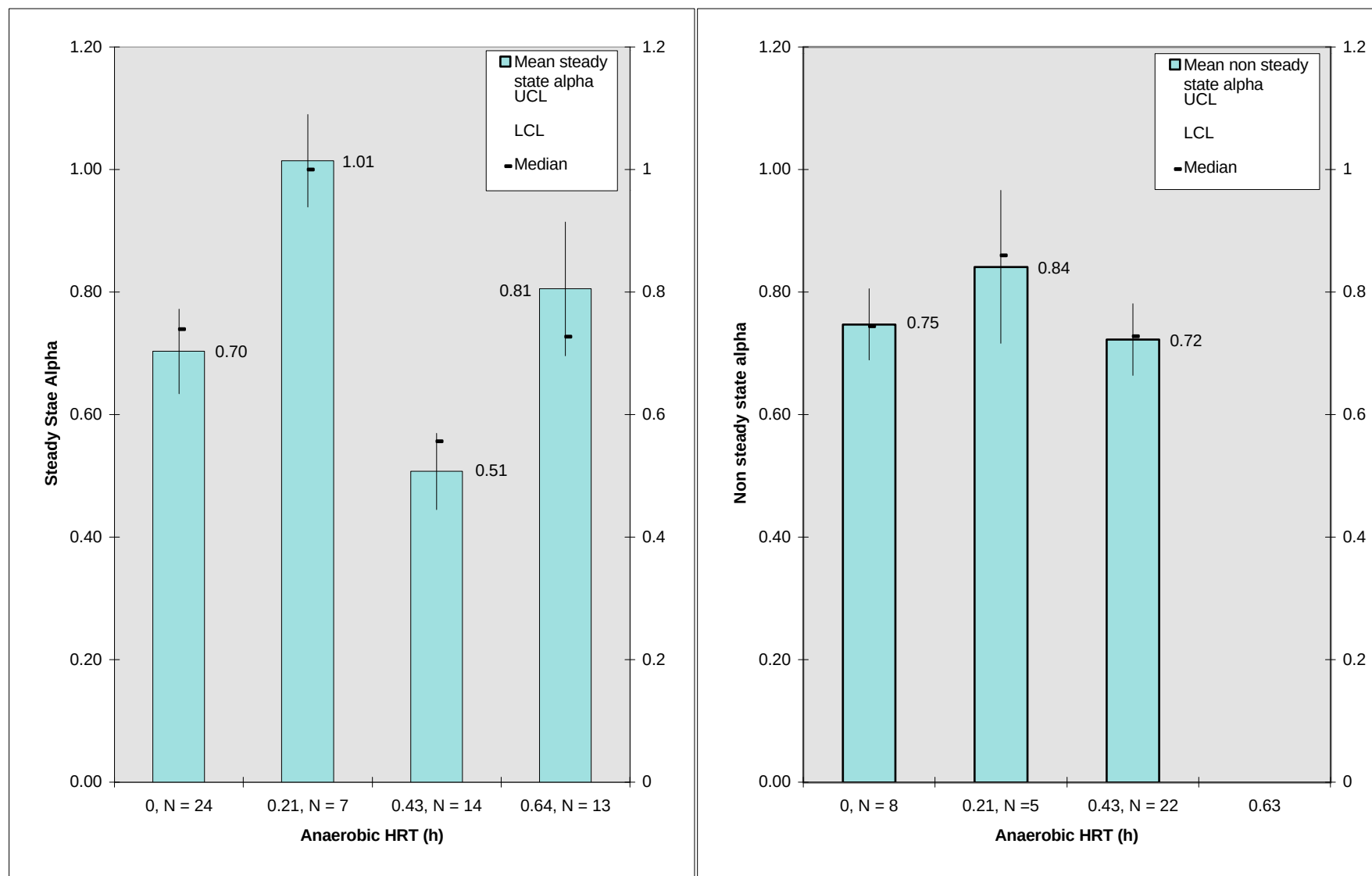


Figure 22. Alpha in pilot plant aeration basin 1 versus anaerobic HRT. Columns show mean alpha, also shown are 5% confidence intervals about mean and median values. **Left:** Alphas determined by steady state methods using bottle OUR. **Right:** Alphas by non steady state analysis.

single factor ANOVA indicated that the null hypothesis that all means were equal should be rejected at the 0.05 significance level ($F = 14.32$, $p = 0.000015$, $\text{power} = 0.9997$).

Further comparisons of the means by the Tukey-Kramer Multiple comparison test at a 0.05 level of significance indicated that the mean of the group with the Anaerobic HRT of 0.21 hours differed from the other three groups. In addition, the mean alphas representing HRTs of 0.43 and 0.64 hours were also significantly different. Thus the ANOVA and the multiple comparison test indicate that a single anaerobic basin with a nominal HRT of 0.21 hours resulted in an increase in alpha over the group mean. Exposure to two and three anaerobic zones with longer anaerobic HRTs up to 0.64 hours did not result in significant differences in alpha relative to untreated influent. The data indicate that the alphas determined by non steady state methods ranged from 0.722 to 0.841 with the peak alpha occurring at an anaerobic HRT of 0.21 hours.

The data for each HRT evaluated had approximately equal variances. Each data group was also distributed normally as evaluated by the Shapiro-Wilk W normality test at the 95% significance level. Table 7 presents a summary of the non steady state alpha data for the varying anaerobic HRT. The data is also shown in Figure 22.

Table 8. Alpha in pilot plant aeration basin 1 measured by non steady state methods.

Anaerobic				Variance	Variance
HRT (h)	Mean	Count	Variance	95% UCL	95% LCL
	Alpha				
0.00.	0.747	8	.00706	.00308	.0292
0.21	0.841	5	.0203	.00729	.168
0.43	0.722	22	.0195	.0116	.0399

Given these characteristics, a single factor, balanced cell ANOVA was used to determine if the means differed between groups. A random sample of five alpha measurements were selected from each group.

Three groups of five random samples selected for each anaerobic HRT group had mean alphas of 0.694, 0.841, 0.744 for anaerobic HRTs of 0.0, 0.21 and 0.43 hours respectively. The overall mean alpha for all 15 samples was 0.760. The single factor ANOVA indicated that the null hypothesis that all means were equal should not be rejected at the 0.05 significance level ($F = 1.02$, $p = 0.3900$, power = 0.187). The test indicates no significant difference among the mean alphas as a result of different treatments. The relatively low power of the test indicates that the null hypothesis may have failed to be rejected due to insufficient sample size.

V. DISCUSSION

Discussion of results

Clean water results. Values for theta and clean water $K_L a_{(20)}$ were determined for both the bench scale reactor and the pilot plant . The calculated theta was quite different for the two types of reactor. The value of theta determined for the bench scale reactor equaled 1.026 The results agree favorably with the often recommended value of theta of 1.024 (ASCE(1992)).

The value of theta determined for the pilot plant aeration system, had a mean value of 1.037, and did not agree with the commonly recommended value of 1.024. Previous research has indicated that the value of theta may vary from 1.008 to 1.047 (EPA 1983) dependent on type of aeration device and basin geometry. The value of theta measured falls within this range. The determination of theta was necessary because the wide variation of temperatures experienced in the field did not allow for testing at or near standard temperature conditions. Oxygen transfer parameter determinations under process conditions were made over a range of temperatures from 9.5 to 24.9 °C. The value of theta was determined over range of temperatures from 8.6 to 19.6 °C, approximating actual conditions encountered. The determined theta represents the best estimate available for the equipment used, field conditions and range of air flows and should be considered the best available site specific value.

$K_L a$ determination method. The results indicated that there were significant differences in the average value of alpha determined by steady state methods (0.60) as compared to non steady state methods (0.80). The non steady state techniques are generally recommended in favor of steady state techniques for several reasons. While the steady state $K_L a$ determination depends on the measurement of a single dissolved oxygen

concentration, and a single OUR determination, the non steady state method depends on a series of dissolved oxygen measurements over an extended time. Non steady state data can be evaluated by statistical means and possible sources of error identified through residual plots. Steady state data are subject to errors induced in the bottle OUR determination techniques by oxygen or substrate limitations, and errors induced by deviations from steady state or homogeneous conditions at the time of sampling. The presence of such errors are not readily detectable through examination of the steady state data alone.

The dual step non steady state method was used to estimate OUR. The results were compared with the OUR measured by the bottle method, and were compared with the estimated beta used as a basis of the steady state test. The results of the dual step method indicated that the values of bottle OUR were, on average, 57% of the in situ OUR. It is reasonable to expect a difference between bottle and in situ OUR when testing continuous flow basins since substrate is held near a constant concentration in the basins whereas substrate is continuously depleted in the test bottle. Mueller and Stensel (1990), using dual non steady state tests, showed values for bottle OUR ranging from approximately 10 to 30 mg/L-h while in situ values for OUR ranged from approximately 10 to 75 mg/L-h. The present study showed a much wider disparity between bottle OUR values and in situ OUR values. This study had a similar range of bottle OUR values: from 10.7 to 32.9 mg/L-h. In situ OUR values ranged from 12.7 to 116.3 mg/L-h. The effect of substrate limited bottle OUR results appeared to be much more magnified in this study. The results pointed to a cause of biasing between steady state and non steady state alpha determinations.

The results of the dual step non steady state method were critically assessed by calculating the beta parameters implied by the dual non steady state method results, and comparing those to beta parameters calculated by combining non steady state K_{La} results and bottle OUR results. The average and range of values of beta resulting from the dual step non steady state data indicated a large degree of error in both the average value

(1.29) and the range (0.59 to 2.04). The anticipated range of beta was approximately 0.97 to 1.0. The beta parameters based on bottle OUR results for the same K_La determinations used in the dual step non steady state method averaged 0.85 and ranged from 0.24 to 3.20. The range was also quite different than expected values, although the average value was closer to the anticipated range. A review of the beta parameter results indicate that the OUR determined by the dual step non steady state test may be inaccurate due to too small a difference in the two K_La measurements making up each pair of the dual test. The same review of beta parameters indicates that the bottle OUR measurements are probably influenced by substrate limitations in the test bottle although the influence may not be as great as the results of the dual step non steady state tests indicate. Results of the non steady state tests indicated that the assumed value of beta used in steady state procedures may have been larger than the actual value of beta, and that inaccuracies in the steady state technique was caused by a combination of inaccuracies in OUR determination and assumed beta.

There are significant implication in the design of BNR treatment systems in regards to the applicability of dual step non steady state method of oxygen transfer parameter estimation. BNR plants depend on a combination of aerated and non aerated basins in which substrate is bio-oxidized. In conventional plants, all oxidation is performed in aerated basins. The operating dissolved oxygen concentration in BNR plants are often kept to a minimum to prevent excessive transport of unwanted dissolved oxygen to other basins. As a result, the operational aeration capacity and peak aeration capacity in BNR plants should less than that for similarly sized conventional systems. The utility of dual non steady state has been shown to be limited by a lack of turn up capacity of the aeration system being tested and, as a consequence, limitations due to the difference in dual values of K_La . In situ OUR determinations by the dual step non steady state method in BNR systems should be critically scrutinized to insure that sufficient aeration capacity is available for sound results.

Primary effluent results. The value of alpha for primary clarifier effluent was determined to be equal to 0.71 in the bench scale reactor. This result is greater than what is often indicated in the literature. The difference may be attributed to the geometry of the bench scale reactor. EPA(1983) has noted that shallower aeration reactors yield higher values of alpha due to the reduced opportunity for bubble coalescence in the shorter travel path from aerator to surface. When the wastewater contains surfactants which increase the propensity for bubbles to coalesce, the measured alpha should be lower for deeper aerators due to the increased travel distance of the bubble. The value of 0.71 for alpha is in line with values cited by Bachman(1987) for bench scale studies of tap water with low concentrations of surface active agent added.

The pilot plant aerators had an average alpha of 0.332 for primary clarifier effluent. This is near values reported in the literature.

When the primary clarifier influent was mixed with return activated sludge, at a 1 to 1 return ratio, an alpha of 0.714 was measured. This indicates that there is an immediate oxygen transfer benefit due to the contact with activated sludge and dilution effects.

Effects of initial anaerobic zones on alpha and surface tension. When the mixture of primary clarifier influent and activated sludge was first contacted in an anaerobic basin followed by contact in an anoxic basin, the mean alpha in the first aeration basin was found to be 0.905. The mean alphas over all the aeration basins was determined to be 0.760. Of three aeration basins however, only the first basin clearly had an alpha in excess of an alpha from a basin treating influent which had not had prior non aerated contact.

Contrary to the reported effect of an increasing alpha along with increasing degrees of treatment, the pilot plant demonstrated decreasing alphas with increasing aerobic and anaerobic treatment. The highest alphas were found in the first aeration basin and the lowest alphas were found in the second and third basins. Statistical analysis

indicated that the higher alphas in the first basin were significant although there was not a significant difference between the second and third basins.

Previous studies have shown an increase in alpha in fully aerated systems as treatment progresses. Boyle(1990) reported an increase in alpha along the length of a plug flow activated sludge basin in the direction of increasing treatment. The results of this study are contrary to that trend. These data show a very high alpha at the beginning of the aeration zone with declining alphas as sequential aerated-non aerated treatment progresses.

Surface tension measurements taken in all three aeration basins show an increase in the mean of the surface tension data as treatment progresses, however, the increase is not statistically significant. It appears from the surface tension data that as the treatment progresses, the surface tension increases and approaches that of clean water. The variation in the data do not allow a statistically significant conclusion in this regard. The statistical analysis indicates that the conclusion that such a trend is expressed in the data cannot be statistically supported at the 95% confidence level.

Nonetheless, if the noted increase in surface tension is an indication of lower surfactant concentrations with treatment, and if significant surfactant concentrations were present initially, the lower concentrations may result in the generation of larger bubbles and consequently contribute to a smaller transfer interfacial surface area.

The bench scale reactor data indicates that as anaerobic treatment progresses there may be a decrease in the alpha of subsequent aeration basins. The data indicated an increase in the mean value of alpha in the bench scale reactor following one anaerobic basin. There was then a drop in alpha following the first anoxic basin (with recycled aerated flow

A similar trend was indicated by the values for alpha in the first aeration basin of the pilot plant operation over the different plant configurations. With one, two and three anaerobic basins in operation, the alpha of the first aeration basin peaked with one anaerobic basin in use and decreased progressively with two and three anaerobic basins.

Alphas for the first aeration basin were larger with anaerobic treatment of wastewater in one and two basins than without anaerobic treatment. The data indicate that a relatively short anaerobic contact may be beneficial to oxygen transfer, however, too long of an anaerobic contact may degrade oxygen transfer performance.

The initial anaerobic basins may produce small molecular weight organic compounds and surfactant fermentation products which enhance oxygen transfer in the first aeration basin but which are also catabolized by respiration and depleted so are not present in the second and third aeration basins. The same fermentation processes may partially destroy large molecular weight surfactants (especially reducing the hydrophilic regions) which are present in the influent and which would be otherwise be expected to hinder oxygen transfer in the first aeration basin. Coexistence of the organics and the remaining surfactants in the first aeration basins may lead to an augmentation in alpha by inhibiting coalescence.

VI. Conclusions

- Effluent from a full scale primary clarifier, used as pilot plant influent, was found to have an alpha (ratio of process to clean water $K_L a$) of 0.71 as determined in a 21 liter bench scale reactor and an alpha of 0.332 as determined in a 0.45 m³ aeration basin of the 2.4 m³ pilot plant.
- Alpha of a 1:1 mixture of primary clarifier effluent with pilot plant return activated sludge was determined to be 0.94 at bench scale and 0.71 at pilot scale.
- An assay of alphas through the initial non aerated treatment zones of the pilot plant using the bench scale reactor indicated that alphas peaked in the effluent of the first anaerobic zone (alpha equal to 1.01) and were lower in the second anaerobic zone and first anoxic zone.
- An assay of alphas in the three pilot plant series sideline aeration basins indicated that alpha was maximum in the first aeration basin (alpha equal to 0.905) and were lower in the second and third aeration basins (0.716 and 0.661) respectively.
- Statistically significant increases in average surface tension were noted from the first to second, and the first to third aeration basins.
- A comparison of pilot plant alphas determined in the first aeration basin following anaerobic nominal hydraulic retention times of 0.0, 0.21, 0.43, and 0.64 hours yielded alpha values of 0.71, 0.94, 0.72, and 0.72 respectively. Like the assay using the bench scale reactor, the alpha values at pilot scale peaked following treatment in only one anaerobic zone (nominal HRT of 0.21 hours).
- The study concludes that exposures in an initial anaerobic reactor as required for biological phosphorus removal may benefit oxygen transfer efficiency through increased alphas, however the benefits of long periods of anaerobic reaction time (over 0.43 hours) are uncertain.

- The geometric temperature correction factor, θ , was determined to be equal to a value of 1.026 in the 21 L bench scale reactor, and equal to 1.038 in the pilot plant. The industry consensus value is 1.024, which is statistically significantly different than the value found for the pilot plant. The value of θ determined for the pilot plant falls within the range of values found in the literature. It was concluded that considerable variation in θ may exist from system to system, and that site determination is necessary, especially if K_{La} is to be determined at temperatures significantly different than standard conditions.
- Significant differences were found between values of α determined by steady state and non steady state methods. The steady state methods were found to be affected by substrate limitations in the bottle method of OUR determinations.
- Dual non steady state testing was found to be affected by limitations on aerator turn up capacity resulting in insufficient differences between paired K_{La} values. In BNR systems other methods to determine instantaneous oxygen uptake rates, such as off gas monitoring should be considered in future studies.

VII. Symbols and Nomenclature

a = volumetric interfacial area (m^2/m^3)
 A, B, C = Parameters of estimate for second order model of $K_L a$
 C = Dissolved oxygen concentration in liquid phase (mg/L)
 C_{∞}^* = measured value of the average equilibrium steady state dissolved oxygen concentration as time approaches infinity in clean water (mg/L)
 $C_{\infty f}^*$ = measured value of the average equilibrium steady state dissolved oxygen concentration as time approaches infinity in process water (mg/L)
 C_0 = Dissolved oxygen concentration at time zero (mg/L)
 C_f = Final dissolved oxygen concentration (mg/L)
 C_i = Influent dissolved oxygen concentration (mg/L)
 C_R = Maximum dissolved oxygen concentration in respiring liquid, as time approaches infinity in process water (mg/L)
 C_{sat} = Saturation concentration of dissolved oxygen at field temperature and pressure (mg/L), also referred to as the book value saturation concentration.
COD = Chemical oxygen demand (mg/L)
 d = day
 f = feet
 g = gram
 h = hour
HRT = Hydraulic residence time (h)
 K_L = Diffusion coefficient (m/h)
 $K_L a$ = Volumetric mass transfer coefficient of clean water (/h)
 $K_L a_{(T)}$ = Volumetric mass transfer coefficient (/h) of clean water at temperature, T
 $K_L a_{f(T)}$ = Volumetric mass transfer coefficient (/h) of process water at temperature, T
 L = liter
MLSS = Mixed liquor suspended solids concentration (mg/L)
OUR = Oxygen uptake rate (mg/L-h)
 Q = Reactor flow (L/h)
 Q_s = Airflow (scfh)
 R = Oxygen uptake rate (mg/L-h)
 scfh = standard cubic feet per hour
SOTE = Standard oxygen transfer efficiency (%)
 t = time (h)
TCOD = Total chemical oxygen demand concentration (mg/L)
TKN = Total Kjeldhal nitrogen concentration (mg/L)
TN = Total nitrogen concentration (mg/L as nitrogen)
TP = Total phosphorus concentration (mg/L as phosphorus)
TSS = Total suspended solids concentration (mg/L)

V = Reactor volume, m^3

VSS = Volatile suspended solids concentration (mg/L)

α = Ratio of process water K_{La} to clean water K_{La}

β = Ratio of process water maximum dissolved oxygen concentration to clean water maximum dissolved oxygen concentration

τ = Probe response constant (h)

q = Theta, geometric temperature correction factor

VIII. References

American Society of Civil Engineers (ASCE) (1992) Standard Measurement of Oxygen Transfer in Clean Water ANSI/ASCE 2 - 91. American Society of Civil Engineers, New York: 1992

ASTM (1989) Annual Book of ASTM Standards, Vol 15.04, American Society for Testing and Materials, Philadelphia, 1989. 117 - 119.

Ashley, Kenneth I., Kenneth J. Hall, and Donald S. Mavinic. (1991) Factors influencing oxygen transfer in fine pore diffused aeration. Water Resources 25.12: 1479-1486.

Backman, Robert. C. (1987) Chemical enhancement and depression of oxygen transfer in industrial wastewaters. Proceedings of the 42nd Industrial Waste Conference, May 12, 13, & 14 Purdue University. Chelsea, MI: Lewis Publishers, Inc.

Baillo, C. R., W. L. Paulson, J. J. McKeown, and H. J. Campbell, Jr. (1986) Accuracy and precision of plant scale and shop clean water oxygen transfer tests. Journal WPCF, 58 290 - 299

Boyle, William C. editor (1986) Aeration Systems Design, Testing Operation and Control Noyes publications Park Ridge , New Jersey..

Boyle, William. C., et al.(1990) Fine Pore Aeration for Wastewater Treatment. Park Ridge NJ: Noyes Data Corporation

Brown, C.L. and C. R. Baillo (1982) Modeling and interpreting oxygen transfer data. Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers, 108: 607 - 628.

Doyle, Michael L., W.C. Boyle, T. Rooney, G. L. Huibregtse (1983) Pilot plant determination of oxygen transfer in fine bubble aeration. Journal Water Pollution Control Federation 55: 1435-40.

Eckenfelder Jr, William W. and D.J. O'Conner (1961) Biological Waste Treatment, Pergamon Press, New York. page 105

EPA(1983) Development of Standard Procedures for Evaluation Oxygen Transfer Devices. EPA-600/2-83-102

Ganczarczyk,J. (1972) The influence of simple phenols on water aeration kinetics The Canadian Journal of Chemical Engineering 50: 185 - 188.

Groves, K.P., G.T. Daiger, and T.J. Simpkin (1992) Evaluation of oxygen efficiency and alpha factor on a variety of diffused aeration systems. Water Environment Research 64: 691-98.

Gurol, Mirat D. and S. Nekouinainni (1985) Effects of organic substances on mass transfer in bubble aeration Journal WPCF 57.3: 235 - 240

Hwang, H. J. and M. K. Stenstrom (1985) Evaluation of fine bubble alpha factors in near full scale equipment. Journal WPCF 57: 1142 - 1151.

Joint Task Force of the Water Environment Federation and the American Society of Civil Engineers (1992) Design of Municipal Wastewater Treatment Plants Volume I: Chapters 1-12 .pg. 578

Leu, H.G., S.H. Lin, C.C. Shyu and C.M. Lin Effects of surfactants and suspended solids on oxygen transfer under various operating conditions Environmental Technology 19: 299-306.

Mancy, K.H. and D.A. Okun (1960) Effects of surface active agents on bubble aeration Journal WPCF 32:351-364.

Microsoft Excel for Windows 95 Version 7.0. CD-ROM. USA: Microsoft Corporation, 1995

Mueller, James A. (1986) Comparison of dual nonsteady state and steady state testing of fine bubble aerators at Whittier Narrows Plant, Los Angeles. in Aeration Systems Design, Testing Operation and Control Boyle, William C. editor Noyes Publications, Park Ridge , New Jersey. 380-403.

Mueller , James A. and J.J. Rysinger (1981) Diffused aerator testing under process conditions. Proceedings of the 36th Industrial Waste Conference, May 12, 13, & 14 Purdue University. Chelsea, MI: Lewis Publishers, Inc.

Mueller, James A. and H.D. Stensel (1990) Biologically enhanced oxygen transfer in the activated sludge process. Research Journal WPCF 62.1: 193-202.

Mueller, James A. and W.C. Boyle (1988) Oxygen transfer under process conditions Journal Water Pollution Control Federation 60: 332-341.

Mueller, James A, S. Nasr, B. J. FitzPatrick, J. Krupa, and F. Shkreli. (1996) Impact of a selector on oxygen transfer - a full-scale demonstration. Paper presented at WEFTEC '96 the 69th annual conference and exposition of the Water Environment Federation, October 5-9, Dallas Texas. Presented October 7, 1996.

NCSS 6.0.22 Released April 4, 1997. CD-ROM. Kaysville, Utah: Number Cruncher Statistical Systems, 1997.

NCSS 97 Released February 9, 1989. CD-ROM. Kaysville, Utah: Number Cruncher Statistical Systems, 1998.

Newbry, Brooks W.(1998) Oxygen-transfer efficiency of fine pore diffused aeration systems: energy intensity as a unifying evaluation parameter Water Environment Research" 70: pg. 323-333.

Philichi, T.L., and Stenstrom, M. K (1989) Effects of dissolved oxygen probe lag on oxygen transfer parameter estimation. Journal Water Pollution Control Federation 61: 83 - 86.

Rieth, Michael G., Steven C.Chiesa., and Robert C.Polta (1995) Effects of operational variables on the oxygen transfer performance of ceramic diffusers. Water Environment Research 67: 781-7

Stenstrom, M. K., L. C. Brown, and H. J. Hwang, (1981) Oxygen transfer parameter estimation, Journal of the Environmental Division, Proceedings of the American Society of Civil Engineers, 107: 379 - 397.

Stenstrom, M. K., and R. G. Gilbert (1981) Effects of alpha, beta and theta factor upon the design, specification and operation of aeration systems. Water Research, 15 643 - 654.

Suescun, J., I. Irizar, X. Ostolaza, E. Ayesa, (1998) Dissolved oxygen control and simultaneous estimation of oxygen uptake rate in activated -sludge plants. Water Research (1998) 70:3 316-322.

Tribe, L. A., C. L. Briens, and A. Margaritis (1995) Determination of the volumetric mass transfer coefficient (K_La) using the dynamic "gas out- gas in" method: analysis of errors caused by dissolved oxygen probes. Biotechnology and Bioengineering, 44 (1995), 388 - 392.

Vinek, V. and J. Sinkule (1993), State of art in measuring volumetric oxygen transfer coefficients in fermentors. Scientific Papers of the University of Chemical Technology, Prague 1/1993 1-48.

Wagner, M and H.J. Popel, (1996) "Surface active agents and their influence on oxygen transfer" Water Science Technology 24:249 - 256.

APPENDIX

APPENDIX A - PILOT PLANT ANALYTICAL DATA

Table A1. Pilot plant analytical data with anaerobic HRT of 0.21 hours.

Date	21-Dec-96	22-Dec-96	23-Dec-96	24-Dec-96	27-Dec-96	28-Dec-96	29-Dec-96	30-Dec-96	1-Jan-97	2-Jan-97	3-Jan-97	5-Jan-97	6-Jan-97
Solids (mg/L)													
Aer TSS	825	755	1100	980	1275	1235	1245	1225	1050	1085	1315	983	835
RAS TSS	1465	1275	1335	1065	1970	2050	1700	1930	1925	1970	2155	1996	1610
Eff TSS	5	2.5	2	7	12	10.5	5.5	4.5	16	4.5	9.5	5.5	11.5
Aer VSS	755	670	865	865	1070	1035	1045	1035	1010				
RAS VSS	1220	1070	1130	930	1630	1750	1450	1600	1575				
% VSS	0.86	0.86	0.82	0.88	0.83	0.85	0.85	0.84	0.87		0.85	0.85	0.85
COD (mg/L)													
Tot in	91	147	89	70	145	88	54	102	84	73	72.3	83.9	77.6
sol in	43	56	38	39	67	46	28	76	36	44	40	40	43.4
An sol 1	29	25	28	27	39	22	16	25	29	28			
An sol 1	29	25	28	27	39	22	16	25	29	28			
Ax sol 1	25	27	22	27	30	24	20	22	21	28			
Ax sol 3	22	23	20	19	28	22	11	21	19	28			
Aer sol 3	19	25	20	19	25	22	15	17	21	24			
Eff sol	17	25	19	19	25	25	11	17	19	25	27.7	30	30.3
Eff tot	19	29	22	21	28	30	14	21	21	25	36.9	64.6	80.7
TCOD/TP Ratio	34.6	53.3	45.2	35.5	51.4	50.6	26.6	48.3	34.9	41.2	47.3	42.2	57.1
TCOD/TKN Ratio	6.6	10.4	11.4	8.2	10.7	8.1	8.6	11.9	10.0	9.8	9.1	9.4	10.9
TKN (mg/L as N)													
Influent	13.71	14.1	7.81	8.57	13.52	10.8	6.28	8.57	8.38	7.43	7.91	8.95	7.14
Effluent TKN	2.28	2.48	0.95	0.76	3.62	2.28	0.57	1.71	1.72	2.67	5.24	2.28	3.33
Eff ammonia	1.74	2.18	0.38	0.43	2.9	0.05	1.19	1.43	1.43	1.95	4.18	1.71	3.4
Ions													
<i>Nitrate (as N)</i>													
Influent	0.79	0.79	1.27	0.86	0.67	1.89	1.67	1.62	1.77	1.82	2.6		1.477
An sol 1	2.72	2.49	3.44	4.31	2.61	2.45	3.89	2.28	3.05	1.78			
An sol 1	2.72	2.49	3.44	4.31	2.61	2.45	3.89	2.28	3.05	1.78			
Ax sol 3	3.87	3.51	4.39	7.84	3.21	1.84	4.35	2.86	4.22	2			
Aer sol 3	4.08	3.73	4.73	7	3.76	2.22	4.79	3.16	4.64	2.28			
Eff sol	4.06	3.84	4.62	7.21	3.77	2.39	4.72	2.95	4.5	1.97	0.59		1.741
<i>Nitrite (as N)</i>													
Influent	0	0	0	0	0	0	0	0	0	0	0		
An sol 1	0.65	0.63	0.62	0	0.79	1.06	0.56	0.68	0.53	0.8			
An sol 1	0.65	0.63	0.62	0	0.79	1.06	0.56	0.68	0.53	0.8			
Ax sol 3	0.87	0.9	0.72	0	1.04	0.95	0.42	0.87	0.72	1.06			
Aer sol 3	0.93	0.93	0.78	0.36	1.19	1.23	0.6	1.01	0.89	1.14			
Eff sol	0.92	0.95	0.84	0.35	1.15	1.3	0.58	1.05	0.87	1.19	0.92		1.223
<i>Phosphate (as P)</i>													
Influent	1.21	1.36	0.91	0.73	0.97	0.78	0.84	0.69	0.94	0.61	0.59		0.49
An sol 1	0.92	1.12	1.21	1.36	0.98	0.77	0.86	0.75	0.79	0.7			
An sol 1	0.92	1.12	1.21	1.36	0.98	0.77	0.86	0.75	0.79	0.7			
Ax sol 3	0.87	0.98	0.88	1.15	0.96	1.29	0.89	0.74	0.78	0.92			
Aer sol 3	0.86	0.78	0.85	1.02	0.94	1.13	0.92	0.74	0.7	0.87			
Eff sol	0.83	0.91	0.84	1.14	1.01	0.88	0.91	0.4	0.77	0.89	0.73		0.541
TP (mg/L as P)													
Influent	2.63	2.76	1.97	1.97	2.82	1.74	2.03	2.11	2.41	1.77	1.53	1.99	1.36
Effluent	1.59	1.62	1.67	2.1	1.87	1.65	1.73	1.42	1.53	1.64	1.53	1.64	1.8
Percent Total P Removal	68.4%	67.0%	57.4%	42.1%	64.2%	49.4%	55.2%	81.0%	68.0%	49.7%	52.3%	100.0%	60.2%
P Wasted g/d as P	3.96	3.62	5.28	4.70	6.12	5.93	5.98	5.88	5.04	5.21	6.31	4.72	4.01
P available, g/d as P	24.82	26.58	16.28	16.86	24.74	13.11	16.24	17.21	21.34	14.16	10.43	17.06	10.88
P removed, g/d as P	11.38	12.48	3.28	-1.42	10.40	0.98	3.28	7.55	9.63	1.42	0.00	3.83	-4.82
Excess P removal	7.42	8.85	-2.00	-6.13	4.28	-4.94	-2.69	1.67	4.59	-3.79	-6.31	-0.89	-8.82
Calculated P in Waste Sludge (%)	7.19%	8.61%	1.55%	-0.76%	4.25%	0.42%	1.37%	3.21%	4.78%	0.68%	0.00%	2.03%	-3.00%
Nitrogen Balance													
Total Nitrogen Inf (mg/L as N)	14.5	14.9	9.1	9.4	14.2	12.7	8.0	10.2	10.2	9.3	10.5		8.6
Total Nitrogen Eff (mg/L as N)	7.3	7.3	6.4	8.3	8.5	6.0	5.9	5.7	7.1	5.8	6.8		6.3
Total Nitrogen Wasted (g as N)	7.9	7.2	10.6	9.4	12.2	11.9	12.0	11.8	10.1	10.4	12.6		8.0
Total Nitrogen Available	144.9	152.4	82.6	90.2	135.2	102.6	81.8	96.7	97.8	82.9	90.8		87.1
Total Denitrification	71.3	76.1	18.7	2.7	49.6	61.7	10.8	37.3	23.4	27.0	28.5		17.4
Denitrification Efficiency	49%	50%	23%	3%	37%	60%	13%	39%	24%	33%	31%		20%

Table A1. Pilot plant analytical data with anaerobic HRT of 0.21 hours.

Date	8-Jan-97	10-Jan-97
Solids (mg/L)		
Aer TSS	1065	1255
RAS TSS	2150	2195
Eff TSS	5	0.5
Aer VSS		
RAS VSS		
% VSS	0.85	0.85
COD (mg/L)		
Tot in	80.7	67.3
sol in	43.5	41.3
An sol 1		
An sol 1		
Ax sol 1		
Ax sol 3		
Aer sol 3		
Eff sol	27.9	27.5
Eff tot	53.5	40.5
TCOD/TP Ratio	41.0	29.1
TCOD/TKN Ratio	10.2	7.1
TKN (mg/L as N)		
Influent	7.9	9.52
Effluent TKN	5.24	5.6
Eff ammonia	5.42	5.53
Ions		
<i>Nitrate (as N)</i>		
Influent	1.164	1.554
An sol 1		
An sol 1		
Ax sol 3		
Aer sol 3		
Eff sol	0.883	0.527
<i>Nitrite (as N)</i>		
Influent		
An sol 1		
An sol 1		
Ax sol 3		
Aer sol 3		
Eff sol		
<i>Phosphate (as P)</i>		
Influent	0.51	0.599
An sol 1		
An sol 1		
Ax sol 3		
Aer sol 3		
Eff sol	0.672	0.777
TP (mg/L as P)		
Influent	1.97	2.31
Effluent	2.24	2.04
Percent Total P Removal	-13.7%	11.7%
P Wasted g/d as P	5.11	6.02
P available, g/d as P	16.45	19.26
P removed, g/d as P	-2.95	2.95
Excess P removal	-8.07	-3.07
Calculated P in Waste Sludge (%)	-1.45%	1.23%
Nitrogen Balance		
Total Nitrogen Inf (mg/L as N)	9.1	11.1
Total Nitrogen Eff (mg/L as N)	6.1	6.1
Total Nitrogen Wasted (g as N)	10.2	12.0
Total Nitrogen Available	90.9	108.4
Total Denitrification	22.0	42.1
Denitrification Efficiency	24%	39%

Table A2. Pilot plant analytical data for anaerobic HRT of 0.43 hours.

Date	5-Feb-97	7-Feb-97	10-Feb-97	12-Feb-97	14-Feb-97	16-Feb-97	17-Feb-97	19-Feb-97	20-Feb-97	21-Feb-97	22-Feb-97	24-Feb-97	28-Feb-97	3-Mar-97	5-Mar-97
Solids (mg/L)															
Aer TSS	1015	1220	730	840	1955	1730				1990				2430	2450
RAS TSS	1545	2130	1550	950										4290	4165
Eff TSS	16.5	18	57	24										8	14
Aer VSS															
RAS VSS	1545														
% VSS															
COD (mg/L)															
Tot in	136.0	130.0	110.0	151.0			111.6			101.0		107.0	138.3	95.7	75.7
sol in	61.0	87.0	71.0	68.0			57.0			55.0		49.0	57.5	22.0	36.3
An sol 1	45.8	58.0	65.0	37.0			50.7			39.0		35.0		12.5	18.9
An sol 2	38.2	41.0	47.0	82.0			36.7			38.0		40.0		7.8	20.5
An sol 2	38.2	41.0	47.0	82.0			36.7			38.0		40.0		7.8	20.5
Ax sol 1	42.8	31.0		76.0			39.8			28.0		32.0		3.1	42.6
Ax sol 3	50.4	25.0		41.0			35.1			25.0		29.0		9.4	18.9
Aer sol 1	53.5	19.0		34.0			39.0			35.0		27.0		25.1	26.8
Aer sol 3	91.9	64.0		43.0			67.9			43.0		34.0		22.0	17.3
Eff sol		59.0	80.0	34.0			35.1			28.0		32.0	24.9	23.5	12.6
Eff tot	58.1	77.0	140.0	68.0			36.7			80.0		43.0	24.9	28.2	18.9
TCOD/TP Ratio	37.4	36.4	42.0	34.0			41.5			39.6		51.4	50.1	65.1	95.8
TCOD/TKN Ratio	6.9	8.0	6.3	16.0			7.4			6.5		8.4	7.5	16.6	12.1
TKN (mg/L as N)															
Influent	19.61	16.15	17.53	9.46			15	15.23		15.46		12.69	18.46	5.77	6.23
Effluent	15.68	20.76	8.08	15.46			10.61	7.15		11.77		10.84	4.38	0	1.73
Eff ammonia	13.78	14.85	14.19	14.3			8.2	10.2		10.6				0.288	11.88
Estimated Eff Ammonia									10.4		10.7				
Ions (mg/L)															
Nitrate (as N)															
Influent	0.90		0.97				0.74							1.92	6.22
An sol 1	0.37		0.32				0.27							3.95	11.04
An sol 2	0.14		0.27				0.02							3.65	10.04
Ax sol 3							0.01							6.12	12.03
Aer sol 3	0.11						0.05							6.42	12.56
Eff sol	0.09		0.01				0.08							5.91	12.37
Nitrite (as N)															
Influent										0.25		0.23	0.26	0.14	0.19
An sol 1										0.00		0.05		0.25	0.27
An sol 2										0.00		0.00		0.29	0.30
Ax sol 3										0.00		0.00		0.15	0.04
Aer sol 3										0.12		0.07		0.03	0.00
Eff sol										0.10		0.06	0.34	0.03	0.00
Phosphate (as P)															
Influent	1.36		0.71				1.09							0.21	0.14
An sol 1	1.04		0.65				0.90							0.34	0.25
An sol 2	1.13		0.60											0.36	0.22
Ax sol 3							0.82							0.52	0.24
Aer sol 3	1.09						0.79							0.50	0.30
Eff sol	1.05		1.01				0.76							0.51	0.30
TP (mg/L as P)															
Influent	3.64	3.57	2.62	4.44			2.69	3.08		2.55		2.08	2.76	1.47	0.79
Effluent	2.65	2.83	3.58	3.29			1.8	1.94		2.17		2.06	2.31	1.68	0.94
Percent Total P Removal	71.2%	100.0%	61.5%				71.9%							65.3%	61.8%
P Wasted g/d as P	2.44	2.93	1.75	2.02			4.15	4.46		4.78		5.30	5.30	5.83	5.88
P available, g/d as P	37.40	36.14	26.92	46.58			25.29	29.24		23.13		17.46	24.90	10.26	2.77
P removed, g/d as P	10.83	8.10	-10.51	12.59			9.74	12.48		4.16		0.22	4.92	-2.30	-1.64
Excess P removal	8.40	5.17	-12.26	10.57			5.59	8.01		-0.62		-5.09	-0.38	-8.13	-7.52
Calculated P in Waste Sludge (%)	11.12%	6.91%	-14.99%	15.61%			5.86%	6.99%		2.18%		0.10%	2.32%	-0.99%	-0.70%
Nitrogen Balance															
Total Nitrogen Inf (mg/L as N)	20.5		18.5				15.7							7.8	12.6
Total Nitrogen Eff (mg/L as N)	15.8		8.1				10.7							5.9	14.1
Total Nitrogen Wasted (g as N)	9.7		7.0				16.6							23.3	23.5
Total Nitrogen Available	193.9		262.3				129.3							65.5	225.9
Total Denitrification	42.1		106.9				38.7							-2.7	-39.5
Denitrification Efficiency	21.7%		40.7%				29.9%							-4.1%	-17.5%

Table A2. Pilot plant analytical data for anaerobic HRT of 0.43 hours.

Date	7-Mar-97	10-Mar-97	12-Mar-97	14-Mar-97	17-Mar-97	19-Mar-97	21-Mar-97	24-Mar-97	26-Mar-97	28-Mar-97	31-Mar-97	2-Apr-97	7-Apr-97	9-Apr-97	11-Apr-97
Solids (mg/L)															
Aer TSS	2125	2000	2105	2190	2275	1795	1850	1690	1565	1580	1725				1490
RAS TSS	3720	3710	3945	3540	3370	2915	2990	3025	2635	2570	2790				2385
Eff TSS	7	15	6.5	9	4.5	113	10.5	7.5	4.5	7	13.5				4
Aer VSS															
RAS VSS															
% VSS															
COD (mg/L)															
Tot in	87.0	130.0	117.0	100.0	212.0	96.0	148.0	80.0	79.0	97.0	149.0	121.0			
sol in	39.0	64.0	67.0	88.0	56.0	57.0	11.0	40.8	35.0	46.5	40.0	49.0			
An sol 1	17.0	35.0	28.0	30.0	34.0	51.0	22.0	32.9		27.0	24.0	18.0			
An sol 2	23.0	38.0	26.0	40.0	33.0	48.0	16.0	23.5	26.5	31.0	16.0	29.0			
An sol 2	23.0	38.0	26.0	40.0	33.0	48.0	16.0	23.5	26.5	31.0	16.0	29.0			
Ax sol 1	23.0	35.0	28.0	32.0	23.0	51.0	16.0	25.0	20.0	47.0	14.0	23.0			
Ax sol 3	25.0	26.0	35.0	32.0	18.0	52.0	72.0	27.0	67.0	19.0	16.0	31.0			
Aer sol 1	14.0	59.0	26.0	23.0	23.0	51.0	24.0	19.0	30.5	27.0	8.0	11.0			
Aer sol 3	39.0	19.0	26.0	19.0	23.0	55.0	14.0	24.0	32.0	23.0	12.0	11.0			
Eff sol	22.0	24.0	20.0	22.0	17.0	56.5	32.0	11.0	14.5	28.0	26.0	17.0			
Eff tot	18.0	29.0	30.0	22.0	25.0	192.0	25.0	22.0	31.0	27.0	16.0	17.0			
TCOD/TP Ratio	69.6	71.4	60.3	35.7	96.4	40.0	47.7	40.4	30.0	43.9	37.4	37.3			
TCOD/TKN Ratio	12.4	8.4	7.1	7.2	18.6	6.0	8.4	4.7	4.2	9.5	10.2	7.7			
TKN (mg/L as N)															
Influent	7.04	15.46	16.38	13.84	11.42	16	17.7	17.2	18.8	10.2	14.6	15.7	19.3	16.4	12.2
Effluent	0	4.5	2.31	1.15	4.5	1.6	2.2	2.2	2.2	0	0.2	0	1.8	0.44	1.2
Eff ammonia	0.115	4.96	2.134	0.173	3.22	0	0.17	0	0.14	0.17	0.69	3.32	1.28	0.83	0.67
Estimated Eff Ammonia															
Ions (mg/L)															
Nitrate (as N)															
Influent	2.05	0.92	0.60		0.70	0.88	1.56	0.82	2.45	1.05	1.04	0.84	0.64	1.26	1.44
An sol 1	4.56	0.21	0.17		0.49	3.42	4.54	2.78	8.66	5.64	6.32	1.91	1.67	3.70	4.53
An sol 2	4.78	0.12	0.05		0.14	2.66	4.24	2.43	7.83	4.70	5.68	1.69	0.85	2.70	4.30
Ax sol 3	6.18	0.15	0.94		1.11	5.13	6.07	5.13	11.77	8.07	8.94	3.00	3.87	6.96	7.42
Aer sol 3	7.25	0.69	1.68		2.47	6.39	7.21	6.66	12.24	8.94	9.20	3.93	5.05	8.09	8.21
Eff sol	7.21	0.73	1.83		2.91	6.89	7.15	6.36	12.40	9.55	9.57	3.75	5.10	8.45	8.38
Nitrite (as N)															
Influent	0.16	0.19	0.25	0.20	0.17	0.19	0.29	0.16	0.39	0.10	0.17	0.21	0.17	0.29	0.21
An sol 1	0.19	0.26	0.23	0.30	0.20	0.27	0.24	0.42	0.28	0.16	0.14	0.49	0.63	0.44	0.22
An sol 2	0.18	0.19	0.19	0.31	0.19	0.20	0.20	0.51	0.34	0.29	0.26	0.64	0.67	0.56	0.32
Ax sol 3	0.17	0.37	0.32	0.12	0.18	0.38	0.33	0.33	0.13	0.09	0.09	0.63	1.16	0.39	0.23
Aer sol 3	0.07	0.27	0.29	0.01	0.08	0.28	0.29	0.27	0.18	0.03	0.01	0.50	0.73	0.33	0.23
Eff sol	0.08	0.24	0.28	0.02	0.09	0.24	0.28	0.10	0.07	0.02	0.00	0.53	0.70	0.17	0.10
Phosphate (as P)															
Influent	0.75	0.88	1.28		0.85	1.12	1.07	0.91	1.21	0.93	1.35	1.43	1.68	1.44	1.49
An sol 1	0.59	0.91	1.29		1.15	0.82	0.86	1.05	1.03	1.06	1.31	1.18	1.58	1.43	1.33
An sol 2	0.63	0.95	1.36		1.16	0.88	0.01	1.12	1.06	1.02	1.39	1.16	1.55	1.48	1.34
Ax sol 3	0.63	0.95	1.13		1.26	0.77	0.91	1.21	2.60	1.05	1.49	1.04	1.63	1.60	1.41
Aer sol 3	0.66	0.92	1.05		1.15	0.82	0.94	1.17	0.96	1.09	1.42	1.06	1.56	1.54	1.50
Eff sol	0.58	0.92	1.08		1.18	0.76	0.99	1.14	0.97	1.14	1.42	1.07	1.57	1.57	1.45
TP (mg/L as P)															
Influent	1.25	1.82	1.94	2.8	2.2	2.4	3.1	1.98	2.63	2.21	3.98	3.24	3.28	2.83	2.29
Effluent	0.82	1.3	1.03	2.2	2.2	2.4	1.7	1.93	1.53	1.78	2.17	1.82	2.19	2.25	2.01
Percent Total P Removal	53.7%	49.3%	44.3%		46.5%	68.4%	68.1%	42.6%	63.2%	48.5%	64.3%	66.9%	52.3%	44.6%	36.9%
P Wasted g/d as P	5.10	4.80	5.05	5.26	5.46	4.31	4.44	4.06	3.76	3.79	4.14	3.86	3.86	3.86	3.86
P available, g/d as P	8.58	15.12	16.18	25.39	18.62	21.96	29.49	17.61	25.03	20.39	39.42	31.59	32.03	27.11	21.20
P removed, g/d as P	4.71	5.69	9.96	6.57	0.00	0.00	15.32	0.55	12.04	4.71	19.81	15.54	11.93	6.35	3.06
Excess P removal	-0.39	0.89	4.91	1.31	-5.46	-4.31	10.88	-3.51	8.28	0.91	15.67	11.68	8.06	2.48	-0.80
Calculated P in Waste Sludge (%)	2.31%	2.96%	4.93%	3.12%	0.00%	0.00%	8.63%	0.34%	8.01%	3.10%	11.96%	10.05%	7.72%	4.11%	1.98%
Nitrogen Balance															
Total Nitrogen Inf (mg/L as N)	9.3	16.6	17.2		12.3	17.1	19.5	18.2	21.6	11.4	15.8	16.7	20.1	18.0	13.8
Total Nitrogen Eff (mg/L as N)	7.3	5.5	4.4		7.5	8.7	9.6	8.7	14.7	9.6	9.8	4.3	7.6	9.1	9.7
Total Nitrogen Wasted (g as N)	20.4	19.2	20.2		21.8	17.2	17.8	16.2	15.0	15.2	16.6	15.5	15.5	15.5	14.3
Total Nitrogen Available	82.1	167.2	166.4		98.6	152.1	173.9	158.7	199.2	110.9	161.8	204.2	198.9	185.3	131.4
Total Denitrification	1.0	102.3	119.9		30.5	74.0	90.8	88.0	61.3	4.3	49.4	121.0	121.5	81.9	31.3
Denitrification Efficiency	1.2%	61.2%	72.1%		30.9%	48.7%	52.2%	55.4%	30.8%	3.9%	30.5%	59.3%	61.1%	44.2%	23.8%

Table A2. Pilot plant analytical data for anaerobic HRT of 0.43 hours.

Date	14-Apr-97	16-Apr-97	18-Apr-97
Solids (mg/L)			
Aer TSS	1540	1670	
RAS TSS	2420	2040	
Eff TSS	13	9.5	
Aer VSS			
RAS VSS			
% VSS			
COD (mg/L)			
Tot in			
sol in			
An sol 1			
An sol 2			
An sol 2			
Ax sol 1			
Ax sol 3			
Aer sol 1			
Aer sol 3			
Eff sol			
Eff tot			
TCOD/TP Ratio			
TCOD/TKN Ratio			
TKN (mg/L as N)			
Influent	12.6	23.5	18.8
Effluent	3.9	4.2	2.4
Eff ammonia	2.55		
Estimated Eff Ammonia			
Ions (mg/L)			
<i>Nitrate (as N)</i>			
Influent	1.43		
An sol 1	2.45		
An sol 2	1.62		
Ax sol 3	1.53		
Aer sol 3	3.79		
Eff sol	4.77		
<i>Nitrite (as N)</i>			
Influent			
An sol 1			
An sol 2			
Ax sol 3			
Aer sol 3			
Eff sol			
<i>Phosphate (as P)</i>			
Influent	1.62		
An sol 1	1.48		
An sol 2	1.53		
Ax sol 3	1.45		
Aer sol 3	1.51		
Eff sol	1.50		
TP (mg/L as P)			
Influent			
Effluent			
Percent Total P Removal			
P Wasted g/d as P			
P available, g/d as P			
P removed, g/d as P			
Excess P removal			
Calculated P in Waste Sludge (%)			
Nitrogen Balance			
Total Nitrogen Inf (mg/L as N)	14.0		
Total Nitrogen Eff (mg/L as N)	8.7		
Total Nitrogen Wasted (g as N)	14.5		
Total Nitrogen Available	124.2		
Total Denitrification	44.0		
Denitrification Efficiency	35.4%		

Table A3. Plant analytical data for anaerobic HRT of 0.64 h

Date	10-Sep	15-Sep	17-Sep	26-Sep	3-Oct	6-Oct	8-Oct	10-Oct	22-Oct	24-Oct	31-Oct	5-Nov
Solids (mg/L)												
Aer TSS	1910	1585	1690	1860	2175	1795	1965	2310	2115	1770	1905	1915
RAS TSS	4500	3165	4630	3595	3630	2520	3045	4175	2450	5965	5020	3410
Eff TSS	2	3	11.5	10	9	14	9.5	2.5	4.5	13.5	9.5	38
Aer VSS												
RAS VSS												
% VSS												
COD (mg/L)												
Tot in	320	154	72	207	261	232	240	139	128	119	97	167
sol in	63	61	42	43	51	89	40	63	52	66	42	53
An sol 1	43	74	30	20	35	69	40	66	41	41	28	37
An sol 3	39	32	44	12	34	42	20	34	30	38	24	35
Ax sol 1	37	23	34	12	32	34	24	42	26	47	23	35
Ax sol 3	51	17	30	27	32	23	22	42	28	28	20	33
Aer sol 3	34	23	34	31	30	27	22	50	38	28	18	31
Eff sol	40	19	26	31	30	42	30	39	25	23	20	30
Eff tot	40	23	44	63	34	42	46	39	44	34	26	33
TCOD/TP Ratio	92.0	51.2	17.5	40.0	43.0	42.4		54.7	49.4	29.9	32.2	35.6
TCOD/TKN Ratio	35.7	8.1	7.8	12.3	13.5	9.4	12.9	9.8	7.7	6.7	5.6	11.1
TKN (mg/L as N)												
Influent	9.0	19.0	9.2	16.8	19.3	24.6	18.6	14.2	16.7	17.7	17.3	15.0
Effluent	1.1	1.1	1.1	2.2	1.1	1.2	3.4	0.0	3.4	2.0	1.5	1.3
Eff ammonia	0.82	0.83	0	1.24	0.2	0	0.31	0.34	0.78	0.08	0.51	
Ions (mg/L)												
<i>Nitrate (as N)</i>												
Influent				0.02					1.45		0.28	0.48
An sol 3	0.04	0.021	3.04	4.31	0.96	5.32	4.91	4.41	4.79	9.06	0.54	1.32
Ax sol 3	1.4	3.91	6.75	5.65	4.85	1.33	1.12	0.855	1	2.1	5.73	1.25
Aer sol 3	2.26	5.03	7.17	6.21	5.64	6.87	6.11	5.97	5.91	9.9	7.19	1.22
Eff sol	2.04	5.1	7.19	6.04	5.16	6.87	6.19	5.89	5.46	10.21	7.13	1.21
<i>Nitrite (as N)</i>												
Influent	0	0	0	0.1	0	0	0	0	1.06	0	0	0
An sol 3	0	0.18	0.56	0	0	0.61	0.64	0.44	0.94	0	1.35	0
Ax sol 3	0.64	0.97	0	0	0	0.6	0	0	0.94	0.42	0	0
Aer sol 3	0.7	1.08	0	0.02	0	0.68	0	0.12	0.99	0.44	0	0
Eff sol	0.71	1.02	0	0	0.22	0.58	0	0	0.89	0.26	1.31	0
<i>Phosphate (as P)</i>												
Influent									0.48		0.72	1.1
An sol 3	0.56	1.44	0.9	1.61	1.59	1.56	1.10	0.92	1	1.84	0.72	1.32
Ax sol 3	0.47	0.8	1.02	1.45	1.58	1.38	1.14	0.92	1	1.86	0.5	1.25
Aer sol 3	0.37	0.71	0.89	1.39	1.57	1.29	1.00	0.85	0.92	1.75	0.43	1.22
Eff sol	0.59	0.64	0.92	1.41	3.08	1.03	0.88	0.81	0.89	1.77	0.45	1.21
TP (mg/L as P)												
Influent	3.48	3.01	4.11	5.18	6.07	5.47		2.54	2.59	3.98	3.01	4.69
Effluent Sol	0.84	0.91	1.78	1.63	2.64	2.04		1.57	2.59	1.69	0.51	1.16
Percent Total P Removal	83.0%	78.7%	77.6%	72.8%	49.3%	81.2%		68.1%	65.6%	55.5%	85.0%	74.2%
P Wasted (g/d as P)	9.2	7.6	8.1	8.9	10.4	8.6		11.1	10.2	8.5	9.1	9.2
P available (g/d as P)	28.9	25.3	36.9	47.8	56.0	51.2		16.7	18.2	35.1	23.8	42.1
P removed (g/d as P)	28.9	23.0	25.5	38.9	37.5	37.5		10.6	0.0	25.1	27.4	38.6
Excess P removal	19.8	15.4	17.4	29.9	27.1	28.9		-0.5	-10.2	16.6	18.2	29.4
Calculated P in Waste Sludge (%)	7.9%	7.6%	7.9%	10.9%	9.0%	10.9%		2.4%	0.0%	7.4%	7.5%	10.5%
Nitrogen Balance												
Total Nitrogen Inf (mg/L as N)	9.0	19.0	9.2	16.9	19.3	24.6	18.6	14.2	19.2	17.7	17.5	15.5
Total Nitrogen Eff (mg/L as N)	3.9	7.2	8.3	8.3	6.5	8.7	9.6	5.9	9.7	12.5	9.9	2.6
Total Nitrogen Wasted (g/d as N)	36.7	30.4	32.4	35.7	41.8	34.5	37.7	44.4	40.6	34.0	36.6	36.8
Total Nitrogen Available (g/d as N)	58.1	174.3	56.4	138.5	159.4	221.7	132.3	115.0	141.4	138.5	144.9	118.1
Total Denitrification (g.d as N)	19.0	98.3	-22.3	58.8	98.3	140.2	61.2	46.8	63.4	23.0	46.9	104.8
Denitrification Efficiency	33%	56%	-39%	42%	62%	63%	46%	41%	45%	17%	32%	89%

Table A4. Pilot plant analytical data with anaerobic HRT of 0.64 h with acetate feed.

Date	Before Acetate Addition			During Acetate Addition						
	7-Dec-96	8-Dec-96	9-Dec-96	11-Dec-96	12-Dec-96	13-Dec-96	16-Dec-96	17-Dec-96	18-Dec-96	19-Dec-96
Solids (mg/L)										
Aer TSS	1445	1685	1750	1970	1755	1720	1210	1295	1190	1230
RAS TSS	3065	2810	2985	3005	3715	3080	2920	3350	2165	2345
Eff TSS	4	9.5	4.5	5	1	2	12	8	3	5
Aer VSS	1165	1315	1405	1763	1495	1435	1025	1010	1115	1060
RAS VSS	2470	2270	2390	2555	3100	2525	2460	2775	1865	2005
% VSS	0.81	0.80	0.80	0.87	0.84	0.83	0.84	0.81	0.89	0.86
COD(mg/L)										
Tot in	167	196	83	154	105	119	85	105	101	104
sol in	81	87	35	47	52	57	37	44	51	50
An sol 1	46	22	15	42	37	31	35	30	30	35
An sol 3	37	35	15	30	33	28	35	22	32	29
Ax sol 1	29	34	19	30	32	33	29	28	24	28
Ax sol 3	30	22	19	24	29	26	24	34	26	28
Aer sol 3	24	20	15	25	29	33	25	21	24	28
Eff sol	23	20	15	28	27	26	25	22	18	23
Eff tot	24	25	18	30	29	28	35	30	26	28
TCOD/TP Ratio	73.9	78.1	26.7	29.1	61.8	58.9	23.3	44.1	59.1	48.8
TCOD/TKN Ratio	7.9	9.1	6.9	8.9	8.8	8.6	6.8	9.6	7.6	9.8
TKN(mg/L as N)										
Influent	21.0	21.6	12.1	17.4	12.0	13.9	12.5	11.0	13.3	10.6
Effluent	2.0	1.5	1.1	0.2	0.8	0.4	1.9	3.6	3.3	1.7
Eff ammonia		0.43	0.10	0.10	0.00	0.26	1.71	2.66	3.08	1.47
Ions (mg/L)										
<i>Nitrate (as N)</i>										
Influent	0.47	0.32	1.02	2.16	0.52	0.31	0.81	1.97	0.47	0.67
An sol 3	3.23	4.31	4.7	5.21	2.72	1.89	1.99	0.42	0.01	1.27
Ax sol 3	6.76	8.12	8.08	7.99	5.55	4.48	4.48	0.07	0.02	2.37
Aer sol 3	7.38	8.74	8.42	8.13	6.38	6.1	5.12	1.03	0.52	3.07
Eff sol	7.56	8.84	8.57	8.1	5.9	6.06	5.11	1.08	0.38	2.68
<i>Nitrite (as N)</i>										
Influent	0	0	0	0.85	0	0	0	0.37	0	0
An sol 3	0	0.51	0	0	0.62	0.48	0.57	0	0	0
Ax sol 3	0.95	0.87	0.53	0	0.88	0.54	0.95	0	0	0
Aer sol 3	1.12	0.83	0.37	0	0.97	0.57	1.03	0	0	0
Eff sol	0.94	0.74	0.37	0	0.94	0.45	1.04	0.74	0	0
<i>Phosphate (as P)</i>										
Influent	1.34	1.31	1.14	1.39	1.26	1.28	1.3	1.22	1.45	1.02
An sol 3	1.14	1.15	0.91	0.82	1.06	0.9	1.01	0.82	0.84	0.63
Ax sol 3	0.78	0.92	0.9	0.65	0.91	0.71	0.97	0.84	0.74	0.54
Aer sol 3	0.8	0.99	0.91	0.66	0.86	0.67	0.96	0.68	0.67	0.49
Eff sol	0.77	0.9	0.86	0.64	0.83	0.68	0.86	0.7	0.67	0.54
TP (mg/L as P)										
Influent	2.26	2.51	3.11	5.29	1.7	2.02	3.65	2.38	1.71	2.13
Effluent	0.89	0.59	0.51	0.67	0.62	0.84	0.89	0.85	1.07	0.71
Percent Total P Removal	65.9%	64.1%	72.3%	87.9%	51.2%	66.3%	76.4%	70.6%	60.8%	74.6%
P Wasted g/d as P	6.94	8.09	8.40	9.46	8.42	8.26	5.81	6.22	5.71	5.90
P available, g/d as P	17.80	19.38	25.64	48.44	10.18	13.85	34.14	19.83	13.00	17.41
P removed, g/d as P	14.99	21.01	28.45	50.56	11.82	12.91	30.21	16.74	7.00	15.54
Excess P removal	8.06	12.92	20.05	41.11	3.40	4.66	24.40	10.53	1.29	9.64
Calculated P in Waste Sludge (%)	5.40%	6.49%	8.47%	13.37%	3.51%	3.91%	13.00%	6.73%	3.07%	6.58%
Nitrogen Balance										
Total Nitrogen Inf (mg/L as N)	21.5	21.9	13.1	20.4	12.5	14.2	13.4	13.3	13.8	11.3
Total Nitrogen Eff (mg/L as N)	10.5	11.0	10.1	8.3	7.6	6.9	8.1	5.4	3.7	4.4
Total Nitrogen Wasted (g as N)	27.7	32.4	33.6	37.8	33.7	33.0	23.2	24.9	22.8	23.6
Total Nitrogen Available	185.6	196.3	98.8	183.7	95.0	121.2	120.8	110.4	125.3	97.9
Total Denitrification	92.5	86.7	-0.1	94.1	20.1	47.1	34.8	61.4	87.5	52.4
Denitrification Efficiency	50%	44%	0%	51%	21%	39%	29%	56%	70%	54%

APPENDIX B - OXYGEN TRANSFER TEST RESULT DATABASE

Table B1. Oxygen transfer data summary for pilot plant and bench scale reactor.

File	File Sheet	Date	Page	Anaerobic					Airflow (scfh)	OUR		Temp (C)	Kla (20) (		C _{ss} (mg/L)	C _{sat} (book)		KLa (Clean)	Alpha	Beta
				HRT	Reactor	Basin	Contents	Method		(mg/ L-h)	(/h)		/h)	Q(gpd)						
PRIEFF-1.xls	BR BVML1 Kla 1a	29-Aug		0.64	BR	Bench	BVML	SS	31.8	8.26	22.5	1.024	7.78	4.65		0	9.82	0.793		
PRIEFF-1.xls	BR BVML1 Kla 2a	24-Sep	III-24	0.64	BR	Bench	BVML	SS	44.7	8.26	23	1.024	7.69	2.75		0	9.82	0.783		
PRIEFF-1.xls	BR BVML1 Kla 3a	7-Oct	III-30	0.64	BR	Bench	BVML	DR	9.55	7.15	20.8	1.024	7.02	7.40		0	9.82	0.714	0.973	
PRIEFF-1.xls	BR BVML1 Kla 4a	11-Oct	III-35	0.64	BR	Bench	BVML	NSS	10.3	6.3	20.8	1.024	6.18	5.70		0	9.82	0.629	1	
PRIEFF-1.xls	BR BVML1 Kla 4b	11-Oct	III-36	0.64	BR	Bench	BVML	NSS	10.3	7.15	21.3	1.024	6.93	7.80		0	9.82	0.706	1	
PRIEFF-1.xls	BR BVML1 Kla 5a	14-Oct	III-41	0.64	BR	Bench	BVML	NSS	0	5.56	23.5	1.024	5.12	6.91		0	9.82	0.521	1.03	
PRIEFF-1.xls	BR BVML1 Kla 6a	16-Oct	III-45	0.64	BR	Bench	BVML	NSS	0	5.56	23.5	1.024	5.12	7.31		0	9.82	0.521	1.04	
PRIEFF-1.xls	BR BVML1 Kla 7a	17-Oct	III-50	0.64	BR	Bench	BVML	NSS	0	5.56	24	1.024	5.06	7.32		0	9.82	0.515		
PRIEFF-1.xls	BR PPML1 Kla 1a	19-Sep	III-21	0.64	BR	Bench	PPML	NSS	11	8.84	17.5	1.024	9.38	8.149	8.97	0	9.82	0.955	not measured	
PRIEFF-1.xls	BR PPML1 Kla 2a	14-Oct	III-42	0.64	BR	Bench	PPML	NSS	0	7.74	24.9	1.024	6.89	5.607	7.75	0	9.82	0.702	0.98	
PRIEFF-1.xls	BR PPML1 Kla 3a	25-Oct	III-60	0.64	BR	Bench	PPML	NSS	14.8	7.72	19.1	1.024	7.88	7.078	8.68	0	9.82	0.803		
PRIEFF-1.xls	BR PPML1 Kla 4a	6-Nov	III-63	0.64	BR	Bench	PPML	NSS	17.4	8.69	19.3	1.024	8.83	6.84	8.64	0	9.82	0.9		
PPstep1KLaIV49	PPaer1stepKLaIV49	1/9/97	IV-49	0.21	BR	Bench	PPML	NSS	17.8	8.50	13.4	1.024	9.94	7.80	9.79	0	9.82	1.012	1.011	
PRIEFF-1.xls	BR PRI Kla 1a	21-Aug		0.64	BR	Bench	PriEff	NSS	6.54	8.32	22.3	1.024	7.88	7.208	8.14	0	9.82	0.803		
PRIEFF-1.xls	BR PRI Kla 2a	26-Aug		0.64	BR	Bench	PriEff	NSS	7.24	6.46	24.7	1.024	5.78	6.266	7.78	0	9.82	0.589		
PRIEFF-1.xls	BR PRI Kla 3a	19-Sep	III-22	0.64	BR	Bench	PriEff	NSS	7.24	6.8	20.5	1.024	6.72	7.881	8.44	0	9.82	0.684	0.94	
PRIEFF-1.xls	BR PRI Kla 4a	24-Sep	III-25	0.64	BR	Bench	PriEff	NSS	3.73	6.53	23.2	1.024	6.06	7.319	8.01	0	9.82	0.617	0.987	
PRIEFF-1.xls	BR PRI Kla 5a	7-Oct	III-29	0.64	BR	Bench	PriEff	NSS	0	5.53	20.3	1.024	5.49	8.22	8.47	0	9.82	0.559	0.976	
PRIEFF-1.xls	BR PRI Kla 6a	11-Oct	III-34	0.64	BR	Bench	PriEff	NSS	0	8.94	21	1.024	8.73	8.723	8.36	0	9.82	0.889	1.004	
PRIEFF-1.xls	BR PRI Kla 7a	14-Oct	III-43	0.64	BR	Bench	PriEff	NSS	0	7.83	21	1.024	7.64	6.817	8.36	0	9.82	0.778	0.979	
PRIEFF-1.xls	BR PRI Kla 8a	16-Oct	III-47	0.64	BR	Bench	PriEff	NSS	0	7.08	21	1.024	6.91	6.842	8.36	0	9.82	0.704	0.97	
PRIEFF-1.xls	BR PRI Kla 9a	17-Oct	III-48	0.64	BR	Bench	PriEff	NSS	0	9.12	21	1.024	8.90	8.382	8.36	0	9.82	0.907	1.009	
PRIEFF-1.xls	BR PRI Kla 10a	25-Oct	III-61	0.64	BR	Bench	PriEff	NSS	0	8.67	23.3	1.024	8.01	7.104	7.99	0	9.82	0.816	0.977	
PRIEFF-1.xls	BR PRI Kla 11a	6-Nov	III-64	0.64	BR	Bench	PriEff	NSS	0	6.81	22.5	1.024	6.42	8.004	8.11	0	9.82	0.654	0.978	
PRIEFF-1.xls	BR PRI Kla 12a	16-Dec	III-84	0.64	ace	BR	Bench	PriEff	NSS	0	4.75	14.9	1.024	5.36	8.526	9.47	0	9.82	0.546	0.978
PRIEFF-1.xls	BR PRI Kla 13a	2-Jan	IV-25	0.21	BR	Bench	PriEff	NSS	0	7.62	18	1.024	7.99	8.498	8.87	0	9.82	0.814	0.978	
PRIEFF-1.xls	BR PRI Kla 14a	3/8/97	V - 58	0.43	BR	Bench	PriEff	NSS	0	4.68	9.5	1.024	6.00	11.89	10.69	0	9.82	0.611	0.978	
PRIEFF-1.xls	BR PRI Kla 15a	9-Jun	VI - 65	0.43	BR	Bench	PriEff	NSS	0	5.32	16.2	1.024	5.82	8.982	9.21	0	9.82	0.593	0.978	
PPaerstep1KLaA2	PPaer1ssKLaA1	3/26/97	V-96	0.43	PP		1 Inf+RAS	SS	20	24	3.91	15.4	1.037	4.63	2.15	9.23	253.8	5.56	0.832	0.98
PPaerstep1KLaA2	PPaer1stepKLaC1	3/26/97	V-97	0.43	PP		1 Inf+RAS	NSS	60	27	9	15.20	1.037	10.72	5.508	9.42	249.60	14.13	0.759	1.0288
PPaerstep1KLaA1	PPaer1ssKLaC1	3/27/97	VI-05	0.43	PP		1 Inf+RAS	SS	60	28.3	11.27	15.2	1.037	13.42	5.95	9.23	249.6	14.13	0.95	0.98
PPaerstep1KLaA1	PPaer1stepKLaB1	3/27/97	VI-06	0.43	PP		1 Inf+RAS	NSS	40	27.3	6.97	14.80	1.037	8.42	4.376	9.49	249.60	10.06	0.837	0.9543
PPaerstep1KLaA1	PPaer1stepKLaC1	3/27/97	VI-09	0.43	PP		1 Inf+RAS	NSS	60	38.2	9.08	16.50	1.037	10.32	3.368	9.16	249.60	14.13	0.73	0.8661
PPaerstep1KLaA3	PPaer1ssKLaA1	4/4/97	VI-13	0.43	PP		1 Inf+RAS	SS	20	29.3	3.60	14.8	1.037	4.36	0.95	9.30	213.6	5.56	0.783	0.98
PPaerstep1KLaA3	PPaer1ssKLaA2	4/4/97	VI-13	0.43	PP		1 Inf+RAS	SS	20	29.4	3.47	15	1.037	4.16	0.7	9.27	213.6	5.56	0.749	0.98
PPaerstep1KLaA3	PPaer1ssKLaA3	4/4/97	VI-13	0.43	PP		1 Inf+RAS	SS	20	26.5	3.20	14.8	1.037	3.87	0.85	9.30	213.6	5.56	0.696	0.98
PPaerstep1KLaA3	PPaer1ssKLaA4	4/4/97	VI-16	0.43	PP		1 Inf+RAS	SS	20	42.5	5.17	16.5	1.037	5.88	0.69	8.97	213.6	5.56	1.057	0.98
PPaerstep1KLaA3	PPaer1ssKLaA5	4/4/97	VI-16	0.43	PP		1 Inf+RAS	SS	20	35.9	4.21	16.6	1.037	4.77	0.45	8.95	213.6	5.56	0.857	0.98
PPaerstep1KLaA3	PPaer1stepKLaB1	4/4/97	VI-14	0.43	PP		1 Inf+RAS	NSS	40	35.5	7.3	15.20	1.037	8.79	2.851	9.42	213.60	10.06	0.874	0.88
PPaerstep1KLaA3	PPaer1ssKLaB1	4/4/97	VI-14	0.43	PP		1 Inf+RAS	SS	40	35.5	6.18	15.3	1.037	7.34	2.8	9.20	213.6	10.06	0.73	0.98
PPaerstep1KLaA3	PPaer1ssKLaB2	4/4/97	VI-15	0.43	PP		1 Inf+RAS	SS	40	30.4	5.33	15.5	1.037	6.28	2.72	9.17	213.6	10.06	0.625	0.98
PPaerstep1KLaA3	PPaer1ssKLaB3	4/4/97	VI-15	0.43	PP		1 Inf+RAS	SS	40	32.1	5.63	15.8	1.037	6.56	2.7	9.10	213.6	10.06	0.652	0.98
PPaerstep1KLaA3	PPaer1stepKLaC1	4/4/97	VI-17	0.43	PP		1 Inf+RAS	NSS	60	36.5	8.15	16.70	1.037	9.26	3.09	9.12	213.60	14.13	0.655	0.8921
PPaerstep1KLaA3	PPaer1ssKLaC1	4/4/97	VI-17	0.43	PP		1 Inf+RAS	SS	60	36.5	6.97	16.7	1.037	7.86	3.05	8.94	213.6	14.13	0.556	0.98
PPaerstep1KLaA4	PPaer1ssKLaA1	4/4/97	VI-19	0.43	PP		1 Inf+RAS	SS	20	38.8	4.44	17.2	1.037	4.92	0.23	8.84	213.6	5.56	0.885	0.98
PPaerstep1KLaA4	PPaer1ssKLaB1	4/4/97	VI-19	0.43	PP		1 Inf+RAS	SS	40	38.6	4.67	17.8	1.037	5.06	0.48	8.73	213.6	10.06	0.503	0.98
PPaerstep1KLaA4	PPaer1stepKLaC1	4/4/97	VI-20	0.43	PP		1 Inf+RAS	NSS	60	40.2	8.56	17.10	1.037	9.58	1.172	9.04	213.60	14.13	0.678	0.6639
PPaerstep1KLaA4	PPaer1ssKLaC1	4/4/97	VI-20	0.43	PP		1 Inf+RAS	SS	60	40.2	5.38	17.1	1.037	5.98	1.17	8.86	213.6	14.13	0.423	0.98
PPaerstep1KLaA5	PPaer1ssKLaA1	4/5/97	VI-22	0.43	PP		1 Inf+RAS	SS	20	27.8	3.63	15.8	1.037	4.23	1.3	9.30	224.4	5.56	0.761	0.98
PPaerstep1KLaA5	PPaer1ssKLaA2	4/5/97	VI-22	0.43	PP		1 Inf+RAS	SS	20	27.8	3.63	15.8	1.037	4.23	1.3	9.30	224.4	5.56	0.761	0.98
PPaerstep1KLaA5	PPaer1stepKLaB1	4/5/97	VI-22	0.43	PP		1 Inf+RAS	NSS	40	27.9	6.87	15.90	1.037	7.98	3.184	9.27	213.60	10.06	0.793	0.8537
PPaerstep1KLaA5	PPaer1ssKLaB1	4/5/97	VI-22	0.43	PP		1 Inf+RAS	SS	40	27.6	5.34	15.9	1.037	6.20	3.05	9.08	224.4	10.06	0.616	0.98
PPaerstep1KLaA5	PPaer1stepKLaC1	4/5/97	VI-23	0.43	PP		1 Inf+RAS	NSS	60	32	8.02	16.30	1.037	9.18	2.842	9.19	224.40	14.13	0.65	0.7999

Table B1. Oxygen transfer data summary for pilot plant and bench scale reactor.

File	File Sheet	Date	Page	Anaerobic					Airflow (scfh)	OUR		Temp (C)	Theta	Kla (20) (		C _{ss}		Csat	KLa (Clean)	Alpha	Beta
				HRT	Reactor	Basin	Contents	Method		(mg/ L-h)	KLa (/h)			/h)	(mg/L)	(mg/L)	Q(gpd)				
PPaerstep1KLaA5	PPaer1ssKLaC1	4/5/97	VI-21	0.43	PP	1	Inf+RAS	SS	60	28	9.32	15.5	1.037	10.98	5.35	9.30	224.4	14.13	0.777	0.98	
PPaerstep1KLaA5	PPaer1ssKLaC2	4/5/97	VI-23	0.43	PP	1	Inf+RAS	SS	60	32.2	5.85	16.5	1.037	6.64	2.77	8.97	224.4	14.13	0.47	0.98	
PPaerstep1KLaA6	PPaer1ssKLaA1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	20	34.5	3.91	16.8	1.037	4.39	0.25	8.92	224.4	5.56	0.79	0.98	
PPaerstep1KLaA6	PPaer1ssKLaA2	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	20	38.2	4.38	16.9	1.037	4.90	0.3	8.90	224.4	5.56	0.882	0.98	
PPaerstep1KLaA6	PPaer1ssKLaB1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	40	34.6	4.19	16.8	1.037	4.71	0.65	8.92	224.4	10.06	0.468	0.98	
PPaerstep1KLaA6	PPaer1stepKLaC1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	60	37.1	8.16	16.30	1.037	9.42	1.327	9.19	224.40	14.13	0.667	0.6568	
PPaerstep1KLaA6	PPaer1ssKLaC1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	60	35.8	4.89	17	1.037	5.45	1.3	8.88	224.4	14.13	0.386	0.98	
Pilotkla	PP ML Kla 2a	31-Aug	I-91	0.64	PP	1	ML	SS	60	16.7	10.51	22	1.037	9.72	5.9	8.024	120	14.13	0.688		
Pilotkla	PP ML Kla 2b	31-Aug	I-91	0.64	PP	1	ML	SS	60	17.9	11.10	22	1.037	10.27	5.9	8.024	120	14.13	0.727		
Pilotkla	PP ML Kla 5a	14-Oct	III-37	0.64	PP	1	ML	SS	60	24.2	7.93	18.9	1.037	8.27	4.90	8.54	120	14.13	0.585		
Pilotkla	PP ML Kla 6a	25-Oct	III-59	0.64	PP	1	ML	SS	60	30.4	9.73	17.75	1.037	10.61	5.12	8.742	120	14.13	0.751	0.971	
Pilotkla	PP ML Kla 7a	6-Nov	III-63	0.64	PP	1	ML	SS	60	17.4	9.01	17.5	1.037	9.93	6.20	8.788	120	14.13	0.703	0.988	
PilotSSKLa	PPgroup.ML KLaA1	7-Dec	III-66	0.64	PP	1	ML	SS	60	23.8	14.85	13	1.037	14.76	7.60	9.681	120	14.13	1.045	0.98	
PilotSSKLa	PPgroup.ML KLaB1	8-Dec	III-68	0.64	PP	1	ML	SS	60	23.7	13.39	13.5	1.037	11.06	6.85	9.57	240	14.13	0.783	0.98	
PilotSSKLa	PPgroup.ML KLaC1	9-Dec	III-70	0.64	PP	1	ML	SS	60	14.5	12.46	12	1.037	8.42	7.60	9.902	240	14.13	0.596	0.98	
PilotSSKLa	PPgroup.ML KLaA2	7-Dec	III-66	0.64	PP	2	ML	SS	60	22.1	13.66	13	1.037	13.37	7.55	9.681	120	14.13	0.946	0.98	
PilotSSKLa	PPgroup.ML KLaB2	8-Dec	III-68	0.64	PP	2	ML	SS	60	20.8	12.30	13.5	1.037	9.67	6.85	9.57	240	14.13	0.685	0.98	
PilotSSKLa	PPgroup.ML KLaC2	9-Dec	III-71	0.64	PP	2	ML	SS	60	19.2	8.86	12	1.037	7.35	6.40	9.902	240	14.13	0.52	0.98	
PilotSSKLa	PPgroup.ML KLaA3	7-Dec	III-67	0.64	PP	3	ML	SS	60	21.2	16.42	13	1.037	11.24	7.25	9.681	360	14.13	0.796	0.98	
PilotSSKLa	PPgroup.ML KLaB3	8-Dec	III-69	0.64	PP	3	ML	SS	60	18.5	14.34	13.5	1.037	7.38	6.40	9.57	600	14.13	0.523	0.98	
PilotSSKLa	PPgroup.ML KLaC3	9-Dec	III-72	0.64	PP	3	ML	SS	60	18.3	16.56	12	1.037	10.65	7.60	9.902	360	14.13	0.754	0.98	
PilotSSKLa	PPgroup.ML KLaD1	12/13/96	III-74	0.64	ACE	PP	1	ML	SS	60	22	9.70	14.3	1.037	9.32	6.50	9.405	120	14.13	0.659	0.98
PilotSSKLa	PPgroup.ML KLaE1	12/16/96	III-80	0.64	ACE	PP	1	ML	SS	40	19.7	8.87	14.8	1.037	10.72	5.80	9.303	256.8	10.06	1.066	0.98
PilotSSKLa	PPgroup.ML KLaF1	12/16/96	III-85	0.64	ACE	PP	1	ML	SS	20	21	3.05	15	1.037	3.66	1.60	9.267	256.8	5.56	0.658	0.98
PilotSSKLa	PPgroup.ML KLaG1	12/17/96	III-88	0.64	ACE	PP	1	ML	SS	40	13.7	9.47	13.8	1.037	11.87	7.80	9.515	40.2	10.06	1.18	0.98
PilotSSKLa	PPgroup.ML KLaH1	12/18/96	III-92	0.64	ACE	PP	1	ML	SS	40	17.1	8.31	14	1.037	10.35	6.90	9.469	75.6	10.06	1.028	0.98
PilotSSKLa	PPgroup.ML KLaD2	12/13/96	III-74	0.64	ACE	PP	2	ML	SS	60	13.5	9.17	14.3	1.037	5.93	6.60	9.405	240	14.13	0.42	0.98
PilotSSKLa	PPgroup.ML KLaE2	12/16/96	III-83	0.64	ACE	PP	2	ML	SS	40	23.2	7.43	14.5	1.037	6.48	5.00	9.368	248.4	10.06	0.644	0.98
PilotSSKLa	PPgroup.ML KLaF2	12/16/96	III-86	0.64	ACE	PP	2	ML	SS	20	21.3	2.91	15	1.037	3.22	1.35	9.267	248.4	5.56	0.58	0.98
PilotSSKLa	PPgroup.ML KLaG2	12/17/96	III-89	0.64	ACE	PP	2	ML	SS	40	17.4	7.21	13.6	1.037	9.10	6.65	9.552	65.4	10.06	0.905	0.98
PilotSSKLa	PPgroup.ML KLaH2	12/18/96	III-93	0.64	ACE	PP	2	ML	SS	40	13.1	5.08	14	1.037	6.33	6.70	9.469	17.28	10.06	0.629	0.98
PilotSSKLa	PPgroup.ML KLaD3	12/13/96	III-74	0.64	ACE	PP	3	ML	SS	60	12.8	10.89	14.3	1.037	5.93	6.75	9.405	300	14.13	0.419	0.98
PilotSSKLa	PPgroup.ML KLaE3	12/16/96	III-82	0.64	ACE	PP	3	ML	SS	40	22.6	8.02	14.5	1.037	5.30	4.15	9.368	600	10.06	0.527	0.98
PilotSSKLa	PPgroup.ML KLaF3	12/16/96	III-87	0.64	ACE	PP	3	ML	SS	20	23.3	3.52	15	1.037	3.53	1.35	9.267	480	5.56	0.634	0.98
PilotSSKLa	PPgroup.ML KLaG3	12/17/96	III-90	0.64	ACE	PP	3	ML	SS	40	20.9	6.85	13.9	1.037	8.55	4.45	9.487	384	10.06	0.85	0.98
PilotSSKLa	PPgroup.ML KLaH3	12/18/96	III-93	0.64	ACE	PP	3	ML	SS	40	20.1	5.56	14.3	1.037	6.85	3.75	9.405	396	10.06	0.681	0.98
PPstep1KLaIV30	PPaer1stepKLaIV30	1/2/97	IV-30	0.21	PP	1	ML	NSS	20	11.4	3.49	14.2	1.037	4.32	5.30	9.62	80	5.56	0.776	0.976	
PPstep1KLaIV30	PPaer1stepKLaIV31	1/2/97	IV-31	0.21	PP	1	ML	NSS	40	10.1	5.16	14.2	1.037	6.37	7.76	9.62	80	10.06	0.633	1.101	
PPstep1KLaIV44	PPaer1stepKLaIV44	1/7/97	IV-44	0.21	PP	1	ML	NSS	60	14.8	9.41	13	1.037	12.15	8.79	9.88	0	14.13	0.86	1.048	
PPstep1KLaIV44	PPaer1stepKLaIV45	1/7/97	IV-45	0.21	PP	1	ML	NSS	20	14.8	4.29	13.1	1.037	5.52	6.66	9.86	0	5.56	0.993	1.024	
PPstep1KLaIV49	PPaer1stepKLaIV50	1/9/97	IV-50	0.21	PP	1	ML	NSS	20	17.5	4.07	13.1	1.037	5.24	5.50	9.86	0	5.56	0.943	0.994	
PilotSSKLa	PPgroup.ML KLaI1	12/22/96	IV-10	0.21	PP	1	ML	SS	40	10.4	7.15	12.2	1.037	9.50	8.00	9.856	79.8	10.06	0.944	0.98	
PilotSSKLa	PPgroup.ML KLaJ1	12/23/96	IV-15	0.21	PP	1	ML	SS	60	12.5	12.54	13.8	1.037	15.72	8.30	9.515	79.8	14.13	1.112	0.98	
PilotSSKLa	PPgroup.ML KLaK1	12/31/96	IV-17	0.21	PP	1	ML	SS	20	16.5	4.95	16	1.037	5.72	5.20	9.064	75.6	5.56	1.03	0.98	
PilotSSKLa	PPgroup.ML KLaL1	1/2/97	IV-28	0.21	PP	1	ML	SS	20	15.5	4.33	14.2	1.037	5.35	5.20	9.432	79.8	5.56	0.962	0.98	
PilotSSKLa	PPgroup.ML KLaM1	1/5/97	IV-35	0.21	PP	1	ML	SS	20	14.5	4.02	14.7	1.037	4.88	5.00	9.331	97.2	5.56	0.877	0.98	
PilotSSKLa	PPgroup.ML KLaN1	1/7/97	IV-41	0.21	PP	1	ML	SS	20	14.2	5.01	12.7	1.037	6.53	6.30	9.745	76.8	5.56	1.175	0.98	
PilotSSKLa	PPgroup.ML KLaO1	1/9/97	IV-47	0.21	PP	1	ML	SS	20	19	4.37	13.4	1.037	5.56	4.60	9.598	79.8	5.56	1	0.98	
PilotSSKLa	PPgroup.ML KLaI2	12/22/96	IV-11	0.21	PP	2	ML	SS	40	9.21	7.22	12.2	1.037	9.60	8.00	9.856	79.8	10.06	0.954	0.98	
PilotSSKLa	PPgroup.ML KLaJ2	12/23/96	IV-15	0.21	PP	2	ML	SS	40	8.55	3.82	13.8	1.037	4.79	6.60	9.515	79.8	10.06	0.476	0.98	
PilotSSKLa	PPgroup.ML KLaK2	12/31/96	IV-17	0.21	PP	2	ML	SS	20	15.1	3.98	16	1.037	4.61	4.50	9.064	87	5.56	0.829	0.98	
PilotSSKLa	PPgroup.ML KLaL2	1/2/97	IV-28	0.21	PP	2	ML	SS	20	13.9	3.43	14.2	1.037	4.24	4.50	9.432	87	5.56	0.763	0.98	
PilotSSKLa	PPgroup.ML KLaM2	1/5/97	IV-35	0.21	PP	2	ML	SS	20	13.4	2.54	14.7	1.037	3.08	3.30	9.331	78	5.56	0.555	0.98	

Table B1. Oxygen transfer data summary for pilot plant and bench scale reactor.

File	File Sheet	Date	Page	Anaerobic				Airflow (scfh)	OUR		Temp (C)	Theta	Kla (20) (		C _{ss} (mg/L)	Csat	KLa (Clean)	Alpha	Beta	
				HRT	Reactor	Basin	Contents		Method	(mg/ L-h)			(/h)	h)		(book) (mg/L)				Q(gpd)
PilotSSKLa	PPgroup.ML KLaN2	1/7/97	IV-41	0.21	PP	2	ML	SS	20	13.4	3.62	12.7	1.037	4.73	5.40	9.745	56	5.56	0.851	0.98
PilotSSKLa	PPgroup.ML KLaO2	1/9/97	IV-47	0.21	PP	2	ML	SS	20	16.1	3.36	13.4	1.037	4.27	4.10	9.598	73.2	5.56	0.768	0.98
PilotSSKLa	PPgroup.ML KLaI3	12/22/96	IV-11	0.21	PP	3	ML	SS	40	10.5	5.21	12.4	1.037	6.87	5.40	9.856	346.2	10.06	0.683	0.98
PilotSSKLa	PPgroup.ML KLaJ3	12/23/96	IV-15	0.21	PP	3	ML	SS	40	10.5	8.41	13.8	1.037	10.55	6.20	9.515	597.6	10.06	1.049	0.98
PilotSSKLa	PPgroup.ML KLaK3	12/31/96	IV-18	0.21	PP	3	ML	SS	20	17.9	3.62	16	1.037	4.19	2.25	9.064	398.4	5.56	0.754	0.98
PilotSSKLa	PPgroup.ML KLaL3	1/2/97	IV-29	0.21	PP	3	ML	SS	20	14.8	3.11	16	1.037	3.60	2.30	9.064	368.4	5.56	0.647	0.98
PilotSSKLa	PPgroup.ML KLaM3	1/5/97	IV-36	0.21	PP	3	ML	SS	20	13.7	3.07	14.7	1.037	3.73	2.55	9.331	362.4	5.56	0.67	0.98
PilotSSKLa	PPgroup.ML KLaN3	1/7/97	IV-42	0.21	PP	3	ML	SS	20	26.4	5.44	12.7	1.037	7.10	3.20	9.745	369	5.56	1.277	0.98
PilotSSKLa	PPgroup.ML KLaO3	1/9/97	IV-48	0.21	PP	3	ML	SS	20	19.9	3.26	13.4	1.037	4.14	1.85	9.598	388	5.56	0.745	0.98
PPstep1KLaV-36	PPaer1stepKLaB2	2/20/97	V-36	0.43	PP	1	ML	NSS	40	17.4	4.97	14.2	1.037	6.14	4.367	9.62	126.6	10.06	0.61	0.911
PPstep1KLaV-39	PPaer1stepKLaB2	2/22/97	V-39	0.43	PP	1	ML	NSS	40	14	4.76	13.5	1.037	6.03	4.443	9.77	126.6	10.06	0.599	0.853
PPstep1KLaV-48	PPaer1stepKLaB2	3/4/97	V-48	0.43	PP	1	ML	NSS	40	10.7	4.45	14.2	1.037	5.50	3.53	9.62	126.6	10.06	0.547	0.699
PPstep1KLaV-48	PPaer1stepKLaC1	3/4/97	V-48	0.43	PP	1	ML	NSS	60	10.5	6.29	14.2	1.037	7.77	4.443	9.62	126.6	14.13	0.55	0.709
PPstep1KLaV-55	PPaer1stepKLaB1	3/8/97	V-55	0.43	PP	1	ML	NSS	40	25.4	5.68	14.2	1.037	7.01	2.935	9.62	126.6	10.06	0.697	0.823
PPstep1KLaV-55	PPaer1stepKLaC1	3/8/97	V-55	0.43	PP	1	ML	NSS	60	25.4	6.56	14.2	1.037	8.10	4.169	9.62	126.6	14.13	0.574	0.903
PPstep1KLaV-62	PPaer1stepKLaC1	3/13/97	V-62	0.43	PP	1	ML	NSS	60	32.7	4.92	14.2	1.037	6.08	5.454	9.62	399.6	14.13	0.43	1.631
PPstep1KLaV-64	PPaer1stepKLaB1	3/17/97	V-64	0.43	PP	1	ML	NSS	40	25.5	6.58	14.5	1.037	8.04	4.607	9.56	67.2	10.06	0.8	0.928
PPstep1KLaV-64	PPaer1stepKLaC1	3/17/97	V-64	0.43	PP	1	ML	NSS	60	25.1	7.69	15.2	1.037	9.16	5.454	9.42	67.2	14.13	0.648	0.967
PPstep1KLaV-66	PPaer1stepKLaB1	3/18/97	V-66	0.43	PP	1	ML	NSS	40	14.3	6.07	15.2	1.037	7.23	5.046	9.42	65.4	10.06	0.718	0.833
PPstep1KLaV-66	PPaer1stepKLaC1	3/18/97	V-68	0.43	PP	1	ML	NSS	60	17.3	7.88	15.5	1.037	9.29	5.746	9.42	65.4	14.13	0.657	0.886
PPstep1KLaV-66	PPaer1stepKLaB2	3/18/97	V-70	0.43	PP	1	ML	NSS	40	16.2	5.86	15.8	1.037	6.83	4.313	9.37	65.4	10.06	0.679	0.797
PPstep1KLaV-74	PPaer1stepKLaB1	3/18/97	V-74	0.43	PP	1	ML	NSS	40	30.8	7.83	15.2	1.037	9.33	3.721	9.42	160.2	10.06	0.928	0.879
PPstep1KLaV-74	PPaer1stepKLaC1	3/18/97	V-74	0.43	PP	1	ML	NSS	60	32.9	9.11	15.5	1.037	10.73	4.879	9.42	160.2	14.13	0.759	0.975
PPstep1KLaA2	PPaer1stepKLaB1	3/20/97	V-74	0.43	PP	1	ML	NSS	40	31.8	7.98	15.8	1.037	9.30	3.713	9.29	160.2	10.06	0.925	0.89
PPstep1KLaA2	PPaer1stepKLaC1	3/20/97	V-76	0.43	PP	1	ML	NSS	60	32.9	8.95	15.8	1.037	10.43	4.891	9.29	160.2	14.13	0.738	0.99
PPstep1KLaA5	PPaer1stepKLaB1	3/25/97	V-92	0.43	PP	1	ML	NSS	40	25.8	8.11	14.50	1.037	9.92	3.981	9.56	317.40	10.06	0.986	0.88
PPstep1KLaA5	PPaer1stepKLaC1	3/25/97	V-93	0.43	PP	1	ML	NSS	60	26.5	8.91	14.90	1.037	10.73	5.061	9.27	317.40	14.13	0.76	1.03
PPstep1KLaVI-66	PPaer1stepKLaC1	6/9/97	VI-66	0.43	PP	1	ML	NSS	60	10.7	10.2	17.1	1.037	11.30	7.088	9.04	120.00	14.13	0.799	0.98
PPstep1KLaVI-67	PPaer1stepKLaC1	6/9/97	VI-67	0.43	PP	1	ML	NSS	60	17.6	10.9	17.1	1.037	12.09	6.614	9.04	120.00	14.13	0.855	0.98
PPstep1KLaVI-68	PPaer1stepKLaC1	6/9/97	VI-68	0.43	PP	1	ML	NSS	60	19.4	10.7	17.5	1.037	11.74	6.454	8.97	120.00	14.13	0.831	0.99
PPstep1KLaVI-69	PPaer1stepKLaC1	6/9/97	VI-69	0.43	PP	1	ML	NSS	60	17.3	10.4	17.8	1.037	11.27	6.54	8.97	120.00	14.13	0.798	0.98
PPstep1KLaV-48	PPaer1stepKLaB2	3/4/97	V-48	0.43	PP	1	ML	SS	40	10.7	4.45	14.2	1.037	2.41196	3.5	9.62	126.6	10.06	0.240	0.98
PPstep1KLaV-55	PPaer1stepKLaB1	3/8/97	V-55	0.43	PP	1	ML	SS	40	25.4	5.68	14.2	1.037	4.36026	2.9	9.62	126.6	10.06	0.433	0.98
PPstep1KLaV-64	PPaer1stepKLaB1	3/17/97	V-64	0.43	PP	1	ML	SS	40	25.5	6.58	14.5	1.037	5.89931	4.6	9.56	67.2	10.06	0.586	0.98
PPstep1KLaV-66	PPaer1stepKLaB1	3/18/97	V-66	0.43	PP	1	ML	SS	40	14.3	6.07	15.2	1.037	4.06487	5.0	9.42	65.4	10.06	0.404	0.98
PPstep1KLaV-74	PPaer1stepKLaB1	3/18/97	V-74	0.43	PP	1	ML	SS	40	30.8	7.83	15.2	1.037	6.48362	3.7	9.42	160.2	10.06	0.644	0.98
PPstep1KLaA2	PPaer1stepKLaB1	3/20/97	V-76	0.43	PP	1	ML	SS	40	31.8	7.98	15.8	1.037	6.67349	3.7	9.29	160.2	10.06	0.663	0.98
PPstep1KLaA5	PPaer1stepKLaB1	3/25/97	V-92	0.43	PP	1	ML	SS	40	25.8	8.11	14.5	1.037	6.72039	4.0	9.56	317.40	10.06	0.668	0.98
PPstep1KLaI/V30	PPaer1stepKLaI/V30	1/2/97	IV-30	0.21	PP	1	ML	SS	20	11.4	3.49	14.2	1.037	3.45983	5.3	9.62	80	5.56	0.622	0.98
PPstep1KLaI/V44	PPaer1stepKLaI/V45	1/7/97	IV-45	0.21	PP	1	ML	SS	20	14.8	4.29	13.1	1.037	4.9201	6.7	9.86	0	5.56	0.885	0.98
PPstep1KLaV-48	PPaer1stepKLaB2	3/4/97	V-48	0.43	PP	1	ML	SS	60	10.5	6.29	14.2	1.037	3.00397	4.4	9.625	126.6	14.13	0.213	0.98
PPstep1KLaV-55	PPaer1stepKLaB1	3/8/97	V-55	0.43	PP	1	ML	SS	60	25.4	6.56	14.2	1.037	5.62974	4.2	9.625	126.6	14.13	0.398	0.98
PPstep1KLaV-64	PPaer1stepKLaB1	3/17/97	V-64	0.43	PP	1	ML	SS	60	25.1	7.69	15.2	1.037	7.43909	5.5	9.418	67.2	14.13	0.526	0.98
PPstep1KLaV-66	PPaer1stepKLaB1	3/18/97	V-66	0.43	PP	1	ML	SS	60	17.3	7.88	15.5	1.037	5.86949	5.7	9.418	65.4	14.13	0.415	0.98
PPstep1KLaV-74	PPaer1stepKLaB1	3/18/97	V-74	0.43	PP	1	ML	SS	60	32.9	9.11	15.5	1.037	9.01536	4.9	9.418	160.2	14.13	0.638	0.98
PPstep1KLaA2	PPaer1stepKLaB1	3/20/97	V-76	0.43	PP	1	ML	SS	60	32.9	8.95	15.8	1.037	9.17448	4.9	9.287	160.2	14.13	0.649	0.98
PPstep1KLaA5	PPaer1stepKLaB1	3/25/97	V-92	0.43	PP	1	ML	SS	60	26.5	8.91	14.9	1.037	9.88557	5.1	9.268	317.4	14.13	0.700	0.98
PPstep1KLaI/V30	PPaer1stepKLaI/V30	1/2/97	IV-30	0.21	PP	1	ML	SS	40	10.1	5.16	14.2	1.037	8.738	7.8	9.625	80	10.06	0.869	0.98
PPstep1KLaI/V44	PPaer1stepKLaI/V45	1/7/97	IV-45	0.21	PP	1	ML	SS	60	14.8	9.41	13	1.037	16.5261	8.8	9.878	0	14.13	1.170	0.98
Pilotkla	PP Peff Kla 1a	31-Aug	I-93,94	0.64	PP	1	PriEff	NSS	60	5.49	4.5	23.5	1.037	3.96	6.93	7.96	0	14.13	0.28	
Pilotkla	PP Peff Kla 3a	19-Sep	III-17,18	0.64	PP	1	PriEff	NSS	60	6.57	5.18	22.5	1.037	4.73	7.188	8.11	0	14.13	0.335	0.979

Table B2. Oxygen transfer data summary for pilot plant aeration basin #1.

File	File Sheet	Date	Page	Anaerobic					Airflow (scfh)	OUR		Temp (C)	Theta	Kla (20)	C _{ss} (mg/L)	C _{sat} (book)		KLa (Clean)	Alpha	Beta
				HRT	Reactor	Basin	Contents	Method		(mg/ L-h)	(/h)					Q(gpd)				
PPaerstep1KLaA1	PPaer1stepKLaB1	3/27/97	VI-06	0.43	PP	1	Inf+RAS	NSS	40	27.3	6.97	14.80	1.037	8.42	4.38	9.49	249.60	10.06	0.837	0.954
PPaerstep1KLaA1	PPaer1stepKLaC1	3/27/97	VI-09	0.43	PP	1	Inf+RAS	NSS	60	38.2	9.08	16.50	1.037	10.32	3.37	9.16	249.60	14.13	0.730	0.866
PPaerstep1KLaA3	PPaer1stepKLaB1	4/4/97	VI-14	0.43	PP	1	Inf+RAS	NSS	40	35.5	7.3	15.20	1.037	8.79	2.85	9.42	213.60	10.06	0.874	0.880
PPaerstep1KLaA3	PPaer1stepKLaC1	4/4/97	VI-17	0.43	PP	1	Inf+RAS	NSS	60	36.5	8.15	16.70	1.037	9.26	3.09	9.12	213.60	14.13	0.655	0.892
PPaerstep1KLaA4	PPaer1stepKLaC1	4/4/97	VI-20	0.43	PP	1	Inf+RAS	NSS	60	40.2	8.56	17.10	1.037	9.58	1.17	9.04	213.60	14.13	0.678	0.664
PPaerstep1KLaA5	PPaer1stepKLaB1	4/5/97	VI-22	0.43	PP	1	Inf+RAS	NSS	40	27.9	6.87	15.90	1.037	7.98	3.18	9.27	213.60	10.06	0.793	0.854
PPaerstep1KLaA5	PPaer1stepKLaC1	4/5/97	VI-23	0.43	PP	1	Inf+RAS	NSS	60	32	8.02	16.30	1.037	9.18	2.84	9.19	224.40	14.13	0.650	0.800
PPaerstep1KLaA2	PPaer1ssKLaA1	3/26/97	V-96	0.43	PP	1	Inf+RAS	SS	20	24	3.91	15.4	1.037	4.63	2.15	9.23	253.8	5.56	0.832	0.980
PPaerstep1KLaA1	PPaer1ssKLaC1	3/27/97	VI-05	0.43	PP	1	Inf+RAS	SS	60	28.3	11.27	15.2	1.037	13.42	5.95	9.23	249.6	14.13	0.950	0.980
PPaerstep1KLaA3	PPaer1ssKLaA1	4/4/97	VI-13	0.43	PP	1	Inf+RAS	SS	20	29.3	3.60	14.8	1.037	4.36	0.95	9.30	213.6	5.56	0.783	0.980
PPaerstep1KLaA3	PPaer1ssKLaA2	4/4/97	VI-13	0.43	PP	1	Inf+RAS	SS	20	29.4	3.47	15	1.037	4.16	0.70	9.27	213.6	5.56	0.749	0.980
PPaerstep1KLaA3	PPaer1ssKLaA3	4/4/97	VI-13	0.43	PP	1	Inf+RAS	SS	20	26.5	3.20	14.8	1.037	3.87	0.85	9.30	213.6	5.56	0.696	0.980
PPaerstep1KLaA3	PPaer1ssKLaA4	4/4/97	VI-16	0.43	PP	1	Inf+RAS	SS	20	42.5	5.17	16.5	1.037	5.88	0.69	8.97	213.6	5.56	1.057	0.980
PPaerstep1KLaA3	PPaer1ssKLaA5	4/4/97	VI-16	0.43	PP	1	Inf+RAS	SS	20	35.9	4.21	16.6	1.037	4.77	0.45	8.95	213.6	5.56	0.857	0.980
PPaerstep1KLaA3	PPaer1ssKLaB1	4/4/97	VI-14	0.43	PP	1	Inf+RAS	SS	40	35.5	6.18	15.3	1.037	7.34	2.80	9.20	213.6	10.06	0.730	0.980
PPaerstep1KLaA3	PPaer1ssKLaB2	4/4/97	VI-15	0.43	PP	1	Inf+RAS	SS	40	30.4	5.33	15.5	1.037	6.28	2.72	9.17	213.6	10.06	0.625	0.980
PPaerstep1KLaA3	PPaer1ssKLaB3	4/4/97	VI-15	0.43	PP	1	Inf+RAS	SS	40	32.1	5.63	15.8	1.037	6.56	2.70	9.10	213.6	10.06	0.652	0.980
PPaerstep1KLaA3	PPaer1ssKLaC1	4/4/97	VI-17	0.43	PP	1	Inf+RAS	SS	60	36.5	6.97	16.7	1.037	7.86	3.05	8.94	213.6	14.13	0.556	0.980
PPaerstep1KLaA4	PPaer1ssKLaA1	4/4/97	VI-19	0.43	PP	1	Inf+RAS	SS	20	38.8	4.44	17.2	1.037	4.92	0.23	8.84	213.6	5.56	0.885	0.980
PPaerstep1KLaA4	PPaer1ssKLaB1	4/4/97	VI-19	0.43	PP	1	Inf+RAS	SS	40	38.6	4.67	17.8	1.037	5.06	0.48	8.73	213.6	10.06	0.503	0.980
PPaerstep1KLaA4	PPaer1ssKLaC1	4/4/97	VI-20	0.43	PP	1	Inf+RAS	SS	60	40.2	5.38	17.1	1.037	5.98	1.17	8.86	213.6	14.13	0.423	0.980
PPaerstep1KLaA5	PPaer1ssKLaA1	4/5/97	VI-22	0.43	PP	1	Inf+RAS	SS	20	27.8	3.63	15.8	1.037	4.23	1.30	9.30	224.4	5.56	0.761	0.980
PPaerstep1KLaA5	PPaer1ssKLaA2	4/5/97	VI-22	0.43	PP	1	Inf+RAS	SS	20	27.8	3.63	15.8	1.037	4.23	1.30	9.30	224.4	5.56	0.761	0.980
PPaerstep1KLaA5	PPaer1ssKLaB1	4/5/97	VI-22	0.43	PP	1	Inf+RAS	SS	40	27.6	5.34	15.9	1.037	6.20	3.05	9.08	224.4	10.06	0.616	0.980
PPaerstep1KLaA5	PPaer1ssKLaC1	4/5/97	VI-21	0.43	PP	1	Inf+RAS	SS	60	28	9.32	15.5	1.037	10.98	5.35	9.30	224.4	14.13	0.777	0.980
PPaerstep1KLaA5	PPaer1ssKLaC2	4/5/97	VI-23	0.43	PP	1	Inf+RAS	SS	60	32.2	5.85	16.5	1.037	6.64	2.77	8.97	224.4	14.13	0.470	0.980
PPaerstep1KLaA6	PPaer1ssKLaA1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	20	34.5	3.91	16.8	1.037	4.39	0.25	8.92	224.4	5.56	0.790	0.980
PPaerstep1KLaA6	PPaer1ssKLaA2	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	20	38.2	4.38	16.9	1.037	4.90	0.30	8.90	224.4	5.56	0.882	0.980
PPaerstep1KLaA6	PPaer1ssKLaB1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	40	34.6	4.19	16.8	1.037	4.71	0.65	8.92	224.4	10.06	0.468	0.980
PPaerstep1KLaA6	PPaer1stepKLaC1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	60	37.1	8.16	16.30	1.037	9.42	1.33	9.19	224.40	14.13	0.667	0.657
PPaerstep1KLaA6	PPaer1ssKLaC1	4/5/97	VI-25	0.43	PP	1	Inf+RAS	SS	60	35.8	4.89	17	1.037	5.45	1.30	8.88	224.4	14.13	0.386	0.980
PPstep1KLaIV30	PPaer1stepKLaIV30	1/2/97	IV-30	0.21	PP	1	ML	NSS	20	11.4	3.49	14.2	1.037	4.32	5.30	9.62	80	5.56	0.776	0.976
PPstep1KLaIV30	PPaer1stepKLaIV31	1/2/97	IV-31	0.21	PP	1	ML	NSS	40	10.1	5.16	14.2	1.037	6.37	7.76	9.62	80	10.06	0.633	1.101
PPstep1KLaIV44	PPaer1stepKLaIV44	1/7/97	IV-44	0.21	PP	1	ML	NSS	60	14.8	9.41	13	1.037	12.15	8.79	9.88	0	14.13	0.860	1.048
PPstep1KLaIV44	PPaer1stepKLaIV45	1/7/97	IV-45	0.21	PP	1	ML	NSS	20	14.8	4.29	13.1	1.037	5.52	6.66	9.86	0	5.56	0.993	1.024
PPstep1KLaIV49	PPaer1stepKLaIV50	1/9/97	IV-50	0.21	PP	1	ML	NSS	20	17.5	4.07	13.1	1.037	5.24	5.50	9.86	0	5.56	0.943	0.994
PPstep1KLaV-36	PPaer1stepKLaB2	2/20/97	V-36	0.43	PP	1	ML	NSS	40	17.4	4.97	14.2	1.037	6.14	4.37	9.62	126.6	10.06	0.610	0.911
PPstep1KLaV-39	PPaer1stepKLaB2	2/22/97	V-39	0.43	PP	1	ML	NSS	40	14	4.76	13.5	1.037	6.03	4.44	9.77	126.6	10.06	0.599	0.853
PPstep1KLaV-48	PPaer1stepKLaB2	3/4/97	V-48	0.43	PP	1	ML	NSS	40	10.7	4.45	14.2	1.037	5.50	3.53	9.62	126.6	10.06	0.547	0.699
PPstep1KLaV-48	PPaer1stepKLaC1	3/4/97	V-48	0.43	PP	1	ML	NSS	60	10.5	6.29	14.2	1.037	7.77	4.44	9.62	126.6	14.13	0.550	0.709
PPstep1KLaV-55	PPaer1stepKLaB1	3/8/97	V-55	0.43	PP	1	ML	NSS	40	25.4	5.68	14.2	1.037	7.01	2.94	9.62	126.6	10.06	0.697	0.823
PPstep1KLaV-55	PPaer1stepKLaC1	3/8/97	V-55	0.43	PP	1	ML	NSS	60	25.4	6.56	14.2	1.037	8.10	4.17	9.62	126.6	14.13	0.574	0.903
PPstep1KLaV-62	PPaer1stepKLaC1	3/13/97	V-62	0.43	PP	1	ML	NSS	60	32.7	4.92	14.2	1.037	6.08	5.45	9.62	399.6	14.13	0.430	1.631
PPstep1KLaV-64	PPaer1stepKLaB1	3/17/97	V-64	0.43	PP	1	ML	NSS	40	25.5	6.58	14.5	1.037	8.04	4.61	9.56	67.2	10.06	0.800	0.928
PPstep1KLaV-64	PPaer1stepKLaC1	3/17/97	V-64	0.43	PP	1	ML	NSS	60	25.1	7.69	15.2	1.037	9.16	5.45	9.42	67.2	14.13	0.648	0.967
PPstep1KLaV-66	PPaer1stepKLaB1	3/18/97	V-66	0.43	PP	1	ML	NSS	40	14.3	6.07	15.2	1.037	7.23	5.05	9.42	65.4	10.06	0.718	0.833
PPstep1KLaV-66	PPaer1stepKLaC1	3/18/97	V-68	0.43	PP	1	ML	NSS	60	17.3	7.88	15.5	1.037	9.29	5.75	9.42	65.4	14.13	0.657	0.886
PPstep1KLaV-66	PPaer1stepKLaB2	3/18/97	V-70	0.43	PP	1	ML	NSS	40	16.2	5.86	15.8	1.037	6.83	4.31	9.37	65.4	10.06	0.679	0.797
PPstep1KLaV-74	PPaer1stepKLaB1	3/18/97	V-74	0.43	PP	1	ML	NSS	40	30.8	7.83	15.2	1.037	9.33	3.72	9.42	160.2	10.06	0.928	0.879
PPstep1KLaV-74	PPaer1stepKLaC1	3/18/97	V-74	0.43	PP	1	ML	NSS	60	32.9	9.11	15.5	1.037	10.73	4.88	9.42	160.2	14.13	0.759	0.975
PPstep1KLaA2	PPaer1stepKLaB1	3/20/97	V-74	0.43	PP	1	ML	NSS	40	31.8	7.98	15.8	1.037	9.30	3.71	9.29	160.2	10.06	0.925	0.885
PPstep1KLaA2	PPaer1stepKLaC1	3/20/97	V-76	0.43	PP	1	ML	NSS	60	32.9	8.95	15.8	1.037	10.43	4.89	9.29	160.2	14.13	0.738	0.992
PPstep1KLaA5	PPaer1stepKLaB1	3/25/97	V-92	0.43	PP	1	ML	NSS	40	25.8	8.11	14.50	1.037	9.92	3.98	9.56	317.40	10.06	0.986	0.883
PPstep1KLaA5	PPaer1stepKLaC1	3/25/97	V-93	0.43	PP	1	ML	NSS	60	26.5	8.91	14.90	1.037	10.73	5.06	9.27	317.40	14.13	0.760	1.027

Table B2. Oxygen transfer data summary for pilot plant aeration basin #1.

File	File Sheet	Date	Page	Anaerobic				Method	OUR		Temp (C)	Theta	Kla (20) (/h)	C _{ss} (mg/L)	C _{sat} (book)		KLa (Clean)	Alpha	Beta	
				HRT	Reactor	Basin	Contents		Airflow (scfh)	(mg/ L-h)					Q(gpd)					
PPstep1KLaVI-66	PPaer1stepKLaC1	6/9/97	VI-66	0.43	PP	1	ML	NSS	60	10.7	10.2	17.1	1.037	11.30	7.09	9.04	120.00	14.13	0.799	0.977
PPstep1KLaVI-67	PPaer1stepKLaC1	6/9/97	VI-67	0.43	PP	1	ML	NSS	60	17.6	10.9	17.1	1.037	12.09	6.61	9.04	120.00	14.13	0.855	0.977
PPstep1KLaVI-68	PPaer1stepKLaC1	6/9/97	VI-68	0.43	PP	1	ML	NSS	60	19.4	10.7	17.5	1.037	11.74	6.45	8.97	120.00	14.13	0.831	0.988
PPstep1KLaVI-69	PPaer1stepKLaC1	6/9/97	VI-69	0.43	PP	1	ML	NSS	60	17.3	10.4	17.8	1.037	11.27	6.54	8.97	120.00	14.13	0.798	0.985
Pilotkla	PP ML Kla 2a	31-Aug	I-91	0.64	PP	1	ML	SS	60	16.7	10.51	22	1.037	9.72	5.90	8.024	120	14.13	0.688	
Pilotkla	PP ML Kla 2b	31-Aug	I-91	0.64	PP	1	ML	SS	60	17.9	11.10	22	1.037	10.27	5.90	8.024	120	14.13	0.727	
Pilotkla	PP ML Kla 5a	14-Oct	III-37	0.64	PP	1	ML	SS	60	24.2	7.93	18.9	1.037	8.27	4.90	8.54	120	14.13	0.585	
Pilotkla	PP ML Kla 6a	25-Oct	III-59	0.64	PP	1	ML	SS	60	30.4	9.73	17.75	1.037	10.61	5.12	8.742	120	14.13	0.751	0.971
Pilotkla	PP ML Kla 7a	6-Nov	III-63	0.64	PP	1	ML	SS	60	17.4	9.01	17.5	1.037	9.93	6.20	8.788	120	14.13	0.703	0.988
PilotSSKLa	PPgroup.ML KLaA1	7-Dec	III-66	0.64	PP	1	ML	SS	60	23.8	14.85	13	1.037	14.76	7.60	9.681	120	14.13	1.045	0.980
PilotSSKLa	PPgroup.ML KLaB1	8-Dec	III-68	0.64	PP	1	ML	SS	60	23.7	13.39	13.5	1.037	11.06	6.85	9.57	240	14.13	0.783	0.980
PilotSSKLa	PPgroup.ML KLaC1	9-Dec	III-70	0.64	PP	1	ML	SS	60	14.5	12.46	12	1.037	8.42	7.60	9.902	240	14.13	0.596	0.980
PilotSSKLa	PPgroup.ML KLaD1	12/13/96	III-74	0.64 w/acetat	PP	1	ML	SS	60	22	9.70	14.3	1.037	9.32	6.50	9.405	120	14.13	0.659	0.980
PilotSSKLa	PPgroup.ML KLaE1	12/16/96	III-80	0.64 w/acetat	PP	1	ML	SS	40	19.7	8.87	14.8	1.037	10.72	5.80	9.303	256.8	10.06	1.066	0.980
PilotSSKLa	PPgroup.ML KLaF1	12/16/96	III-85	0.64 w/acetat	PP	1	ML	SS	20	21	3.05	15	1.037	3.66	1.60	9.267	256.8	5.56	0.658	0.980
PilotSSKLa	PPgroup.ML KLaG1	12/17/96	III-88	0.64 w/acetat	PP	1	ML	SS	40	13.7	9.47	13.8	1.037	11.87	7.80	9.515	40.2	10.06	1.180	0.980
PilotSSKLa	PPgroup.ML KLaH1	12/18/96	III-92	0.64 w/acetat	PP	1	ML	SS	40	17.1	8.31	14	1.037	10.35	6.90	9.469	75.6	10.06	1.028	0.980
PilotSSKLa	PPgroup.ML KLaI1	12/22/96	IV-10	0.21	PP	1	ML	SS	40	10.4	7.15	12.2	1.037	9.50	8.00	9.856	79.8	10.06	0.944	0.980
PilotSSKLa	PPgroup.ML KLaJ1	12/23/96	IV-15	0.21	PP	1	ML	SS	60	12.5	12.54	13.8	1.037	15.72	8.30	9.515	79.8	14.13	1.112	0.980
PilotSSKLa	PPgroup.ML KLaK1	12/31/96	IV-17	0.21	PP	1	ML	SS	20	16.5	4.95	16	1.037	5.72	5.20	9.064	75.6	5.56	1.030	0.980
PilotSSKLa	PPgroup.ML KLaL1	1/2/97	IV-28	0.21	PP	1	ML	SS	20	15.5	4.33	14.2	1.037	5.35	5.20	9.432	79.8	5.56	0.962	0.980
PilotSSKLa	PPgroup.ML KLaM1	1/5/97	IV-35	0.21	PP	1	ML	SS	20	14.5	4.02	14.7	1.037	4.88	5.00	9.331	97.2	5.56	0.877	0.980
PilotSSKLa	PPgroup.ML KLaN1	1/7/97	IV-41	0.21	PP	1	ML	SS	20	14.2	5.01	12.7	1.037	6.53	6.30	9.745	76.8	5.56	1.175	0.980
PilotSSKLa	PPgroup.ML KLaO1	1/9/97	IV-47	0.21	PP	1	ML	SS	20	19	4.37	13.4	1.037	5.56	4.60	9.598	79.8	5.56	1.000	0.980

Table B3. Data for steady state alpha profile through pilot plant.

File	File Sheet	Date	Page	Anaerobic HRT	Reactor	Basin	Contents	Method	Airflow (scfh)	OUR (mg/L-h)	KLa (/h)	Temp (C)	Theta	KLa (20) (/h)	Css (mg/L)	Csat(book) (mg/L)	Q(gpd)	KLa (Clean)	Alpha	Beta
PilotSSKLa	PPgroup.ML KLaA1	12/07/96	III-66	0.64	PP	1	ML	SS	60	23.79	14.85	13	1.037	14.76	7.6	9.68	120	14.13	1.04	0.98
PilotSSKLa	PPgroup.ML KLaB1	12/08/96	III-68	0.64	PP	1	ML	SS	60	23.73	13.39	13.5	1.037	11.06	6.85	9.57	240	14.13	0.78	0.98
PilotSSKLa	PPgroup.ML KLaC1	12/09/96	III-70	0.64	PP	1	ML	SS	60	14.48	12.46	12	1.037	8.42	7.6	9.90	240	14.13	0.60	0.98
PilotSSKLa	PPgroup.ML KLaD1	12/13/96	III-74	0.64 w/ acetate	PP	1	ML	SS	60	21.98	9.70	14.3	1.037	9.32	6.5	9.40	120	14.13	0.66	0.98
PilotSSKLa	PPgroup.ML KLaE1	12/16/96	III-80	0.64 w/ acetate	PP	1	ML	SS	40	19.72	8.87	14.8	1.037	10.72	5.8	9.30	256.8	10.06	1.07	0.98
PilotSSKLa	PPgroup.ML KLaF1	12/16/96	III-85	0.64 w/ acetate	PP	1	ML	SS	20	21.02	3.05	15	1.037	3.66	1.6	9.27	256.8	5.56	0.66	0.98
PilotSSKLa	PPgroup.ML KLaG1	12/17/96	III-88	0.64 w/ acetate	PP	1	ML	SS	40	13.69	9.47	13.8	1.037	11.87	7.8	9.52	40.2	10.06	1.18	0.98
PilotSSKLa	PPgroup.ML KLaH1	12/18/96	III-92	0.64 w/ acetate	PP	1	ML	SS	40	17.13	8.31	14	1.037	10.35	6.9	9.47	75.6	10.06	1.03	0.98
PilotSSKLa	PPgroup.ML KLaI1	12/22/96	IV-10	0.21	PP	1	ML	SS	40	10.44	7.15	12.2	1.037	9.50	8	9.86	79.8	10.06	0.94	0.98
PilotSSKLa	PPgroup.ML KLaJ1	12/23/96	IV-15	0.21	PP	1	ML	SS	60	12.51	12.54	13.8	1.037	15.72	8.30	9.52	79.8	14.13	1.11	0.98
PilotSSKLa	PPgroup.ML KLaK1	12/31/96	IV-17	0.21	PP	1	ML	SS	20	16.47	4.95	16	1.037	5.72	5.2	9.06	75.6	5.56	1.03	0.98
PilotSSKLa	PPgroup.ML KLaL1	01/02/97	IV-27	0.21	PP	1	ML	SS	20	15.52	4.33	14.2	1.037	5.35	5.2	9.43	79.8	5.56	0.96	0.98
PilotSSKLa	PPgroup.ML KLaA2	12/07/96	III-66	0.64	PP	2	ML	SS	60	22.06	13.66	13	1.037	13.37	7.55	9.68	120	14.13	0.95	0.98
PilotSSKLa	PPgroup.ML KLaB2	12/08/96	III-68	0.64	PP	2	ML	SS	60	20.76	12.30	13.5	1.037	9.67	6.85	9.57	240	14.13	0.68	0.98
PilotSSKLa	PPgroup.ML KLaC2	12/09/96	III-71	0.64	PP	2	ML	SS	60	19.22	8.86	12	1.037	7.35	6.4	9.90	240	14.13	0.52	0.98
PilotSSKLa	PPgroup.ML KLaD2	12/13/96	III-74	0.64 w/ acetate	PP	2	ML	SS	60	13.52	9.17	14.3	1.037	5.93	6.6	9.40	240	14.13	0.42	0.98
PilotSSKLa	PPgroup.ML KLaE2	12/16/96	III-83	0.64 w/ acetate	PP	2	ML	SS	40	23.15	7.43	14.5	1.037	6.48	5	9.37	248.4	10.06	0.64	0.98
PilotSSKLa	PPgroup.ML KLaF2	12/16/96	III-86	0.64 w/ acetate	PP	2	ML	SS	20	21.27	2.91	15	1.037	3.22	1.35	9.27	248.4	5.56	0.58	0.98
PilotSSKLa	PPgroup.ML KLaG2	12/17/96	III-89	0.64 w/ acetate	PP	2	ML	SS	40	17.40	7.21	13.6	1.037	9.10	6.65	9.55	65.4	10.06	0.90	0.98
PilotSSKLa	PPgroup.ML KLaH2	12/18/96	III-93	0.64 w/ acetate	PP	2	ML	SS	40	13.14	5.08	14	1.037	6.33	6.7	9.47	17.28	10.06	0.63	0.98
PilotSSKLa	PPgroup.ML KLaI2	12/22/96	IV-11	0.21	PP	2	ML	SS	40	9.21	7.22	12.2	1.037	9.60	8	9.86	79.8	10.06	0.95	0.98
PilotSSKLa	PPgroup.ML KLaJ2	12/23/96	IV-15	0.21	PP	2	ML	SS	40	8.55	3.82	13.8	1.037	4.79	6.60	9.52	79.8	10.06	0.48	0.98
PilotSSKLa	PPgroup.ML KLaK2	12/31/96	IV-17	0.21	PP	2	ML	SS	20	15.06	3.98	16	1.037	4.61	4.5	9.06	87	5.56	0.83	0.98
PilotSSKLa	PPgroup.ML KLaL2	01/02/97	IV-28	0.21	PP	2	ML	SS	20	13.86	3.43	14.2	1.037	4.24	4.5	9.43	87	5.56	0.76	0.98
PilotSSKLa	PPgroup.ML KLaA3	12/07/96	III-67	0.64	PP	3	ML	SS	60	21.17	16.42	13	1.037	11.24	7.25	9.68	360	14.13	0.80	0.98
PilotSSKLa	PPgroup.ML KLaB3	12/08/96	III-69	0.64	PP	3	ML	SS	60	18.47	14.34	13.5	1.037	7.38	6.4	9.57	600	14.13	0.52	0.98
PilotSSKLa	PPgroup.ML KLaC3	12/09/96	III-72	0.64	PP	3	ML	SS	60	18.31	16.56	12	1.037	10.65	7.6	9.90	360	14.13	0.75	0.98
PilotSSKLa	PPgroup.ML KLaD3	12/13/96	III-74	0.64 w/ acetate	PP	3	ML	SS	60	12.78	10.89	14.3	1.037	5.93	6.75	9.40	300	14.13	0.42	0.98
PilotSSKLa	PPgroup.ML KLaE3	12/16/96	III-82	0.64 w/ acetate	PP	3	ML	SS	40	22.62	8.02	14.5	1.037	5.30	4.15	9.37	600	10.06	0.53	0.98
PilotSSKLa	PPgroup.ML KLaF3	12/16/96	III-87	0.64 w/ acetate	PP	3	ML	SS	20	23.27	3.52	15	1.037	3.53	1.35	9.27	480	5.56	0.63	0.98
PilotSSKLa	PPgroup.ML KLaG3	12/17/96	III-90	0.64 w/ acetate	PP	3	ML	SS	40	20.89	6.85	13.9	1.037	8.55	4.45	9.49	384	10.06	0.85	0.98
PilotSSKLa	PPgroup.ML KLaH3	12/18/96	III-93	0.64 w/ acetate	PP	3	ML	SS	40	20.06	5.56	14.3	1.037	6.85	3.75	9.40	396	10.06	0.68	0.98
PilotSSKLa	PPgroup.ML KLaI3	12/22/96	IV-11	0.21	PP	3	ML	SS	40	10.52	5.21	12.4	1.037	6.87	5.4	9.86	346.2	10.06	0.68	0.98
PilotSSKLa	PPgroup.ML KLaJ3	12/23/96	IV-15	0.21	PP	3	ML	SS	40	10.46	8.41	13.8	1.037	10.55	6.20	9.52	597.6	10.06	1.05	0.98
PilotSSKLa	PPgroup.ML KLaK3	12/31/96	IV-18	0.21	PP	3	ML	SS	20	17.87	3.62	16	1.037	4.19	2.25	9.06	398.4	5.56	0.75	0.98
PilotSSKLa	PPgroup.ML KLaL3	01/02/97	IV-29	0.21	PP	3	ML	SS	20	14.75	3.11	16	1.037	3.60	2.3	9.06	368.4	5.56	0.65	0.98

Table B4. Bench scale reactor profile of initial non aerated pilot plant basin measured oxygen transfer parameters.

Basin	Average KLa(20) (/h)	Average Alpha	Average SOTR (kg/hr)	Average OUR (mg/l-hr)	Average Beta
Inf + RAS	9.20	0.94	1.30	30.66	0.79
An #1	9.85	1.00	1.41	34.27	0.80
An #2	9.09	0.93	1.18	37.75	0.74
Ax #1	4.89	0.50	1.09	36.22	1.26

Basin	KLa(20) (/h)	Alpha	SOTR (kg/hr)	OUR (mg/L-hr)	Calculated Beta
Inf + RAS	10.72	1.09	1.46	31.38	0.76
Inf + RAS	8.26	0.84	1.27	30.76	0.86
Inf + RAS	8.62	0.88	1.17	29.83	0.76
An #1	9.09	0.93	1.41	33.18	0.86
An #1	10.59	1.08	1.40	33.18	0.74
An #1	9.88	1.01	1.42	36.46	0.80
An #2	7.33	0.75	1.20	39.50	0.92
An #2	11.11	1.13	1.24	39.48	0.62
An #2	8.84	0.90	1.09	34.26	0.69
Ax #1	4.25	0.43	1.04	34.40	1.36
Ax #1	5.52	0.56	1.14	38.04	1.15

Table B5. Results of 21 liter batch reactor, determination of clean water $KLa_{(20)}$ and Theta

		$\theta = 1.026, KLa_{(20)} = 9.82$					
Temp	KLa_f	$KLa_{(20)},$	$KLa_{(20)},$	Predicted			
		$\theta=1.024)$	$\theta=1.026)$	KLa_f	95% LCL	95% UCL	
2.2	5.23	7.98	8.19	6.27	4.30	8.23	
4.3	6.52	9.46	9.68	6.61	4.64	8.57	
6.8	7.13	9.75	9.94	7.04	5.07	9.00	
11.25	6.65	8.18	8.29	7.87	5.91	9.84	
12.2	9.02	10.85	10.98	8.06	6.10	10.03	
13.8	9.04	10.47	10.57	8.40	6.43	10.36	
14.8	8.98	10.16	10.24	8.61	6.65	10.58	
16.4	9.74	10.61	10.66	8.97	7.00	10.93	
17.8	10.36	10.91	10.95	9.29	7.32	11.26	
24	10.36	9.42	9.37	10.86	8.90	12.83	
24.2	9.28	8.40	8.35	10.92	8.95	12.88	
24.6	10.05	9.01	8.95	11.03	9.06	12.99	
25.1	11.87	10.52	10.44	11.17	9.20	13.13	
27	12.49	10.58	10.47	11.72	9.75	13.68	
28	12.03	9.95	9.84	12.02	10.05	13.98	

Table B6. Pilot plant clean water K_La data.

Basin	Airflow (scfs)	Temp (°C)	K_{Laf} (/h)	$K_La_{(20)}$ (/h)	
				$\theta = 1.038$	$C_{max}/C_{sat}(\text{book})$
AER #1	20	9.00	3.08	4.65	1.07
AER #1	20	9.00	3.88	5.85	1.01
AER #1	20	9.20	4.19	6.28	1.00
AER #1	20	9.80	4.76	6.97	0.99
AER #1	40	8.70	6.76	10.31	1.01
AER #1	40	9.20	7.47	11.19	1.01
AER #1	40	9.30	7.58	11.31	1.01
AER #1	40	9.60	7.91	11.67	1.01
AER #1	40	8.60	5.91	9.06	1.03
AER #1	40	9.00	6.21	9.37	1.00
AER #1	40	14.70	7.66	9.34	1.00
AER #1	40	15.40	8.32	9.88	1.00
AER #1	40	15.80	8.61	10.07	0.99
AER #1	40	16.40	8.80	10.07	0.97
AER #1	40	18.60	9.19	9.68	1.05
AER #1	40	18.80	9.92	10.38	1.02
AER #1	40	19.20	10.18	10.49	1.04
AER #1	40	19.60	10.52	10.68	1.03
AER #1	40	19.50	10.54	10.74	1.00
AER #1	60	8.90	9.48	14.36	1.03
AER #1	60	8.95	9.58	14.49	1.02
AER #1	60	9.00	10.28	15.51	0.99
AER #1	60	9.45	9.87	14.64	0.99
AER #2	20	12.80	3.53	4.62	1.02
AER #2	20	12.80	4.58	6.00	1.03
AER #2	20	12.70	4.56	5.99	1.01
AER #2	20	12.50	4.58	6.07	1.01
AER #2	40	13.00	7.39	9.60	1.03
AER #2	40	13.25	7.54	9.71	1.02
AER #2	40	13.30	7.68	9.87	1.01
AER #2	40	12.50	7.89	10.44	1.00
AER #2	60	13.00	10.43	13.56	1.01
AER #2	60	13.20	10.55	13.60	1.00
AER #2	60	12.50	10.27	13.59	0.97
AER #2	60	12.50	10.67	14.12	1.03
AER #3	20	14.00	3.56	4.45	1.01
AER #3	20	14.90	4.20	5.08	1.01
AER #3	20	14.40	4.18	5.16	1.03
AER #3	20	14.65	4.78	5.84	1.00
AER #3	40	14.30	6.52	8.07	1.00
AER #3	40	15.10	7.86	9.44	0.98
AER #3	40	14.40	8.16	10.07	0.99
AER #3	40	14.80	8.61	10.45	1.01
AER #3	60	13.00	10.43	13.56	1.01
AER #3	60	15.10	11.66	14.00	1.00
AER #3	60	14.50	11.88	14.59	1.01
AER #3	60	14.90	12.44	15.05	1.00

VITA

Arthur W. Nair was born in Washington D. C. in 1954 and raised in Rockville, Maryland. He attended Montgomery College, Rockville, Maryland from 1971 to 1973, receiving an Associate in Arts degree in Engineering. From 1973 through 1975 Mr. Nair attended the University of Maryland, College Park, Maryland and received a Bachelor of Science degree in Civil Engineering with concentrations in environmental and water resources engineering. As an undergraduate student Mr. Nair worked summers for the U.S. Army Corps of Engineers performing field surveys out of their Baltimore, Maryland and Waltham, Massachusetts district offices. Following graduation Mr. Nair joined the consulting engineering firm of Dewberry and Davis of Fairfax, Virginia as a civil engineer performing hydraulic and hydrologic analyses in their flood plain planning and mapping group. In 1977, Mr. Nair relocated to the Marion, Virginia office of Dewberry and Davis where he was involved in the planning, design and construction management of water and waste water treatment, waste water collection, water distribution, industrial development, and flood plain management projects in the Blue Ridge and Appalachian regions of southwestern Virginia and east Tennessee. He received his Virginia Professional Engineering license in 1981 and was elected as an Associate in the firm in 1985. In 1993 he left the Marion office as an assistant branch manager and accepted a position as the project manager of an environmental services group in the Roanoke, Virginia office of Dewberry and Davis. There he was responsible for all environmental services performed in the office including site assessments, landfill design and construction management, ground water monitoring and hazardous waste management. In 1996, following completion of a major project, Mr. Nair left Dewberry and Davis and enrolled full time at the Virginia Polytechnic Institute and State University, Blacksburg, Virginia to pursue research interests in environmental engineering. Mr. Nair received a Masters of Science Degree in Environmental Engineering from Virginia Polytechnic Institute and State University in December 1998.