CARBON, NITROGEN, AND PHOSPHORUS REMOVAL IN A SEQUENCING BATCH REACTOR AT LOW TEMPERATURES

by

© Daryl Michael McCartney

A thesis

submitted in partial fulfillment

of the requirements for the degree of Master of Science

in the Division of Environmental Engineering

Department of Civil Engineering

The University of Manitoba

October, 1988

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ISBN 0-315-47971-X

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DARYL MICHAEL McCARTNEY

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ABSTRACT

In many communities of Canada, the temperature of wastewaters may fall below 5°C. These low temperatures affect nutrient removal performance. To study this, four parallel sequencing batch reactors (SBR's) operating in a 12h biological phosphorus removal cycle were fed synthetic substrate at constant food to microorganism (F:M) loads of 0.05, 0.11, 0.21, and 0.30 g COD g VSS^{-1} d^{-1}, while the temperature was decreased incrementally from 10 through 6, 4, 2, and 0.5°C.

The observed yield (Y) and the endogenous decay (k_d) coefficients values were found to decrease with temperature decrease. The net effect was a decrease in sludge production as the temperature decreased. A low F:M ratio was observed to cause deflocculation of activated sludge flocs and a consequent increase in the effluent volatile suspended solid concentration. Settleability performance was not affected by decreasing temperature. Reaction rates were calculated to be second, zero-, and between zero- and first-order for soluble organic carbon (SOC) removal, nitrification, and denitrification, respectively. Nitrification was found to be the most temperature-sensitive reaction, followed by denitrification, with SOC removal being the least sensitive. Significant nitrification could not be achieved below 4°C.

Caution must be exercised when choosing temperature correction factors and/or reaction rates from literature sources. Because of the change in sludge production observed in this study, it is suggested that the mass loading (F:M ratio) be preferred over biological solids retention time (BSRT) as a control parameter used by a treatment plant operator, when large wastewater temperature variations are expected.

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PREFACE

Winnipeg, Manitoba, with a long-term average temperature of -19.5°C in January, has the distinction of being the coldest city (population > 100,000) in Canada (Bailey, 1987).

The Whiteshell Provincial Park, located in southeastern Manitoba along the Ontario border, is comprised of numerous freshwater lakes isolated by the undulations of the Pre-Cambrian Shield. The park, rich in natural beauty, has attracted much tourism and now contains approximately 2,000 shoreline cottages. With no stringent wastewater management system in place, the more populated lakes are now in the early stages of eutrophication. Sequencing batch reactor (SBR) systems offer the promise of low-cost phosphorus and nitrogen removal for areas, such as this park, where wastewater lagoons are not practical.

One cannot spend one's entire life in this area without understanding the great need for low temperature studies into biological wastewater treatment. The potential of SBR systems for use in the climate of southern Manitoba was therefore the impetus for this investigation.

ACKNOWLEDGEMENTS

The willpower to prepare this thesis was assisted and encouraged by several individuals. Special gratitude is extended to:

Staff of the Civil Engineering Department: Dr. Jan Oleszkiewicz for his enthusiasm, knowledge, and guidance; Ms. Judy Tingley for her neverending assistance, support, and respect for quality; Dr. Art Sparling for his coy wisdom and lunchtable banter; Mr. Andrew Romanek for his analytical assistance; and Mr. Stan Mateja and Mr. John Clark for their experience and craftsmanship in the building of the reactors.

Dr. Emery Z. Lajtai of the Geological Engineering Department for being an all-around nice guy, and also for serving on my Thesis Review Committee on very short notice.

Fellow students: Mr. Dave Woytowich who defines hard work through example; Mr. Shahab Shafai for his sincere concern for all things; Mr. Vijay Thadani for his wit, and for sharing the rent for two years; and Dr. Barry Hilton for a different view.

My family: Mom, Dad, Gary, and Crystal, who pointed me in the right direction and gave me their support; and Ms. Anne Poynton for her understanding, her willingness to put on a lab coat when needed, and for accepting my proposal of marriage.

Ms. Wendy Seversen for creating this presentation of words and tables.

DEDICATION

To Pepper. He never said much as we shared more than 10 years of life, but he was always there. The walks will be missed, but not forgotten.

CHAPTER 1

INTRODUCTION

The wastewater engineering literature is replete with information on activated sludge, a remarkable bioengineering material. To conceive a treatment plant design, this mass of diverse microorganisms must be considered a homogeneous mixture, but in theory biological wastewater treatment systems are perhaps subject to more variability than any other engineering material (Gaudy and Gaudy, 1988). This variability stems from the way different species of microorganisms selectively and symbiotically develop, depending upon the governing environmental conditions. Some of the more important environmental conditions are wastewater flow, temperature, type and concentration of energy and growth substrates, nutrient concentration, pH and buffering capacity, percent biodegradable fraction of substrates, concentrations of toxic substances, and suspended solids concentration. The operating conditions must then be engineered with respect to these factors, and also consider the potential variability of these factors. Some of the operating control parameters considered in the design of an activated sludge process are effluent quality desired, process modification selection, hydraulic retention time (HRT), dissolved oxygen and aeration requirements, mixing and turbulence, biological mass concentration, mass loading or the food to microorganisms ratio (F:M), biological solids retention time (BSRT), and solid-liquid separation.

A sequencing batch reactor (SBR) modification of the activated sludge process was chosen for this study. The SBR's were operated using a proven combined biological phosphorus and nitrogen removal sequence (Figure 1.1) (Manning, 1986). This cycle was selected to

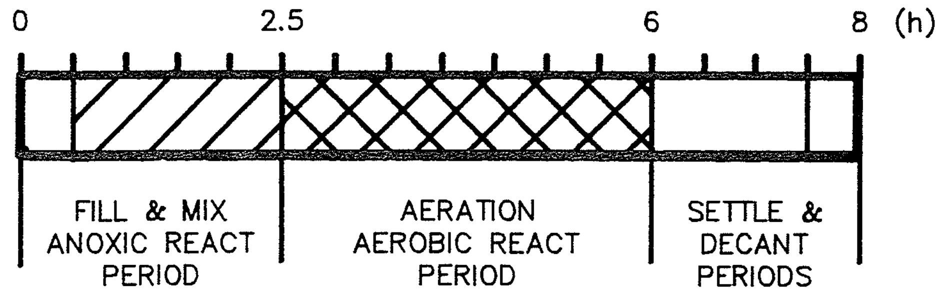


Figure 1.1 Eight hour SBR cycle, optimized for biological nitrogen and phosphorus removal (after Manning, 1986).

observe the effect of decreasing temperature on nitrification, denitrification, and bacteriological polyphosphate storage. This was accomplished by operating four reactors at constant F:M ratios of 0.046, 0.112, 0.209, and 0.301 d^{-1} (COD:MLVSS) and decreasing the temperature from 10°C to 0.5°C at incremental temperatures of 6°C, 4°C, and 2°C. All the other previously mentioned environmental and design parameters were kept constant.

CHAPTER 2

AEROBIC BIOLOGICAL TREATMENT

The first investigations into the use of aerobic biological treatment date back to the late 19th century, and by the early 20th century, many experiments were being carried out (Ganczarczyk, 1983; Metcalf and Eddy, 1978). By the 1930's, it was a standard method of wastewater treatment (Rittmann, 1987).

The two most common aerobic wastewater treatment processes are the attached growth (trickling filter) and the suspended growth (activated sludge) systems. Both processes have the same basic goals: the oxidation of particulate and soluble organic matter to H_2O, CO_2, NH_4-N and other constituents; and the oxidation of NH_4-N to NO_3-N. Accompanying these oxidations is the synthesis of new biomass. Retaining this biomass within the system facilitates more rapid removal of the organic load from the wastewater due to the lowering of the food to microorganisms (F:M).

The major difference between the suspended growth and attached growth processes is how the biomass is retained in the system. As the name indicates, the biomass of attached growth processes forms biofilms on support media within the system. Specially manufactured plastics with good hydraulic characteristics and high surface area to volume ratios are now commonly used as the support media where rocks were used in the past. The amount of biomass in this process is controlled by the surface area available for biofilm growth. In suspended growth systems, the biomass is not attached to a surface. The biomass is retained in the system by separating the suspended solids from the treated waste-

water in a sedimentation basin. The biomass is then returned to the aeration basin via the underflow and the wastewater supernatant proceeds to the next treatment process. The recycled biomass is then resuspended in the aeration basin and brought into contact with untreated wastewater (Figure 2.1). The ability to separate the biomass from the liquid depends upon the formation of biological flocs within the aeration basin. The flocs are much larger than individual microorganism cells and settle out more readily (Figure 5.12).

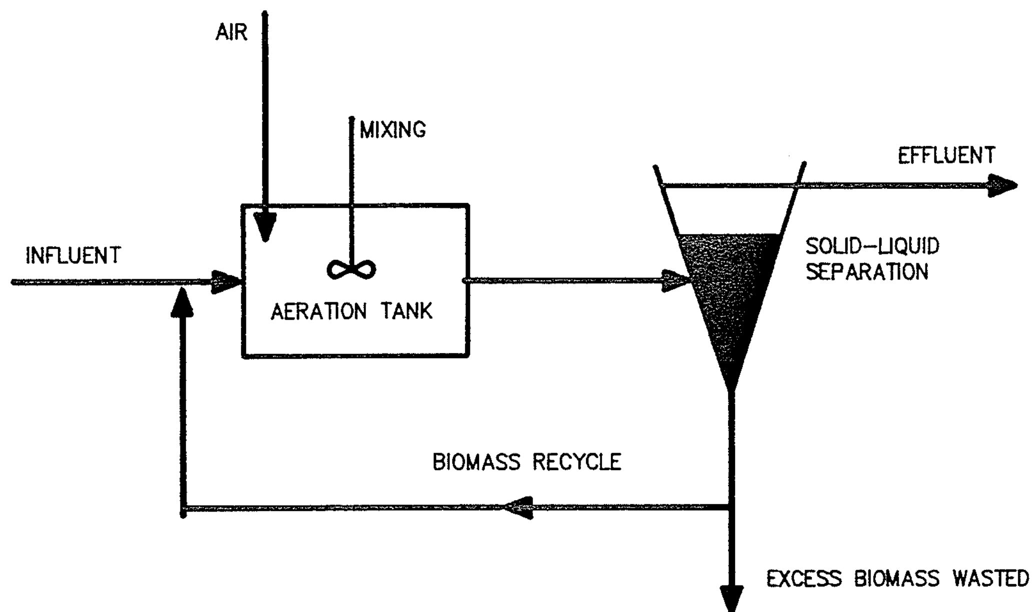


Figure 2.1 Basic activated sludge concept with sludge recycle

In the suspended growth sequencing batch reactor (SBR), modification of the activated sludge process, the sedimentation basin is eliminated from the treatment works. Instead, the aeration basin is used as a sedimentation basin by temporarily stopping the mixing and/or

aeration supplied to the basin. Under the quiescent conditions that develop, the biomass settles and after sufficient time has elapsed, the supernatant is decanted. During these settle and decant periods, the untreated wastewater flow to the system may either be diverted to another basin or allowed to continue flowing into the aeration basin, depending upon the chosen design.

2.1 THE SUSPENDED GROWTH ACTIVATED SLUDGE PROCESS

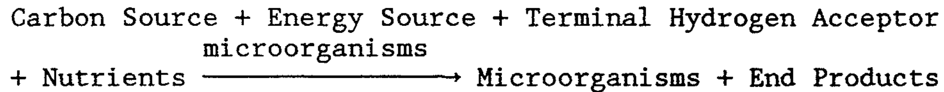
The activated sludge process is essentially a chemical reaction that is mediated or catalyzed by the enzymes of the microorganisms present in the system. As in any chemical reaction, the two principles which govern are:

1. the relative concentrations of the reactants which will determine the final concentrations of the products; and
2. the rate at which the reaction moves toward equilibrium.

The various stoichiometric equations of the process will be presented first, followed by a discussion on the factors affecting the reaction rates.

It is essential in the design of any biological treatment system to develop a mass balance in order to establish the necessary quantity of material inputs into the system, such as nutrients and oxygen, and to evaluate the resulting quantity of material outputs, such as waste biological sludge, and end products. The most direct and probably the simplest way to begin a mass balance is to write a balanced stoichiometric equation for the overall reaction taking place in the system (McCarty, 1975).

Grady and Lim (1980) presented, in general terms, the equation for microbial growth, written as:



This equation, representative of nonphotosynthetic microorganisms, divides the metabolism into basal and growth metabolisms. The carbon in the basal component (energy source) ends up as carbon dioxide, whereas the carbon in the growth component (cell synthesis) ends up in the cell material (Grady and Lim, 1980; Henze, 1979). It is generally true for all bacterially mediated reactions that the electron donor for the energy reaction is the same as the electron donor for the synthesis reaction, and also that these reactions are oxidation-reduction reactions and involve the transfer of electrons. Therefore, if all the reactions are written as half reactions on an electron equivalent basis, they can be easily compared and combined. Table 2.1, which is adapted from McCarty (1975) contains a list of oxidation reactions useful for constructing most bacterially mediated reactions of interest in activated sludge.

McCarty (1975) presented an overall stoichiometric equation for these reactions which contains three oxidation half reactions, one for the electron donor (R_d), one for the electron acceptor (R_a), and one for bacterial cells (R_c). The overall reaction (R) can then be obtained as follows:

$$R = R_d - f_e R_a - f_s R_c \quad (1.1)$$

Table 2.1 Oxidation half reactions (after McCarty, 1975).

Half Reactions
1. Reactions for Bacterial Cell Synthesis (R_c)
Ammonia as Nitrogen Source:
$0.05\ C_5H_7O_2N + 0.45\ H_2O = 0.2\ CO_2 + 0.05\ HCO_3^- + 0.05\ NH_4^+ + H^+ + e^-$
Nitrate as Nitrogen Source:
$0.036\ C_5H_7O_2N + 0.393\ H_2O = 0.036\ NO_3^- + 0.179\ CO_2 + 1.04\ H^+ + e^-$
2. Reactions for Electron Acceptors (R_a)
Oxygen:
$0.5\ H_2O = 0.25\ O_2 + H^+ + e^-$
Nitrate:
$0.1\ N_2 + 0.6\ H_2O = 0.2\ NO_3^- + 1.2\ H^+ + e^-$
3. Organic Donors (Heterotrophic Reactions)
Domestic Wastewater:
$0.02\ C_{10}H_{19}O_3N + 0.36\ H_2O = 0.18\ CO_2 + 0.02\ NH_4^+ + 0.02\ HCO_3^- + H^+ + e^-$
Acetate:
$0.125\ CH_3COO^- + 0.375\ H_2O = 0.125\ CO_2 + 0.125\ HCO_3^- + H^+ + e^-$

The terms f_e and f_s represent the fractions of the electron donor which are used for energy and for synthesis, respectively. The sum of these fractions must equal 1, and is based on the observed yield (Y). Grady and Lim (1980) presented the equation

$$f_s = 1.42Y \tag{1.2}$$

where Y = the observed yield based on the grams of volatile solids formed divided by the grams of COD removed.

To arrive at this equation, an empirical bacterial cell formula of $C_5H_7O_2N$ was used.

A detailed calculation of f_s is beyond the scope of this discussion, but two unique explanations of how to calculate it can be obtained in the aforementioned references (McCarty, 1975; Grady and Lim, 1980).

Unfortunately, the microorganism population variations, due to environmental conditions and the complexity of even the simplest biomolecules make it difficult to quantitatively predict the stoichiometry of the transformations involved in the activated sludge process. In order to apply Equation (1.1), the chemical composition of the electron donor, the electron acceptor, and the cells synthesized must be known.

The composition of the electron acceptor will depend upon the environmental conditions present in the reactor. If the environment is aerobic, oxygen will be the acceptor. If it is anoxic (no molecular oxygen), it will depend on the type of reaction taking place. For example, during denitrification, nitrate serves as the electron acceptor. The half reactions for oxygen and nitrate are listed in Table 2.1.

The chemical composition of a wastewater is seldom known, and therefore it is difficult to determine the electron donor. If this was the case, the waste could be analyzed for C, H, O, and N, and then the

empirical formula constructed from the results. A half reaction could then be written for that formula (Grady and Lim, 1980; McCarty, 1975). Using this method, the empirical formula for domestic wastewater was estimated to be $C_{10}H_{19}O_3N$ and the half reaction is shown in Table 2.1 (McCarty, 1975). As an alternative, if the COD, organic nitrogen, organic carbon, and volatile solids content of the waste are known, they can be used to generate the half reaction. McCarty (1975) discusses this method in detail. The chemical composition of the electron donor or donors is usually known when operating under experimental conditions. If a single compound was used, its empirical formula would be used to develop the half reaction.

It is impossible to select a chemical formula to represent the organic composition of microbial cells that would be valid over a range of growth conditions. The empirical formula, $C_5H_7O_2N$, is the most widely accepted one in the wastewater engineering field. Another formula, which includes phosphorus ($C_{60}H_{87}O_{23}N_{12}P$) has been proposed, but using this formula would only serve to complicate the half reactions.

The rates at which these chemical reactions move toward thermodynamic equilibrium depends upon the kinetics of the system. The kinetics of the activated sludge process are expressed by substrate utilization and biological growth relationships. Before showing the development of these relationships, it is best to refer to the words of Gaudy and Gaudy (1988): "Kinetic expressions are vital for practical engineering reasons and useful as quantitative predictive expressions of proven mechanistic theory, but in themselves do not provide definite

proof of any theory of mechanism. The needed kinetic descriptions are based on repeated experimentation." In fact, these relationships are influenced by several parameters, most of which cannot be considered in a simple equation. A complex kinetic model proposed by Henze (1979) was based on soluble organics, products of hydrolysis from biological degradable suspended solids, and internal degradation of cell structures (endogenous respiration). The relationships between heterotrophs, nitrifiers, and predators were also considered. Eckenfelder and Watkin (1984) based the active biomass on the degradable fraction of mixed liquor volatile suspended solids (MLVSS) and then used this to develop a modified kinetic relationship for process design. However, these more complicated models usually give way to the more simple kinetic expressions that are only concerned with the growth limiting substrate concentration and the gross estimate of biomass, usually the MLVSS concentration.

2.1.1 Reaction Rates

The rate of substrate utilization (removal from bulk liquid) is usually expressed by reaction orders. A reaction order may be determined as the order with respect to time or the order with respect to concentration. For a given reaction, these orders are not always the same, due to autocatalysis. This difference will not be discussed, because under the normal design conditions, the order with respect to time will equal the order with respect to concentration.

Zero order reactions proceed at a rate independent of the reactant concentration. Letting C represent the concentration of A at any time,

t, then the rate equation can be expressed as:

$$- \frac{dC}{dt} = k \tag{2.1}$$

$- \frac{dC}{dt}$ = rate of change in concentration of A with time, mass volume^{-1} time^{-1}; and

k = reaction rate constant, mass volume^{-1} time^{-1}.

Integrating Equation 2.1. and evaluating the constant of integration gives the formulation:

$$C = C_o - kt \tag{2.2}$$

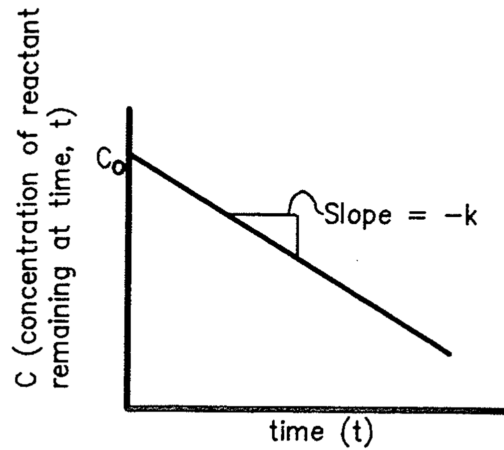
A plot of reactant concentration remaining (C) versus time using Equation 2.2 for a zero-order reaction in a batch reactor is shown in Figure 2.2(a). The response is linear when plotted on arithmetic paper.

First-order reactions proceed at a rate directly proportional to the concentration of one reactant. If first-order kinetics are followed, the rate of disappearance of A is described by the equation:

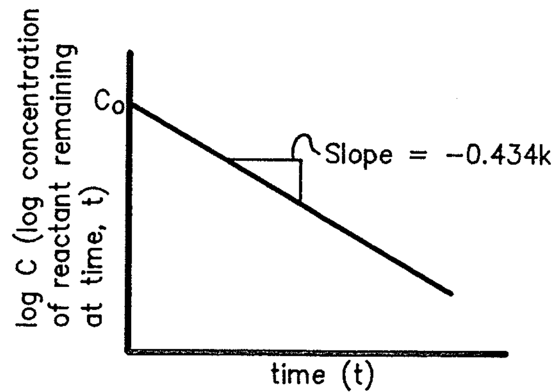
$$- \frac{dC}{dt} = k(C)^1 = kC \tag{2.3}$$

Integrating Equation 2.3 and letting $C = C_o$ at $t = 0$ gives an integrated rate law (Benefield et al., 1982) of the form:

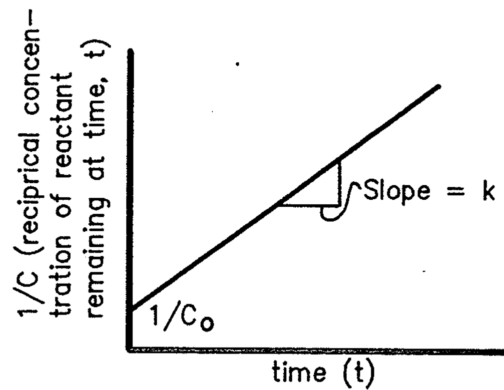
$$\log \left[\frac{C_o}{C} \right] = \frac{kt}{2.3} \tag{2.4}$$



a. Zero-order reaction $[C=C_o-kt]$



b. First-order reaction $[\log(C_o/C)=(kt/2.3)]$



c. Second-order reaction $[1/C-1/C_o=kt]$

Figure 2.2 Linear plots of reaction rate equations (after Benefield et al., 1982)

A plot of log C versus time of a batch reactor process for a first-order reaction is shown in Figure 2.2(b). The semi-log plot is linear.

If second order kinetics are followed, the rate of disappearance of A is described by the equation:

$$-\frac{dC}{dt} = k(C)^2 \tag{2.5}$$

Integrating this second-order reaction equation gives the equation:

$$\frac{1}{C} - \frac{1}{C_o} = kt \tag{2.6}$$

A plot of C^{-1} versus time of a batch reactor process for a second-order reaction is shown in Figure 2.2(c). The arithmetic plot will give a linear trace.

Thus, the reaction order of a particular substrate in a batch reactor system can be determined by making the appropriate concentration versus time plot and noting any deviation from linearity.

2.1.2 Process Kinetics

The mathematical descriptions of microbial growth, pioneered by Monod in the early 1940's were based upon his enzyme-substrate complex hypothesis. His theory was that the overall biological reaction is dependent on the catalytic activity of the enzymes, and he proposed the following equation:

$$E + S \rightleftarrows ES \rightleftarrows E + P \tag{2.7}$$

where E = enzyme,

S = substrate,

ES = enzyme-substrate complex, and

P = product.

The relationship, which was later proven to be correct, led to the development of the equation:

$$v = \frac{V_m \, C}{k_s + C} \tag{2.8}$$

where v = instantaneous velocity (reaction rate),

V_m = maximum velocity,

k_s = the dissociation constant of the ES complex, and

C = substrate concentration

This equation is referred to as the Michaelis-Menton equation. The k_s term is also called the saturation constant, or the half velocity constant, and is equal to the substrate concentration when the reaction rate is equal to V_{max} divided by 2. This is easily demonstrated by making k_s = C in Equation 2.8. This equation is a rectangular hyperbola and is illustrated graphically in Figure 2.3. The reaction rate or instantaneous velocity, v, can be equal to specific substrate utilization, specific substrate formation, or specific microorganism growth. The equation is valid only if v is measured over a short enough time so that no more than 5% of the substrate is utilized over the assay period (Segel, 1976).

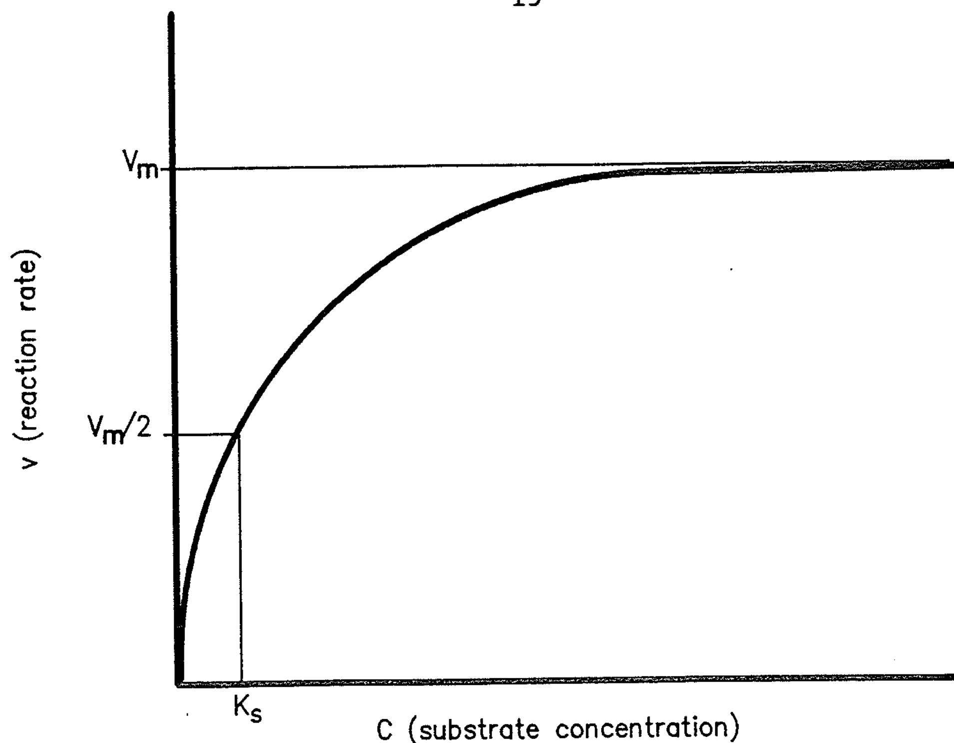


Figure 2.3 Graphical representation of the Michaelis-Menton Equation.

Equation 2.8 is important in that it shows the effect of substrate concentration on reaction rates. As can be seen in Figure 2.3, at low substrate concentrations, the reaction rate is very dependent upon substrate concentration, but at higher substrate concentrations, the reaction rate remains constant. According to the equation, the reaction rates progress from first-order to zero-order as the substrate concentration increases from zero. At substrate concentrations near zero, higher reaction orders may result due to initial substrate-enzyme complexing of starved cells. The half velocity constant, k_s, has been referred to as the shape factor because of its effect on the hyperbola. Simple stated, the lower the value of k_s, the higher the enzyme-substrate affinity.

The kinetic expressions for the reaction rates are then dependent upon the type of reactor being used. Reactor system models used are the completely mixed batch reactor, the completely mixed continuous-flow reactor, the plug-flow reactor, and the plug-flow reactor with longitudinal dispersion. The SBR system is a completely mixed batch reactor and the aforementioned kinetic expressions can be directly applied to the system.

Lawrence and McCarty (1970) stated the importance of the parameter called biological solids retention time (BSRT), defined by the equation:

$$BSRT \equiv \frac{(X)_T}{(\Delta X/\Delta t)_T} \tag{2.9}$$

where $(X)_T$ = total active biomass in treatment system

$(\Delta X/\Delta t)_T$ = total active biomass withdrawn from the system daily, this includes both solids purposely wasted and those lost in the effluent.

Also under steady-state conditions

$$BSRT = \frac{1}{\mu} \tag{2.10}$$

where μ = specific growth rate.

Therefore, by controlling the BSRT one controls the specific growth rate and thus the physiological state of the organisms in the system (Benefield and Randall, 1980). Two other parameters of interest are the observed cell yield coefficient (Y) and the mass loading or, alterna-

tively, the food to microorganism (F:M) ratio. The observed cell yield is defined as

$$Y = \frac{X}{C} \tag{2.11}$$

where X = mass of cells produced,

C = mass of substrate removed.

Normally in batch reactors, Y is measured just after the substrate has been removed in order to omit the effects of endogenous respiration. Y would then be the true yield (Y_T). The F:M ratio is defined as:

$$F:M = \frac{C_o \cdot Q}{(X)_T} \tag{2.12}$$

where C_o = influent substrate concentration, and

Q = flow into system.

The BSRT, Y, and F:M ratio are related by the equation:

$$\frac{1}{BSRT} = \mu = Y\ F{:}M\ E - k_d \tag{2.13}$$

where E = substrate removal efficiency, and

k_d = decay coefficient (specific decay rate).

The specific decay rate (k_d) is the decrease in biomass which has been equated to maintenance energy requirements and endogenous metabolism.

Many other kinetic expressions useful in the design of activated sludge systems are found in Benefield and Randall (1980), Metcalf and Eddy (1978), and Grady and Lim (1980).

2.1.3 Temperature Effects

Three temperatures, termed the cardinal temperatures, are used to characterize the effect of temperature on a microbial species. The minimum and maximum temperatures define the range where growth is possible, while the optimum temperature is that where growth is most rapid. The optimum temperature for most microorganisms is closer to the maximum temperature than to the minimum temperature (Gaudy and Gaudy, 1988; Stanier et al., 1986). Microorganisms are classified as psychrophiles, mesophiles, or thermophiles. The optimum growth temperatures for these classifications are below 20°C, between 20 and 45°C, and above 45°C, respectively. Most microorganisms are mesophilic (Gaudy and Gaudy, 1988). Psychrotrophs are mesophiles that can grow at temperatures within the psychrophilic range. Growth at temperatures of 0°C and below occur, but usually only where water exists in a liquid state.

The growth response of a pure culture to temperature change is shown in Figure 2.4. Growth rate at the minimum temperature is usually very low and the rate increases exponentially with increasing temperature, reaching a maximum at the optimum temperature. Usually the growth rate falls abruptly a few degrees above the optimum. Temperatures above the maximum growth temperatures are generally lethal, whereas temperatures below the minimum growth temperature are not normally lethal.

The cellular factors that determine the temperature limits of growth are not well understood, but two components of cells are thought to play a major role. The phospholipid bilayer that makes up the cell membrane becomes more viscous with lower temperatures. This slows down

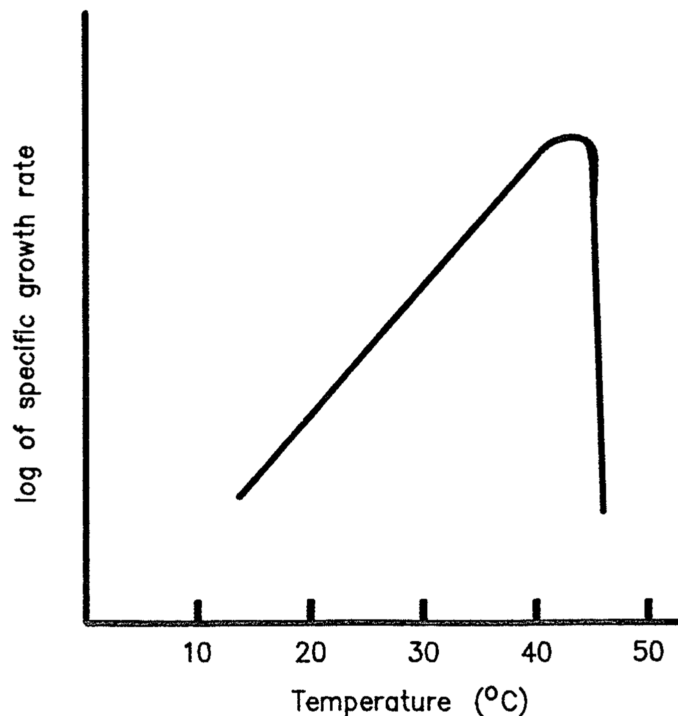


Figure 2.4 Effect of temperature on growth rate of a pure culture.

the transport of nutrients across the membrane, thus limiting growth. Eventually, the transport mechanisms will not allow enough nutrients across the membrane to support any growth. However, the phospholipid bilayer can respond to different temperatures by changing the degree of saturation of its fatty acids. The melting points of these lipids increase with the degree of saturation of the fatty acids. Therefore, a high degree of unsaturated fatty acids in the phospholipid bilayer of psychrophiles is expected to be found. Microorganisms can also vary the percentages of saturated and unsaturated fatty acids in response to temperature changes. <u>Escherichia coli</u>, for example, can vary the percentages by almost threefold when grown at 10 and 43°C (Gaudy and

Gaudy, 1988). At high temperatures, the lipids have increasingly more saturated fatty acids, but the membrane lipids may melt, causing leakage of cell contents and irreparable damage.

Proteins are also affected by changes in temperature. The three-dimensional structure of proteins is altered by low and high temperatures. Alteration of the structure usually results in reduced catalytic activity of the affected protein. At low temperature, weakening of the hydrophobic bonds cause slight conformational changes (Stanier et al., 1986), while high temperature may cause thermal denaturation (loss of three-dimensional structure) which results in loss of function and is usually irreversible (Gaudy and Gaudy, 1988).

The growth rate response of a pure culture to temperature change, shown in Figure 2.4, does not represent the growth rate response of an activated sludge system, because of the large population variation. Activated sludge will show significant growth from temperatures close to the freezing point up to 30°C. Temperatures above or below these are considered outside the normal operating range of an activated sludge plant. However, the response of activated sludge across this temperature range is similar to Figure 2.4 in that the growth rate increases exponentially with increasing temperature.

Arrhenius, in 1889, proposed that the effect of temperature on the reaction-rate constant in a chemical reaction may be related to the activation energy (E_o) by the equation:

$$k = Ae^{-E_o/RT} \tag{2.14}$$

where k = reaction-rate constant,

A = constant,

R = ideal gas constant (1.98 calories $mole^{-1}$ $degree^{-1}$),

E_o = activation energy (calories $mole^{-1}$), and

T = reaction temperature (°K).

Or, in linear form:

$$\ln k = - \frac{E_o}{R}\frac{1}{T} + \ln A \qquad (2.15)$$

Plotting experimental data using Equation 2.15 is useful in determine the value for E_o of a particular reaction. A plot of ln k versus 1/T is linear with the slope of the line equal to $-E_o/R$, Figure 2.5. By definition, the slope of this line will remain constant as long as E_o and A remain constant over the experimental data range. The integrated form of the Arrhenius Equation (2.14) is

$$\ln \frac{k_2}{k_1} = \left(\frac{E_o}{R}\right)\frac{T_2 - T_1}{T_2 T_1} \qquad (2.16)$$

where k_2 and k_1 are the specific rate constant at T_2 and T_1, respectively. For convenience, biological wastewater engineers consider the quantity E_o $(RT_2T_1)^{-1}$ to be a constant. Thus, Equation 2.16 may be approximated by the expression:

$$\ln \frac{k_2}{k_1} = \text{constant } (T_2 - T_1) \qquad (2.17)$$

which can be written in the form:

$$\frac{k_2}{k_1} = e^{\text{constant}\ (T_2 - T_1)} \tag{2.18}$$

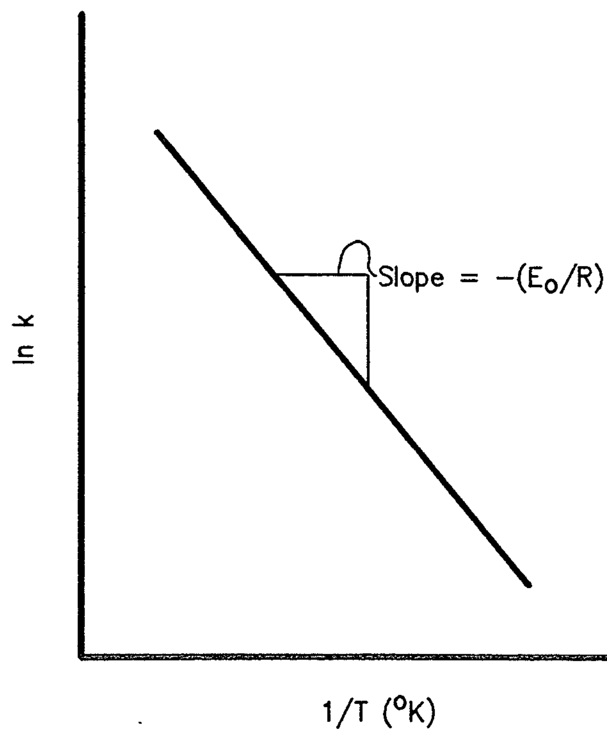


Figure 2.5 Arrhenius plot for determining activation energy (after Benefield et al., 1982)

The temperature coefficient term (θ) is then substituted for the value of e^{constant} and Equation 2.18 takes the form:

$$\frac{k_2}{k_1} = \theta^{(T_2 - T_1)} \tag{2.19}$$

Many biological processes do not follow this relationship to temperature, but some processes do within a narrow temperature range (Benefield and Randall, 1980).

2.2 SEQUENCING BATCH REACTOR (SBR)

Sequencing batch reactor (SBR) technology is being implemented at an increasing rate in North America and abroad. According to Barth (1985), at facilities of up to 19,000 m^3d^{-1}, the SBR process is favoured over the continuous flow process, due to total life-cycle cost savings, ease of operation, and reliability. Therefore, the application of SBR technology is well suited to small communities, industries and large building complexes. The cycle of an SBR could easily be adjusted to conform to the wide daily flow variations of these wastewater sources. Another unique application of this technology is in the treatment of hauled septage. A septage treatment plant must be designed for high organic loading and large fluctuations in influent flow. SBR's have proven to be well-suited for all these applications (Wilderer et al., 1986; Irvine et al., 1979; Wilderer, 1984; Melcer et al., 1987; Lo et al., 1985; Tate and Eckenfelder, 1986; Irvine et al., 1983).

The conceptual difference between batch and continuous flow systems was simply stated by Barth (1983), "... continuous flow processes have spatially related unit operations, where unit operations are timed sequentially in batch processes." The five distinct periods of a single SBR cycle are FILL; REACT; SETTLE; DECANT; and IDLE. The duration of these periods is controlled by level sensors and/or timing devices that

operate automatic water and air supply systems. Various operating strategies can be employed by manipulating the FILL and REACT periods. If the FILL period was instantaneous, the REACT period would simulate plug flow kinetics. If the FILL period occurred over the duration of the REACT period, then continuous flow kinetics would be observed. By controlling the mixing and oxygen supply to the reactor, the REACT period can be broken into AEROBIC REACT and ANOXIC/ANAEROBIC REACT periods, enabling even more manipulation of operating strategies. The ability to control the feed, mixing, and aeration periods independently using a one-sludge single reactor system is what makes the SBR process so attractive from a treatment objective standpoint. Economical benefits are also realized by the elimination of the separate reactors usually needed for a continuous process as well as the secondary clarifier and the subsequent return sludge appurtenances.

2.2.1 History of Batch Processes

According to Barth (1983), historical technology is replete with examples of batch treatment of wastewater. Irvine (1985) also states that sewage treatment studies between 1884 and 1912 were conducted in FILL and DECANT tanks. Aeration was sometimes used, but no relevant improvements were noted. The one exception to this, according to Irvine (1985), was reported in 1943 by Sir Thomas Wardle (1893), who stated: "A distinctive feature of the process (a FILL and DECANT reactor without either chemical addition or filter media) is that the precipitated impurities which accumulate at the bottom of the tank form a medium in conjunction with air to clarify the inflowing foul water." Unfortunate-

ly, Wardle's studies were not further investigated.

The FILL and DECANT strategies were being investigated because it was recognized, in land treatment practices, that intermittent irrigation of the wastewater was necessary for reaeration of the soil to occur. These investigations, in the late 19th century, led to the key finding that oxygen had to be supplied in the proper amount for active biological oxidation, and thus the removal of organic matter (Barth, 1983).

The findings from the experiments of Clark and de Gage (1912) may be assumed to represent the invention of the activated sludge process (Ganczarczyk, 1983). They observed the presence of sludge produced from the aeration of sewage and that the presence of this sludge improved the treatment effects. However, the continuation of these studies led Clark to the development of immersed aerated filters and not to the suspended growth process.

Research in the direction of suspended growth development was being carried out in Manchester, England by Fowler, Ardern, and Lockett. These researchers coined the phrase "activated sludge", which is now so commonly used to refer to the settled biological matter that was retained in their bench-scale FILL and DECANT reactors (Ardern and Lockett, 1914; 1915). Working with 2.3 litre flasks, containing raw municipal wastewater from Manchester, they showed that the batch aeration period to achieve nitrification could be reduced from 5 weeks to 9 hours if the sludge that accumulated from each batch were retained in the flask after decanting the nitrified liquid (Barth, 1983).

The full-scale (two 83 m^3 tanks) implementation of the Manchester

batch experiments was conducted in Salford, England in 1914. That same year, Jones (1914) patented the continuous method and in April of 1916, the first continuous flow activated sludge treatment plant was put into operation in Worcester, England. In 1915, a full-scale batch system was put into operation in Milwaukee, Wisconsin. From 1916 to 1926, many large activated sludge treatment plants were being constructed in England and the American continent (Irvine, 1985; Ganczarczyk, 1983; Arora et al., 1985). The first system built in Canada was located at Brampton, Ontario.

By 1920, large-scale batch systems were no longer considered viable and in almost all cases, these batch systems were converted to continuous flow systems. Irvine (1985) cited the three main disadvantages of the FILL and DECANT system listed in a paper by Ardern (1927). These were: (1) the high energy that must be dissipated during the discharge of the decanted supernatant; (2) increased operator attention; and (3) clogging of diffusors due to the periodic settling of sludge. As a result of these problems, the cost of building and operating a batch system was greater than that of the continuous system.

The next serious effort into the area of FILL and DECANT systems was done by Pasveer in the late 1950's and early 1960's. This system, which is commonly known as the oxidation ditch or continuous loop reactor (CLR) has also become known as the Pasveer Ditch. The first plant was put into service in 1954 at Voorshopen, Holland. Since the original plant in Holland, the oxidation ditch has become a significant treatment technique in Europe, Australia, South Africa, and North America. By 1976, North America alone had well over 500 plants (Irvine,

1985; Mandt and Bell, 1982).

Rejuvenation of SBR studies began in 1967 at Texas A and M University and by 1979, the usefulness of these systems had been well established (Irvine, 1985). These investigations were made possible by the concurrent development of programmable logic controllers (microprocessor-based timing devices) and automated control valves. The first full-scale operating SBR facility was in Culver, Ind. in 1982. As of 1988, Manitoba had at least 5 full-scale operating SBR plants.

2.2.2 SBR Process Theory

According to Irvine (1985), the cycle of an SBR causes severe microorganism selection pressures. A system which includes an ANOXIC REACT period followed by an AEROBIC REACT period subjects the mixed culture of microorganisms to feast and famine conditions as well as high and essentially zero dissolved oxygen conditions. These selection conditions create an environment favouring microorganisms with a higher ribonucleic acid (RNA) content (Irvine, 1985). On a unit mass basis, cells with a higher RNA content are able to utilize substrate more rapidly. Therefore, a unit mass of microorganisms from an SBR are capable of processing a greater quantity of substrate at a rate greater than is possible in a conventional continuous flow system.

A second major observation was that the selective SBR environment inhibited the growth of filamentous microorganisms. Irvine (1985) credits Chiesa with proving the hypothesis that the alternating high and low substrate concentrations in an SBR limits the growth of filaments while allowing normal growth of floc forming organisms. According to

Irvine (1985), Chiesa showed that the sludge volume index (SVI) of an SBR culture was independent of sludge age and mass loading and directly related to the fraction of time a two-hour FILL period was aerated. According to the author, this is misleading in that it seems to indicate that the mass loading (F:M) will not affect the settleability performance of the biomass.

Irvine (1985) introduced a F:M ratio correction factor (f) by only considering the fraction of the total cycle time that the organisms are under aeration, using the equation:

$$F:M = \frac{Q\ S_o}{f(X)_T} \tag{2.20}$$

Comparing this to Equation 2.12, the only difference is the f term in the denominator. Using this correction factor is similar to only considering the biomass within the aeration basin and excluding the biomass in the secondary clarifier and return sludge lines of a continuous flow system. It is the author's belief that aeration time considerations should be separate and the total biomass inventory should be considered when calculating the F:M ratio; therefore, this correction factor will not be used herein.

The unsteady nature of the SBR cycle does not allow the application of the kinetic-based definitions of continuous flow systems. A full-scale SBR system has been shown to achieve consistent effluent volatile suspended solids (VSS) and organic carbon concentrations at BSRT's and uncorrected F:M ratios ranging from 10 to 100 d, and 0.38 to 0.14 kg BOD_5 kg $MLVSS^{-1}d^{-1}$, respectively (Irvine et al., 1985, Irvine, 1985).

The hydraulic residence time (HRT) of an SBR reactor is usually based on the flow variations of the wastewater influent rather than a kinetic equation.

All this information indicates that the proper application of SBR systems can be achieved with greater room for error than the conventional continuous-flow process.

CHAPTER 3.

BIOLOGICAL NITROGEN AND PHOSPHORUS REMOVAL

Nitrogen and phosphorus along with carbon, oxygen, hydrogen, and sulfur, are considered essential nutrients for biological growth. Therefore, the potential to remove these nutrients in biological systems depends upon our understanding of how and why nitrogen and phosphorus are utilized by microorganisms. This understanding has grown tremendously in the past 20 years, to the point where full-scale biological treatment plants are now achieving a high degree of nitrogen and phosphorus removal.

This discussion will be confined to biological treatment processes, but there are many physical-chemical treatment processes, particularly for phosphorus removal, that should still be considered as alternatives. These physical-chemical treatment processes are discussed at length in De Renzo (1978), US EPA (1987), US EPA (1975), and EPS (1973).

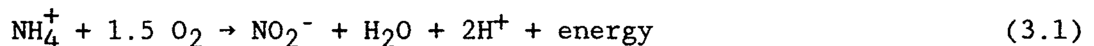
3.1 NITROGEN REMOVAL

Excessive nitrogen in a wastewater effluent can deplete the dissolved oxygen levels in receiving waters, exert a toxicity toward aquatic life, stimulate aquatic growth leading to accelerated eutrophication, present a public health hazard, affect chlorine demand during disinfection, and affect the suitability of wastewater for reuse. Biological nitrogen removal is generally the most economic alternative, but depends upon the wastewater characteristics and the treatment objectives regarding ammonia nitrogen (NH_3-N) and nitrate nitrogen (NO_3-N).

Nitrogen as NH_3-N is incorporated in the amino acid and nucleotide building blocks of microorganisms through assimilatory reactions. These

building blocks are then used to synthesize protein, ribonucleic acid (RNA), and deoxyribonucleic acid (DNA) within the cell. These reactions are carried out by all cells and the removal of nitrogen from the waste stream is dependent upon the wastage of cells from the system, which is directly related to the BSRT. Intracellular nitrogen content has been found to range from 9% to about 14%, depending upon the environmental and operating conditions of the system.

Nitrogen removed above the stoichiometric growth requirements depends upon the dissimilatory metabolic processes of nitrification and denitrification. The nitrification reactions are carried out by autotrophic microorganisms that reduce CO_2 to the oxidation state of cellular carbon, which requires large expenditures of energy. The sequential oxidation of NH_3-N to nitrite (NO_2-N) and NO_3-N is carried out according to the reactions:



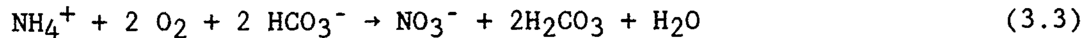
$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + H_2O + 2H^+ + \text{energy} \quad (3.1)$$

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^- + \text{energy} \quad (3.2)$$

where Equation 3.1 is carried out principally by organisms of the genera Nitrosomonas and Nitrosococcus and Equation 3.2 is carried out principally by members of the genera Nitrobacter and Nitrosocystis (Barnes and Bliss, 1983). The biochemistry is more complex than that shown in Equations 3.1 and 3.2.

Factors affecting nitrification kinetics are total alkalinity concentration, pH, dissolved oxygen concentration, toxic substance concentrations, NH_3-N concentration, BOD_5:TKN ratio, and temperature.

The overall stoichiometric nitrification reaction including alkalinity is shown as:



$$NH_4^+ + 2\ O_2 + 2\ HCO_3^- \rightarrow NO_3^- + 2H_2CO_3 + H_2O \qquad (3.3)$$

Neglecting cell synthesis, it has been shown that 7.14 mg of alkalinity as $CaCO_3$ is destroyed per mg of NH_3-N oxidized. If the alkalinity is not sufficient, these changes will have a depressing effect on pH in the system. The pH optimum for nitrification is between 8.0 and 9.0, but nitrifying bacteria are active between pH 6.0 and 10. Dissolved oxygen concentrations should not fall below 3 to 4 mg O_2 L^{-1} in order to avoid oxygen limitation. Organic sulfur compounds, cyanide, phenols, and aniline compounds have been reported as powerful toxicants to nitrifying bacteria (Christensen and Harremoes, 1978). Barnes and Bliss (1983) published a table of compounds toxic to nitrifiers.

Nitrification has been described as a zero-order reaction with respect to substrate and at concentrations of > 5 mg L^{-1} NH_3-N the growth rate of nitrifiers is close to the maximum growth rate. However, due to the high energy demands of autotrophic reactions, the biodegradable organic carbon:TKN ratio of the influent is very important. All the biodegradable organic carbon must be consumed before nitrification will take place. This requires the lowering of the F:M ratio and/or increasing the aeration time. According to Rittmann (1987), the ratio of the maximum specific growth rate of heterotrophs to autotrophs is approximately 13.6 at 20°C. Therefore, to avoid the washing out of nitrifiers, it is important to be concerned with the relationship

between the limiting growth rate (that of the nitrifiers) and the sludge age of the system:

$$\text{limiting growth rate} = \frac{1}{\text{BSRT}} \tag{3.4}$$

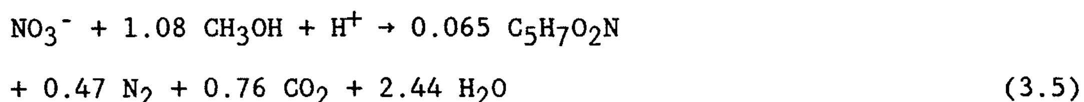
Good discussions of this relationship are presented in Christensen and Harremoes (1978), Barnes and Bliss (1983), Benefield and Randall (1980), US EPA (1975), Grady and Lim (1980), Metcalf and Eddy (1979), and De Renzo (1978). A relationship between the fraction of nitrifying organisms and the BOD_5:TKN ratio was presented by Metcalf and Eddy (1979). It presented a percent nitrifying population varying from 35 to 2.9 at BOD_5:TKN ratios of 0.5 to 9, respectively.

There have been many relationships developed between temperature and nitrifier growth rate. None of these models have been generally accepted, probably due to the effects of other factors on nitrification rates. The relationships contain temperature correction factors (θ) ranging from 1.08 to 1.13 at temperatures between 5 and 20°C (Benefield and Randall, 1980; Christensen and Harremoes, 1978; Characklis and Gujer, 1979). In treatment processes which combine nitrification, denitrification, and biological phosphorus removal, nitrification has been observed to be the most temperature sensitive reaction (US EPA, 1987).

When the ammonia content of the reactor environment becomes too low for assimilatory reactions, nitrates can be used as a source of nitrogen. The nitrates would first have to be reduced to NH_3-N before incorporation into the cellular components. This is usually not the

case in biological wastewater treatment reactors, and the assimilatory removal of NO_3-N is minimal. Biological denitrification is the most common way to remove NO_3-N from a waste stream.

Denitrifying organisms use NO_3-N as a terminal electron acceptor in the absence of dissolved oxygen. These organisms are heterotrophs, and the overall NO_3-N removal reaction (including both assimilation and dissimilation reactions), according to Benefield and Randall (1980) was given by McCarty as:



$$NO_3^- + 1.08\ CH_3OH + H^+ \rightarrow 0.065\ C_5H_7O_2N + 0.47\ N_2 + 0.76\ CO_2 + 2.44\ H_2O \quad (3.5)$$

It is believed that if NO_3-N is available, the dissolved oxygen concentrations are below 0.1 mg L^{-1} and a useable organic carbon source is available, denitrification will proceed as a zero-order reaction. Several facultative heterotrophic microorganisms can carry out denitrification reactions using a variety of organic carbon sources.

Denitrification is usually done in combination with nitrification if total nitrogen removal is required. However, industrial waste streams high in NO_3-N concentration may use only denitrification to treat the wastewater.

3.2 PHOSPHORUS REMOVAL

The need for phosphorus control has stemmed from our understanding of accelerated eutrophication. Eutrophication is the natural process of filling in freshwater lakes with organic and clastic sediments. The

majority of the organic sediment comes from the microscopic and macroscopic organisms found in our surface waters which would grow at an exponential rate if all the necessary nutrients were available. However, this is usually not the case, and the missing or limiting nutrient is commonly phosphorus. Nitrogen has also been identified as a limiting nutrient, but more often than not, the limiting nutrient is phosphorus. Accelerated eutrophication is caused when this limiting nutrient is supplied in enough quantity to stimulate higher growth rates, and thus shortening the lake's life cycle. A good discussion of this subject is contained in Vallentyne (1974).

It has been approximately 20 years since biological phosphorus uptake in excess of normal stoichiometric requirements was reported. At the time, all that was known was that an anaerobic stage had to be followed by an aerobic stage for enhanced removals to occur. Biological phosphorus removal has been the subject of a great deal of research, since this first report and now a few requirements are known to be needed to stimulate growth of polyphosphate accumulating organisms. The oxidation-reduction potential (ORP) must be less than -150 mV to ensure adequate anaerobic conditions, the removal of NO_3-N below 0.2 mg L^{-1} is a prerequisite for phosphorus release and high volatile fatty acid concentrations are needed. It has been found that _Acinetobacter_ and some other microorganisms release phosphorus under anaerobic conditions in the presence of acetate and subsequently take up phosphorus in the aerobic stage. According to Eckenfelder (1987), researchers reported that certain organisms, especially _Acinetobacter_, while being strict aerobes and therefore expected to be at a disadvantage in an anaerobic

zone, had the ability to transport acetate through the cell wall and accumulate poly β-hydroxybutyrate (PHB) in the cell, using stored polyphosphate as an energy source. When the cell reaches the aerobic section of the plant, the stored PHB is used up during the formation of adenosine triphosphate (ATP), and replenishment of the phosphate pool.

According to US EPA (1987), biological phosphorus removal systems have been designed at about twice the total hydraulic detention time for treatment of 10°C wastewater versus 20°C wastewater. This difference was due to the effect of temperature on the nitrification-denitrification design and, reportedly, is not related to the phosphorus removal design. Oldham and Dew (1979) reported that bench-scale studies achieved 90% biological phosphorus removal down to 6°C.

3.3 COMBINED REMOVAL SYSTEMS

Combined systems that remove nitrogen via nitrification/denitrification and phosphorus via enhanced polyphosphate uptake are marketed under the trade names: Modified Bardenpho Process, A^2/O Process, and the UCT Process. Basically, these processes are single sludge systems that use many compartments (also known as selectors) in order to change the environment conditions (mainly dissolved oxygen level) as the mixed liquor passes through the system.

Biological phosphorus removal was first accomplished in a full-scale SBR at Culver (Irvine, 1985). Although only 40% of the total nitrogen load was removed, the author believes that with further modifications to the SBR operating sequence, a full-scale demonstration of > 90% nitrogen and phosphorus removal is not long in the future.

CHAPTER 4

EXPERIMENTAL OBJECTIVES AND APPROACH

The study was initiated to test the effects of low temperatures on the performance of sequencing batch reactors (SBR's). The reactors were operated using a proven biological phosphorus removal cycle (Figure 1.1) (Manning and Irvine, 1985). The mass loadings were kept as constant as possible, in order to observe the effects of the decreasing temperatures on the biomass kinetics. The detailed objective of this study was to test phosphorus, nitrogen, and carbon removal in four parallel SBR's at incrementally decreasing temperature, with constant duration of individual periods within a 12h cycle.

In order to satisfy the objectives outlined, five distinct SBR investigations were completed. The investigations, along with their respective durations, are presented in chronological order in Table 4.1. The bulk of the experimental work was done in the second investigation. For this reason, the second investigation is considered the primary investigation, while the others are considered as supplementary investigations.

4.1 THE PRIMARY INVESTIGATION

The primary investigation was undertaken to observe the effects of temperature and F:M ratio on carbon and nitrogen removal in 4 SBR reactors. The reactors operated under a 12-hour cycle, as shown in Figure 4.1. The cycle consisted of a 0.5 h FILL period; a 3 hour ANOXIC/ANAEROBIC REACT period; a 6 h AEROBIC REACT period; a 1.5 h SETTLE period; a 0.5 h DECANT period; and a 0.5 h IDLE period. The REACT periods were both completely mixed (stirred at 60 r.p.m.), but air

Table 4.1 Chronological Order of the Experimental Investigations

No.	Investigation	Duration
1	Enhanced biological phosphorus removal in an 8 hour cycle at 10°C	40 days
2	Carbon and nitrogen removals in a 12 hour cycle at temperatures of 10, 6, 4, 2, and 0.5°C	152 days
3	Effects of the carbon substrates on carbon removal rates at 0.5°C	1 day
4	Effects of synthetic versus raw sewage on nitrification at 6°C	33 days
5	Enhanced biological phosphorus removal in an 8 hour cycle at 20°C	60 days

was also supplied to the AEROBIC REACT period. The F:M (COD:MLVSS) ratios were 0.044, 0.110, 0.220, and 0.330 d^{-1} for reactor 1 (R1), reactor 2 (R2), reactor 3 (R3), and reactor 4 (R4), respectively. The temperature was lowered incrementally from 10°C to 0.5°C with 6°C, 4°C, and 2°C being the intermediate temperatures. The operating control parameters are presented in Table 4.2. The MLVSS concentrations, and thus the F:M ratios of the reactors were kept constant by measuring the MLVSS concentrations daily and then calculating the amount of mixed liquor that had to be wasted using the equation:

$$Q_w = \frac{(MLVSS_m - MLVSS_o)\ V}{MLVSS_m} \tag{4.1}$$

where Q_w = waste mixed liquid flow, L,

$MLVSS_m$ = measured MLVSS concentration, mg L^{-1}

$MLVSS_o$ = operating MLVSS concentration, mg L^{-1}, and

V = volume of the reactor, L.

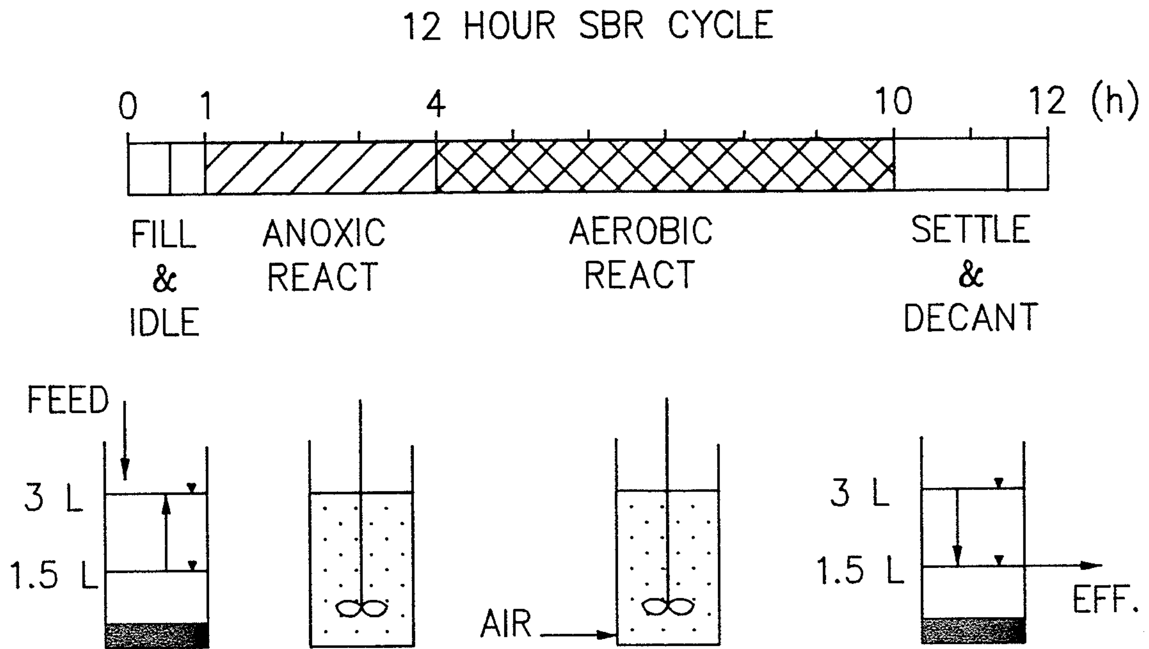


Figure 4.1 Twelve hour SBR cycle

The operating MLVSS concentrations were 3000, 1200, 1200, and 800 mg L^{-1} for R1, R2, R3, and R4, respectively.

The biological sludge for this investigation was obtained from a previous low temperature nitrification study (Berquist, 1987). This sludge was supplemented with sludge obtained from a full-scale domestic wastewater non-nitrifying activated sludge plant (South End Pollution Control Center, Winnipeg, Canada).

Table 4.2 Operating control parameters of the primary investigation

Parameters	R1	R2	R3	R4
Full volume (L)	3	3	3	3
Decant volume (L)	1.5	1.5	1.5	1.5
Q (L d^{-1})	3	3	3	3
HRT (d)	1	1	1	1
Influent: SOC (mg L^{-1})	*60 30	60	120	120
TKN-N	40	40	40	40
NH_3-N	*33.5 36.8	33.5	27.1	27.1
NO_2/NO_3-N	0	0	0	0
TP-P	12	12	12	12
TOC:N:P	*5:3.3:1 2.5:3.3:1	5:3.3:1	10:3.3:1	10:3.3:1
MLVSS (mg L^{-1})	3000	1200	1200	800
F:M (d^{-1}): TOC	*0.02 0.01	0.050	0.100	0.150
COD	*0.044 0.022	0.110	0.220	0.330
**BOD	*0.034 0.017	0.085	0.170	0.255

* The first value is for days 18 to 78 and the second value is for days 85 to 152
** Estimated values, after Manning (1986)

4.1.1 Apparatus

The major apparatus used in the investigation consisted of 4 reactors, an environmental chamber, a stirrer, aeration equipment, feed and effluent pumps, and timers.

The four reactors were clear plexiglass cylinders with an inside diameter of 107 mm, an outside diameter of 120 mm, and a height of 440 mm. The reactors had a maximum volume of 4 L, but operated at a full volume of 3 L. They were calibrated to the nearest 100 mL, and had ports located at the 1.0 L, 1.5 L, and 2.0 L levels. A sketch of a reactor is shown in Figure 4.2. A photograph of the four reactors operating at full volume is shown in Figure 4.3. The inside walls of the reactors were cleaned twice each week to prevent bacterial attachment.

The reactors were set up in a walk-in environmental chamber manufactured by Econaire Systems Ltd., Winnipeg, Manitoba, Canada. The chamber maintained the operating temperature within a $\pm$ 0.5°C tolerance. Figures 4.4 and 4.5 contain photographs of the experimental apparatus set up and operating inside the environmental chamber.

A 6 reactor paddle stirrer (Model No. 7790-300) manufactured by Phipps and Bird Co., of Richmond, Virginia, U.S.A. was used to mix the contents of the reactors. Each paddle stirrer shaft was modified by attaching a second paddle extension (Figure 4.2). The dual paddle stirrer shafts are made of stainless steel, and were manufactured in the machine shop of the Department of Civil Engineering, University of Manitoba. The mixer was raised 320 mm, to accommodate the reactors, by slipping 570 mm long copper pipes over its legs.

Air cadet diaphragm pumps (model number 7530-25) manufactured by Cole Parmer Instrument Co. of Chicago, Illinois, U.S.A. were used to supply air to the reactors. The pumping rate was controlled by a 12-volt power supply (model number 2630), also manufactured by Cole Parmer

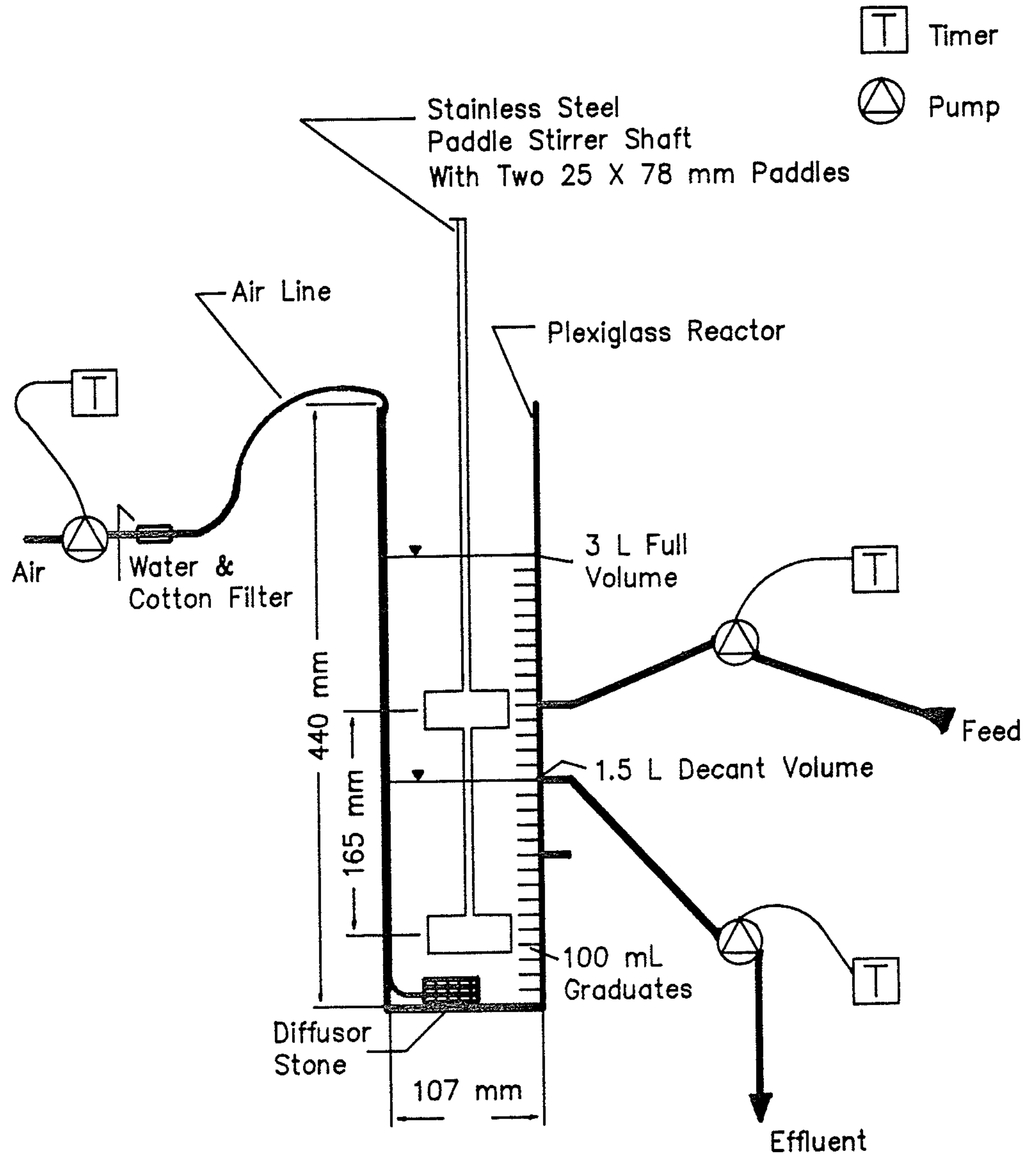


Figure 4.2 Schematic of a single reactor

Instrument Co. The air was bubbled through a water trap and then passed through a glass and cotton wool filter to remove oil and any particulate matter. The air then passed through Masterflex tubing (6404-14) and was discharged through diffusor stones (Fisher Scientific Cop., Pittsburgh, U.S.A., catalogue number 11-139B, 1986) located at the bottom of the

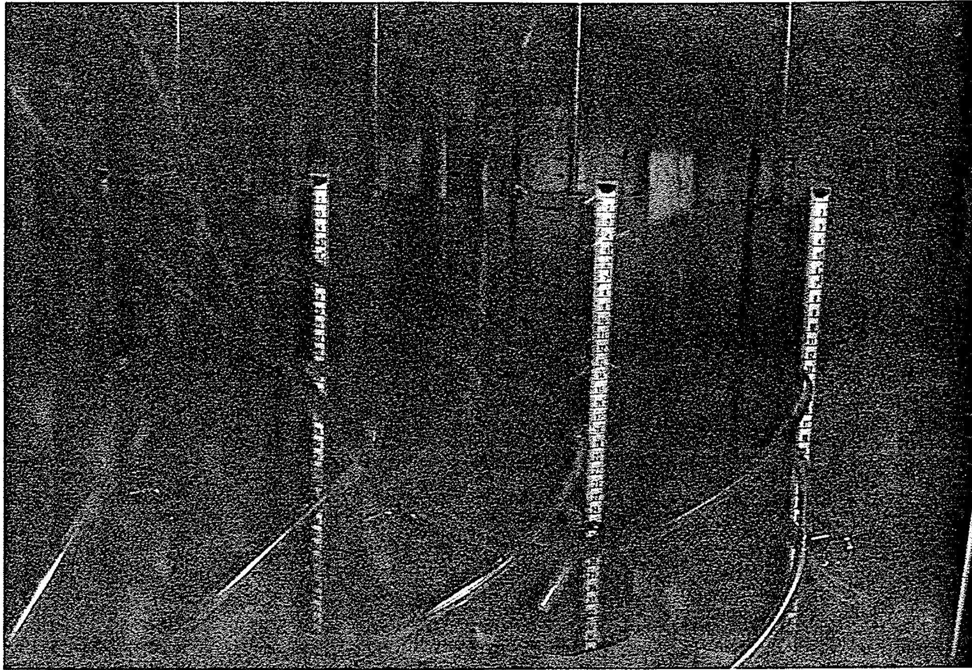


Figure 4.3 Operating reactors

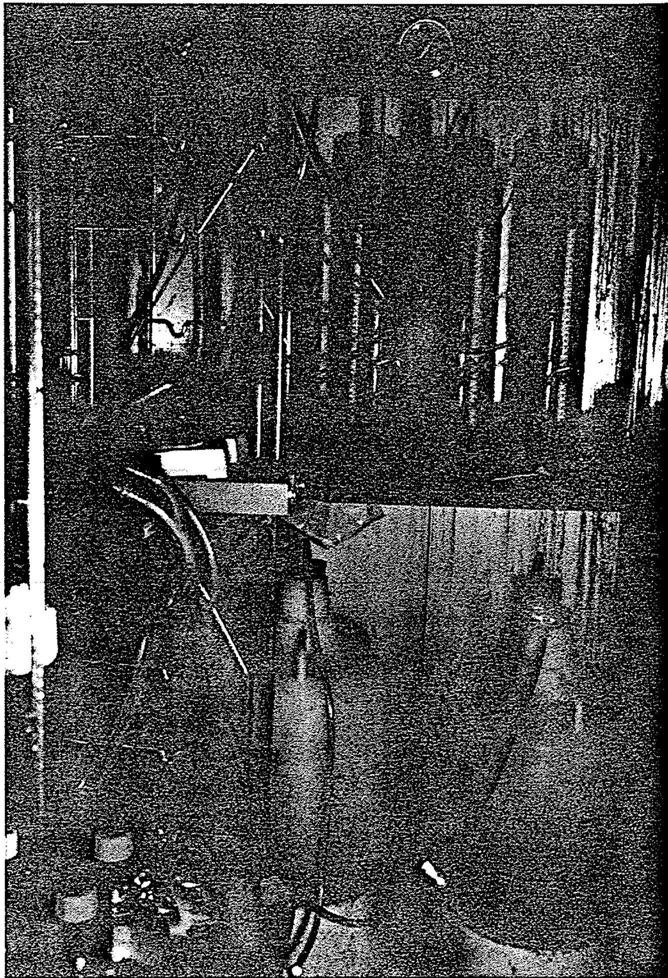


Figure 4.4 Operating reactors and appurtenances

Figure 4.5 Walk-in environmental chamber

reactors. The air supply tubing was inserted through 10-mm diameter clear plexiglass tubing that had been glued to the inside of the reactors to avoid tangling problems (Figure 4.2).

All influent and effluent pumping was done using Masterflex peristaltic variable speed pumps (model number 7553-10) complete with standard Masterflex pumpheads (7015 series) manufactured by Cole Parmer Instrument Co., Chicago, U.S.A. Masterflex neoprene tubing (6404-15) was used in the pump heads and 6 mm inside diameter Tygon tubing (R-3603

formulation, manufactured by Fisher Scientific Co.) was used as carrier tubing.

Two 20 L Nalgene carboy jugs were calibrated and used as feed containers. Four calibrated plastic buckets were used to collect the effluent from each reactor.

The mixer, aeration pumps, and feed and effluent pumps were all controlled using four 24-hour timers manufactured by AMF/Paragon (model number C102-00).

4.1.2 Synthetic Feed

All feed stock solutions and final solutions were made using deionized water. A synthetic feed was prepared for the reactors using glucose, acetate and casein hydrolysate (amino acids) as organic substrates. Those substrates were assumed to represent the hydrolysis products of the carbohydrate, lipid, and protein fractions of a wastewater (Manning, 1986). A stock solution using equal amounts (by mass) of each organic substrate was prepared (Table 4.3). Final feed concentrations were obtained from the stock solution by using dilution factors of 1:10, 1:20, and 1:40 to yield final TOC feed concentrations of 120, 60, and 30 mg L^{-1}, respectively.

Table 4.3 Organic stock and feed concentrations

Component	Chemical Formula	Stock Solution (gL^{-1})
Casein hydrolysate	$C_8H_{12}N_2O_3$	10.0
Glucose	$C_6H_{12}O_6$	10.0
Sodium acetate	$CH_3COONa \cdot 3H_2O$	23.7

Macronutrient stock solutions and final feed concentrations are presented in Table 4.4. Three ammonia nitrogen feed concentrations were needed because of the organic nitrogen contained in the casein hydrolysate. To achieve a TKN-N concentration of 40 mg L^{-1} in the feed, the ammonium sulphate supplement concentrations had to vary as the concentration of the casein hydrolysate changed. All the elemental stock solutions shown in Table 4.4 were stored separately, except for the manganese and magnesium solutions, which were made together.

Table 4.4 Macronutrient stock solutions and final feed concentrations

Element	Compound	Stock Solution (g L^{-1})	Feed Dilution	Final Feed Concentration (mg L^{-1})
Nitrogen	$(NH_4)_2SO_4$			
R1-R2		15.80	1:10	33.5
R1		17.36	1:10	36.8
R3-R4		12.76	1:10	27.1
Alkalinity	Na_2CO_3	26.5	1:10	250 (as $CaCO_3$)
Phosphorus	KH_2PO_4	26.37	1:100	6.0
	K_2HPO_4	33.75	1:100	6.0
Calcium	$CaCl_2 \cdot 2H_2O$	11.01	1:100	3.0
Manganese	$MnSO4 \cdot H_2O$	4.61	1:100	1.5
Magnesium	$MgSO_4 \cdot 7H_2O$	42.58	1:100	4.2
Iron	$FeCl_3 \cdot 6H_2O$	4.84	1:100	1.0

The micronutrient stock solution was made according to the information presented in Table 4.5. All the compounds were mixed together. A dilution of 1:100 yielded a final feed concentration of 0.1 mg L^{-1} for all the elements indicated in Table 4.5.

Table 4.5 Micronutrient stock solution, diluted 1:100 to yield element concentrations of 0.1 mg L^{-1}

Compound	Element	Stock Concentration (mg L^{-1})
$NiCl_2 \cdot 6H_2O$	Nickel	810
$CoCl_2 \cdot 6H_2O$	Cobalt	808
$CuSO_4 \cdot 5H_2O$	Copper	786
H_3BO_3	Boron	1,144
$ZnSO_4 \cdot 7H_2O$	Zinc	880
$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$		
	Molybdenum	2,576
$AlCl_3 \cdot 6H_2O$	Aluminum	1,790

The final feed concentrations were prepared daily. The disinfection of all feed apparatus (jugs and tubing) was done weekly using a 1:50 dilution of a 5.25% sodium hypochlorite solution.

4.1.3 Sampling and Analysis Program

The sampling and analysis program of the primary investigation had two distinct parts: the routine weekly program and the track study program.

The weekly program involved the routine monitoring of the reactors. The weekly sampling and analysis program is outlined in Table 4.6. All effluent samples were taken directly from the supernatant of the reactors at the end of the SETTLE period, except for the effluent VSS concentrations. These concentrations were determined by taking samples from the well-mixed effluent buckets. The effluent VSS concentrations of the reactors' supernatants were periodically measured to ensure that

Table 4.6 Weekly sampling and analysis program for the primary investigation

Parameters	Frequency of Sampling	Frequency of Analysis
Temperature, Q, MLSS, MLVSS, Q_w supernatant clarity	M, Tu, W, Th, F	M, T, W, Th, F
Effluent VSS	M, Th	M, Th
pH, ZSV, SVI total alkalinity	Tu, F	Tu, F
Influent: TKN-N, NH_3-N Effluent: TKN-N, NH_3-N	Tu, F	Tu
Influent: SOC, TP-P Effluent: SOC, TP-P, NO_2/NO_3-N	Tu, Fr	Fr
Dissolved oxygen, air flow		Periodically
Microscopic investigation		Two times at each temperature increment

the effluent buckets yielded representative samples. Influent samples were taken directly from feed containers.

The track study program monitored the reactors through the REACT periods of a single 12 hour cycle. The studies were done once for each temperature investigated. The sampling times (recorded as hours after feeding) for each temperature are given in Table 4.7. The feed was given to the reactors instantaneously at t=0 for the track studies, instead of taking the usual 1/2 hour in the FILL period. The initial or starting concentrations (at t=0) were not obtained from direct measurements in the reactors, but calculated by adding the reactor's effluent and feed concentrations and then dividing by 2.

Table 4.7 Track study sampling program for the primary investigation

Temperature (°C)	10	6	4	2	0.5
	Sampling times (hours after feeding)				
	0.50	0.25	0.25	0.25	0.25
	1.00	0.25	0.50	0.50	0.50
	2.00	1.00	1.00	1.00	1.00
	3.00	3.00	3.00	3.00	3.00
AERATION BEGINS					
	3.50	3.25	3.25	3.25	3.25
	4.00	4.00	3.50	3.50	3.50
	5.00	5.00	4.00	4.00	4.00
	7.00	7.00	5.00	5.00	5.00
	9.00	9.00	7.00	7.00	7.00
			9.00	9.00	9.00
				11.00	
				14.50	R1 only
				19.50	

Samples of the mixed liquor removed from the reactors were immediately centrifuged to separate the biological mass from the bulk liquid. The supernatants from the centrifuged samples were then passed through 0.45 μm glass filters to remove any remaining microorganisms. The samples were then analyzed for NO_2/NO_3-N immediately. The remainder of the sample was preserved for later analysis of TKN-N, NH_3-N, TP-P, and SOC.

The following analytical techniques were used in the experiment. The temperatures of the reactors were measured using a mercury bulb thermometer which was immersed in a container of water situated next to the reactors. The environmental chamber was also equipped with a thermocouple that monitored and recorded the temperature on a 24-hour basis.

The flow was checked at the end of the FEED period <u>in situ</u> by using the calibration on the reactors.

Total suspended solids and volatile suspended solids were deter-

mined using Gooch crucibles according to procedures 209C and 209D, respectively, contained in Standard Methods (APHA et al., 1985). The Gooch crucibles were cooled for 1 hour and 15 minutes and 2 hours after respective heating temperatures of 105°C and 550°C.

The pH was determined using the glass electrode method contained in method 423 of Standard Methods (APHA et al., 1985).

The ZSV and SVI were both determined according to Standard Methods (APHA et al., 1985). Both determinations were done _in situ_ using calibrations contained on the reactors.

The TKN-N, NH_3-N, and NO_2/NO_3-N analysis were done according to Standard Methods (APHA et al., 1985), 420 A, 417 B, and 418 F, respectively.

The TOC measurements were performed using a Dohrmann DC-80 Total Organic Carbon Analyzer equipped with an ultraviolet detector, automatic sampler, and an integrator.

The total phosphorus analysis was done using an autoanalyzer according to method 424 E (APHA et al., 1985).

The membrane electrode method in accordance with APHA et al. (1985) was used for dissolved oxygen determinations.

When required, TKN-N, NH_3-N, and TOC samples were preserved by adding 0.1 mL of 36 N sulfuric acid per 125 ml of sample and stored at 4°C. Phosphorus samples were preserved by freezing them at -20°C.

4.2 SUPPLEMENTARY INVESTIGATIONS

The remaining four investigations outlined in Table 4.1 were termed the supplementary investigations. Their procedures will be given in

this chapter.

4.2.1 Phosphorus Removal at 10°C

Before the primary investigation was started, an eight hour cycle (Figure 1.1) that had achieved over 90% enhanced biological phosphorus removal (Manning and Irvine, 1985) at 20°C was used in an attempt to achieve similar results at 10°C. When enhanced biological phosphorus removal had been achieved, the temperature of the reactors was to be lowered incrementally down to 0.5°C. However, after 40 days of operation at 10°C, no enhanced phosphorus removal was detected. The experiment was aborted and the primary investigation was undertaken.

All four reactors were operated under identical conditions. The same feed was used as for the primary investigation. The feed concentrations were identical to that of R1 of the primary investigation. The MLSS concentrations were maintained at 1400 mg L^{-1} in all reactors. The NO_2/NO_3-N concentration was measured at the end of the ANOXIC/ANAEROBIC REACT period. COD measurements were also done during this investigation. The closed reflux colourimetric method in accordance with APHA et al. (1985) was used for COD determination.

4.2.2 Organic Substrate Removal Rates

During the 0.5°C track study, the acetic acid and glucose concentrations were also analyzed. The acetic acid concentrations were analyzed on a Gow-Mac 750 gas chromatograph equipped on a Gow-Mac 750 gas chromatograph equipped with a borosilicate glass column filled with 80/100 mesh Chromasorb 101 media and a flame ionization detector. The

glucose concentrations were analyzed on a Waters high pressure liquid chromatograph (HPLC) equipped with a Biorad HPX-85H column and refractive index detector.

4.2.3 Synthetic Versus Raw Sewage

After the primary investigation, an attempt was made to compare the nitrification efficiencies of reactors under identical operating conditions, except for the feed source. R1 used the same synthetic substrate as the primary investigation, while R2 was fed a domestic wastewater obtained from the primary effluent weirs of the South End Pollution Control Center, Winnipeg, Canada. The experiment was started at a temperature of 6°C. When above 90% nitrification had been achieved in both reactors, the temperature was to be lowered to 4°C, and then to 2°C. Unfortunately, after 33 days, only 20% and 4% nitrification was achieved in R1 and R2, respectively. The experiment was terminated due to time limitations.

4.2.4 Phosphorus Removal at 20°C

When the primary investigation was complete, another attempt was made to duplicate the results of Manning (1986). R3 was operated under the same parameters given in Chapter 4.2.1, except that the temperature was 20°C and the hydraulic retention was 12 hours. This investigation was continued until enhanced biological phosphorus removal was detected in the reactor.

CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSION

The experiment consisted of five investigations as shown in Chapter 4, Table 4.1. The results of the primary investigation are reported in this chapter, with the results of the four supplementary investigations included where relevant. All the original experimental data is contained in Appendix I. The daily and track study analytical methodology is outlined in Chapter 4, Tables 4.6 and 4.7, respectively. All tables and figures in this chapter were constructed from these results.

5.1 F:M RATIOS AND BSRT'S

The food to microorganism (F:M) ratios were calculated using the equation:

$$F:M = \frac{SOC_I \cdot Q}{MLVSS \cdot V} \tag{5.1}$$

where

$F:M$ = mg SOC mg $MLVSS^{-1} d^{-1}$,

SOC_I = influent soluble organic carbon, mg L^{-1},

Q = flow, L d^{-1},

$MLVSS$ = mixed liquor volatile suspended solids, mg L^{-1},

V = reactor volume, L.

The F:M ratios based on influent chemical oxygen demand (COD) were then calculated by multiplying Equation 5.1 by the COD:SOC ratio of 2.2. This ratio was derived from the COD and SOC measurements of the feed substrate which resulted in a correlation coefficient of 0.9. Details of the correlation are shown in Appendix II. The objective and measured

F:M ratios are presented in Table 5.1. A statistical analysis of the measured F:M ratios is also presented in this table. The F:M ratios were kept relatively constant throughout the investigation, and the averages were found to be 0.046, 0.112, 0.209, and 0.301 d^{-1} for reactors R1 to R4, respectively. A second average F:M ratio of 0.024 d^{-1} was also calculated for R1 from day 85 to day 152. For consistency all further F:M ratios reported in the text will be based on COD values.

Table 5.1 Design and measured F:M ratios for Reactors 1 to 4

Reactor	Days	Design F:M		Measured F:M				
		*COD	SOC	*COD Avg	SOC			
					Avg	St.Dev	Max	Min
R1	18 to 78	0.044	0.02	0.046	0.021	0.003	0.026	0.018
R1	85 to 152	0.022	0.01	0.024	0.011	0.001	0.015	0.009
R2	18 to 152	0.110	0.05	0.112	0.051	0.004	0.059	0.044
R3	18 to 152	0.220	0.10	0.209	0.095	0.010	0.125	0.077
R4	18 to 152	0.330	0.15	0.301	0.137	0.018	0.189	0.103

*These COD values are based on an empirical correlation obtained between measured COD and SOC values. The COD:SOC ratio was found to equal 2.2. The correlation development is contained in Appendix II.

Table 5.2 Average Biological Solids Retention Times (BSRT)-days

	Temperature (°C)				
Reactor (F:M)	10	6	4	2	0.5
R1 (0.046)	134.1	114.6	106.4	91.7	*
R2 (0.112)	18.6	17.1	17.6	19.0	21.4
R3 (0.209)	7.0	9.2	10.9	13.4	15.3
R4 (0.301)	4.6	6.2	7.3	7.7	8.1

* Value not calculable due to addition of wasted sludge from reactor 2.

The biological solids retention times (BSRT) were calculated using the formula:

$$BSRT = \frac{MLVSS \cdot V}{(MLVSS \cdot Q_W) + VSS_E \cdot (Q - Q_W)} \qquad (5.2)$$

where: VSS_E = effluent volatile suspended solids, mg L^{-1}

The average BSRT values were assessed after a temperature stabilization period that allowed conditions to develop that were thought to represent pseudo steady-state conditions. The resulting average BSRT's are presented in Table 5.2. The average BSRT of R1 decreased by 32% as the temperature decreased from 10°C to 2°C. However, R2, R3, and R4 had respective BSRT increases of 15%, 12%, and 76% as the temperature decreased from 10 to 0.5°C. A linear relationship was observed when the BSRT's of R3 and R4 were plotted versus temperature, Figure 5.1. The correlation coefficients are 0.98 and 0.99 for R3 and R4, respectively.

The BSRT is related to the F:M ratio by Equation 2.13, where Y is

equal to the observed yield in this study. Therefore, Figure 5.1 indicates that the values for Y and/or k_d did not remain constant over the temperature changes, since the values for F:M and E were relatively constant, as indicated by Tables 5.1 and 5.3, respectively.

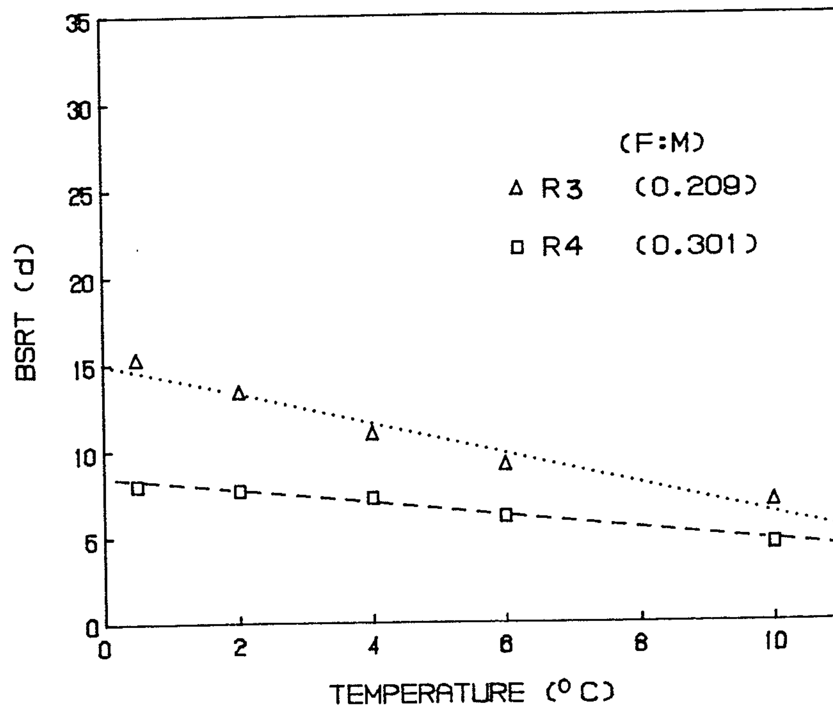


Figure 5.1 BSRT's of R3 and R4

The inverse BSRT values versus the F:M E values were plotted for the five temperature phases, Figure 5.2. The value of Y for each temperature was then determined from the slope of each plot. The Y values are 0.87, 0.60, 0.50, 0.45, and 0.42 g VSS g COD^{-1} for the respective temperatures 10 through 0.5°C. The respective k_d values are 0.035, 0.014, 0.007, 0.005, and 0.007 d^{-1}. The correlation coefficients for these plots are 1.0, 1.0, 0.99, 0.98, and 0.95 for temperatures 10, 6, 4, 2, and 0.5°C, respectively. A plot of the corresponding Y and k_d

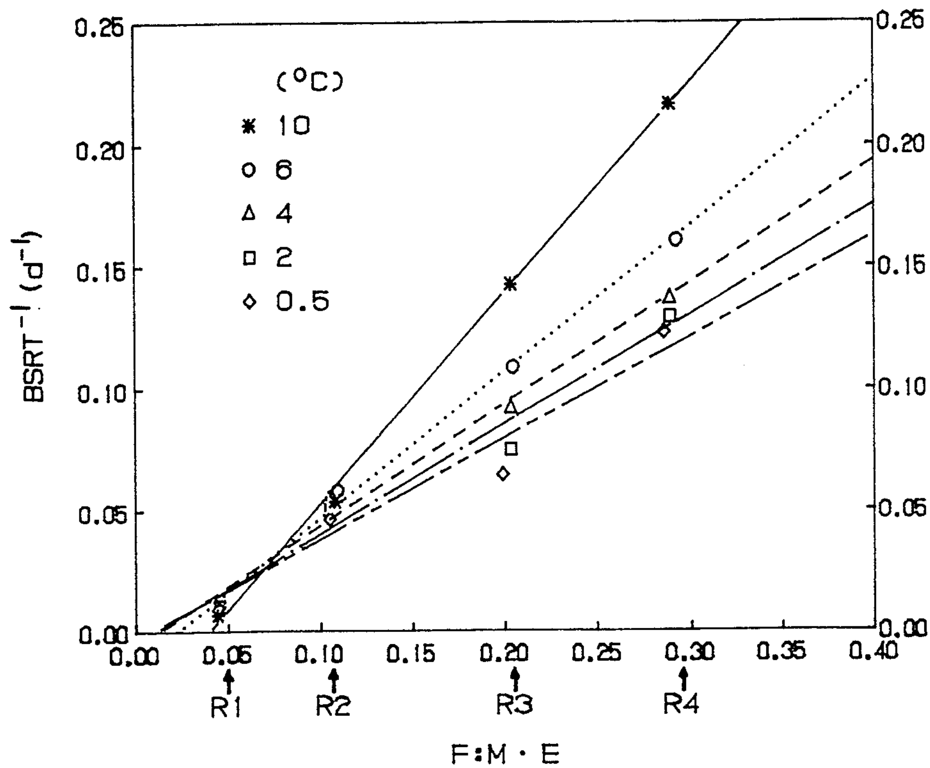


Figure 5.2 Cell yield and decay determination plots

values are presented in Figure 5.3. Arrhenius plots of these values both had correlation coefficients of 0.99 (Figure 5.4). The resulting temperature coefficients were θ_Y = 1.074 and θ_{k_d} = 1.246.

Sayigh and Malina (1978) found Y and k_d to be constant over the temperature range 4 to 20°C. The respectively coefficient values were 1.48 g VSS g COD^{-1} and 0.2 d^{-1}. They used domestic sewage as a substrate and the BSRT was kept constant across the temperature. Gaudy and Gaudy (1988) stated that a lowering of temperature often causes an increase in Y and a decrease in k_d. However, Friedman and Schroeder (1972) reported a maximum Y at 20°C. The Y decreased as the temperature was increased or decreased from 20°C. Using a synthetic substrate, they

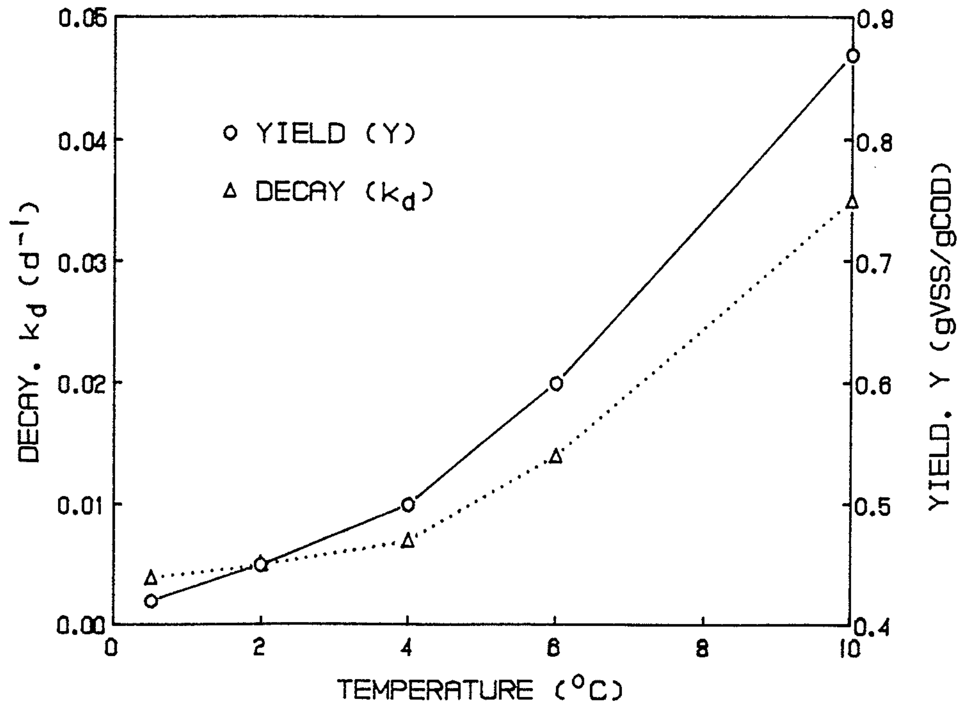


Figure 5.3 Yield and decay coefficients plotted versus temperature

reported Y values of 0.64, 0.74, and 1.1 g VSS g COD^{-1} at temperatures of 3.7, 12.4, and 20.0°C, respectively. Muck and Grady (1974) also reported Y to decrease as the temperature either increased or decreased from 20°C, but found k_d to decrease with a decrease in temperature. Christensen and Harremoes (1978) reported Y values of 0.83 and 0.50 g VSS g COD^{-1} for a traditional activated sludge process and an activated sludge process with nitrification, respectively. As the aforementioned values indicate, it is difficult to compare Y values obtained under different environmental conditions.

The decrease of Y at lower temperatures is not due only to an increase in k_d. As seen in Figure 5.3, both Y and k_d decreased as the temperature decreased, but the decrease in Y relative to k_d caused less biomass to be produced at lower temperatures. The k_d rates would be

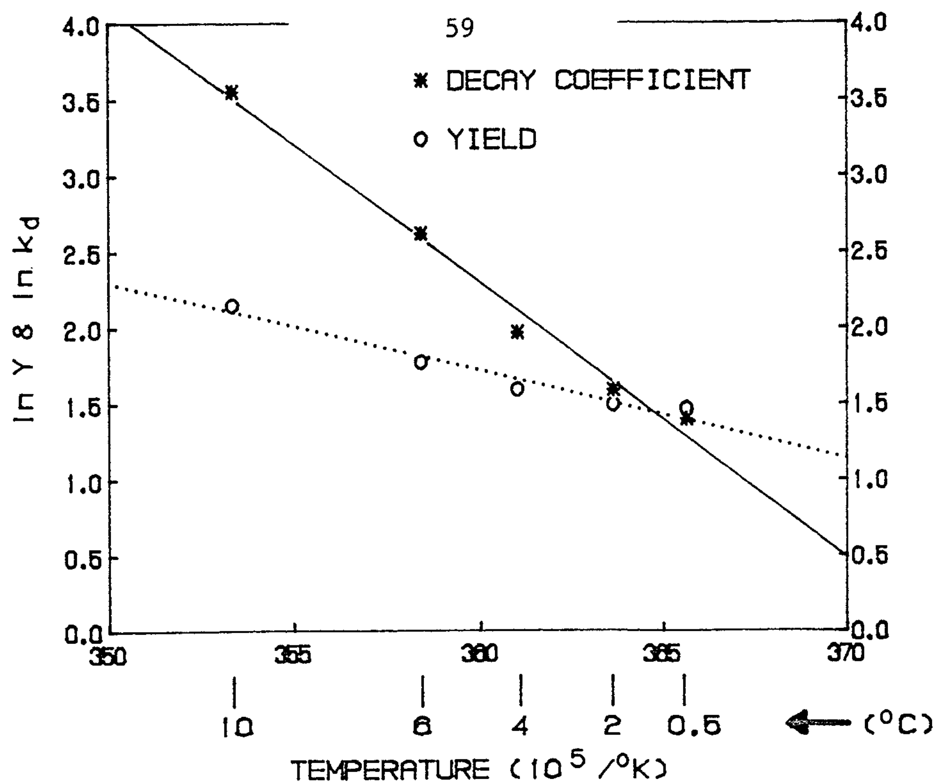


Figure 5.4 Arrhenius plot of biological yield and decay coefficients

expected to decrease, as does any reaction rate, with a lowering of temperature. The decrease in Y values may be attributed to the organisms using more of the substrate for energy production rather than cell synthesis. This greater need for energy can be related to the physiology of the microorganisms at different temperatures. The phospholipid bilayer that makes up the cell membrane becomes more viscous with lower temperatures. Therefore, as the temperature approaches the freezing point, it would take more energy to move the proteins (enzymes) through the cell membrane. These enzymes are responsible for the transfer work of moving substrate into the cells, enabling metabolic activities to continue.

The reason the BSRT of R2 was not as significantly affected by temperature when compared to R3 and R4 is shown in Figure 5.2. The

lower the F:M ratio, the smaller the change in the BSRT expected across temperatures. The decrease in BSRT of R1 was due to the increasing effluent VSS concentrations as the experiment progressed (Figure 5.5).

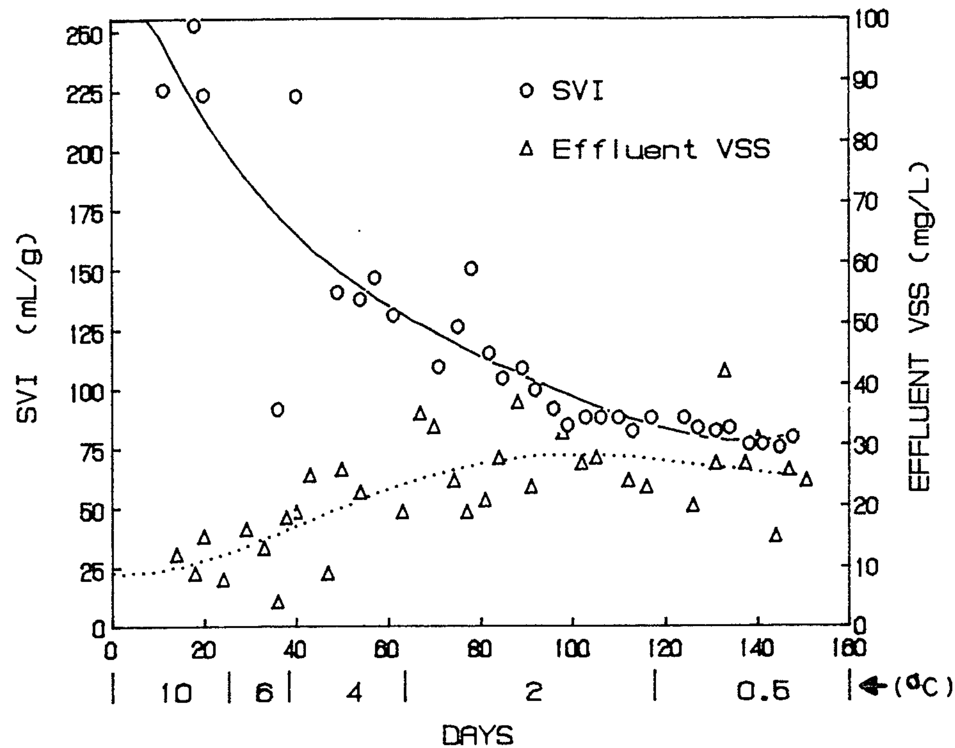


Figure 5.5 Settleability data of R1

The F:M ratio of R1 remained relatively constant without having to intentionally waste any biological solids. Equation 5.2 shows that an increase in effluent VSS concentration will decrease the BSRT if all other parameters remain constant.

In an attempt to restore complete nitrification in R1 at 2°C, two things were done: after day 83 the feed SOC concentration was reduced to 30 mg L^{-1} (which halved the F:M ratio); and after day 92 all solids wasted from R2 were added to R1. The latter attempt is the reason for

no BSRT calculation for R1 at 0.5°C in Table 5.2. It was interesting to note that even though biological solids were being added to R1 the MLVSS was actually decreasing due to the lowering of the feed SOC concentration, i.e., the microorganisms in R1 were subjected to carbon limited conditions after day 83, and subsequently endogenous respiration was reducing the MLVSS concentration.

5.2 SETTLING PROPERTIES AND MICROSCOPIC OBSERVATIONS

The sludge volume index (SVI) data were determined in situ. The effluent VSS concentrations were determined by measuring the VSS in the effluent buckets twice per week. Therefore, all VSS in the effluents were accounted for. The SVI and effluent VSS concentrations for R1 through R4 are shown in Figures 5.4 through 5.7, respectively.

The effluent VSS concentrations of R2 decreased from day 0 to day 80 while R1 had increasing concentrations over this same time period. After day 80, the concentrations were 27.0 ± 6.4 and 7.9 ± 3.5 mg L^{-1} for R1 and R2, respectively. The effluent VSS concentrations of R3 and R4 decreased from day 0 to day 60. After day 60, the average effluent VSS concentrations were 10.0 ± 4.7 and 9.4 ± 3.7 mg L^{-1} for R3 and R4, respectively.

The relatively high effluent VSS concentrations in R1 after day 80 were caused by the sludge aging, i.e. the sludge actually becoming as old as the calculated BSRT. The sludge in R1 was approximately 50 days old on day 4 of the experiment, and this is considerably less than the calculated BSRT value of 134 days shown in Table 5.2 at 10°C. The actual age of the sludge would not be constant, but would be increasing

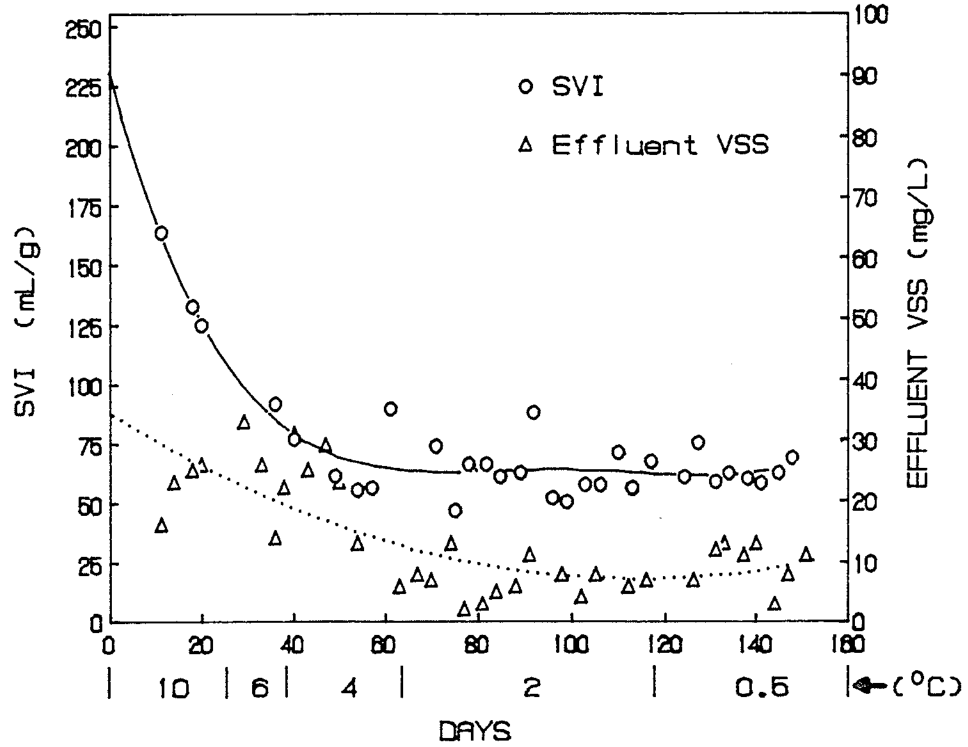


Figure 5.6 Settleability data of R2

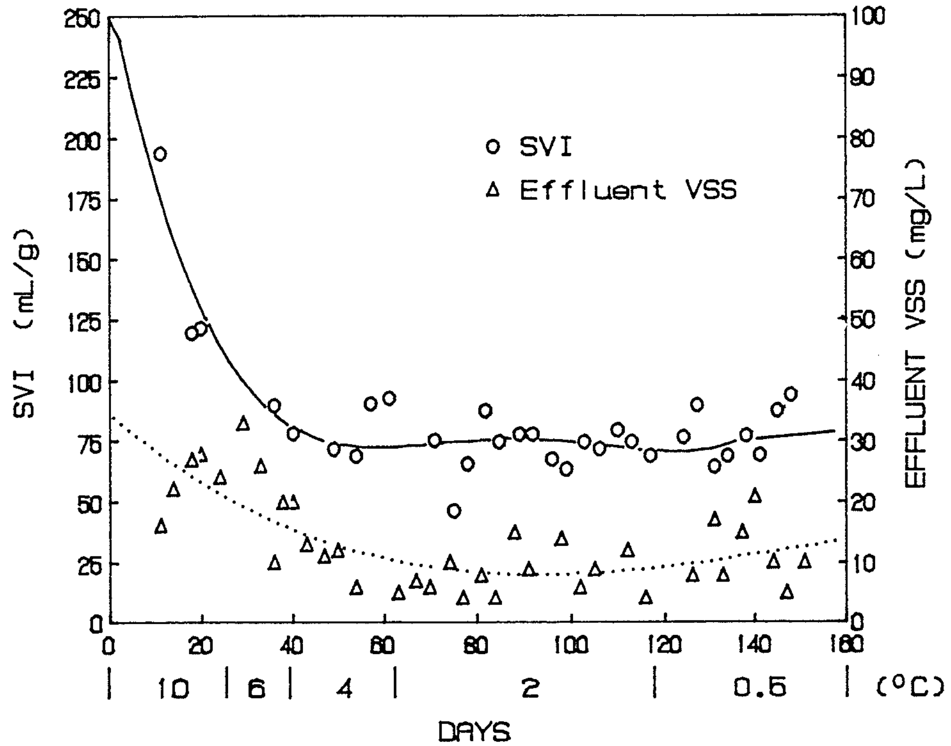


Figure 5.7 Settleability data of R3

as the test period progressed from day 4.

Researchers have found that effluent VSS carryover increases dramatically above a certain BSRT. Based on a criterion of minimal solids lost in the effluent, Bisogni and Lawrence (1971) recommended a BSRT maintained in the range of 4 to 9 days. Pitman (1975) recommended keeping BSRT below 30 days due to the floc break-up caused by a lack of food. This deflocculation is characterized by high effluent VSS concentrations and an effluent that appears cloudy (Pipes, 1979). If the effluent VSS are high and the effluent is clear with individually visible particles in it, it is said that pinpoint floc is being produced. A cloudy supernatant was first observed in R1 on day 63 and continued until the end of the experiment. This indicated a deflocculating sludge at a BSRT of 80 days ± 10 days.

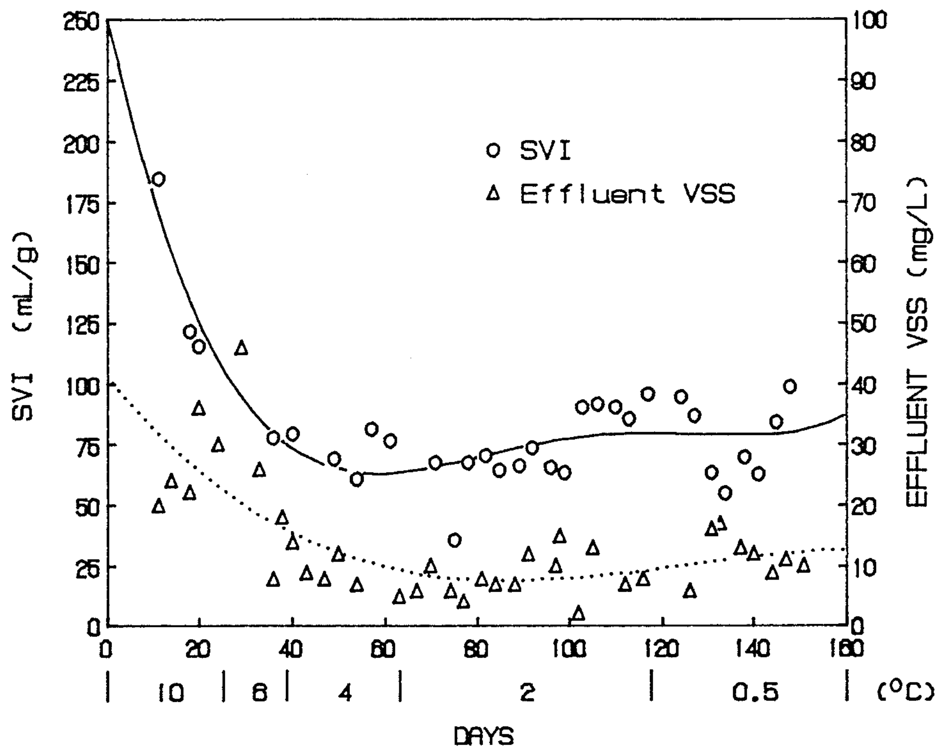


Figure 5.8 Settleability data of R4

As the effluent VSS concentration of R1 was increasing, a concurrent development was observed. The colour of some of the sludge flocs was becoming darker and the darker flocs were observed to settle more slowly than the lighter flocs, resulting in two layers of settled flocs in the bottom of R1 during the SETTLE period. These layers are shown clearly in Figure 5.8. Unfortunately, microscopic observations did not distinguish between the two types of flocs. In actuality, the sludge flocs looked similar in all four reactors of all temperatures studied.

Figure 5.9 Dark and light-coloured flocs observed on Day 71 in R1 after 20 minutes of settling (boundary indicated by red marks)

This was surprising, giving the dramatic difference of R1 flocs visible with the naked eye. What was thought to be a typical sludge floc is shown in Figure 5.9 at 150X magnification.

Eukaryotic organisms were not present in large numbers in the biomass; however, when found, the only organism observed looked like an underdeveloped stalked ciliate, and is shown in Figure 5.10 and 5.11 at 600X magnification. Their numbers did not appear to decrease as the temperature was lowered, but no formal enumerations were attempted to confirm or disprove this.

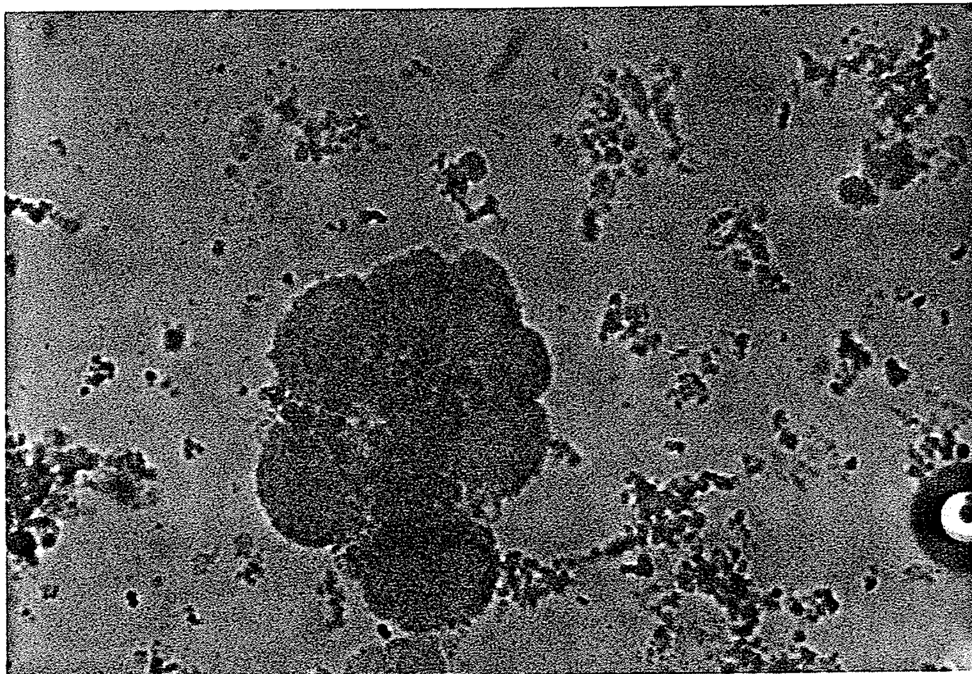


Figure 5.10 Microphotograph of typical sludge floc (150X)

The SVI data also showed a superior performance in R2, R3, and R4 when compared to R1. After day 91 the sludge wasted from R2 was added to

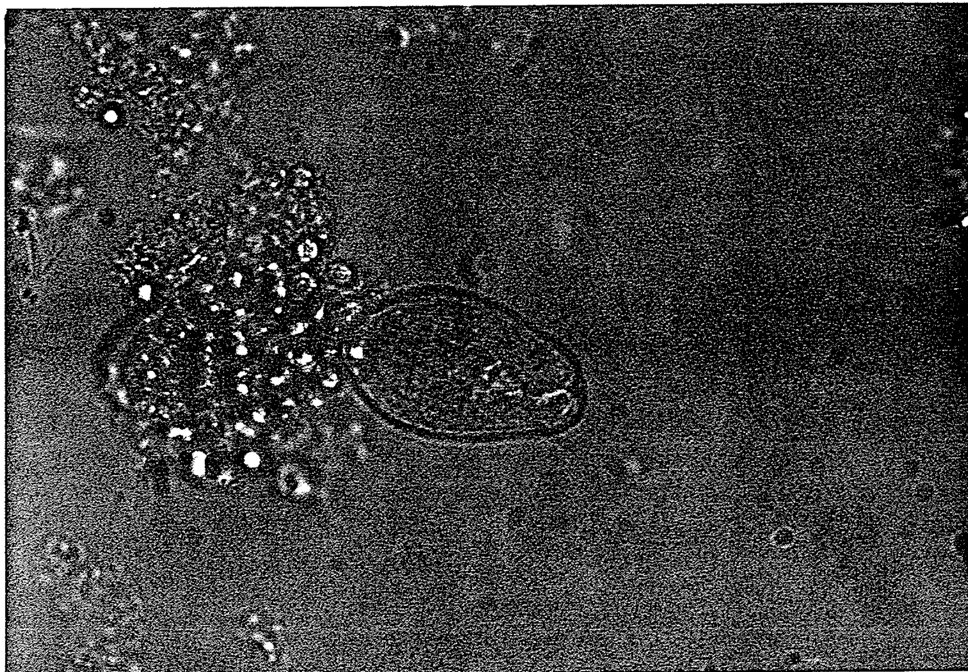


Figure 5.11 Photomicrograph of eukaryotic organism observed in sludge (600X)

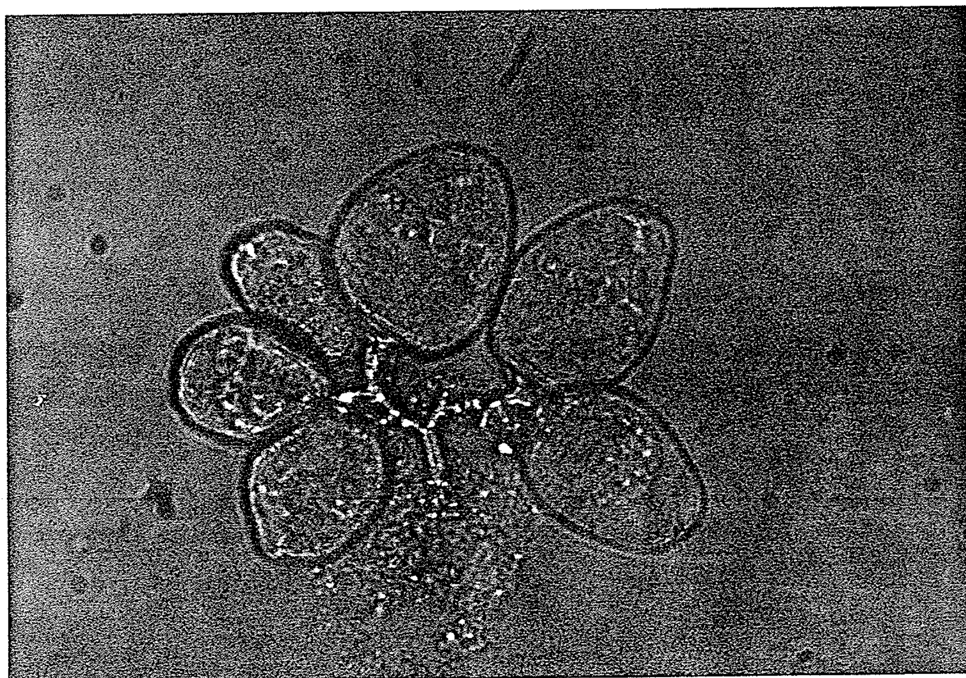


Figure 5.12 Photomicrograph of a group of eukaryotic organisms (600X)

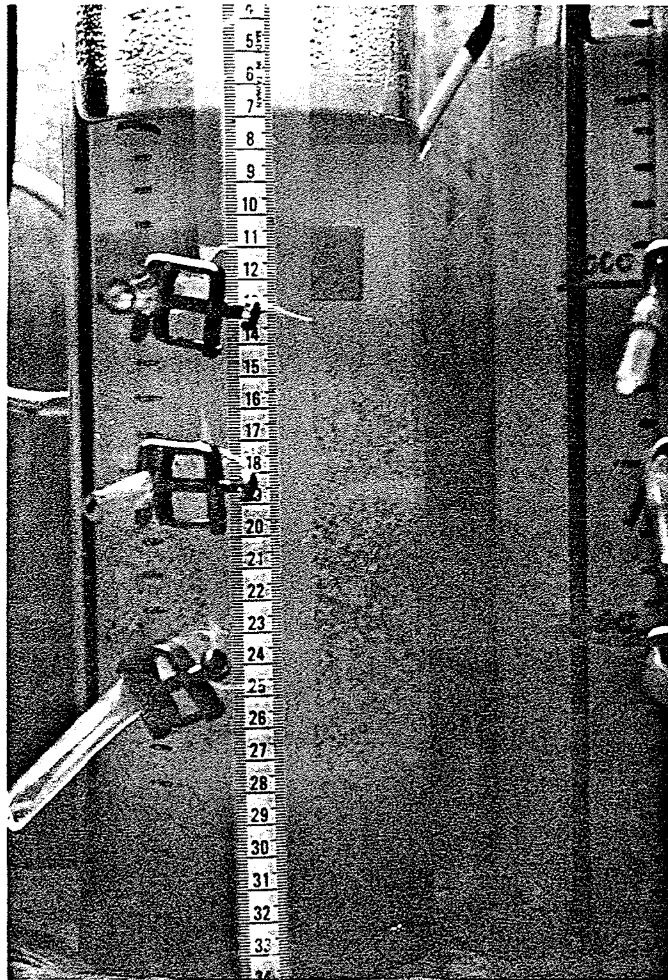


Figure 5.13 Settling sludge flocs on Day 71 in R3 and R4 after 2 minutes of settling

R1. The SVI values before this day are in the range 225 to 110 mL g^{-1}. However, R2, R3, and R4 consistently achieved values below 100 mL g^{-1} after day 30.

Zone settling velocity (ZSV) data could only be measured accurately for R1. The MLSS concentrations of the other three reactors were too low to promote hindered settling. Sludge flocs in R3 and R4, 2 minutes into SETTLE period, are shown in Figure 5.12. Figure 5.13 is of all the reactors after 4 minutes of settlement. The ZSV data for R1 is shown in

Figure 5.14. The data indicates better settling as the experiment progressed.

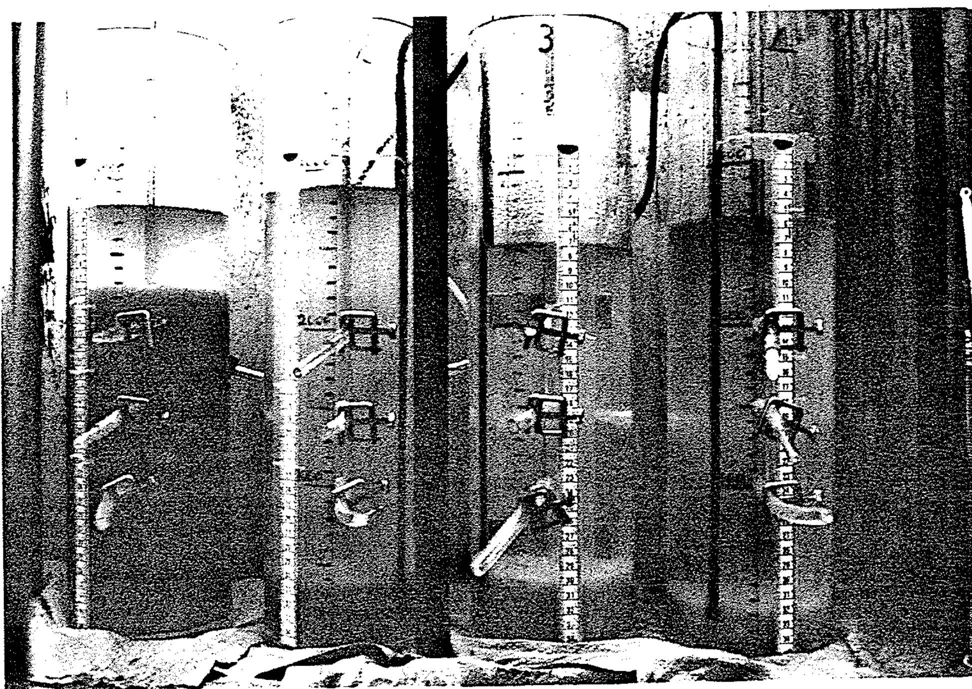


Figure 5.14 Reactors after 4 minutes of settling on Day 71

It was assumed that the generally higher SVI and effluent VSS concentrations at the beginning of the experimental period were due to the adjustment of the F:M ratios in all reactors on day 0. It will be shown in later chapters that the process efficiency in terms of carbon and nitrogen removal was not effected by these changes. Since the SVI and effluent VSS concentrations (except for R1) improved after day 0, it would indicate that the sludge separation efficiencies depended more on the F:M ratio adjustments rather than the temperature changes in the study.

5.3 CARBON REMOVAL

The average daily carbon performance data is presented in Table 5.3. This data indicates that the SOC removal efficiency was very consistent through all F:M ratios and temperatures investigated. Irvine (1985) and Melcer et al (1987) have reported that greater than 90% carbon removal efficiencies over varied loadings was easily attainable in sequential batch reactors. In a continuous flow system Topnik (1976) reported a 91% COD removal efficiency at 0°C and a F:M (COD:MLVSS) ratio of 0.1 d^{-1}.

An accidental observation was made on day 127 of the experiment. An error was made in the preparation of the feed for R3 and R4 resulting in an influent SOC concentration of 225.0 mg L^{-1} and consequent F:M ratios (COD:MLVSS) of 0.409 and 0.627 g COD g g^{-1} d^{-1}, respectively. The resulting effluent SOC concentrations were 11.7 and 15.0 mg L^{-1} resulting in removal efficiencies of 95 and 93% for R3 and R4, respectively. The organisms handled the shock loading even though the temperature was only 0.5°C at the time.

The track study results for carbon removal for R1 to R4 are presented in Figures 5.15 to 5.18, respectively. It must be noted that the initial or starting values (at t = 0) are not obtained from direct measurements in the reactors, but are calculated by adding the reactor's effluent and feed SOC concentrations and then dividing by 2. Assuming that this method for obtaining the initial SOC concentrations are accurate, the figures show two distinct removal steps through a single cycle. The concentration profiles in R1 do not show the two removal steps as clearly as R2, R3, and R4, because of its lower F:M ratio. The

Table 5.3 Daily Soluble Organic Carbon Performance Data

Reactor (F:M)	Temperature	Influent $\bar{x} \pm s$ (mg/L)	Effluent $\bar{x} \pm s$ (mg/L)	% Removal
R1	10	60.0 ± 4.4	2.3 ± 0.5	96
(0.046)	6	63.6 ± 1.0	1.7 ± 0.5	97
	4	63.7 ± 3.5	2.0 ± 0.5	97
	2	59.8 ± 2.4	1.9 ± 0.5	97
(0.024)	2	31.9 ± 2.9	2.4 ± 0.5	92
	0.5	30.3 ± 2.9	2.5 ± 0.9	92
R2	10	60.0 ± 4.4	2.7 ± 0.7	96
(0.112)	6	63.6 ± 1.0	2.0 ± 0.3	97
	4	63.7 ± 3.5	3.3 ± 0.6	95
	2	63.0 ± 4.0	3.5 ± 0.5	94
	0.5	59.0 ± 3.3	3.7 ± 1.0	94
R3	10	122.7 ± 9.9	3.5 ± 0.8	97
(0.209)	6	125.7 ± 4.4	3.0 ± 0.8	98
	4	124.5 ± 3.8	3.6 ± 0.6	97
	2	117.9 ± 3.9	4.1 ± 1.5	97
	0.5	111.0 ± 8.3	5.2 ± 1.3	95
R4	10	122.7 ± 9.9	4.7 ± 1.7	96
(0.301)	6	125.7 ± 4.4	3.9 ± 1.5	97
	4	124.5 ± 3.8	5.5 ± 1.4	96
	2	117.9 ± 3.9	4.6 ± 0.7	96
	0.5	111.0 ± 8.3	5.3 ± 1.1	95

data from R1 and R2 will not be included in any further discussions in regards to track study carbon removals because of their low F:M ratios.

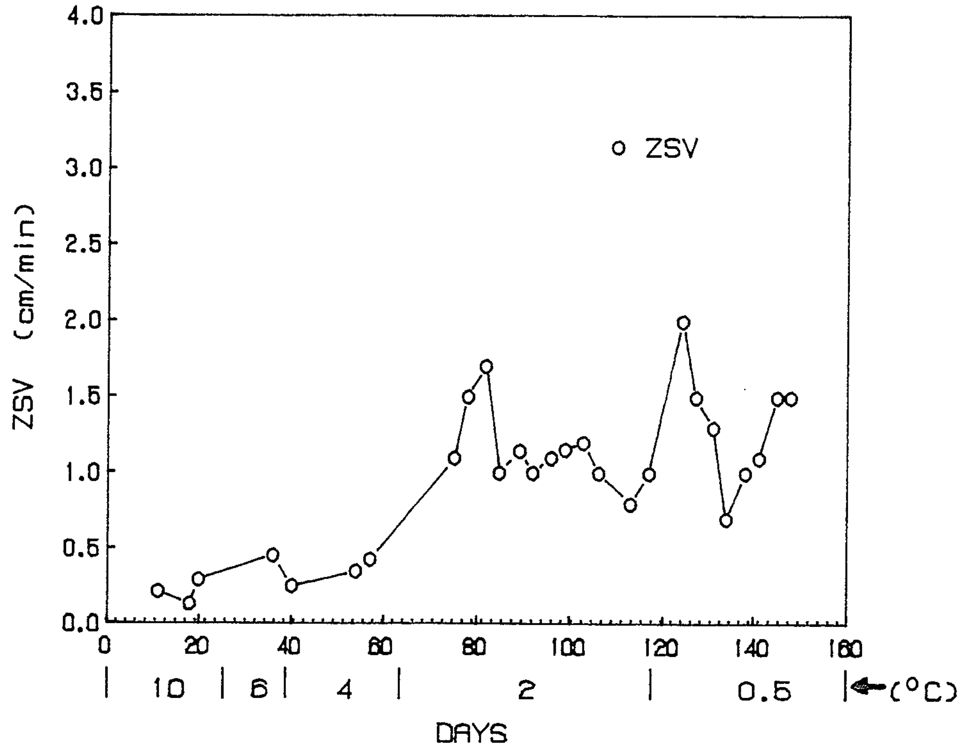


Figure 5.15 Zone settling velocity data for R1

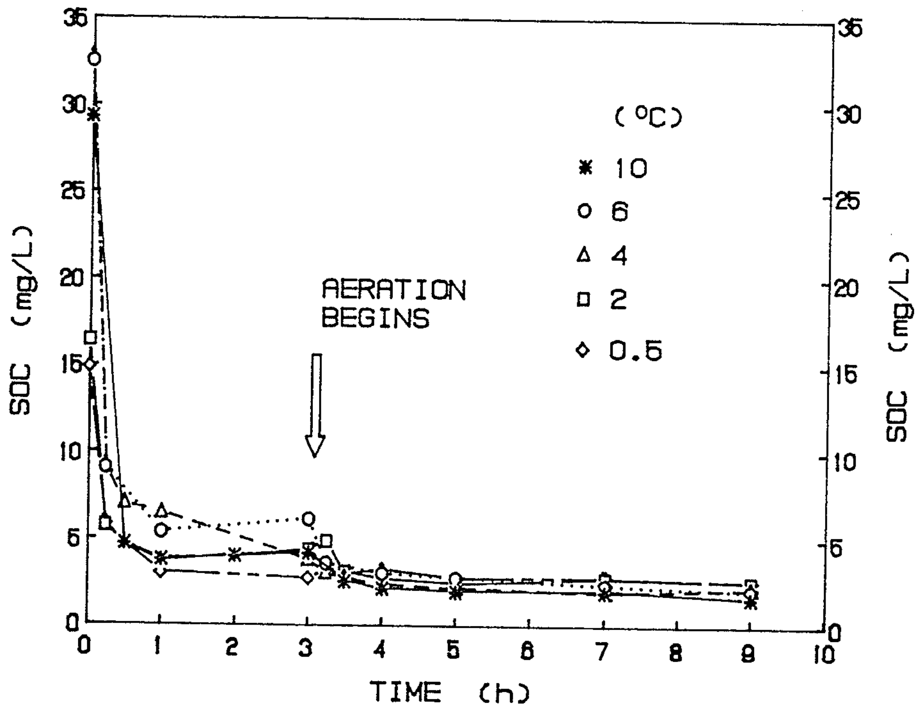


Figure 5.16 Carbon removal track studies of R1

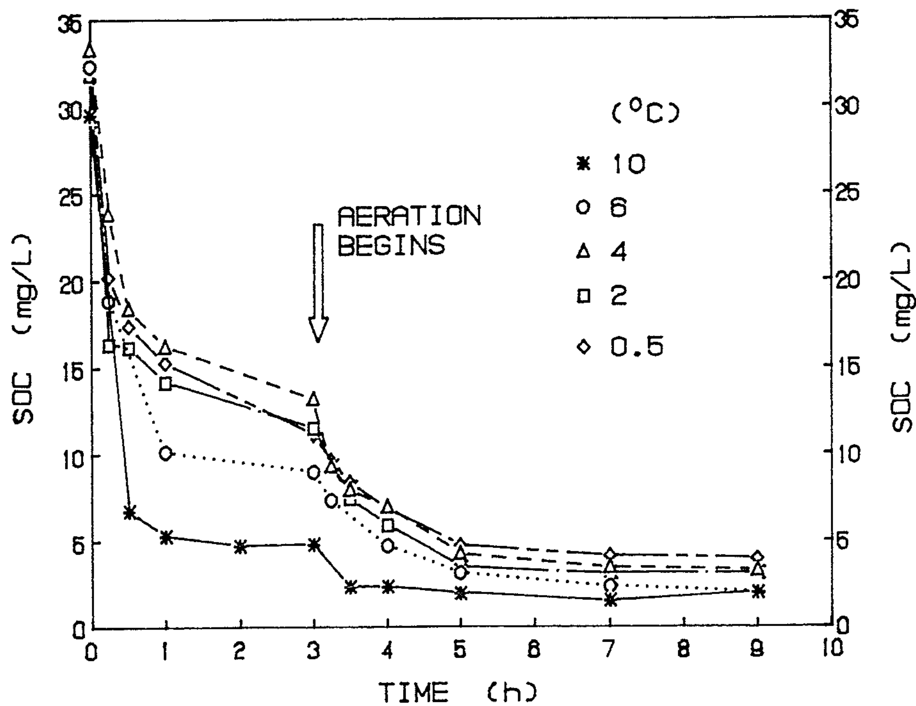


Figure 5.17 Carbon removal track studies of R2

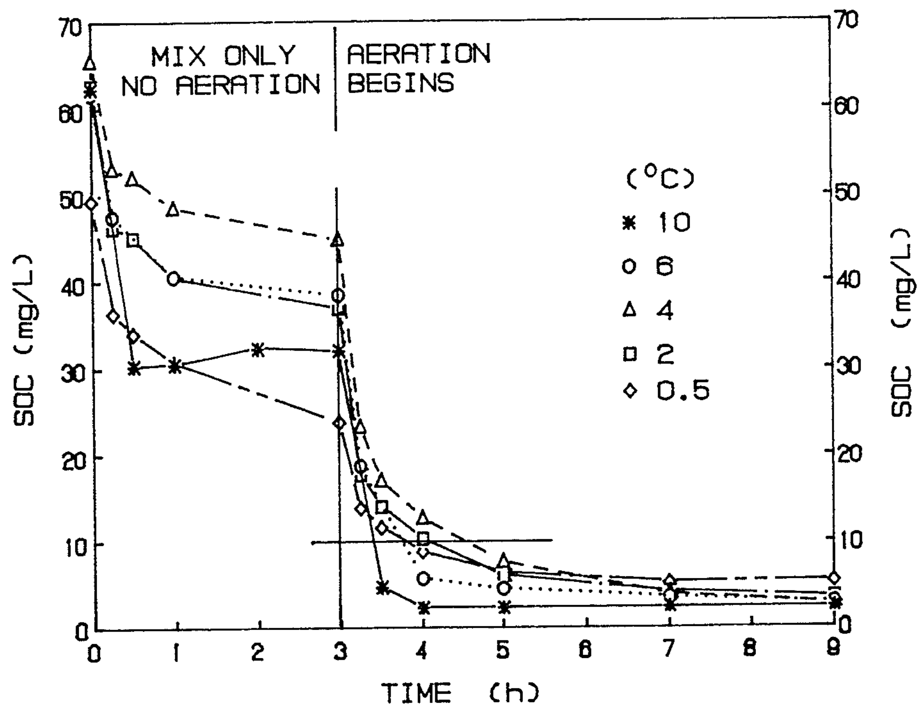


Figure 5.18 Carbon removal track studies of R3

The first removal phase occurs at the beginning of the ANOXIC/ ANAEROBIC REACT period when the biological mass first comes into contact with the substrate. The second removal phase occurs at the beginning of the AEROBIC REACT period when aeration begins.

The first removal phase can be attributed to biosorption, and the presence of the terminal electron acceptors O_2 and NO_3. Biosorption refers to the rapid transport of organic molecules onto or into the starved cells because of the sudden increase in substrate concentration outside the cells. This biosorption would be coupled with aerobic and anaerobic respiration. Once all the terminal electron acceptors are reduced, the rates of carbon removal from the bulk liquid decrease rapidly. The second removal phase, at the beginning of the AEROBIC REACT period, is attributed to aerobic respiration.

The second removal phase was chosen to compare the SOC removal rates at the various temperatures. During the track studies at 4, 2, and 0.5°C, R3 and R4 were calculated to have second-order SOC removal rates between hours 3 and 7. The SOC concentrations were too low to determine the reaction orders at the higher temperatures.

The specific carbon removal rates (K_c), mg SOC removal g VSS^{-1} h^{-1}, varied considerably depending upon how the data was analyzed. The K_c values calculated for the first hour of the AEROBIC REACT period are presented in Figure 5.19. The plotted rates would indicate the optimum K_c at 4°C for both R3 and R4. However, if accurate comparisons are to be made, all reactions must be saturated with respect to substrate. Unfortunately, for the most part these reactors were operating under substrate limited conditions. The problem of carbon limited conditions

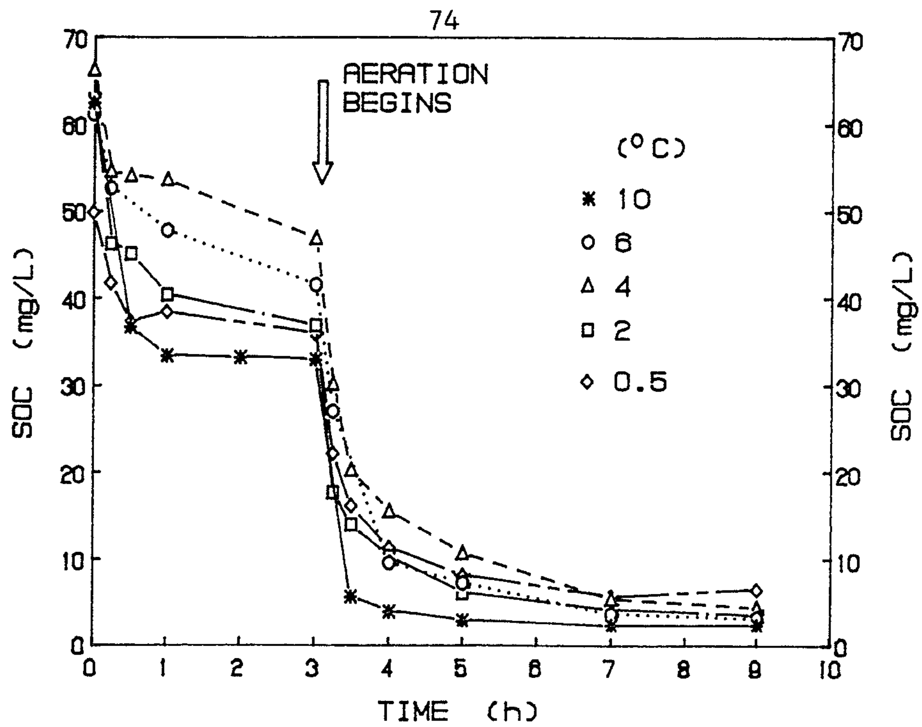


Figure 5.19 Carbon removal track studies of R4

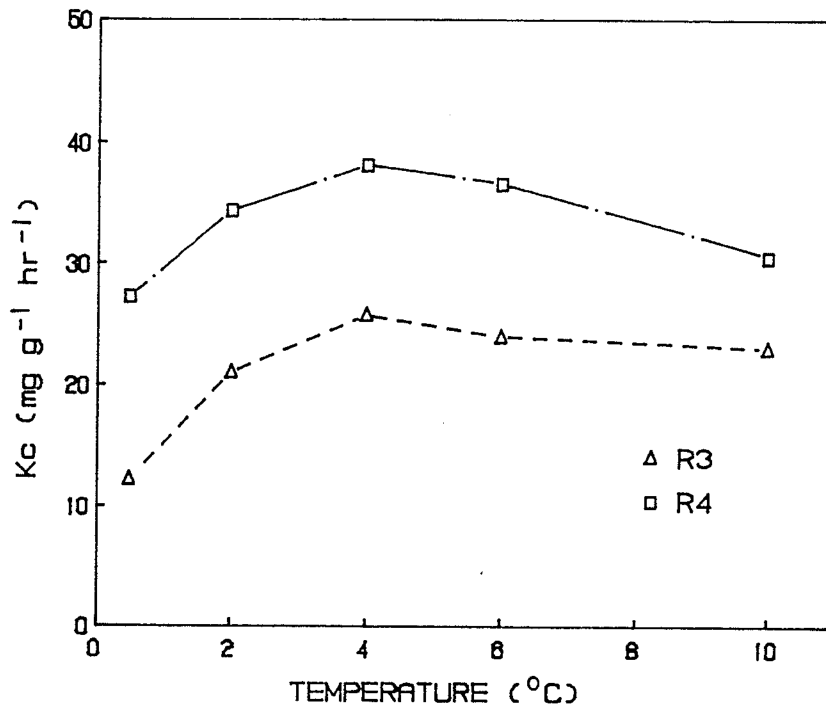


Figure 5.20 Specific carbon removal rates for R3 and R4

is illustrated clearly in Figure 5.20, where the rates from Figure 5.19 are plotted versus SOC concentration rather than temperature. This figure shows an increase in K_c with an increase in SOC concentration regardless of temperature. However, returning to Figures 5.17 and 5.18, it appears that the area underneath the plots, between hours 3 and 5, is less at 10°C than at 0.5°C. This would indicate higher removals at 10 rather than at 4°C. To account for this larger area under the lower temperature plots an imaginary line was drawn at a SOC concentration of 10 mg L^{-1}. The rates, K_c, were then recalculated based upon the time needed to reduce the initial SOC concentration at the beginning of the AEROBIC REACT period to 10 mg L^{-1}.

The corrected K_c plots, shown in Figure 5.21, indicate that the reactions at higher temperatures reached the 10 mg L^{-1} baseline sooner. The corrected plots show an anomaly at 4°C that can not be easily explained. However, on day 55 of the experiment a cooling system failure caused the temperature in the reactors to reach 29°C. The environmental chamber containing the reactors operated at 29°C for approximately 6 hours before the reactors were moved to another cold room. At the time there were no upsets in any of the daily removal efficiencies. Seven days later the track study data for 4°C was obtained. At the time the sludge ages for R3 and R4 were 10.9 and 7.3 days, respectively. Therefore, there should have been time for recovery. However, there is no other plausible explanation for the lower K_c values at 4°C. The highest K_c rates were based on the corrected rates were measured in R4 and ranged from 57.5 to 19.2 mg g^{-1} h^{-1} at 10 and 0.5°C, respectively.

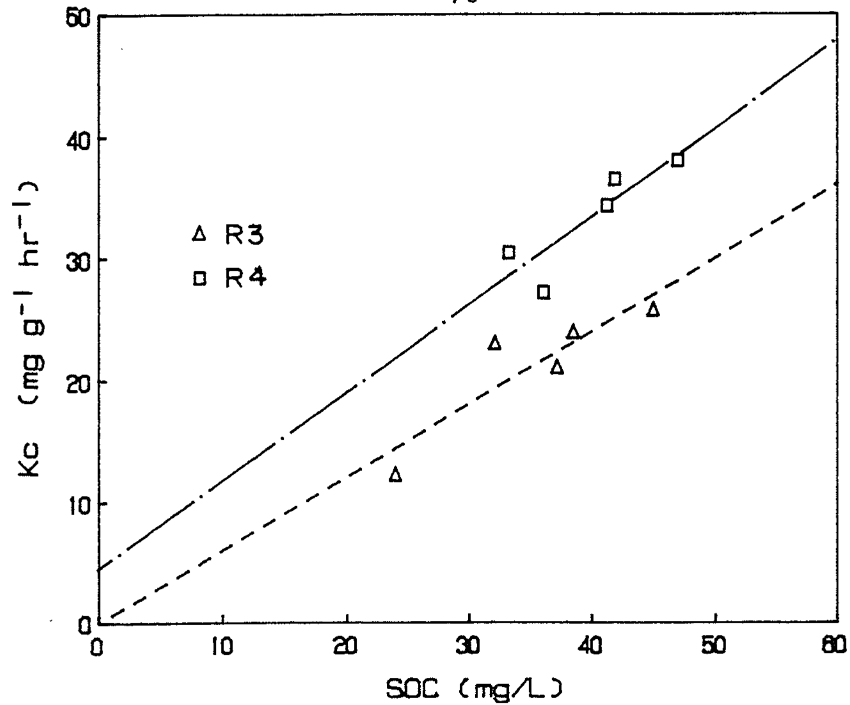


Figure 5.21 Specific carbon removal rates plotted versus initial carbon concentrations for R3 and R4

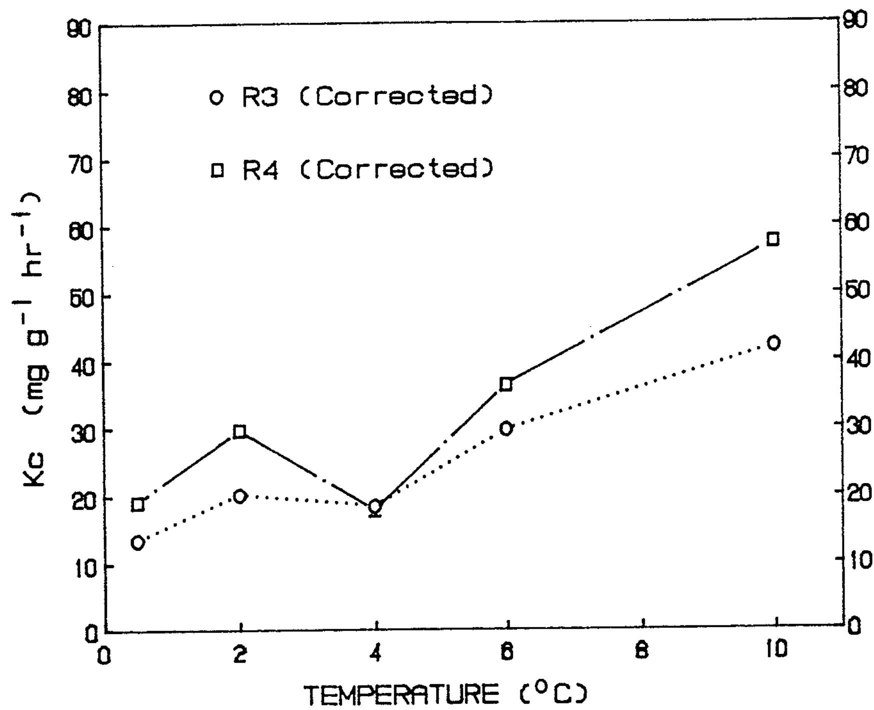


Figure 5.22 Corrected specific carbon removal rates for R3 and R4

It was thought that the temperature correction coefficient, θ, (as defined in Chapter 2.1.3) could not be directly applied to this data because of the substrate limited conditions. However, the Arrhenius plots of the corrected K_c rates show a good correlation. The plots in Figure 5.22 have correlation coefficients of 0.96 and 0.83 for R3 and R4 respectively. The corresponding θ_c values are 1.122 and 1.113 for R3 and R4 respectively. Friedman and Schroeder (1972) in an activated sludge study found θ_c equal to 1.047 (3.7 to 20°C). Other researchers, as reported by Characklis and Gujer (1979), found θ_c values ranging from 1.244 (0 to 15°C) to 1.113 (0 to 20°C) for pure *Pseudomonas* and psychrophilic cultures, respectively. Henry (1974) reported values of 1.208 and 1.182 (1°C to 4°C) for pure mesophilic and pure psychrophilic cultures, respectively. The latter two cultures showed increased activity up to the maximum temperature studied, 18°C. This would indicate that the optimum temperature for both organisms is at or above 18°C. Metcalf and Eddy (1979) report θ_c values of 1.00 to 1.04 for activated sludge processes. These values are for reactions near 20°C and are probably not valid over a wide temperature range. The wide range of all the aforementioned values would indicate that its practical use is very suspect unless the derivation of the values were achieved under the identical conditions facing a design engineer, and are not used over too wide a temperature range.

It has been found that, at low temperatures, psychrophiles are less sensitive to changes in temperature than mesophiles, therefore an increase of psychrophilic bacteria in a mixed culture system moderates the effect of cold temperature on wastewater treatment (Henry, 1974).

The same study found the psychrophilic species were the dominant population when the BSRT was decreased. This was explained by the fact that since psychrophiles grow faster than mesophiles at low temperatures, the increasing of the BSRT enabled mesophiles to avoid washout.

5.3.1 Supplementary Results

It was thought that during a track study of carbon removal it would help discern the mechanisms involved if the values for the three organic compounds in the feed were monitored separately. It was decided that the glucose and acetic acid concentrations would be determined during the track study at 0.5°C. The casein hydrolysate fraction would then be the difference between the SOC concentration and the sum of the glucose and acetic acid concentrations. The results of this study for R4 are presented in Figure 5.23. All the concentrations are expressed as equivalent carbon.

An analytical problem was discovered in the glucose determination. During the second sampling run, there was a difference in glucose concentration analyzed immediately after collection and analyzed after storage on the following day. Unfortunately, it was thought that the filtering of the samples (0.45 μm membrane) would be enough to stop any further degradation of glucose. This was not the case however, as the glucose samples stored at 4°C overnight showed zero glucose concentration when analyzed the next day. There must have been an enzyme present in the samples that escaped filtration and continued to break down the glucose. It was fortunate that the first three glucose concentrations were analyzed immediately and are considered accurate.

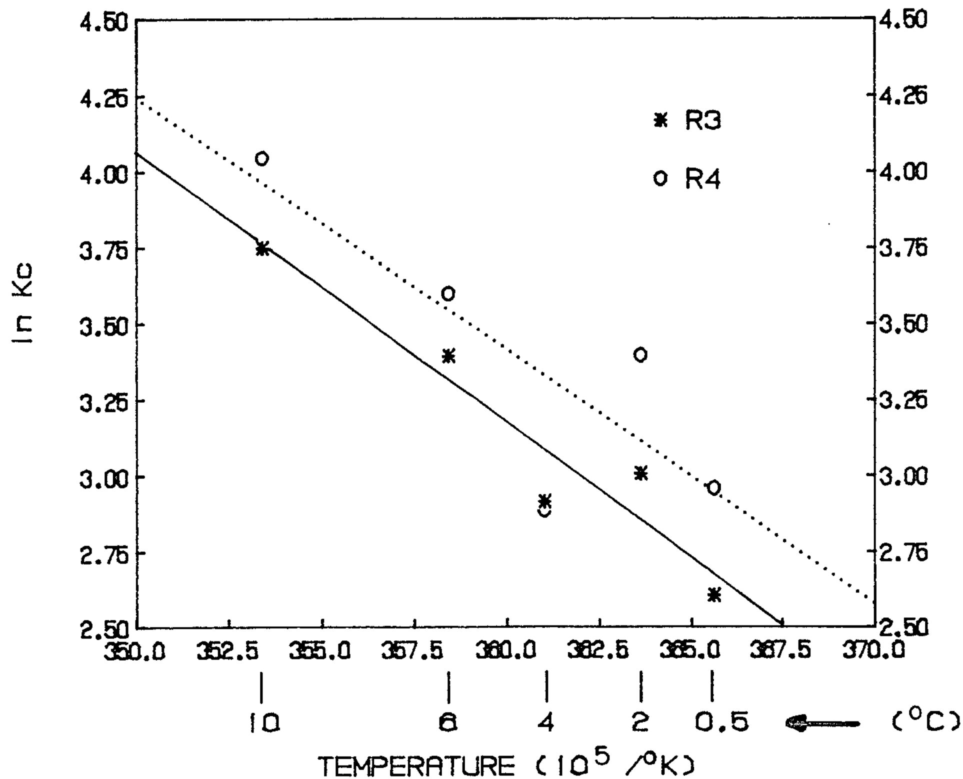


Figure 5.23 Arrhenius plots of specific carbon removal rates for R3 and R4

After 30 minutes the glucose concentration continued to drop while the SOC and acetic acid concentrations remained relatively constant until the beginning of the AEROBIC REACT period. The 30 minute glucose value is the last valid concentration. After the first 30 minutes of the ANOXIC/ANAEROBIC REACT period the SOC concentration of the bulk liquid remained constant. Therefore, it can be assumed that the glucose concentration did not drop, i.e., if no SOC removed from the bulk liquid there could be no glucose removal over this same period. Replotting Figure 5.23 incorporating this assumption results in the removal profile as shown in Figure 5.24.

The SOC profile in Figure 5.24 closely follows that of the combined glucose and acetic acid profile during the first 3.5 h. This shows that

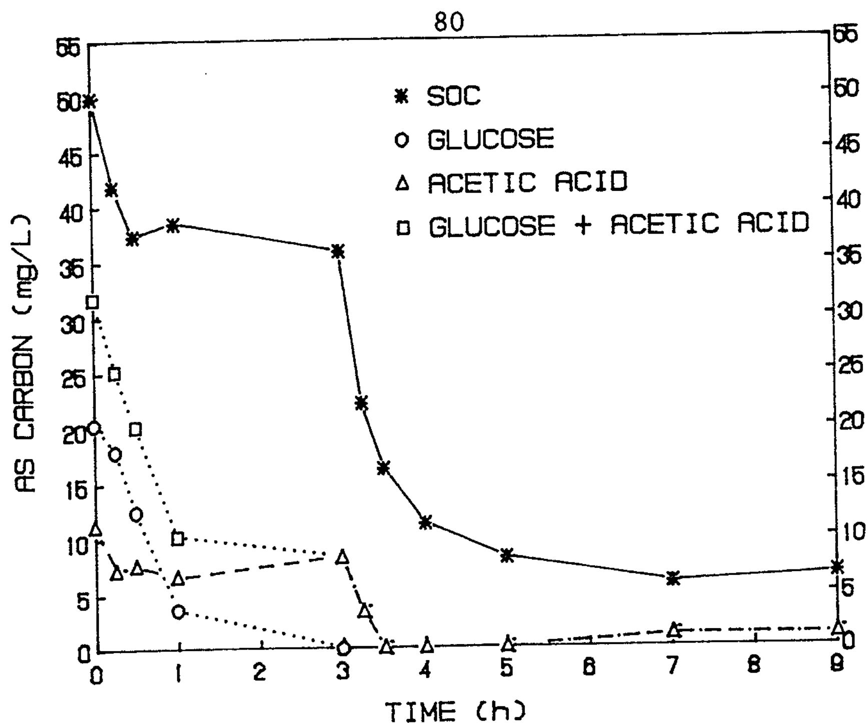


Figure 5.24 Track study of organic constituents in R3 at 0.5°C

both glucose and acetic acid are quickly removed from the bulk liquid during metabolic activity. The casein carbon fraction was estimated to be 18.2, 17.0, and 16.4 mg L^{-1} at times equal to 0, 3 and 3.5 h, respectively. This would indicate that the casein remained essentially unmetabolized until both the glucose and acetic acid were utilized. Corroboration of this observation is found in the catabolitic repression theory associated with glucose metabolism (Stanier et al., 1986). The theory states that glucose inhibits the production of enzymes that will catabolize more complex substrates. The casein was also degraded at a rate much lower than that of the glucose or acetic acid. The maximum removal rate for acetic acid occurred in the first 15 minutes of the AEROBIC REACT period, while the maximum casein removal rate occurred in the time between 3.5 and 4 h. The resulting maximum specific removal

rates were 21.8 and 11.1 mg g^{-1} for acetic acid and casein respectively.

This supplemental investigation illustrates the effect of the type of substrate used on the temperature response reflected in the removal rates. It is probable that if only glucose would have been used, little or no changes in removal rates would have been detected over the temperature range 10 to 0.5°C.

5.4 NITROGEN REMOVAL

The removal of nitrogen was not as successful as the carbon removal. The effluent TKN-N values recorded at 10°C were obtained differently due to two factors. The samples were not filtered and therefore the nitrogen content of the effluent suspended solids was included. Samples were filtered for all other temperatures. A minor error in the colourimetric curve development could have also caused an increase of ≤ 1 mg L^{-1} above the actual value. This error was corrected for the subsequent temperature phases.

5.4.1 Daily Removals

The daily nitrogen removal efficiencies were found to be extremely temperature dependent. The average daily data for TKN-N and NH_3-N are presented in Tables 5.4 and 5.5, respectively.

The nitrification efficiency for average daily removals was calculated based on NH_3-N removal as shown in the following equation:

$$\%N = \frac{(TKN\text{-}N_I - TKN\text{-}N_E)}{TKN\text{-}N_I - (TKN\text{-}N_E - NH_3\text{-}N_E)} \cdot 100 \qquad (5.3)$$

where, $\%N$ = % nitrification,

$TKN\text{-}N_I$ = influent TKN-N,

$TKN\text{-}N_E$ = effluent TKN-N, and

$NH_3\text{-}N_E$ = effluent NH_3-N

Table 5.4 Average Daily TKN-N Data

Temperature (°C)	R1		R2 (mg/L)		R3		R4	
	INF*	EFF.**	INF.	EFF.	INF.	EFF.	INF.	EFF.
10	33.2	2.2	33.2	2.6	32.7	4.5	32.7	6.4
6	37.6	1.5	37.6	6.0	40.8	13.4	40.8	20.6
4	38.0	0.6	37.2	26.2	38.2	27.5	37.7	19.4
2	36.6	28.1	40.0	30.2	39.4	24.7	38.3	23.9
0.5	35.9	30.3	37.4	33.9	36.2	26.3	36.2	27.6

*INF. = Influent; **EFF. = Effluent

Table 5.5 Average Daily NH_3-N Data

Temperature (°C)	R1		R2 (mg/L)		R3		R4	
	INF*	EFF.**	INF.	EFF.	INF.	EFF.	INF.	EFF.
10	28.8	0.3	28.8	0.2	25.2	0.4	25.2	0.3
6	39.2	1.4	39.2	5.1	28.8	12.7	28.8	20.9
4	28.7	0.1	29.4	20.9	24.8	19.7	24.7	16.1
2	30.9	24.1	30.5	27.4	28.2	21.4	27.8	21.2
0.5	30.5	27.1	31.6	30.0	30.1	24.5	31.0	24.8

*INF. = Influent; **EFF. = Effluent

The results of the calculations are presented in Table 5.6. There are no considerations given in Equation 5.3 for NH_3-N removal via cell

Table 5.6 Average Daily Nitrification Efficiencies (%) (based on NH_3-N removals)

Reactor (F:M)	TEMPERATURE (°C)				
	10	6	4	2	0.5
R1 (0.046)	99.2	98.2	99.8	-	-
(0.024)	-	-	-	25.9	17.8
R2 (0.112)	99.5	88.8	32.7	26.1	12.0
R3 (0.209)	98.7	70.4	35.3	40.2	28.6
R4 (0.301)	99.1	48.9	53.3	44.0	27.9

synthesis. Therefore, the higher removals at 2 and 0.5°C for R3 and R4 can be attributed to nitrogen assimilation rather than the oxidation of ammonia by autotrophs.

To account for the nitrogen removed via cell synthesis a synthesis factor (ΔX_N) was subtracted from the TKN-N_I value. This factor was calculated as follows:

$$\Delta X_N = \frac{0.13 \cdot MLVSS}{BSRT} \qquad (5.4)$$

where, ΔX_N = nitrogen removed via assimilation, mg L^{-1}, and 0.13 = fractional content of nitrogen in the VSS (13%).

The values obtained from the combination of Equations 5.3 and 5.4 are shown in Table 5.7. These values, although a more accurate account of true nitrification, still left a lot to be desired in regards to validity. The average effluent NO_2/NO_3-N concentrations are presented in Figure 5.25. Assuming that denitrification was insignificant during the AEROBIC REACT period, Figure 5.25 would be

Table 5.7 Average Daily Nitrification Efficiencies (%) (based on NH_3-N assimilation)

Reactor	TEMPERATURE (°C)				
	10	6	4	2	0.5
R1	98.9	95.9	99.7	15.6	5.9
R2	99.1	81.3	7.8	4.7	-13.3
R3	91.3	40.7	-33.4	11.1	- 0.1
R4	76.7	4.4	9.2	-0.6	-21.6

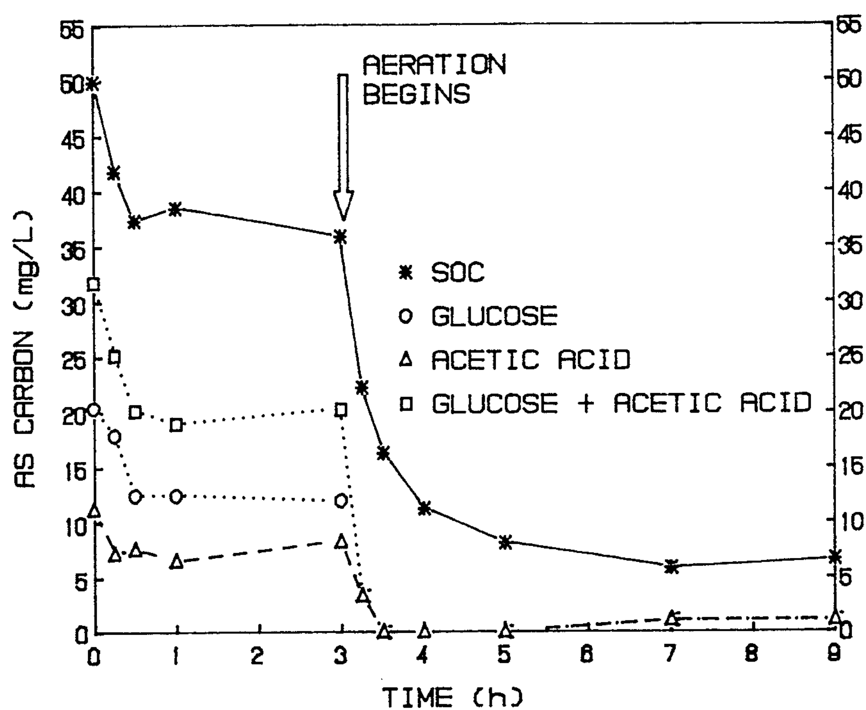


Figure 5.25 Track study of organic constituents in R3 at 0.5°C replotted from Figure 5.24

indicative of the presence of nitrification. Therefore, another equation was developed for nitrification efficiency:

$$\%N = \frac{NO_2/NO_3\text{-}N_E}{NO_2/NO_3\text{-}N_E + NH_3\text{-}N_E} \cdot 100 \qquad (5.5)$$

where, $NO_2/NO_3\text{-}N_E$ = effluent NO_2/NO_3-N.

The data generated by this equation is presented in Table 5.8. These efficiencies were considered valid and thus were plotted in Figure 5.26.

Table 5.8 Average Daily Nitrification Efficiencies (%) (based on NO_2/NO_3-N formation)

Reactor (F:M)	TEMPERATURE (°C)				
	10	6	4	2	0.5
R1 (0.046)	98.3	92.9	99.5	-	-
(0.024)	-	-	-	7.7	3.6
R2 (0.112)	98.8	73.4	7.5	0.0	0.0
R3 (0.209)	96.6	25.7	0.5	0.0	0.0
R4 (0.301)	96.8	4.6	0.0	0.0	0.0

R1 was able to achieve over 90% nitrification above a temperature of 2°C. At 2°C efficiency dropped to below 10%. Increasing the aeration time did not improve nitrification (Figure 5.32). The lack of nitrification in R1 at 2°C was not expected. It has been proven that nitrification does occur at temperatures equal to and below 2°C. Topnik (1976) in a 19L continuous flow reactor, operating at 0°C, with a HRT of 24 hours, a F:M of 0.110 d^{-1} and a MLVSS concentration of 4300 mg L^{-1}, reported an 18% oxidation of the 22 mg L^{-1} NH_3-N in the feed. Oleszkiewicz and Berquist (1988) in a 3 L batch reactor, operating at 2°C, with a HRT of 24 hours, a F:M of 0.07 d^{-1} and a MLVSS concentration

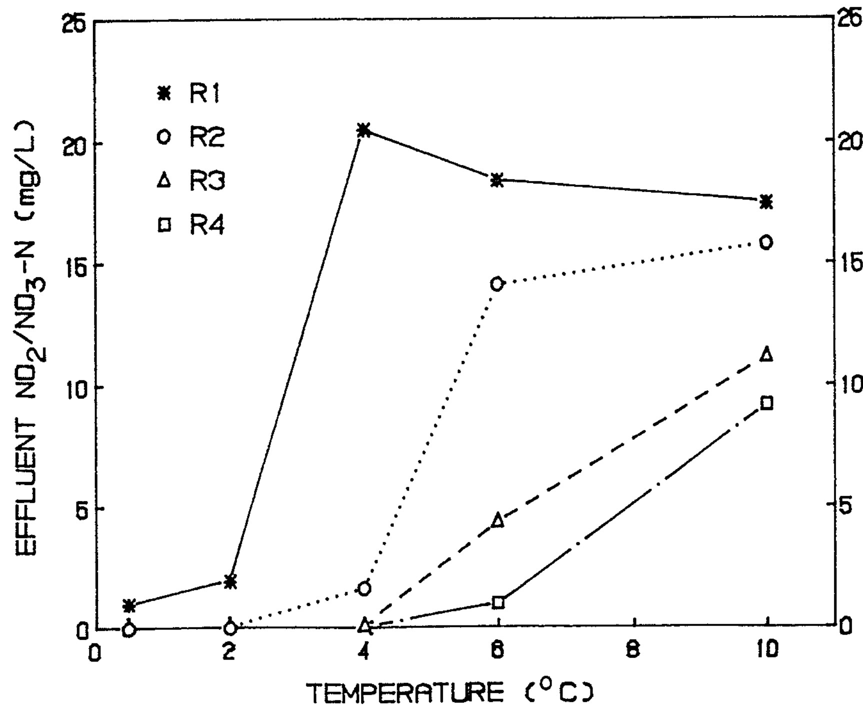


Figure 5.26 Average effluent nitrite/nitrate concentrations

of 3600 mg L^{-1} reported a 90% removal of TKN-N based on an influent TKN-N concentration of 85 mg L^{-1}. Both of the aforementioned studies used primary clarifier effluent from a domestic sewage treatment plant as the feed substrate. The latter researchers supplemented their feed with a high TKN-N pharmaceutical plant effluent containing processed pregnant mare's urine.

Oleszkiewicz and Berquist (1988) found that with a decrease in temperature from 5°C to 2°C a simultaneous 50% decrease in F:M was needed to keep nitrification efficiency above 90% (Figure 5.27). With this in mind, two adjustments were made in R1 to try to restore its nitrification efficiency at 2°C. On day 83 the SOC concentration in the feed was halved to yield a F:M equal to 0.024 d^{-1}. Also starting on day 102, in an effort to improve any micronutrient deficiencies, 10 mg L^{-1}

of yeast extract was fed daily to R1. The 2°C test phase was terminated on day 117 without any improvement in the nitrification efficiency of R1.

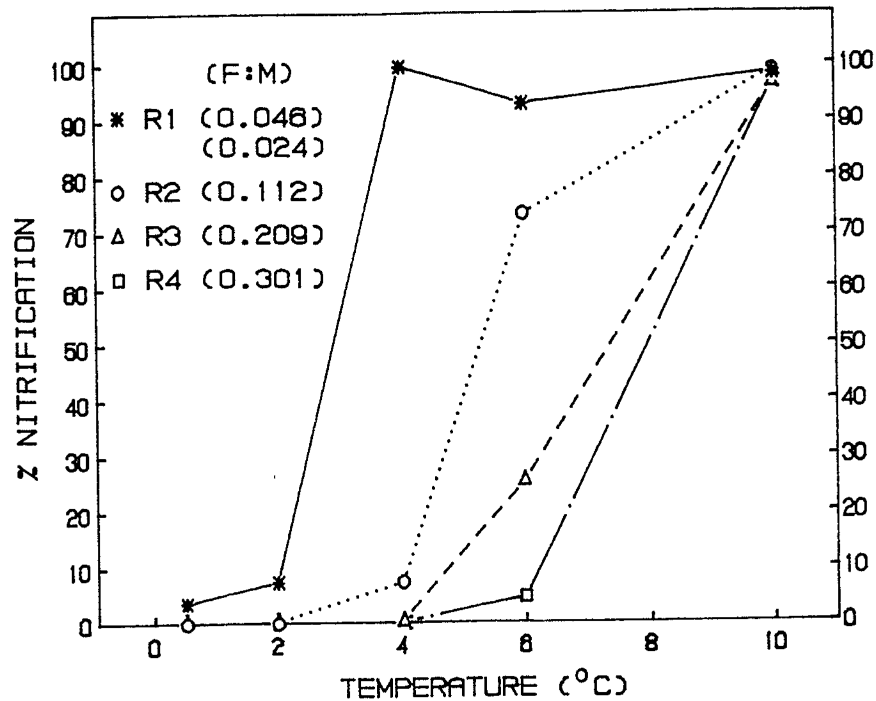


Figure 5.27 Nitrification efficiencies plotted versus temperature

R2 had an 87% loss in nitrification from 6°C to 4°C and complete loss of nitrification at 2°C (based on NO_2/NO_3-N). From 10°C to 6°C R3 and R4 had 61 and 89 per cent reductions in nitrification respectively, and no nitrification at 4°C. Therefore, it was found in this experiment that below 10°C poor nitrification efficiencies will result at F:M values greater than 0.21 d^{-1}. Also, nitrification was essentially lost below 6°C at F:M ratios of 0.112 d^{-1} and higher. The decrease in nitrification efficiency as related to temperature and F:M ratio is best expressed graphically (Figure 5.28).

The average daily denitrification efficiencies of the reactors could only be assessed when significant nitrification was observed

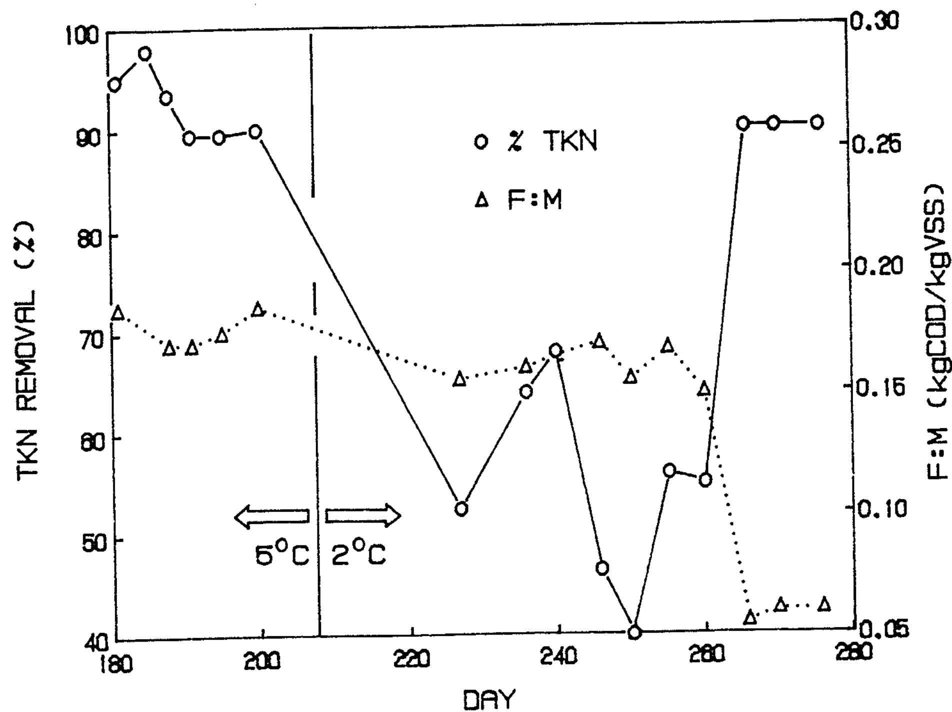


Figure 5.28 Effect of F:M ratio adjustment on nitrification efficiency (after Oleszkiewicz and Berquist, 1988)

because NO_2/NO_3-N was not included in the influent. The NO_2/NO_3-N that was produced during the AEROBIC REACT period was removed during the ANOXIC/ANAEROBIC REACT period of the following cycle. Periodic sampling, done at the end of the ANOXIC/ANAEROBIC REACT period consistently demonstrated that the NO_2/NO_3-N concentrations were at trace levels (<0.1 mg L^{-1} NO_2/NO_3-N). This ensured optimum conditions for enhanced biological phosphorus removal, which, according to Manning (1986) may be inhibited at NO_2/NO_3-N concentrations exceeding 2 mg L^{-1}.

5.4.2 Track Studies

The interactions of the organic carbon and various nitrogen species were observed during the track study analysis. The track

studies of the reactors where 5% or more nitrification was accomplished (Table 5.8) will be presented. This includes R1 at 10, 6, 4 and 2°C; R2 at 10, 6, 4 and 2°C; R3 at 10 and 6; and R4 at 10 and 6°C. Figures 5.29 to 5.39 present the concentration profiles graphically in the respective order of the previous sentence.

The NO_2/NO_3-N formation was found to be a zero order reaction at all relevant temperatures and F:M ratios. The NO_2/NO_3-N removal due to denitrification was found to be between a zero and first order reaction, since the removal plots for zero and first order determinations had correlation coefficients of 0.96 and 0.98, respectively.

The specific nitrification rates (K_N), mg NO_2/NO_3-N formed g VSS^{-1} h^{-1} are shown in Figure 5.40. These rates are the maximum rates obtained at each F:M loading and temperature. The highest K_N rates obtained for 10°C and 6°C were 4.41 and 2.05 mg g^{-1} h^{-1}, respectively. Both rates were measured in R2. The highest K_N at 4°C was 1.02 mg g^{-1} h^{-1} and occurred in R1. These rates are generally higher than those reported in the literature. Christensen and Harremoes (1978) reported K_N of 1.6 mg g^{-1} h^{-1} at 10°C. Palis and Irvine (1985) reported rates between 1.0 and 1.5 mg g^{-1} h^{-1} at room temperature. Oleszkiewicz and Berquist (1988) reported K_N values of 2.3, 1.25, and 0.33 mg g^{-1} h^{-1} at 7, 5, and 2°C, respectively. They also cited a literature source that had reported a maximum K_N of 1.0 mg g^{-1} h^{-1} at 11°C.

Arrhenius plots of the K_N rates for R1 and R2 are shown in Figure 5.41. The rates for R2 were multiplied by 10 before the logarithm was taken.

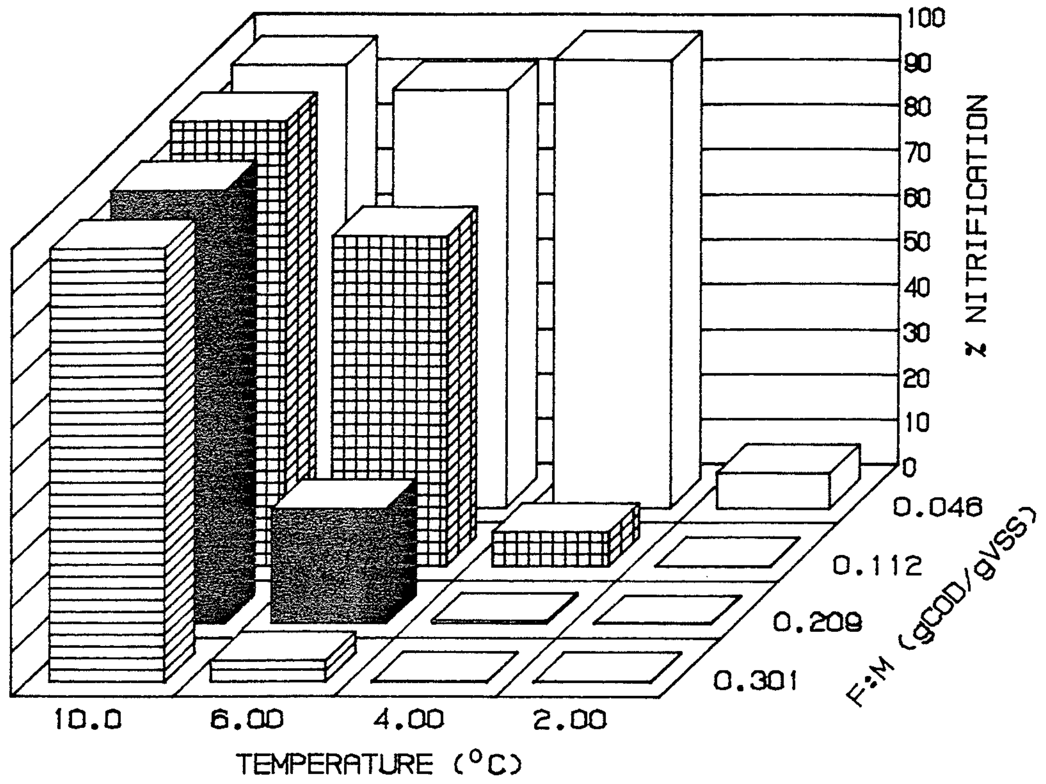


Figure 5.29 Nitrification efficiencies plotted versus temperature and F:M ratio

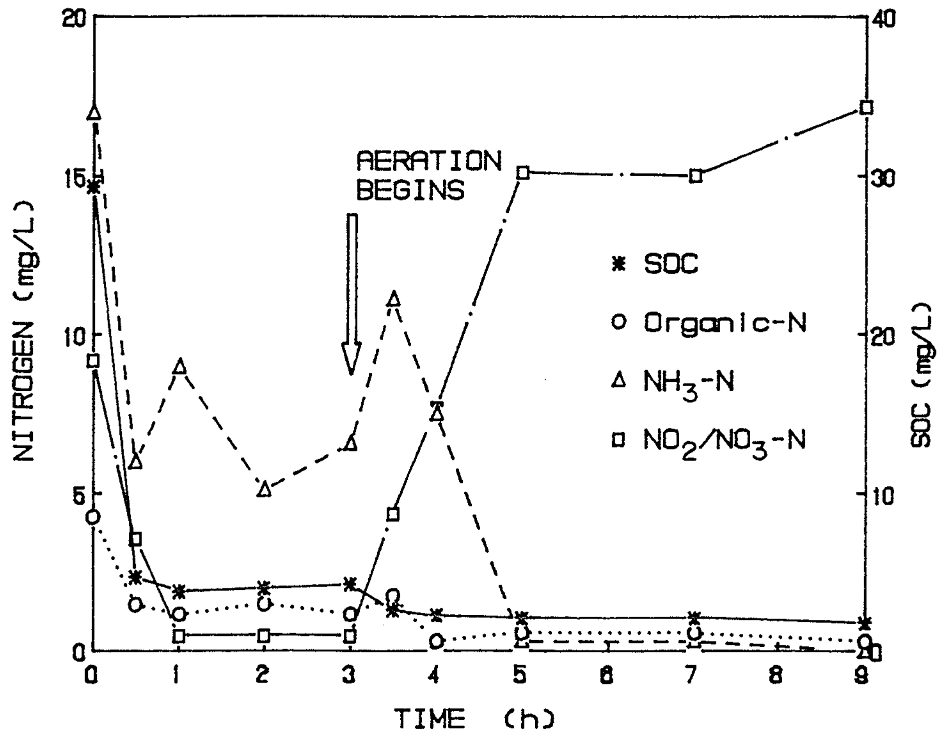


Figure 5.30 Track study of R1 at 10°C

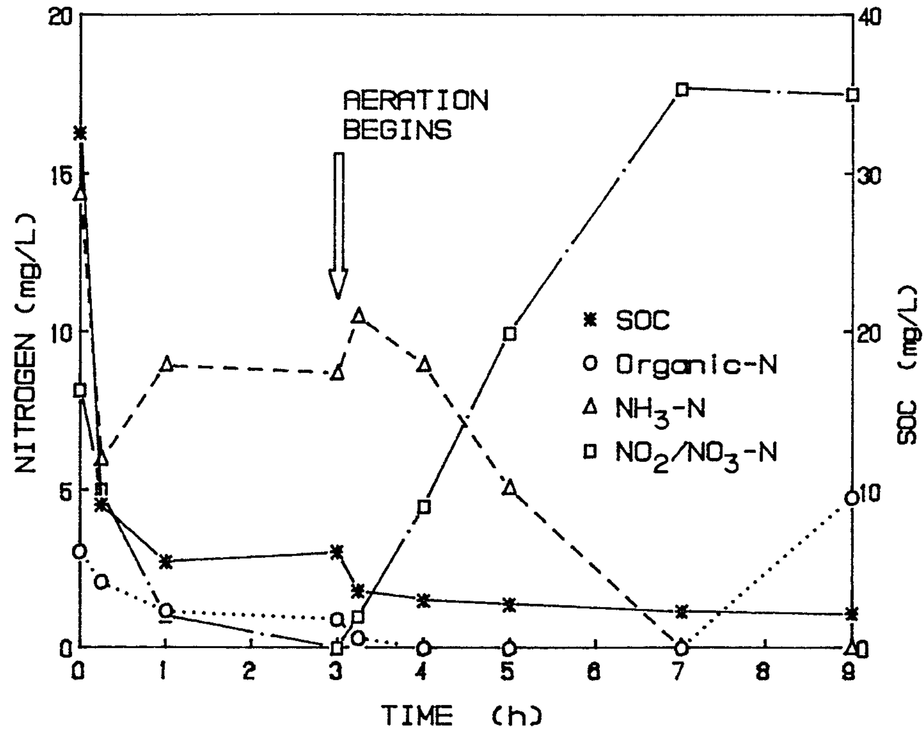


Figure 5.31 Track study of R1 at 6°C

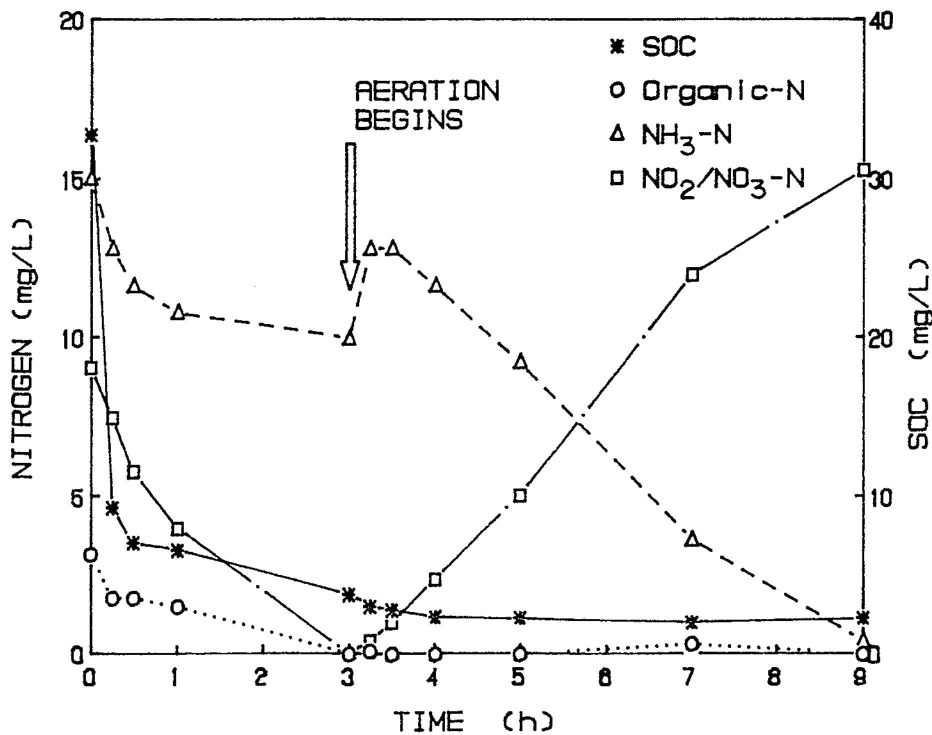


Figure 5.32 Track study of R1 at 4°C

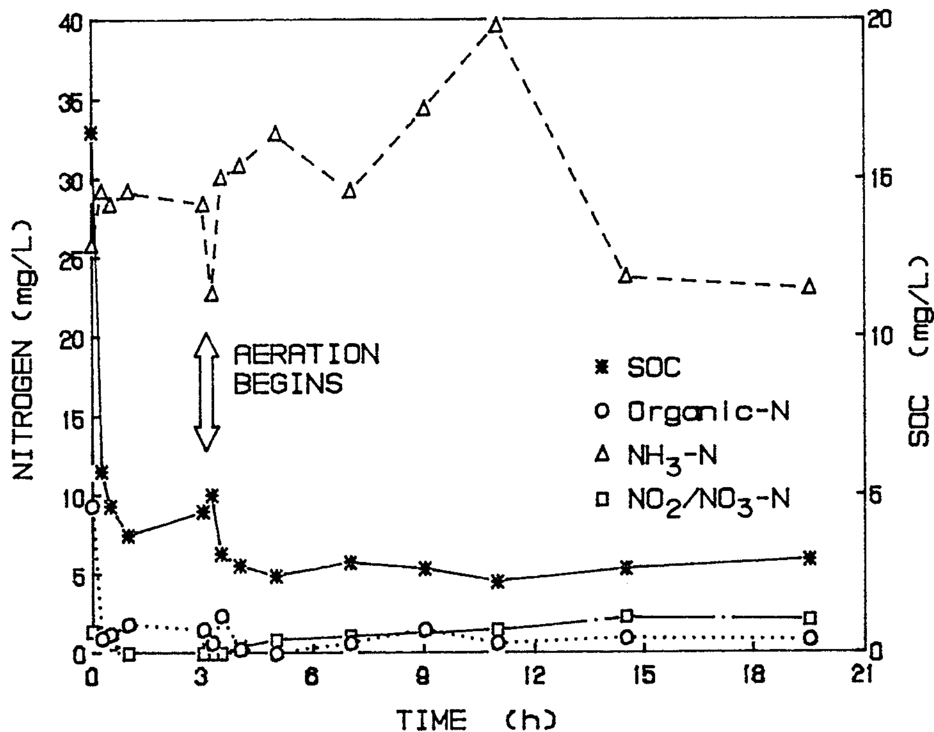


Figure 5.33 Track study of R1 at 2°C

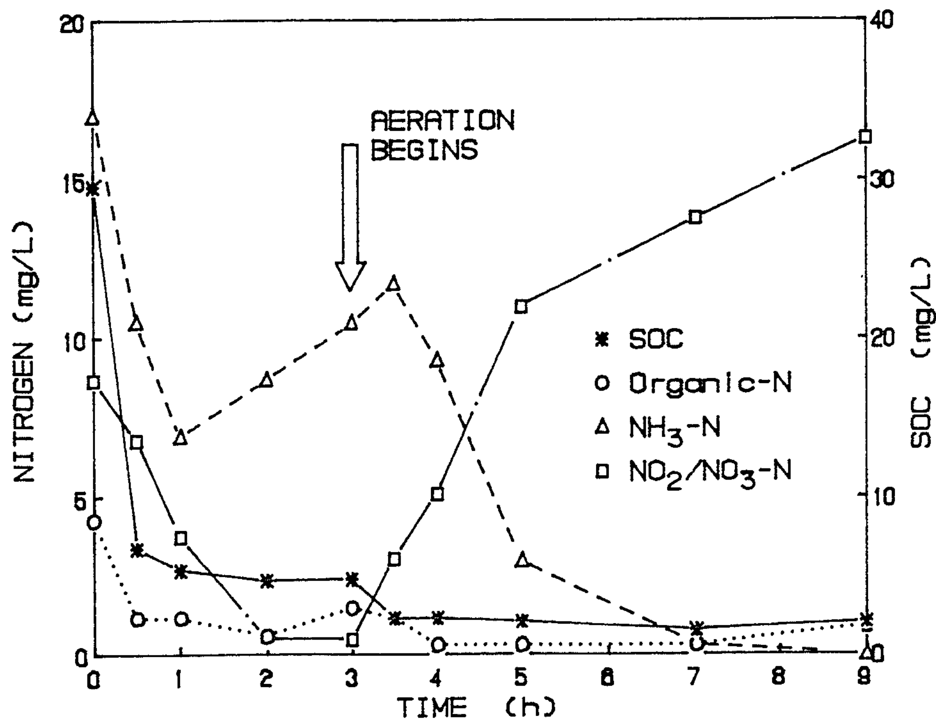


Figure 5.34 Track study of R2 at 10°C

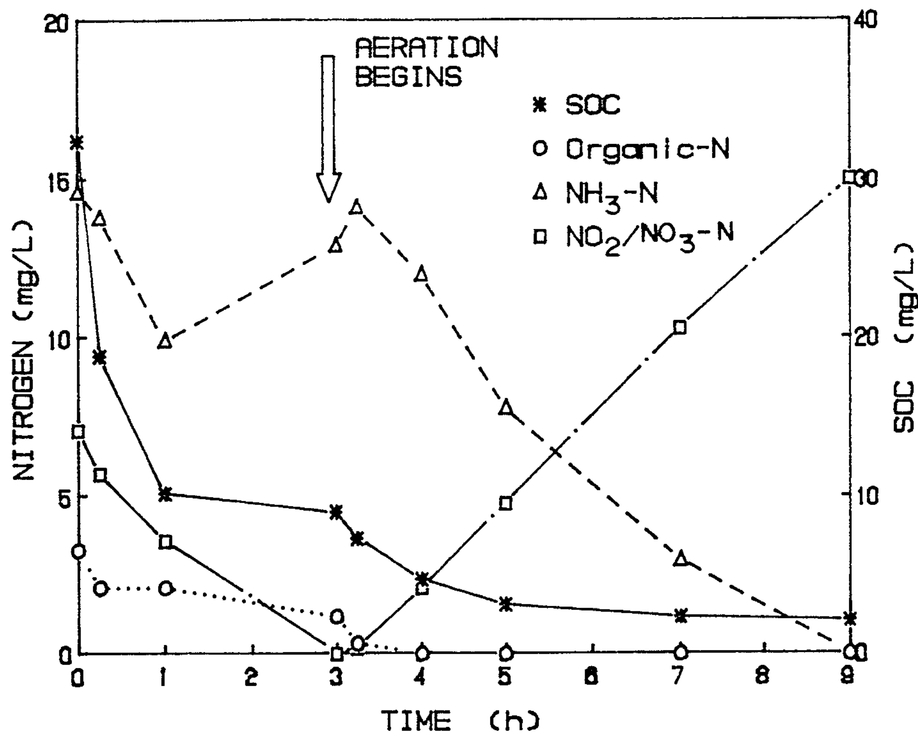


Figure 5.35 Track study of R2 at 6°C

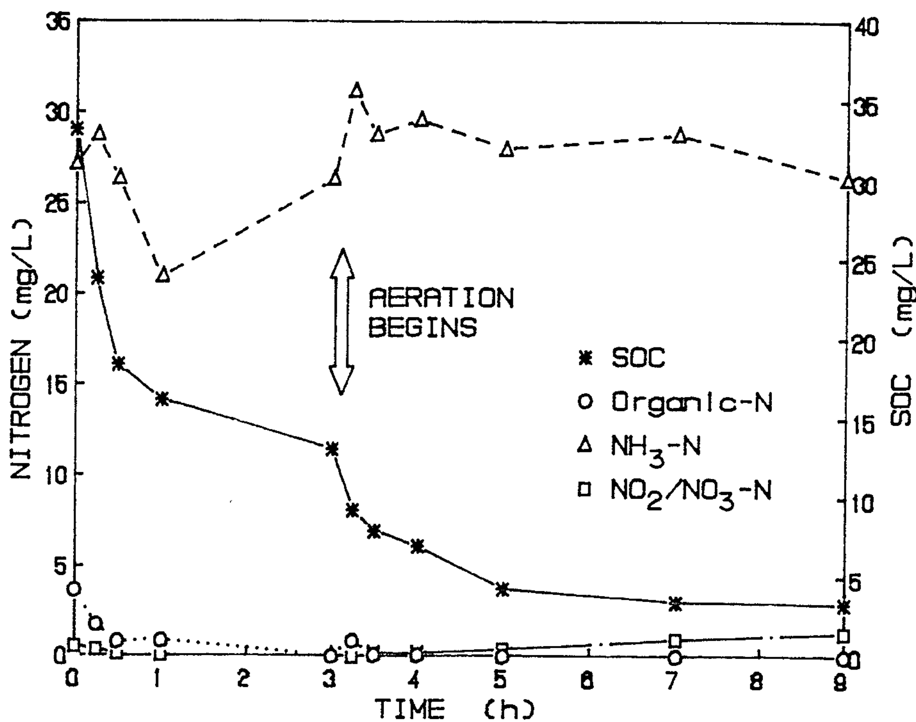


Figure 5.36 Track study of R2 at 4°C

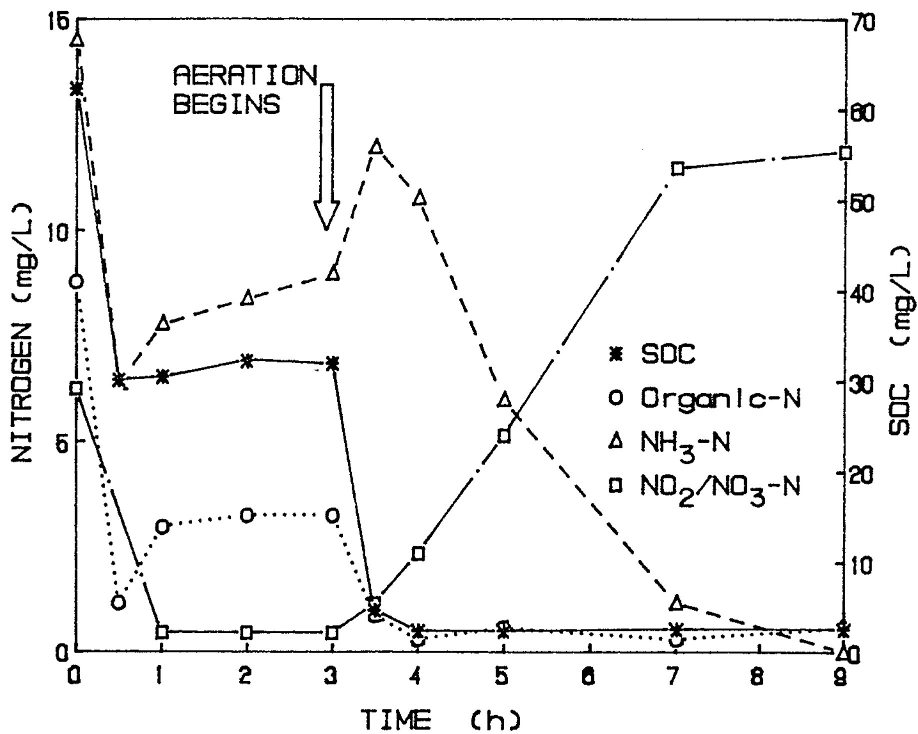


Figure 5.37 Track study of R3 at 10°C

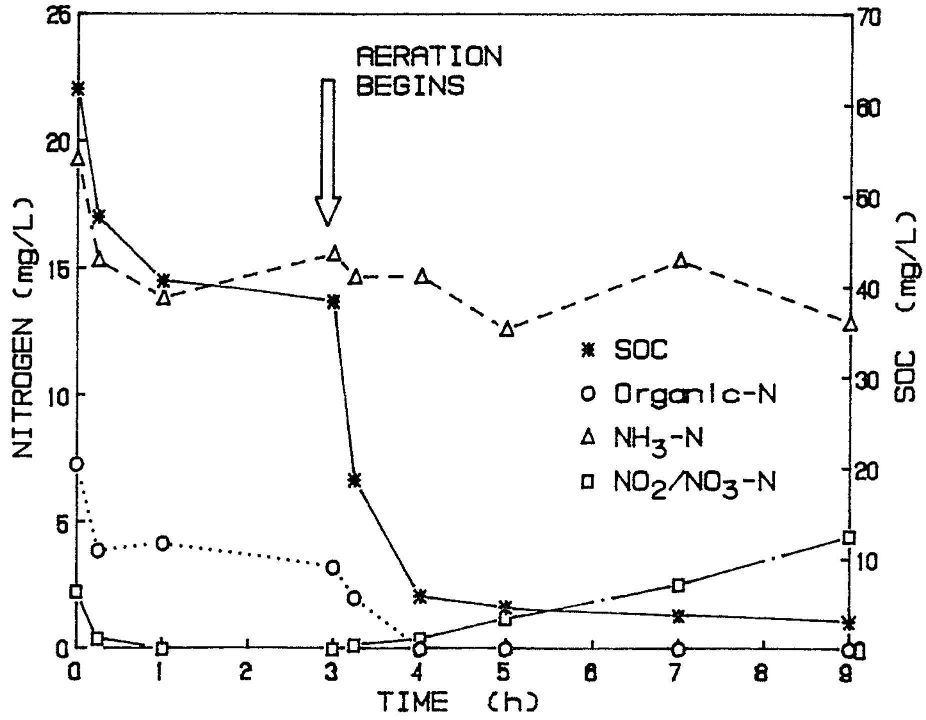


Figure 5.38 Track study of R3 at 6°C

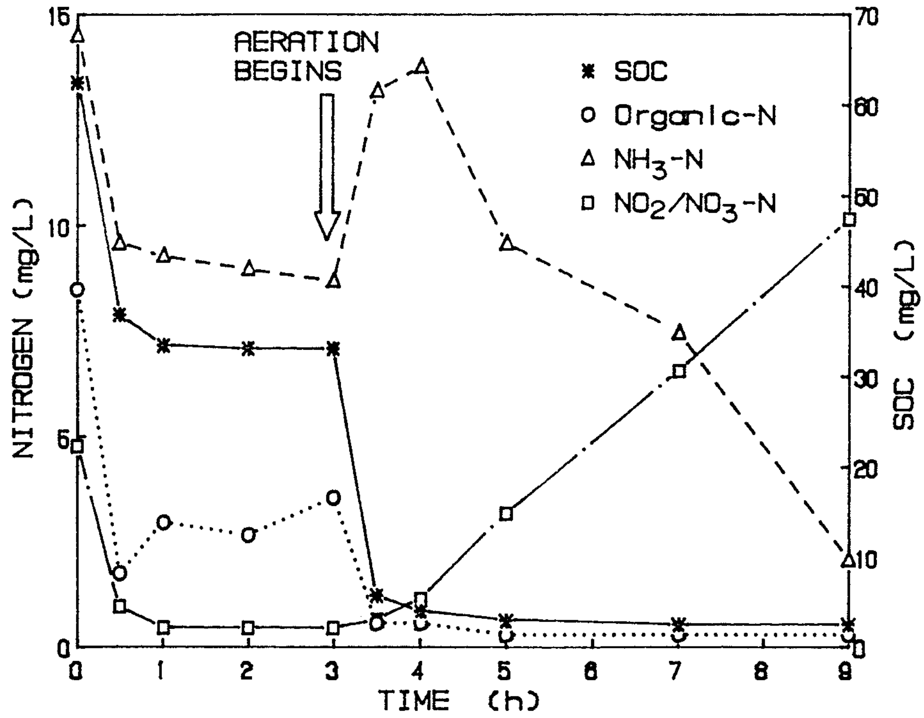


Figure 5.39 Track study of R4 at 10°C

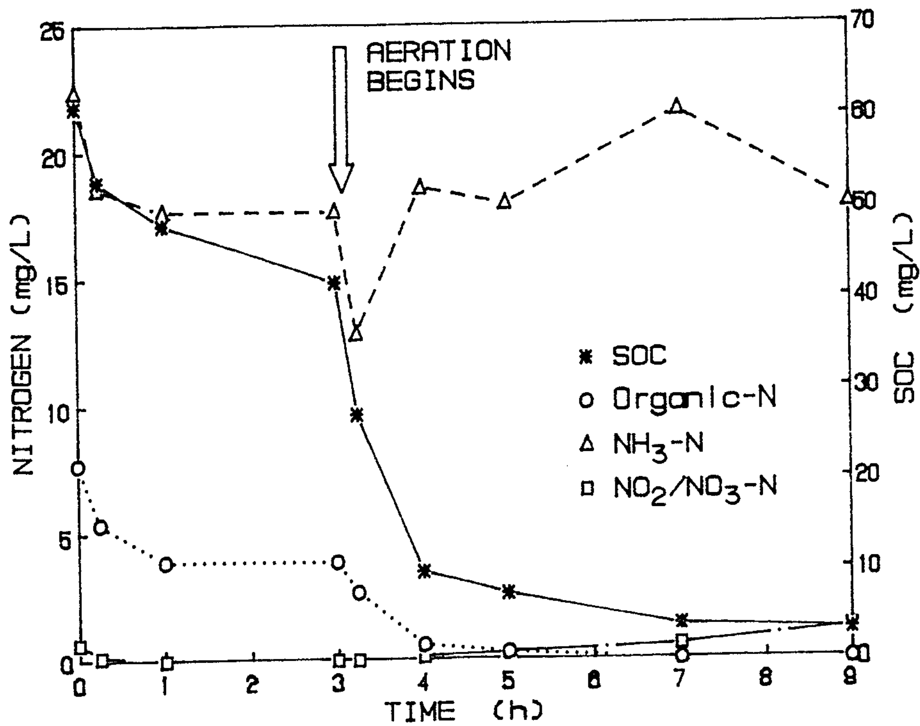


Figure 5.40 Track study of R4 at 6°C

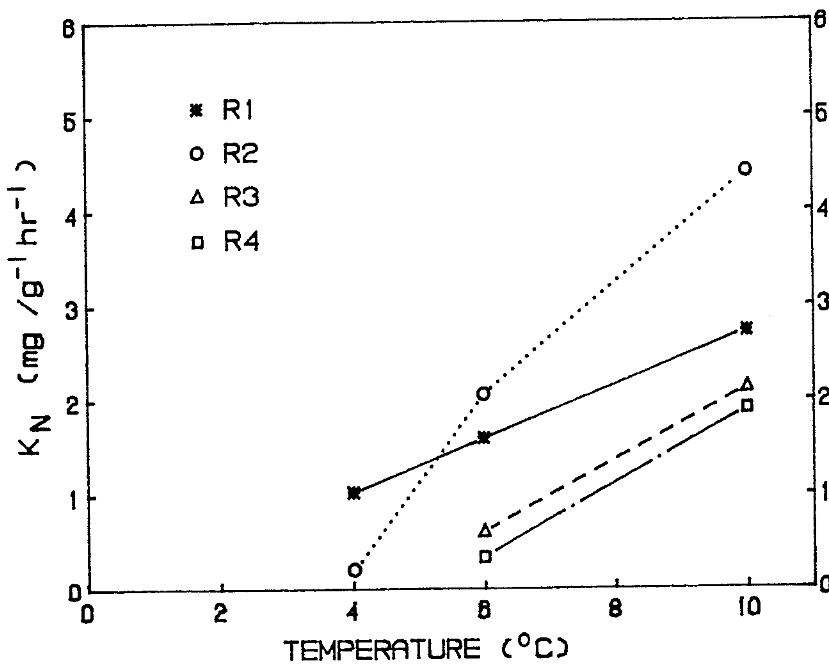


Figure 5.41 Specific nitrification rates plotted versus temperature

This does not effect the slope of the line. The resulting temperature coefficient, θ_N, value for R1 as determined from the slope of the line in Figure 5.41 was 1.174. The correlation coefficient for this line equalled 0.99. The K_N plots for R2 did not show a good correlation (correlation coefficient = 0.89). This was attributed to the lower nitrification efficiency in R2 at 4°C. The nitrification efficiencies are indicated in brackets next to each data point in Figure 5.41.

The temperature correction value determined for R1 (θ_N = 1.174) is significantly higher than those found by other researchers. Christensen and Harremoes (1978) reported a θ_N value of 1.12 (5 to 20°C). Shammas (1986) reported θ_N values of 1.129, 1.061, and 1.028 for respective MLVSS concentrations of 3200, 1200, and 430 mg L^{-1} (4 to 25°C). The temperature dependence was found to be nonlinear between 15°C and 2°C by Oleszkiewicz and Berquist (1988). They defined the temperature effects on nitrification as θ_N = 1.02 (15°C to 7°C) and θ_N = 1.40 (7 to 2°C). This break at 7°C was not found in R1 as shown in Figure 5.41.

As NO_2/NO_3-N was not included in the influent to the reactors, the effects of temperature on denitrification could only be assessed in the reactors which achieved a significant degree of nitrification. The maximum specific denitrification rates (K_{DN}), mg NO_2/NO_3-N removed g $MLVSS^{-1}$ h^{-1}, are presented in Figure 5.42. Generally, the reactors with the higher F:M ratios (higher SOC loading) had the higher K_{DN} rates. The C:N ratios are shown in brackets next to each data point. The K_{DN} data points only include R3 at 6°C and R4 at 10°C. The R3 rate at 10°C was not included because of an analytical error that did not allow a NO_2/NO_3-N measurement until one hour after the start of the ANOXIC/AN-

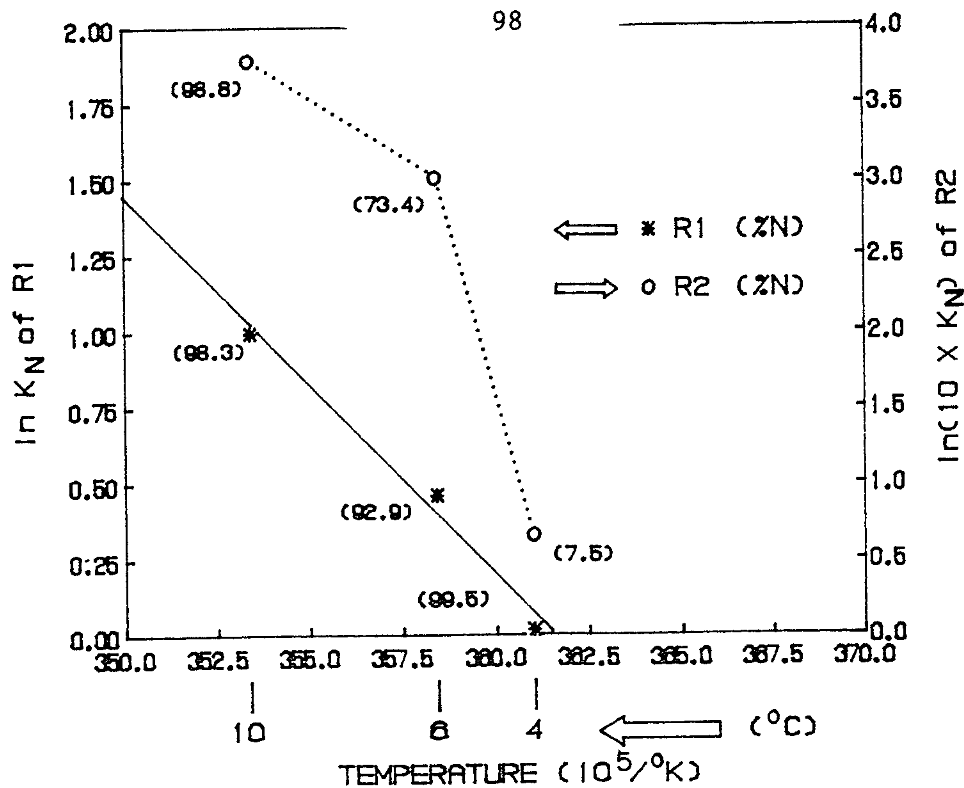


Figure 5.42 Arrhenius plot of specific nitrification rates

AEROBIC REACT period (Figure 5.36). The calculated rate (K_{DN} = 4.48 mg g^{-1} h^{-1}) for this first hour was considered to be erroneous since all other K_{DN} rates in R3 and R4 are based on the first 15 or 30 minutes of the ANOXIC/ANAEROBIC REACT period. The R4 rate at 6°C was not included because only 0.7 mg L^{-1} NO_2/NO_3-N was present at the start of the cycle.

The highest K_{DN} value (K_{DN} = 8.0 mg g^{-1} h^{-1}) occurred in R4 at 10°C. The highest rate at 6°C was 5.6 mg g^{-1} h^{-1} and occurred in R3. Only R1 had denitrification at 4°C with K_{DN} = 1.49 mg g^{-1} h^{-1}. Sutten et al. (1975) reported K_{DN} values of 2.1 mg g^{-1} h^{-1} at 10°C and 1.7 mg g^{-1} h^{-1} at 6°C. The C:N ratio employed by Sutton et al (1975) was 1:1, whereas the C:N ratios were between 27:1 to 3:1 for the rates presented in Figure 5.41. Jewel and Cummings (1975) reported maximum K_{DN} rates from 16 to 19 mg g^{-1} h^{-1} at 20°C using a very concentrated nitrate

wastewater. Palis and Irvine (1985) reported rates of 0.5 mg g^{-1} h^{-1} in a nitrification-denitrification SBR system operating at room temperature. Another SBR study found a similar rate of 0.5 mg g^{-1} h^{-1} at 5°C, using a more nitrogen concentrated wastewater than the latter investigations (Oleszkiewicz and Berquist, 1988). The relatively higher rates reported in Figure 5.42 when compared to the latter two research groups can be attributed to the feed methodology employed. They supplied the feed organic carbon over a time period of 0.5 to 8 h while instantaneous feeding at the beginning of the ANOXIC/ANAEROBIC REACT period was employed in this experiment.

An Arrhenius plot of the K_{DN} values of R1 is shown in Figure 5.43. The correlation coefficient of the best-fit line for these points is 0.97. The resulting temperature coefficient, θ_{DN}, is 1.132. Sutton et al (1975) found a least squares fit Arrhenius temperature dependency rather than a linear relationship (6 to 25°C). Christensen and Haremoes (1978) quoted a θ_{DN} of 1.15 (5 to 20°C) for a combined suspended growth denitrification process using raw sewage as a carbon source. Oleszkiewicz and Berquist reported a two-step temperature dependence, where θ_{DN} = 1.06 (7 to 15°C) and θ_{DN} = 1.40 (2 to 7°C).

An unexplained observation occurred at the beginning of the AEROBIC REACT period. The NH_3-N concentrations increased in the bulk liquid. This trend seemed to be stronger at higher temperatures and nitrification efficiencies, but no correlation could be developed. The cells may have released NH_3-N back into the bulk liquid because of the stress developed in the ANOXIC/ANAEROBIC REACT period.

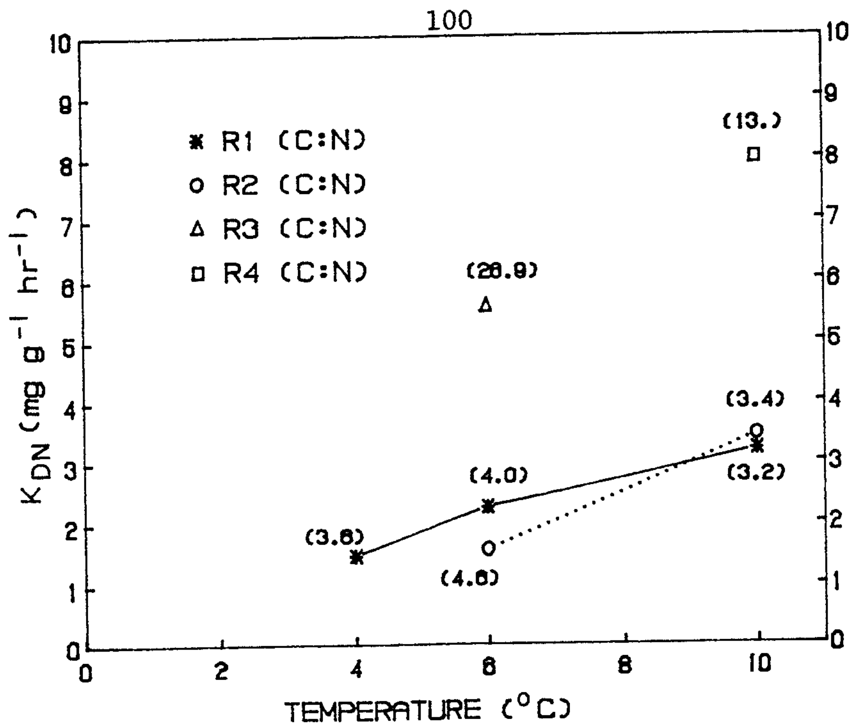


Figure 5.43 Specific denitrification rates plotted versus temperature

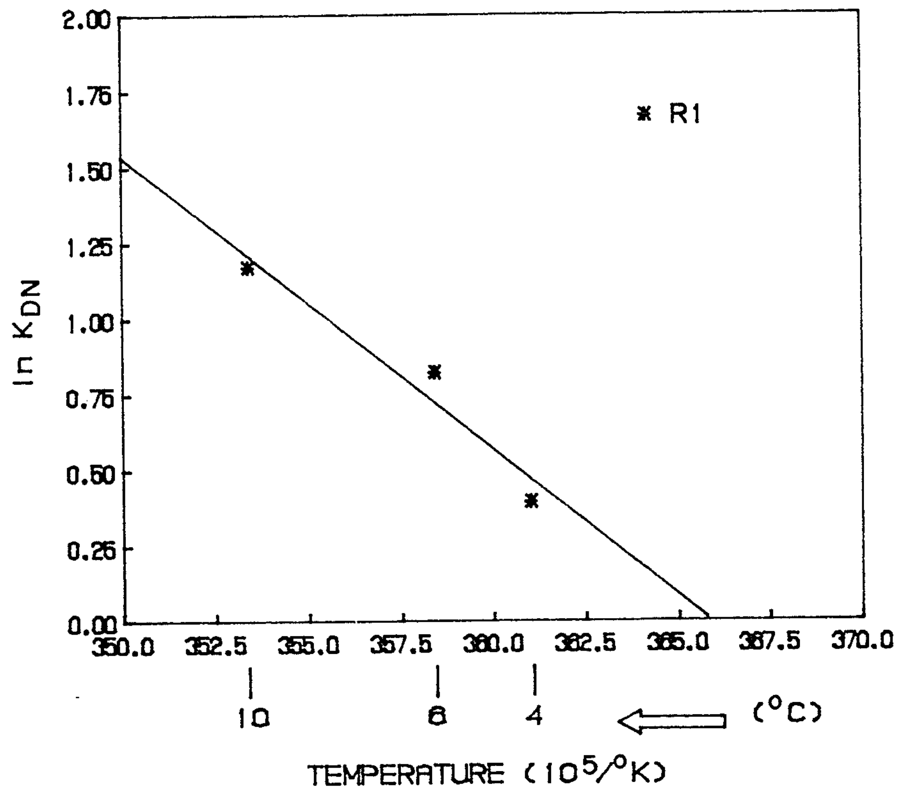


Figure 5.44 Arrhenius plot of specific denitrification rates

5.4.3 Supplementary Experiment and Results

It was suggested that some sort of deficiency in the synthetic substrate may have been the reason for the loss of nitrification in R1 at 2°C, since another study (Oleszkiewicz and Berquist, 1988) had shown above 90% nitrification using a domestic wastewater as a substrate at the same temperature. Therefore, after completing the primary investigation, another experiment was started at 6°C. The biological solids from R1 and R2 were mixed together with some return sludge from a non-nitrifying full-scale activated sludge plant (South End Plant, Winnipeg) and then placed back into R1 and R2. The synthetic substrate as used in the previous investigation was fed to R1, while effluent from the primary clarifier of a domestic wastewater treatment plant (South End Plant, Winnipeg, Manitoba) was fed to R2. The experiment lasted 33 days and the results are presented in Appendix I.

R1 operated at an average C:N:P ratio of 56:40:10 and an average MLVSS concentration of 2280 mg L^{-1}, resulting in a F:M (COD:MLVSS) ratio of 0.054 d^{-1}. The 12 hour cycle was altered slightly from that shown in Figure 4.1. One hour was added to the AEROBIC REACT period by subtracting a 0.5 hour from both the ANOXIC/ANAEROBIC REACT period and the SETTLE period.

The temperature of the reactors was to be lowered to 2°C after greater than 90% nitrification efficiency was achieved in both reactors. However, after 33 days R1 and R2 had achieved respective nitrification efficiencies of only 20 and 4%. It was decided to abort this investigation due to the length of time that would be needed to build-up the nitrifier population in the reactors. However, the experiment did

indicate that the synthetic substrate of R1 had achieved better nitrification than R2.

Another observation was that the nitrification efficiency did not increase immediately when the temperature was raised to 6°C. This would indicate that the nitrifiers had been almost completely washed out of R1 by the end of the primary investigation. This would make sense, because 90 days had passed since the reactors were lowered to 2°C and the BSRT of R1 was approximately 90 d.

5.5 PHOSPHORUS REMOVAL

The primary investigation was designed to study the effects of low temperature on nitrification; therefore, as expected, no indication of enhanced biological phosphorus uptake was observed. In general, the phosphorus removal correlated with the BSRT's of the reactors. The lower the BSRT, the greater the amount of phosphorus removed. As a result, the highest phosphorus removal achieved was in R4 at 10°C.

Increases in soluble phosphorus concentrations were not found during periodic testing of R1 to R4 at the end of the ANOXIC/ANAEROBIC REACT period. Also, based on the amount of soluble phosphorus removed from the reactors, the MLVSS contained approximately 4 to 5% phosphorus. In their study of an enhanced biological phosphorus removal system, Manning and Irvine (1985) measured 58 mg L^{-1} soluble phosphorus at the end of the ANAEROBIC REACT period, with 49 mg L^{-1} of this attributed to release from the sludge. Within 2 hours of aeration beginning, the soluble phosphorus level was reduced to 1 mg L^{-1}. The MLSS in their reactor contained approximately 9% phosphorus. These observations

indicate that no enhanced removals occurred during the primary investigation.

5.5.1 Supplementary Results

As indicated in Table 4.1, two supplementary investigations into biological phosphorus removal were completed. The results from both these investigations are contained in Appendix I. The 8 h SBR cycle, shown in Figure 1.1, was used at 10°C in the first experimental run. The environmental and operating conditions used duplicated the strategy which allowed Manning and Irvine (1985) to achieve 98% soluble phosphorus removals at 20°C. The difference between the experiments, other than temperature, was that the hydraulic retention time (HRT) was 0.5 d in their experiment, while this experimental run had an HRT of 1 d, resulting in the F:M ratio being reduced by half. This reduction in F:M loading was done in order to ensure some nitrification at the lower temperature.

After 40 days of operation, no enhanced phosphorus removal was observed, while over 90% nitrification had been achieved. This was not expected, since Manning and Irvine (1985) had achieved enhanced removals after 2 weeks of operation. Also, according to US EPA (1987) nitrification was cited as the limiting design factor for combined biological nitrogen and phosphorus removal systems at temperatures of 10°C. The experimental run was terminated and the primary investigation was then undertaken.

After the primary investigation was completed, another experimental was done using a single reactor at room temperature. This experiment

duplicated that of Manning and Irvine (1985). The results of this investigation are also presented in Appendix I.

Enhanced phosphorus removal was not observed until day 55. It may have been achieved sooner; however, no measurements were made between days 38 and 55 of the experiment, as the researcher conducting the experiments had to leave town for the Christmas holidays and no-one else was available to do the testing. Upon returning, the researcher discovered that enhanced phosphorus removals had been achieved. This experimental run indicated three possible explanations as to the negative results of the first phosphorus study done at 10°C. The lack of enhanced biological phosphorus removal in the first experiment may have been caused by the lower temperatures, the lower F:M load, the inadequate length of the test run, or most likely, a combination of these. The length of the test run could have been the most critical because the seed organisms were obtained from a non-nitrifying pure oxygen activated sludge plant. The primary and waste activated sludge were not treated at the plant; therefore, influent volatile acid concentrations would have been low. The biomass from this plant would have been low in polyphosphate accumulating organisms due to these operational conditions. Unfortunately, no further experiments were conducted to further elucidate the matter.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The objective of this investigation was to test the effects of low temperatures on the performance of SBR's in regard to the biological removal of carbon, nitrogen, and phosphorus. Four reactors were operated at various F:M ratios in the arrangement of sequencing periods typical for phosphorus and nitrogen removal. The mass loadings (F:M) were kept as constant as possible in order to observe the effects of the decreasing temperatures on the biomass kinetics.

In order to satisfy the objectives, five distinct investigations were completed (Table 4.1). The second investigation was considered the primary investigation, because the majority of the experimental work was done therein. The other four investigations were considered supplementary studies.

The design F:M ratios were maintained constant throughout the experimental period, as shown in Table 5.1. The observed Y decreased with a decrease in temperature. Values for Y were 0.95, 0.60, 0.50, 0.45 g VSS g COD^{-1} d^{-1}, and 0.40 at temperatures of 10, 6, 4, 2, and 0.5°C, respectively. The K_d values also decreased with decreasing temperature, and the respective rates were 0.035, 0.014, 0.007, 0.005, and 0.004 d^{-1}. The net result was a decrease in sludge production as the temperature decreased.

The biological flocs in R1 experienced a degree of defloculation, due to the low carbon loading. This defloculating sludge caused an increase in effluent VSS concentrations and a concurrent decrease in the BSRT of R1. The settleability efficiencies of R2, R3, and R4 operating under higher F:M loads were unaffected by decreasing temperature.

The average daily SOC removals were greater than or equal to 95% at all relevant F:M ratios and temperatures studied (Table 5.3). The highest specific SOC removal rates (K_c) were measured in R4 and ranged from 57.5 to 19.2 mg g^{-1} h^{-1} at 10 and 0.5°C, respectively. Temperature coefficients (θ_c) were determined to be 1.122 and 1.113 for R3 and R4, respectively. A supplementary investigation at 0.5°C indicated that glucose and acetate were rapidly removed from the bulk liquid, while casein was removed at about half the rate of acetate.

The reaction rates with respect to substrate concentrations were calculated to be second-, zero-, and between zero- and first-order rates for SOC removal, nitrification, and denitrification, respectively.

Nitrification efficiencies were extremely dependent on operating temperature and F:M ratio. Figure 5.28 best illustrates this relationship. Significant nitrification (> 10%) could not be achieved below 4°C. The highest specific nitrification rates (K_N) were 4.41, 2.05, and 1.02 mg g^{-1} h^{-1} at 10, 6, and 4°C, respectively. A temperature coefficient (θ_N) for R1 was determined to be 1.174, between 10 and 4°C.

R1 recorded the highest specific denitrification rates (K_{DN}) of 8.0, 5.6, and 1.5 mg g^{-1} h^{-1} at 10, 6, and 4°C. The temperature coefficient (θ_{DN}) was calculated to be 1.132 for denitrification.

No enhanced biological phosphorus removal was achieved in the primary investigation or in a supplementary investigation carried out at 10°C. A third investigation operated at room temperature (21°C) and a higher F:M load recorded enhanced phosphorus removals after 60 days of operation.

Based on the results of this investigation, the following con-

clusions were made:

1. A low F:M ratio resulted in increased solids in the effluent due to deflocculation.
2. A net decrease in daily sludge production was observed as the temperature decreased.
3. All kinetic parameters investigated followed the Arrhenius temperature equation.
4. Temperature did not affect settleability performance.
5. The specific nitrification rate was found to be a zero-order reaction. Denitrification was between a zero- and first-order reaction. Carbon removal was found to be a second-order reaction.
6. Nitrification was the most temperature-sensitive reaction, followed by denitrification with carbon removal being the least sensitive.
7. Nitrification efficiency was best described by using effluent NO_2/NO_3 and NH_3-N concentrations.
8. Above 90% nitrification efficiency was not achieved below 4°C.
9. The carbon removal efficiencies were not affected by low temperatures, due to the overdesign of the reactors with respect to carbon removal.
10. Enhanced biological phosphorus removal was not easily established.

CHAPTER 7

ENGINEERING SIGNIFICANCE AND RECOMMENDATIONS

The decrease in sludge production observed in this study would be of concern to an operator of an activated sludge wastewater treatment plant. Operation manuals and other references often state that controlling the BSRT of a system is often the easiest method of controlling the system. In areas where the temperature of the wastewater is expected to vary considerably, it would be advisable to spend the extra effort in controlling the mass loading (F:M ratio) or to do a study across the temperature range expected to determine changes in the sludge production. Expanding the relationship between the BSRT and the F:M ratio shown in Equation 2.13 results in the equation:

$$\frac{\Delta X}{MLVSS} = \frac{Y\ S_o\ E}{MLVSS\ HRT} - k_d \qquad (6.1)$$

where ΔX = mass of biomass wasted from system, gd^{-1}

S_o = influent substrate concentration, gL^{-1}, and

HRT = hydraulic retention time, d

Assuming the HRT, S_o, and E do not change significantly, which was the case in this study, the only way to keep the BSRT the same at decreasing temperatures would be to decrease the MLVSS concentration in the reactor. The lowering of the MLVSS would then cause the F:M ratio to increase and may lead to the failure of the process to meet desired effluent standards.

This increase in F:M ratio may also have negative effects on an activated sludge system designed for nitrification. The nitrifiers have it hard enough, since it appears that their growth rates decrease more

rapidly, relative to heterotrophs, at lower temperatures, but now the operator will also increase the F:M ratio which will raise the chance of nitrifier washout.

In an attempt to maintain the nitrifiers in a system, a design engineer must also be careful not to have too low an F:M ratio. The low F:M ratio, used to achieve > 90% nitrification at 4°C in this study, resulted in a deflocculating sludge and subsequent increase in effluent suspended solids.

It was found that caution must be used when applying removal rates and temperature correction coefficient values found in the literature. All the environmental as well as the operation conditions must be similar if literature values are to be used by the design engineer. It is recommended that a bench-scale study followed by a pilot plant study be conducted over the temperature conditions expected, in order to determine the design parameters, especially if an industrial wastewater stream is to be treated. However, it is understood that the budget constraints of a project usually dictate the depth of this foresight. If no preliminary studies are feasible, a thorough literature review should be conducted to utilize the existing information.

Based on this investigation, the following recommendations are made:

1. If wastewater temperature variations are expected, the F:M ratio, not the BSRT, should be used as the process control parameter.
2. The F:M ratio should be based on the entire mass of organisms in the system. Corrections should not be made for the fraction of the total cycle time organisms are aerated in batch systems or by

excluding the biomass in the secondary clarifier and the return sludge line of a continuous flow system.

3. Caution must be exercised when using temperature correction coefficients and removal rates from the literature, because of the many other factors involved.

CHAPTER 8.

SUGGESTIONS FOR FURTHER STUDY

Further studies are needed to elucidate the effects of low temperature on nitrification and enhanced biological phosphorus removal. In particular, for nitrification, it is suggested to:

1. Investigate the effects of MLVSS concentration and NH_3-N concentration on nitrification below 4°C. Operating at F:M (COD-MLVSS) ratios of 0.05 g g^{-1} d^{-1} with MLVSS concentrations between 3 and 6 gL^{-1}, one could investigate the effects of various influent NH_3-N concentrations.
2. Conduct viable nitrifier population counts on the mixed liquor as the temperature is decreased, making sure to distinguish between settleable biomass and effluent suspended solids.
3. When nitrification inhibition is established, raise temperature back to previous temperature to see if viability is maintained.

Suggested further studies regarding biological phosphorus removal are:

1. Use seed organisms from an activated sludge plant with parameters more favourable for polyphosphate accumulating organisms. Starting at 20°C and F:M ratios between 0.3 and 0.6 g g^{-1} d^{-1}, determine length of time to establish enhanced biological phosphorus removal in an 8 hour SBR cycle.
2. Determine the effect of low temperatures on polyphosphate accumulating organisms.
3. Attempt to obtain enhanced phosphorus removals in a 12 hour SBR cycle.

REFERENCES

A.P.H.A., A.W.W.A, and W.P.C.F., Standard Methods for the Examination of Water and Wastewater, Published by the American Public Health Association, 16th Ed. (1985).

Ardern, E., "The Activated Sludge Process of Sewage Purification", Journal of the Society of Chemical Industry, V. 36, p. 822 (1927).

Ardern, E., and Lockett, W.T., "Experiments on the Oxidation of Sewage Without the Aid of Filters", Journal of the Society of Chemical Industry, V. 33, p. 523 (1914).

Ardern, E., and Lockett, W.T., "The Oxidation of Sewage Without the Aid of Filters", Journal of the Society of Chemical Industry, V. 34, p. 937 (1915).

Arora, M.L., Barth, E.F., and Umphres, M.B., "Technology Evaluation of Sequencing Batch Reactors", Journal Water Pollution Control Federation, V. 57:8, p. 867-875 (1985).

Bailey, E., "Winter Around the World", Environmental Views, published by Alberta Environment, Edmonton, Alberta, V. 10:3 (1987).

Barnes, D., and Bliss, P.J., Biological Control of Nitrogen in Wastewater Treatment, E. and F.N. Spon Ltd., New York, N.Y. (1983).

Barth, E.F., "Implementation of Sequencing Batch Reactors for Municipal Wastewater Treatment", Published in the Proceedings of the 6th Symposium on Wastewater Treatment, Montreal, Environment Canada, Minister of Supply and Services Canada (En 44-14/83) (1983).

Benefield, L.D., Judkins, J.F. and Weand, B.L., Process Chemistry for Water and Wastewater Treatment, Prentice Hall, Inc., Englewood Cliffs, New Jersey (1982).

Benefield, L.D., and Randall, C.W., Biological Process Design for Wastewater Treatment, Prentice-Hall, Inc., Toronto (1980).

Berquist, S.A., "The Effects of Low Temperatures on the Processes of Nitrification and Denitrification in Sequencing Batch Reactors", B.Sc. Thesis, University of Manitoba (1987).

Bisogni, J.J. and Lawrence, A.W., "Relationships between Biological Solids Retention Time and Settling Characteristics of Activated Sludge", Water Research, V. 5, p. 753-763 (1971).

Characklis, W.G. and Gujer, W., "Temperature Dependency of Microbial Reactions", from Kinetics of Wastewater Treatment, Prog. Wat. Tech., Suppl. 1, Pergamon Press, Great Britain, p. 111-130 (1979).

Christensen, M.H. and Harremoes, P., "Nitrification and Denitrification in Wastewater Treatment", In Water Pollution Microbiology, Edited by R. Mitchell, published by J. Wiley & Sons, New York, V. 2, p. 391-414 (1978).

Clark, H.W. and de Gage, S.M., "Aeration of Sewage as an Aid to Filtration", 44th Annual Report, Massachusetts State Board of Health, 1912.

De Renzo, D.J., Ed., Nitrogen Control and Phosphorus Removal in Sewage Treatment, Pollution Technology review No. 44, Noyes Data Corporation, Park Ridge, N.J. (1978).

Eckenfelder, W.W., "Biological Phosphorus Removal: State of the Art Review", from Pollution Engineering, p. 88-93, September, 1987.

Eckenfelder, W.W. and Watkin, A.T., "A New Design Procedure for Activated Sludge Based on Active Mass", presented at the 8th Symposium on Wastewater Treatment, Montreal, Quebec (1984).

EPS, Chemical Dosage Control for Phosphorus Removal, Environment Canada and Ontario Ministry of the Environment, Project No. 72-5-11 (1973).

Evans, B.W. and Crawford, P.M., "Introduction of Biological Nutrient Removal in Canada", from the Proceedings of the 8th Symposium on Wastewater Treatment, Montreal, Canada, Sponsored by Environmental Protection service, Environment Canada (1985).

Friedman, A.A. and Schroeder, E.D., "Temperature Efects on Growth and Yield of Activated Sludge", Journal Water Pollution Control Federation, V. 44:7, p. 1433-1442 (1972).

Ganczarcyk, J.J., Activated Sludge Process: Theory and Practice, Published by Marcel Dekker, Inc., New York, New York (1983).

Gaudy, Jr., A.F., and Gaudy, E.T., Elements of Bioenvironmental Engineering, Published by Engineering Press, Inc., San Jose, California (1988).

Grady, C.P.L., Jr., and Lim, H.C., Biological Wastewater Treatment, Theory and Applications, Published by Marcel Dekker, Inc., New York, NY (1980).

Henry, J.G., "Psychrophiles in Waste Treatment", Published in Symposium on Wastewater Treatment in Cold Climates, Environmental Protection Service, Environment Canada, Report EPS 3-WP-74-3 (1974).

Henze, M., "Sewage Treatment by Activated Sludge--A Model with Emphasis on Oxygen Consumption and Sludge Composition", Published in "Kinetics of Wastewater Treatment", Proceedings of a Post-Conference Seminar, Prog. Wat. Tech., Pergamon Press (1979).

Irvine, R.L., "Tech. Ass. of SBR's", Prepared for E.P.A., Cincinnati, OH, Feb. 1985 (PB85-167245).

Irvine, R.L., Miller, G., and Bhamrah, A.S., "Sequencing Batch Treatment of Wastewaters in Rural Areas", Journal Water Pollution control Federation, V. 51:2, p. 244-254 (1979).

Irvine, R.L., Ketchum, L.H., Arora, M.L., and Barth, E.F., "An Organic Loading Study of Full-Scale Sequencing Batch Reactors", Journal Water Pollution Control Federation, Vol. 57:8, p. 847-853 (1985).

Irvine, R.L., Ketchum, L.H., Breyfogle, R., and Barth, E.F., "Municipal Application of Sequencing Batch Treatment", Journal Water Pollution Control Federation, V. 55:5, p. 484-488 (1983).

Jewell, W.J., and Cummings, R.J., "Denitrification of Concentrated Nitrate Wastewaters", Journal of the Water Pollution Control Federation, V. 47:9, p. 2281-2291 (1975).

Jones, W., British Patent No. 22737 of November 19 (1914).

Lawrence, A.W. and McCarty, P.L., "Unified Basis for biological Treatment, Design and Operation", Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers, V. 96, p. 757-778 (1970).

Lo, K.V., Bulley, N.R. and Kwong, E., "Sequencing Aerobic Batch Reactor Treatment of Milking Parlour Wastewater", Agricultural Wastes, V. 13, p. 131-136 (1985).

Mandt, M.G. and Bell, B.A., Oxidation Ditches in Wastewater Treatment, Ann Arbor Science, Ann Arbor, Michigan (1982).

Manning, J.F., The Biological Removal of Phosphorus in a Sequencing Batch Reactor, Ph.D. Thesis of the University of Notre Dame, Notre Dame, Indiana (1986).

Manning, J.F. and Irvine, R.L., "The Biological Removal of Phosphorus in a Sequencing Batch Reactor", Journal of the Water Pollution Control Federation, V. 57:1, p. 87-94 (1985).

McCarty, P.L., "Stoichiometry of Biological Reactions", Progress in Water Technology, A Journal of the IAWPR, Published by Pergamon Press, New York, NY, V. 7, p. 157-172 (1975).

Melcer, H., Bedfor, W.K., Topnik, B.H., and Schmidtke, N.W., "Conversion of Small Municipal Wastewater Treatment Plants to Sequencing Batch Reactors", Journal Water Pollution Control Federation, 59:2, 79-85 (1987).

Metcalf and Eddy, Inc., Wastewater Engineering - Treatment, Disposal, and Reuse, 2nd Ed., McGraw-Hill, New York, NY (1978).

Muck, R.E. and Grady, C.P.L., "Temperature Effects on Microbial Growth in CSTR's", Journal of the Environmental Engineering Division, American Society of Civil Engineers, p. 1147-1163 (1974).

Oldham, W.R. and Dew, H.P., "Cold Temperature Operation of the Bardenpho Process", presented at the 14th Canadian Symposium on Water Pollution Research (1979).

Oleszkiewicz, J.A. and Berquist, S.A., "Low Temperature Nitrogen Removal in Sequencing Batch Reactors", In Print, Water Research, 1988.

Palis, J.C. and Irvine, R.L., "Nitrogen Removal in a Low-loaded Single Tank Sequencing Batch Reactor", Journal of the Water Pollution Control Federation, V. 57:1, p. 82-86 (1985).

Pipes, W.O., "Bulking, Deflocculation, and Pinpoint Floc", Journal Water Pollution Control Federation, V. 51:1, p. 62 (1979).

Pitman, A.R., "Bioflocculation as Means of Improving the Dewatering Characteristics of Activated Sludges", Water Pollution Control, p. 688 (1975).

Rittmann, B.E., "Aerobic Biological Treatment", Environ. Sci. Technol. V 21:2, p. 128-136 (1987).

Sayigh, B.A. and Malina, Jr., J.F., "Temperature Effects on the Activated Sludge Process", Journal of Water Pollution control Federation, V. 50:4, p. 678-687 (1978).

Segel, I.H., Biochemical Calculations, John Wiley & Sons, Inc., Toronto, 2nd Ed. (1976).

Sherrard, J.H. and Schroeder, E.D., "Cell Yield and Growth Rate in Activated Sludge", Journal of the Water Pollution Control Federation, V. 45:9, 1889-1897 (1973).

Stanier, R.Y., Ingraham, J.L., Wheelis, M.L. and Painter, P.R. The Microbial World, Prentice-Hall, Toronto, 5th Ed. (1986).

Sutton, P.M., Murphy, K.L. and Dawson, R.N., "Low-temperature biological Denitrification of Wastewater", Journal of the Water Pollution Control Federation, V. 47:1, p. 122-134 (1975).

Tate, S.R. and Eckenfelder, W.W., "Application of Batch Activated Sludge Process", Presented at 41st Purdue Industrial Waste Conference, Purdue, Indiana (1986).

Topnik, B.H., Biokinetics of Low Temperature Waste Assimilation, Ph.D. Thesis, University of Manitoba, Winnipeg, Manitoba, Canada (1976).

US EPA, Process Design Manual for Nitrogen Control, United States Environmental Protection Agency, Cincinnati, OH, (1975).

US EPA, Phosphorus Removal--Design Manual, United States Environmental Protection agency, Cincinnati, OH (1987).

Vallentyne, J.R., The Algal Bowl--Lakes and Man, Environmental Protection Service, Canada (1974).

Wardle, T., "Sewage Treatment and Disposal," Journal of the Royal Sanitary Institute, London, England, 1, 1893.

Wilderer, P.A., "Application of Sequencing Batch Reactor Technology for Industrial Wastewater Treatment", Presented at the 2nd German-Japanese Workshop on Wastewater and Sludge Treatment, Karlsruhe, West Germany (1984).

Wilderer, P.A., Gorg, S., and Hempel, K., "Treatment of Domestic Wastewater from Dwellings and Small Communities in Special Treatment Plants", Presented at the 3rd German-Japanese Workshop on Wastewater and Sludge Treatment, Tsukuba City, Japan (1986).

NOMENCLATURE

BSRT - biological solids retention time, time

C - substrate concentration, mass volume^{-1}

C_o - initial substrate concentration, mass volume^{-1}

COD - chemical oxygen demand, mass volume^{-1}

d - day

E - removal efficiency, percent

E_o - activation energy, calories mole^{-1}

f - F:M ratio correction factor, dimensionless

F:M - food to microorganism ratio, mass mass^{-1} time^{-1}

g - gram

h - hour

HRT - hydraulic retention time, time

k - reaction rate constant, mass volume^{-1} time^{-1}

K - specific reaction rate constant, mass mass^{-1} volume^{-1} time^{-1}

k_d - endogenous decay coefficient, time^{-1}

K_s - half-velocity constant, mass volume^{-1}

L - litre

MLVSS - mixed liquid volatile suspended solids, mass volume^{-1}

μ - specific growth rate, time^{-1}

Q - flow rate, volume time^{-1}

Q - waste flow rate, volume time^{-1}

R - ideal gas constant, 1.98 calories mole^{-1}

SOC - soluble organic carbon, mass volume $^{-1}$

SVI - sludge volume index, volume mass^{-1}

T - temperature

TKN - total kjeldahl nitrogen, mass volume^{-1}

θ - Arrhenius temperature constant, dimensionless

v - reaction velocity, time

V_m - maximum reaction velocity, time

VSS - volatile suspended solids, mass volume^{-1}

X - concentration of microorganisms, mass volume^{-1}

X_T - total active biomass in treatment system, mass

Y - biomass yield coefficient, mass mass^{-1}

ZSV - zone settling velocity, length time^{-1}

APPENDIX I

DAILY DATA

10 deg	Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	TP-P (mg/L) In	TP-P (mg/L) Out
R-1	0	112.7	4.5	39.2	4.4	31.0	0.4	12.4	12.8	9.3
	4	36.0	9.3	16.0	5.2	11.8	0.6	8.3	5.9	7.2
	5									
	6									
	7	70.0	7.5	20.2	4.8	13.6	0.4	10.7	6.0	6.7
	8									
	11	69.3	6.8	31.2	4.0	24.0	0.4	18.6	11.6	11.0
	12									
	13									
	14	11.3	3.0	38.0	3.6	32.8	0.4	21.4	10.6	10.4
	15	68.3								
	17	64.3								
	18	64.3	3.0	33.2	2.0	30.0	0.4	16.5	9.8	8.1
	19	61.7	2.6							
	20	65.6	2.0	33.2	2.4	27.6	0.1	17.5	10.0	8.5
	21									
	22	56.0								
	23	55.5	2.1							
	24	57.1	1.6			34.0	0.1	18.4	12.3	9.1

10 deg	Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	TP-P (mg/L) In	TP-P (mg/L) Out
R-2	0	112.7	6.1	39.2	4.0	31.0	0.4	13.0	12.8	9.6
	4	36.0	10.6	16.0	6.8	11.8	0.6	8.5	5.9	8.2
	5									
	6									
	7	70.0	7.8	20.2	6.8	13.6	0.4	7.6	6.0	6.3
	8									
	11	69.3	5.6	31.2	6.4	24.0	0.4	16.1	11.6	11.1
	12									
	13									
	14	11.3	3.5	38.0	4.4	32.8	0.4	20.5	10.6	10.2
	15	68.3								
	17	64.3								
	18	64.3	3.6	33.2	2.8	30.0	0.2	14.9	9.8	8.6
	19									
	20	65.6	2.5	33.2	2.4	27.6	0.1	15.0	10.0	8.9
	21									
	22	56.0								
	23	55.5	2.5							
	24	57.1	2.0			34.0	0.1	17.4	12.3	8.5

10 deg	Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	TP-P (mg/L) In	TP-P (mg/L) Out

10 deg	Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	TP-P (mg/L) In	TP-P (mg/L) Out
R-3	0	112.7	6.6	39.2	5.2	31.0	0.4	13.0	12.8	10.0
	4	71.0	5.4	31.2	2.8	23.6	0.4	13.7	11.8	10.0
	5									
	6									
	7	140.1	5.5	40.4	4.4	27.2	0.0	11.5	12.0	8.8
	8									
	11	121.0	6.4	44.0	7.6	27.6	0.4	13.9	11.0	10.1
	12									
	13									
	14	111.5	4.9	39.2	3.6	29.4	0.4	*8	12.0	9.8
	15	130.9								
	17	126.6								
	18	126.6	4.6	30.2	3.4	24.0	0.6	11.0	10.2	8.8
	19	127.3	3.8							
	20	137.0	3.0	35.2	5.6	26.4	0.1	10.0	10.2	7.5
	21									
	22	112.0								
	23	110.9	3.7							
	24	122.5	2.5			28.8	0.1	12.5	12.0	5.5

10 deg	Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	TP-P (mg/L) In	TP-P (mg/L) Out
R-4	0	112.7	6.2	39.2	0.8	31.0	0.2	13.0	12.8	9.6
	4	71.0	10.1	31.2	7.4	23.6	1.6	13.4	11.8	10.3
	5									
	6									
	7	140.1	9.8	40.4	9.8	27.2	5.5	7.3	12.0	9.3
	8									
	11	121.0	8.7	44.0	11.6	27.6	3.6	10.5	11.0	9.3
	12									
	13									
	14	111.5	5.6	39.2	6.2	29.4	2.0	*5.5	12.0	9.5
	15	130.9								
	17	126.6								
	18	126.6	6.4	30.2	4.4	24.0	0.4	10.5	10.2	8.6
	19	127.3	6.5							
	20	137.0	4.4	35.2	8.4	26.4	0.1	7.5	10.2	7.9
	21									
	22	112.0								
	23	110.9	3.7							
	24	122.5	2.7			28.8	2.7	9.6	12.0	7.7

6 deg	Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	TP-P (mg/L) In	TP-P (mg/L) Out
R-1	28									
	29	64.4	1.2	33.9	0.0	33.9	0.0	18.0	13.5	10.5
	32									

	33	62.2	2.3	34.4	0.0	42.0	0.0	17.0	11.0	10.4
	34									
	35									
	36	64.0	1.4	37.6	0.0	39.2	0.0	18.7	12.0	12.0
	37	63.8	1.7	37.6	3.0	39.2	2.7	18.0	12.0	-
	38									
R-2	28									
	29	64.4	1.9	33.9	3.9	33.9	2.7	15.0	13.5	10.5
	32									
	33	62.2	2.2	34.4	3.0	42.0	3.0	14.0	11.0	10.2
	34									
	35									
	36	64.0	1.6	37.6	5.1	39.2	4.2	14.8	12.0	11.0
	37	63.8	2.2	37.6	6.9	39.2	6.0	13.3	12.0	11.4
	38									

6 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-3	28									
	29	127.2	2.6	33.9	12.0	33.9	9.0	8.5	11.5	9.5
	32									
	33	131.3	4.1	39.2	11.4	33.6	9.6	7.0	11.6	9.8
	34									
	35									
	36	123.0	2.3	40.8	11.4	28.8	10.8	5.8	11.0	10.5
	37	121.4	3.1	40.8	15.3	28.8	14.7	3.0	11.0	9.2
	38									
R-4	28									
	29	127.1	3.1	31.5	18.3	29.1	19.5	4.0	11.5	10.0
	32									
	33	131.3	3.7	39.2	15.9	33.6	17.7	2.5	11.6	9.8
	34									
	35									
	36	123.0	2.7	40.8	18.3	28.8	19.6	1.6	11.0	10.5
	37	121.4	6.0	40.8	22.8	28.8	22.2	0.4	11.0	10.6
	38									

4 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-1	40	61.6	1.7	35.2	0.0	32.0	0.0	17.5	13.0	10.0
	43	68.0	1.9	40.0	1.2	24.8	0.0	15.4	-	-
	47									
	48	60.2	2.9	39.2	0.6	25.6	0.0	17.5	11.8	10.6
	49									
	50	62.9	1.7	40.0	0.3	30.4	0.0	14.3	10.0	9.5
	52	-								
	53									

	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	54	60.6	1.4	35.3	0.8	26.7	0.5	15.0	12.2	10.0
	56									
	57	69.9	1.9	41.0	0.9	32.0	0.3	20.3	13.4	11.2
	60									
	61	62.9	2.4	35.2	0.3	29.6	0.0	23.0	15.0	10.8
	62									
	63	63.4	2.3					18.2	12.5	12.5

4 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-2	40	61.6	2.2	35.2	4.2	32.0	9.6	9.0	13.0	11.5
	43	68.0	3.5	40.0	13.8	24.8	7.2	7.0	-	-
	47									
	48	60.2	3.2	39.2	15.3	25.6	6.9	6.8	11.8	11.0
	49									
	50	62.9	2.6	40.0	15.0	30.4	13.5	3.5	10.0	10.5
	52									
	53									
	54	60.6	3.7	35.3	27.6	26.7	18.8	1.7	12.2	11.6
	56									
	57	69.9	4.0	41.0	21.9	32.0	20.4	2.1	13.4	11.8
	60									
	61	62.9	3.6	35.2	29.1	29.6	23.4	1.8	15.0	10.8
	62									
	63	63.4	3.3					1.1	12.5	11.5

4 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-3	40	118.0	4.4	34.4	5.4	27.2	13.2	2.5	14.5	9.5
	43	124.0	3.1	34.4	18.9	28.8	16.8	1.8	-	-
	47									
	48	124.6	4.2	37.6	15.9	22.4	9.9	1.0	12.0	10.2
	49									
	50	122.1	3.1	36.7	15.0	24.7	13.8	0.3	10.0	12.0
	52									
	53									
	54	129.3	4.4	38.7	26.7	24.7	18.3	0.0	12.6	9.6
	56									
	57	122.0	3.2	*40	20.7	26.4	17.7	0.5	12.6	11.0
	60									
	61	128.3	3.2	37.6	28.2	24.8	21.0	0.0	13.2	8.6
	62									
	63	127.9	3.2					0.0	13.0	9.5

4 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-4	40	118.0	4.7	34.4	20.1	27.2	17.1	0.8	14.5	9.5
	43	124.0	7.7	34.4	18.3	28.8	19.2	0.5	-	-

47									
48	124.6	6.1	37.6	18.0	22.4	18.0	0.4	12.0	9.2
49									
50	122.1	6.5	36.7	17.3	24.7	17.8	0.0	10.0	11.0
52									
53									
54	129.3	6.2	38.7	21.3	24.7	14.5	0.0	12.6	10.2
56									
57	122.0	3.9	*40	18.3	26.4	16.5	0.0	12.6	10.4
60									
61	128.3	4.0	37.6	19.5	24.8	15.9	0.0	13.2	9.0
62									
63	127.9	4.7					0.0	13.0	9.5

2 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-1	67									
	68									
	69									
	70	62.0	1.7	41.2	19.2	33.6	19.2	6.5	12.5	10.5
	71									
	74									
	75	57.2	1.6	34.0	19.6	30.0	20.8	6.5	12.0	11.4
	76									
	77									
	78	60.1	2.5	36.0	22.0	33.2	22.4	5.8	10.4	11.2
	81									
	82	130.0	2.1	43.2	22.4	32.4	23.2	2.6	10.2	9.2
	83									
	84									
	85	29.6	2.7	41.2	25.2	29.6	18.4	2.6	6.2	6.0
	88									
	89	31.5	1.3	28.0	22.2	27.2	25.2	3.8	5.0	5.0
	90									
	91									
	92	34.2	2.7	33.6	17.6	28.4	22.4	3.5	2.3	5.2
	96	26.8	2.4	26.0	26.0	24.8	21.6	1.8	5.4	5.4
	97									
	98									
	99	33.0	2.3	37.2	28.4	30.4	24.4	2.0	4.2	7.2
	102									
	103	35.5	2.1	39.2	29.2	38.4	28.8	2.0	4.4	4.8
	104									
	105									
	106	28.6	3.0	30.8	26.8	29.2	23.6	2.0	4.0	4.8
	109									
	110	34.5	3.1	35.2	27.2	25.6	22.8	2.0	3.2	3.2
	111									
	112									
	113	34.5	2.5					2.0	2.7	2.1

	Day No.	TOC In	TOC Out	TKN-N In	TKN-N Out	NH3-N In	NH3-N Out	NO2/3	TP-P In	TP-P Out
	116									
	117	30.7	2.2	40.8	28.8	30.8	20.8		13.0	12.0

2 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-2	67									
	68									
	69									
	70	62.0	3.6	41.2	30.6	33.6	28.0	0.4	12.5	10.0
	71									
	74									
	75	57.2	3.2	34.0	28.4	30.0	26.0	0.0	12.0	10.6
	76									
	77									
	78	60.1	4.9	36.0	29.2	33.2	27.2	0.0	10.4	10.2
	81									
	82	130.0	2.7	43.2	27.6	32.4	28.4	0.0	10.2	7.8
	83									
	84									
	85	60.4	3.7	38.8	29.2	25.2	25.2	0.0	5.1	4.8
	88									
	89	62.5	3.2	42.4	32.4	32.4	28.8	0.0	4.0	4.0
	90									
	91									
	92	64.5	4.0	42.0	33.6	27.6	29.2	0.0	3.1	3.4
	96	61.8	3.1	33.6	26.8	28.0	27.2	0.0	5.1	5.2
	97									
	98									
	99	59.5	3.7	44.8	31.2	28.0	26.4	0.0	5.0	4.8
	102									
	103	67.5	2.8	42.0	36.0	38.4	35.2	0.0	4.7	4.4
	104									
	105									
	106	72.5	3.6	38.8	26.0	28.4	25.6	0.0	5.2	3.8
	109									
	110	64.5	3.7	40.8	30.8	24.8	26.0	0.0	3.0	4.4
	111									
	112									
	113	66.0	3.2					0.0	2.8	1.6
	116									
	117	60.4	3.4	42.8	31.2	34.4	22.8	0.0	14.0	13.5

2 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-3	67									
	68									
	69									
	70	119.7	4.0	42.4	24.4	29.6	22.4	0.0	13.0	10.0
	71									
	74									

Day No.	TOC In	TOC Out	TKN-N In	TKN-N Out	NH3-N In	NH3-N Out	NO2/3	TP-P In	TP-P Out
75	114.1	5.5	38.4	24.8	26.0	21.6	0.0	11.8	10.2
76									
77									
78	118.8	20.6	39.2	26.0	28.4	24.0	0.0	13.8	11.2
81									
82	115.0	2.8	53.2	24.0	39.6	24.8	0.0	10.6	8.0
83									
84									
85	-	2.4	28.4	21.2	23.6	18.4	0.0	5.1	4.8
88									
89	110.0	8.3	38.4	30.0	23.6	23.2	0.0	5.0	4.1
90									
91									
92	115.0	4.0	31.6	24.0	25.6	18.0	0.0	5.8	3.2
96	119.5	3.1	31.6	20.0	23.6	19.2	0.0	7.8	3.6
97									
98									
99	118.5	3.9	43.2	24.4	31.2	21.6	0.0	2.2	3.0
102									
103	120.5	3.5	43.2	25.2	32.0	25.6	0.0	0.4	0.8
104									
105									
106	117.5	3.8	42.4	26.8	26.8	22.0	0.0	3.8	3.8
109									
110	116.8	3.2	38.8	22.0	22.0	18.0	0.0	3.8	2.4
111									
112									
113	126.0	4.0					0.0	5.6	0.9
116									
117	121.0	4.4	40.8	28.8	34.4	18.8	0.0	15.0	9.0

2 deg	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-4	67									
	68									
	69									
	70	119.7	5.7	42.4	22.4	29.6	20.4	0.0	13.0	10.0
	71									
	74									
	75	114.1	3.8	38.4	21.2	26.0	21.6	0.0	11.8	9.0
	76									
	77									
	78	118.8	5.7	26.0	22.4	24.0	22.0	0.0	13.8	10.4
	81									
	82	115.0	3.9	53.2	27.6	39.6	28.4	0.0	10.6	9.0
	83									
	84									
	85	-	4.6	28.4	22.4	23.6	18.8	0.0	5.4	5.0
	88									
	89	110.0	4.1	38.4	24.0	23.6	21.6	0.0	5.0	4.1
	90									
	91									

Day No.	TOC In (mg/L)	TOC Out (mg/L)	TKN-N In (mg/L)	TKN-N Out (mg/L)	NH3-N In (mg/L)	NH3-N Out (mg/L)	NO2/3 (mg/L)	TP-P In (mg/L)	TP-P Out (mg/L)
92	115.0	3.9	31.6	22.8	25.6	18.8	0.0	5.8	4.0
96	119.5	5.2	31.6	22.4	23.6	17.6	0.0	7.8	3.4
97									
98									
99	118.5	5.1	43.2	23.6	31.2	21.2	0.0	2.2	2.8
102									
103	120.5	4.5	43.2	24.4	32.0	25.6	0.0	0.4	0.8
104									
105									
106	117.5	4.4	42.4	27.2	26.8	23.2	0.0	3.8	4.0
109									
110	116.8	3.6	38.8	22.0	22.0	16.8	0.0	3.8	3.4
111									
112									
113	126.0	4.3					0.0	5.6	0.9
116									
117	121.0	5.7	40.8	28.8	34.4	19.6	0.0	15.0	11.0

0.5 C

	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-1	123									
	124	35.0	2.1	33.6	34.4	35.6	28.0	2.8	3.0	2.8
	125									
	126									
	127	29.3	2.0	34.0	28.0	28.8	30.4	2.0	---	---
	131	29.0	8.0	36.0	26.0	27.6	24.4	---	5.6	6.6
	132									
	133									
	134	29.0	1.8	36.0	30.4	34.0	26.4	---	4.8	5.2
	137									
	138	34.0	1.8	36.0	32.4	30.4	26.4	1.0	6.4	5.2
	139									
	140									
	141	29.0	2.5	36.4	30.8	32.4	29.2	1.0	3.6	5.0
	144									
	145	26.8	2.4	38.4	33.6	32.4	29.2	1.0	10.8	8.0
	146									
	147									
	148	32.8	4.5	64.0	45.2	42.4	42.4	1.0	11.2	13.6
	151									
	152	27.4	2.6	34.8	31.2	28.0	23.6	1.0		

	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-2	123									
	124	55.0	3.0	32.4	32.4	33.6	28.0	0.0	2.5	2.4
	125									
	126									
	127	61.2	3.2	33.6	32.4	28.0	28.0			
	131	58.0	5.3	34.0	28.8	30.4	30.4		5.0	4.2

Day No.	TOC In	TOC Out	TKN-N In	TKN-N Out	NH3-N In	NH3-N Out	NO2/3	TP-P In	TP-P Out
132									
133									
134	57.0	3.0	39.6	32.4	32.0	31.2		5.6	4.4
137									
138	54.5	2.4	38.9	34.4	28.8	30.4		5.1	4.2
139									
140									
141	64.5	2.7	38.4	35.6	33.2	32.4		4.0	2.8
144									
145	58.0	4.7	39.6	38.4	33.2	32.4		11.0	9.2
146									
147									
148	61.0	4.5	6.8	19.2	0.4	17.2		11.4	13.4
151									
152	61.4	4.2	42.4	36.8	33.2	27.2			

.5 C.	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-3	123									
	124	118.0	5.2	36.4	29.2	38.4	27.2		4.0	1.9
	125									
	126									
	127	225.0	11.7	33.6	28.0	27.2	22.8			
	131	117.5	7.5	33.6	22.8	29.6	22.8		5.8	2.8
	132									
	133									
	134	118.0	7.0	37.2	25.6	31.0	27.2		5.6	5.2
	137									
	138	105.0	4.2	35.2	27.2	28.8	23.6		6.2	4.0
	139									
	140									
	141	111.3	4.2	34.0	26.4	28.0	24.0		2.8	5.4
	144									
	145	108.5	4.1	37.2	28.8	28.0	24.0		9.4	6.8
	146									
	147									
	148	115.5	4.7	42.4	28.0	32.0	25.2		12.0	9.4
	151									
	152	94.2	4.7	36.0	23.2	36.0	26.0			

.5 C.	Day	TOC (mg/L)		TKN-N (mg/L)		NH3-N (mg/L)		NO2/3 (mg/L)	TP-P (mg/L)	
	No.	In	Out	In	Out	In	Out		In	Out
R-4	123									
	124	118.0	4.9	36.4	28.4	38.4	24.8		4.0	1.9
	125									
	126									
	127	225.0	15.0	33.6	32.4	27.2	22.0			
	131	117.5	5.0	33.6	24.4	29.6	24.8		5.2	4.2
	132									
	133									
	134	118.0	7.7	37.2	24.4	31.0	26.4		5.6	5.0

137									
138	105.0	4.4	35.2	26.8	28.8	25.6		6.2	4.0
139									
140									
141	111.3	5.3	34.0	26.4	28.0	26.0		5.0	6.0
144									
145	108.5	4.1	37.2	31.0	28.0	26.0		9.4	7.0
146									
147									
148	115.5	5.4	42.4	31.2	32.0	24.4		12.0	10.0
151									
152	94.2	5.9	36.0	23.2	36.0	23.6			

10 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-1	0	7.5	7.4	170.0	66.0		110	1790	1630		10	0.069
	4	7.5	7.3	168.0	42.0			2040	1970		24	0.018
	5							3180	2900			0.000
	6							3230	2910	+		0.000
	7	8.6	7.0	154.0	20.0		222	3600	3190	200	23	0.022
	8							3340	3090	100		0.000
	11	9.2	8.0	254.0	126.0	0.22	226	3100	2590	10	50	0.027
	12							2990	2790	10		0.000
	13							2900	2600	10		0.000
	14	8.3	7.8	268.0	88.0			2990	2680	10	12	0.004
	15							3060	2720	10		0.025
	17							3000	2690	10		0.024
	18	9.3	7.8	260.0	104.0	0.13	253	3150	2900	10	9	0.022
	19							3060	2470	10		0.025
	20	9.5	7.9	272.0	106.0	0.30	224	2950	2610	10	15	0.025
	21							-	2730	10		0.000
	22							2920	2550	10		0.022
	23							3010	2620	10		0.021
	24							2950	2630	10	8	0.022

10 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-2	0	7.5	7.5	170.0	60.0		118	1890	1750		15	0.064
	4	7.5	7.0	168.0	38.0			1980	1900		27	0.019
	5							1270	1180			0.000
	6							1230	1120	100		0.000
	7	8.6	7.8	154.0	22.0		149	1120	1000	100	29	0.070
	8							1130	1140	100		0.000
	11	9.2	8.2	254.0	138.0	0.20	164	1200	890	100	16	0.078
	12							1160	1060	10		0.000
	13							1110	1020	10		0.000
	14	8.3	7.8	268.0	82.0			1150	1070	10	23	0.011
	15							1220	1100	10		0.062
	17							1260	1130	10		0.057
	18	9.3	8.0	260.0	106.0	0.35	133	1380	1330	290	25	0.048
	19							1200	1020	10		0.000
	20	9.5	7.9	272.0	120.0	0.32	125	1330	1180	10	26	0.056
	21								1150	125		0.000
	22							1260	1110	10		0.050
	23							1320	1160	10		0.048
	24							1340	1250	10	22	0.046

10 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.

10 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-3	0	7.5	7.6	170.0	62.0		127	1350	1450		33	0.078
	4	7.5	7.4	168.0	60.0			1420	1390		29	0.051
	5							1360	1240			0.000
	6							1580	1430	520		0.000
	7	8.6	7.6	154.0	58.0		130	1280	1140	530	23	0.123
	8							1050	1040	520		0.000
	11	9.2	8.1	300.0	186.0	0.26	194	1030	770	10	16	0.157
	12							1290	1190	10		0.000
	13							1360	1250	120		0.000
	14	9.2	8.0	294.0	188.0			1300	1290	209	22	0.086
	15							1390	1260	10		0.104
	17							1500	1310	250		0.097
	18	9.4	8.0	276.0	178.0	0.40	120	1720	1630	775	27	0.078
	19							1230	1040	125		0.122
	20	9.5	8.0	300.0	178.0	0.35	122	1340	1160	125	28	0.118
	21								1360			#VALUE!
	22							1260	1080	10		0.104
	23							1320	1160	10		0.096
	24							1440	1360	100	24	0.090

10 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-4	0	7.5	7.3	170.0	62.0		112	1820	1650		25	0.068
	4	7.5	7.5	168.0	72.0			1120	1120		27	0.063
	5							930	850			0.000
	6							1110	1020	660		0.000
	7	7.2	7.7	154.0	98.0		123	870	760	620	21	0.184
	8							710	710	630		0.000
	11	9.2	8.0	300.0	212.0	0.08	185	800	570	100	20	0.212
	12							940	880	273		0.000
	13							940	830	108		0.000
	14	9.2	7.9	294.0	200.0			1000	950	474	24	0.117
	15							910	830	10		0.158
	17							970	880	250		0.144
	18	9.4	7.9	276.0	178.0	0.25	122	1340	1290	1125	22	0.098
	19							900	720	125		0.177
	20	9.5	7.8	300.0	210.0	0.23	116	900	770	350	36	0.178
	21								910			0.000
	22							780	690	10		0.162
	23							870	770	10		0.144
	24							1110	1050	200	30	0.117

6 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-1	28							2970	2610	10		0.000
	29							2780	2450	10	16	0.026
	32							3100	3030	10		0.000

Reactor	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
	33	9.2	7.9	260.0	108.0			3310	2940	10	13	0.021
	34							3430	3070	10		0.000
	35							3100	2730	10		0.000
	36	9.5	7.7	267.0	110.0	0.46	173	3320	2990	10	4	0.021
	37							3700	3320	10		0.019
	38							3535	3150	10	18	0.000
R-2	28							1440	1290	210		0.000
	29							1260	1130	10	33	0.057
	32							1490	1580	10		0.000
	33	9.2	7.9	260.0	124.0			1680	1530	400	26	0.041
	34							1410	1260	120		0.000
	35							1140	1010	10		0.000
	36	9.5	7.7	267.0	140.0	0.35	92	1230	1150	10	14	0.056
	37							1580	1390	10		0.046
	38							1465	1315	260	22	0.000

6 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-3	28							1640	1440	510		0.000
	29							1310	1160	10	33	0.110
	32							1710	1850	400		0.000
	33	9.2	8.0	286.0	240.0			1760	1590	500	26	0.083
	34							1520	1410	410		0.000
	35							1170	1030	10		0.000
	36	9.4	8.0	297.0	263.0	0.35	90	1410	1290	140	10	0.095
	37							1790	1640	250		0.074
	38							1485	1365	360	20	0.000
R-4	28							1200	1050	710		0.000
	29							900	790	10	46	0.161
	32							1330	1440	600		0.000
	33	9.2	8.2	286.0	278.0			1330	1210	1000	26	0.109
	34							980	920	360		0.000
	35							810	720	10		0.000
	36	9.4	8.1	297.0	307.0		78	940	880	270	8	0.140
	37							1320	1210	350		0.100
	38							950	875	260	18	0.000

4 deg	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-1	40	9.2	7.4	257.0	110.0	0.26	223	3400	3010	10	19	0.020
	43							3370	2980	250	25	0.023
	47							3540	3210	10	9	0.000
	48							1290	3190	160		0.019
	49						141	3720	3380	10		0.000
	50	9.4	7.6					3700	3330	10	26	0.019
	52							3590	3250	10		#VALUE!
	53							3680	3240	10		0.000

	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
	54	9.4	7.4			0.36	138	3850	3440	10	22	0.018
	56							3770	3360	10		0.000
	57					0.43	147	3830	3430	10		0.020
	60							3840	3470	10		0.000
	61	9.3	7.5				131	3830	3430	10		0.018
	62							3880	3460	10		0.000
	63							3860	3430	30	19	0.018

4 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-2	40	9.2	7.9	257.0	183.0	0.24	77	1480	1330	10	31	0.046
	43							1430	1310	250	25	0.052
	47							1280	1210	10	29	0.000
	48							1290	1270	160		0.047
	49						62	1290	1230	70		0.000
	50	9.4	7.7					1340	1290	10	23	0.049
	52							1320	1250	120		0.000
	53							1390	1230	170		0.000
	54	9.4	8.0				56	1420	1290	209	13	0.047
	56							1430	1300	240		0.000
	57						96	1290	1190	10		0.059
	60							1480	1390	400		0.000
	61	9.3	7.8				90	1260	1180	10		0.053
	62							1370	1260	134		0.000
	63							1270	1160	30	6	0.055

4 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-3	40	9.2	8.0	280.0	287.0		79	1680	1530	10	20	0.077
	43							1530	1430	480	13	0.087
	47							1720	1610	730	11	0.000
	48							1420	1380	375		0.090
	49						72	1350	1290	205		0.000
	50	9.4	7.7					1350	1270	210	12	0.096
	52							1250	1190	10		0.000
	53							1670	1500	720		0.000
	54	9.3	8.1				69	1410	1290	209	6	0.100
	56							1450	1350	300		0.000
	57						91	1430	1310	250		0.093
	60							1740	1630	760		0.000
	61	9.3	7.8				93	1370	1260	140		0.102
	62							1430	1310	250		0.000
	63							1390	1250	30	5	0.102

4 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-4	40	9.2	8.0	280.0	280.0		80	1250	1150	10	14	0.103
	43							1080	1010	615	9	0.123

Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
50	9.4	7.8					950	910	300	12	0.134
52							1100	1040	650		0.000
53							930	840	360		0.000
54	9.3	8.1				61	1040	970	525	7	0.133
56							1130	1050	710		0.000
57						82	980	910	360		0.134
60							1270	1180	960		0.000
61	9.3	7.9				77	910	850	170		0.151
62							1030	950	465		0.000
63							910	820	30	5	0.156

2 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-1	67							3650	3300	10	35	0.000
	68							3690	3320	10		0.000
	69							3470	3120	10		0.000
	70							3530	3200	10	33	0.019
	71						110	3580	3230	210		0.000
	74							3300	2920	10	24	0.000
	75					1.10	126	3200	2930	10		0.020
	76							2880	2530	10		0.000
	77							2750	2510	10	19	0.000
	78	9.2	7.8			1.50	151	2420	2340	10		0.026
	81							3880	3020	10	21	0.000
	82					1.70	115	3190	2950	10		0.044
	83							3510	3205	10		0.000
	84							3250	3000	10	28	0.000
	85	9.2	7.9			1.00	105	3320	2960	10		0.010
	88							3160	2810	10	37	0.000
	89	9.1	7.9			1.14	109	3010	2750	10		0.011
	90							2970	2810	10		0.000
	91							3010	2720	10	23	0.000
	92	9.1	7.9			1.00	100	3170	2870	10		0.012
	96	9.1	8.2			1.10	92	3260	2940	10		0.009
	97							3420	3040	10	* 51	0.000
	98							3440	3010	10	32	0.000
	99	9.4	8.0			1.15	85	3530	3320	10		0.010
	102							3070	2700	10	27	0.000
	103	9.4	8.1			1.20	88	3270	2910	10		0.012
	104							3370	3070	10		0.000
	105							3060	2960	10	28	0.000
	106	9.2	8.1			1.00	88	3230	2980	10		0.010
	109							3190	2800	10	* 14	0.000
	110	9.4	8.0				88	3290	3070	10		0.011
	111							3000	2650	10		0.000
	112							3190	2840	10	24	0.000
	113	9.2	7.8			0.80	83	3230	2930	10		0.012
	116							3160	2860	10	23	0.000
	117					1.00	88	3160	2760	10		0.011

	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
	116							3160	2860	10	23	0.000
	117					1.00	88	3160	2760	10		0.011

2 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-2	67							1440	1360	250	8	0.000
	68							1340	1290	100		0.000
	69							1260	1170	10		0.000
	70							1230	1170	10	7	0.053
	71						74	1310	1220	60		0.000
	74							1240	1130	10	13	0.000
	75						47	1420	1350	160		0.042
	76							1480	1260	80		0.000
	77							1450	1350	343	2	0.000
	78	9.2	8.0				67	1240	1220	10		0.049
	81							1480	1330	300	3	0.000
	82						67	1240	1170	10		0.111
	83							1360	1230	10		0.000
	84							1240	1190	10	5	0.000
	85	9.3	8.0				61	1360	1270	160		0.048
	88							1410	1300	240	6	0.000
	89	9.2	8.0				63	1320	1250	130		0.050
	90							1180	1150	10		0.000
	91							1385	1290	220	11	0.000
	92	9.2	7.9				88	1340	1230	85		0.052
	96	9.0	8.4				53	1580	1330	300		0.046
	97							1520	1390	420	* 2	0.000
	98							1285	1020	10	8	0.000
	99	9.4	8.1				51	1310	1230	10		0.048
	102							1370	1160	10	4	0.000
	103	9.4	8.0				58	1440	1260	150		0.054
	104							1340	1230	80		0.000
	105							1370	1240	110	8	0.000
	106	9.2	8.0				58	1430	1300	240		0.056
	109							1450	1220	60	* 2	0.000
	110	9.3	8.1				72	1200	1190	10		0.054
	111							1450	1220	60		0.000
	112							1440	1240	110	6	0.000
	113	9.2	7.9				57	1460	1280	200		0.052
	116							1410	1290	200	7	0.000
	117						68	1450	1170	10		0.052

2 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	T.Alk., mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-3	67							1650	1570	710	7	0.000
	68							1350	1260	100		0.000
	69							1350	1240	10		0.000
	70							1350	1280	190	6	0.094
	71						76	1590	1460	510		0.000
	74							1490	1380	390	10	0.000

	75						47	1440	1310	260		0.087
	76							1480	1230	83		0.000
	77							1470	1300	234	4	0.000
	78	9.2	8.0				66	1520	1440	260		0.083
	81							1610	1350	320	8	0.000
	82						88	1320	1260	150		0.091
	83							1610	1460	544		0.000
	84							1310	1220	60	4	0.000
	85	9.4	7.8				75	1340	1140	10		#VALUE!
	88							1350	1220	60	15	0.000
	89	9.2	7.9				78	1480	1350	295		0.081
	90							1390	1360	330		0.000
	91							1395	1240	100	9	0.000
	92	9.2	7.8				78	1540	1360	370		0.085
	96	9.2	8.4				68	1950	1680	660		0.071
	97							1570	1450	520	* 16	0.000
	98							1480	1170	10	14	0.000
	99	9.4	8.0				64	1560	1480	570		0.080
	102							1470	1220	60	6	0.000
	103	9.4	8.3				75	1560	1420	475		0.085
	104							1380	1280	200		0.000
	105							1490	1330	300	9	0.000
	106	9.2	8.0				72	1390	1250	130		0.094
	109							1550	1320	280	* 1	0.000
	110	9.4	8.0				80	1460	1420	470		0.082
	111							1400	1160	10		0.000
	112							1420	1280	200	12	0.000
	113	8.9	8.0				75	1550	1420	470		0.089
	116							1470	1350	340	4	0.000
	117						69	1550	1270	10		0.095

2 deg	Day No.	pH In	pH Out	T.Alk., mg/L as CaCO3. In	Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M, TOC: MLVSS.
R-4	67							1290	1200	1000	6	0.000
	68							890	820	75		0.000
	69							930	850	10		0.000
	70							1010	960	500	10	0.125
	71						68	980	890	310		0.000
	74							1080	980	550	6	0.000
	75						36	920	860	220		0.133
	76							1010	820	83		0.000
	77							1220	950	410	4	0.000
	78	9.2	8.0				68	980	840	163		0.141
	81							1670	1440	710	8	0.000
	82						71	940	890	310		0.129
	83							1070	950	470		0.000
	84							790	760	10	7	0.000
	85	9.4	8.1				65	1020	830	110		#VALUE!
	88							1170	1000	320	7	0.000
	89	9.2	8.0				67	1030	980	520		0.112
	90							830	790	10		0.000
	91							1170	1050	370	12	0.000

Day No.	pH In	pH Out	T.Alk. In	T.Alk. Out	ZSV	SVI	MLSS	MLVSS	Qw	VSS	F:M
92	9.2	7.9				74	1120	1020	580		0.113
96	9.2	8.3				66	1525	1260	760		0.095
97							1110	1030	680	10	0.000
98							1040	800	10	15	0.000
99	9.4	8.0				64	1040	970	525		0.122
102							1100	870	250	2	0.000
103	9.4	8.2				91	1090	920	400		0.131
104							1050	960	510		0.000
105							990	930	430	13	0.000
106	9.2	8.0				92	990	890	310		0.132
109							1170	940	460	* 0	0.000
110	9.4	8.0				91	910	890	310		0.131
111							1190	1000	610		0.000
112							1040	860	220	7	0.000
113	8.9	8.0				86	970	850	160		0.148
116							1140	1000	610	8	0.000
117						96	1070	870	10		0.139

0.5 C

	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-1	123							2600	2290	10		#VALUE!
	124	9.2	7.9			2.0	88.0	2600	2390	10		0.015
	125							2800	2540	10		#VALUE!
	126							2950	2740	10	20	#VALUE!
	127	9.4	7.9			1.5	84.0	2830	2550	10		0.011
	131	9.2	8.0			1.3	83.0	2820	2480	10	27	0.012
	132							2910	2520	10		0.000
	133							2740	2540	10	42	0.000
	134	9.0	7.9			0.7	84.0	2780	2480	10		0.012
	137							2640	2390	10	27	0.000
	138	9.2	8.3			1.0	77.0	2920	2650	10		0.013
	139							2910	2630	10		0.000
	140							2970	2610	10	31	0.000
	141	9.2	8.1			1.1	77.5	2990	2640	10		0.011
	144							2780	2520	10	15	0.000
	145	9.1	8.3			1.5	76.0	2840	2470	10		0.011
	146							2800	2490	10		0.000
	147							2690	2440	10	26	0.000
	148	9.1	8.4			1.5	80.0	2850	2520	10		0.013
	151							2930	2610	10	24	0.000
	152							3140	2750	10		0.010

	Day No.	pH In	pH Out	T.Alk.,mg/L as CaCO3. In	T.Alk.,mg/L as CaCO3. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
R-2	123							1400	1250	130		0.000
	124	9.2	7.9				61.0	1370	1260	150		0.044
	125							1420	1290	220		0.000
	126							1310	1210	10	7	0.000
	127	9.4	8.2				76.0	1310	1250	130		0.049
	131	9.3	8.0				59.5	1410	1300	240	12	0.045

Day No.	pH In	pH Out	T.Alk. In	T.Alk. Out	ZSV (cm/m)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)	F:M,TOC: MLVSS.
132							1350	1130	10		0.000
133							1280	1190	10	13	0.000
134	9.0	7.9				63.0	1330	1180	10		0.048
137							1470	1360	360	11	0.000
138	9.1	8.2				60.4	1380	1300	240		0.042
139							1240	1110	10		0.000
140							1330	1240	110	13	0.000
141	9.2	8.1				59.0	1410	1240	110		0.052
144							1350	1190	10	3	0.000
145	9.1	8.2				63.0	1320	1180	10		0.049
146							1440	1260	150		0.000
147							1370	1240	110	8	0.000
148	9.2	8.5				69.5	1190	1170	10		0.052
151							1410	1280	200	11	0.000
152							1390	1190			0.052

.5 C.	Day			T.Alk.,mg/L		ZSV	SVI	MLSS	MLVSS	Qw	VSS	F:M,TOC:
		pH	pHas	CaCO3.		(cm/m)	(mL/g)	(mg/L)	(mg/L)	(mL)	(eff)	MLVSS.
	No.	In	Out	In	Out						(mg/L)	
R-3	123							1660	1460	540		0.000
	124	9.2	8.0				77.0	1510	1350	340		0.087
	125							1390	1290	220		0.000
	126							1310	1210	10	8	0.000
	127	9.4	8.1				90.0	1480	1350	370		0.167
	131	9.4	8.1				65.0	1790	1590	590	17	0.074
	132							1580	1360	360		0.000
	133							1350	1250	660	8	0.000
	134	9.4	7.9				69.0	1440	1240	110		0.095
	137							1590	1410	460	15	0.000
	138	9.1	8.2				77.5	1290	1230	80		0.085
	139							1440	1320	280		0.000
	140							1420	1320	280	21	0.000
	141	9.2	8.0				70.0	1420	1250	130		0.089
	144							1560	1400	440	10	0.000
	145	9.2	8.2				88.0	1360	1160	10		0.094
	146							1540	1350	340		0.000
	147							1340	1210	40	5	0.000
	148	9.2	8.2				94.5	1410	1260	150		0.092
	151							1520	1390	420	10	0.000
	152							1420	1220			0.077

.5 C.	Day			T.Alk.,mg/L		ZSV	SVI	MLSS	MLVSS	Qw	VSS	F:M,TOC:
		pH	pHas	CaCO3.		(cm/m)	(mL/g)	(mg/L)	(mg/L)	(mL)	(eff)	MLVSS.
	No.	In	Out	In	Out						(mg/L)	
R-4	123							1350	1210	710		0.000
	124	9.2	8.0				95.0	1050	990	560		0.119
	125							1050	960	510		0.000
	126							830	790	10	6	0.000
	127	9.4	8.1				87.0	1070	1020	610		0.221
	131	9.4	8.2				64.0	1320	1180	720	16	0.100
	132							1030	880	260		0.000
	133							1110	1020	130	17	0.000
	134	9.4	8.1				55.0	1210	1140	680		0.104

137				970	920	400	13	0.000
138	9.1	8.2	70.2	950	860	220		0.122
139				1020	890	310		0.000
140				1000	920	400	12	0.000
141	9.2	8.1	63.0	1050	940	460		0.118
144				1060	930	430	9	0.000
145	9.2	8.1	85.0	980	860	220		0.126
146				1080	950	480		0.000
147				890	840	150	11	0.000
148	9.2	8.2	99.0	1010	930	430		0.124
151				1100	950	480	10	0.000
152				1090	900			0.105

TRACK STUDY DATA

10 deg

	TIME (hours)	SOC (mg/L)	Org.- N (mg/L)	NH3-N (mg/L)	NO2/NO3-N (mg/L)	TP-P (mg/L)
R-1	0.00	29.4	4.3	17.0	9.2	10.7
	0.50	4.8	1.5	6.0	3.6	13.3
	1.00	3.9	1.2	9.0	0.5	9.9
	2.00	4.1	1.5	5.1	0.5	13.2
	3.00	4.3	1.2	6.6	0.5	14.5
	3.50	2.7	1.8	11.1	4.4	14.7
	4.00	2.3	0.3	7.5	7.7	12.4
	5.00	2.1	0.6	0.3	15.1	13.7
	7.00	2.1	0.6	0.3	15.0	12.7
	9.00	1.8	0.3	0.0	17.2	12.1
R-2	0.00	29.6	4.3	17.0	8.7	10.4
	0.50	6.8	1.2	10.5	6.8	9.5
	1.00	5.4	1.2	6.9	3.8	9.4
	2.00	4.8	0.6	8.7	0.5	10.4
	3.00	4.9	1.5	10.5	0.5	10.2
	3.50	2.4	1.2	11.7	3.1	10.4
	4.00	2.4	0.3	9.3	5.1	10.5
	5.00	2.0	0.3	3.0	11.0	10.0
	7.00	1.6	0.3	0.3	13.8	10.4
	9.00	2.1	0.9	0.0	16.3	10.3
R-3	0.00	62.5	8.8	14.5	6.3	8.8
	0.50	30.4	1.2	6.4	------	------
	1.00	30.7	3.0	7.8	0.5	------
	2.00	32.5	3.3	8.4	0.5	9.3
	3.00	32.1	3.3	9.0	0.5	9.8
	3.50	4.8	0.9	12.0	1.2	10.5
	4.00	2.4	0.3	10.8	2.4	9.5
	5.00	2.4	0.6	6.0	5.2	9.6
	7.00	2.6	0.3	1.2	11.5	9.3
	9.00	2.5	0.6	0.0	11.9	8.4
R-4	0.00	62.6	8.5	14.5	4.8	9.9
	0.50	36.9	1.8	9.6	1.0	8.6
	1.00	33.5	3.0	9.3	0.5	9.7
	2.00	33.3	2.7	9.0	0.5	9.4
	3.00	33.2	3.6	8.7	0.5	9.2
	3.50	5.9	0.6	13.2	0.7	9.8
	4.00	4.2	0.6	13.8	1.2	9.3
	5.00	3.0	0.3	9.6	3.2	9.3
	7.00	2.6	0.3	7.5	6.6	8.7
	9.00	2.5	0.3	2.1	10.2	8.7

6 deg

	TIME (hours)	SOC (mg/L)	Org.- N (mg/L)	NH3-N (mg/L)	NO2/NO3-N (mg/L)	TP-P (mg/L)
R-1	0.00	32.6	3.1	14.4	8.2	11.8
	0.25	9.1	2.1	6.0	5.0	
	1.00	5.5	1.2	9.0	1.0	
	3.00	6.2	0.9	8.7	0.0	16.0
	3.25	3.7	0.3	10.5	1.0	
	4.00	3.1	0.0	9.0	4.5	
	5.00	2.9	0.0	5.1	10.0	
	7.00	2.4	0.0	0.0	17.7	
	9.00	2.2	4.8	0.0	17.5	11.0
R-2	0.00	32.4	3.3	14.6	7.1	12.8
	0.25	18.9	2.1	13.8	5.7	
	1.00	10.2	2.1	9.9	3.6	
	3.00	9.0	1.2	12.9	0.0	12.5
	3.25	7.4	0.3	14.1	0.2	
	4.00	4.8	0.0	12.0	2.1	
	5.00	3.2	0.0	7.8	4.8	
	7.00	2.4	0.0	3.0	10.3	
	9.00	2.1	0.0	0.0	15.0	9.5
R-3	0.00	61.8	7.3	19.3	2.3	11.0
	0.25	47.7	3.9	15.3	0.4	
	1.00	40.7	4.2	13.8	0.0	
	3.00	38.5	3.3	15.6	0.0	11.5
	3.25	18.8	2.1	14.7	0.2	
	4.00	5.9	0.0	14.7	0.4	
	5.00	4.7	0.0	12.6	1.2	
	7.00	3.7	0.0	15.3	2.6	
	9.00	3.1	0.0	12.9	4.5	9.5
R-4	0.00	61.2	7.8	22.4	0.7	10.8
	0.25	52.9	5.4	18.6	0.2	
	1.00	48.0	3.9	17.7	0.0	
	3.00	41.8	3.9	17.7	0.0	11.0
	3.25	27.3	2.7	12.9	0.0	
	4.00	9.8	0.6	18.6	0.1	
	5.00	7.4	0.3	18.0	0.3	
	7.00	3.9	0.0	21.6	0.6	
	9.00	3.3	0.0	18.0	1.2	9.0

4 degr

	TIME (hours)	SOC (mg/L)	Org.- N (mg/L)	NH3-N (mg/L)	NO2/NO3-N (mg/L)	TP-P (mg/L)
R-1	0.00	32.8	3.2	15.0	9.1	12.9
	0.25	9.2	1.8	12.8	7.5	
	0.50	7.1	1.8	11.6	5.8	
	1.00	6.6	1.5	10.8	4.0	
	3.00	3.9	0.0	10.0	0.0	13.0
	3.25	3.1	0.1	12.8	0.4	
	3.50	2.9	0.0	12.8	1.0	
	4.00	2.4	0.0	11.6	2.4	
	5.00	2.3	0.0	9.2	5.0	
	7.00	2.0	0.3	3.6	12.0	
	9.00	2.3	0.0	0.4	15.3	11.0
R-2	0.00	33.3	3.7	27.2	0.6	12.9
	0.25	23.9	1.8	28.8	0.4	
	0.50	18.4	0.8	26.4	0.2	
	1.00	16.2	0.9	21.0	0.1	
	3.00	13.2	0.0	26.4	0.0	11.5
	3.25	9.3	0.9	31.2	0.0	
	3.50	8.0	0.1	28.8	0.2	
	4.00	7.0	0.1	29.6	0.2	
	5.00	4.3	0.0	28.0	0.4	
	7.00	3.5	0.0	28.8	1.0	
	9.00	3.4	0.0	26.4	1.3	10.5
R-3	0.00	65.6	4.5	24.0	0.0	10.9
	0.25	53.2	4.2	20.8	0.0	
	0.50	52.2	3.6	22.8	0.0	
	1.00	48.7	0.0	20.0	0.0	
	3.00	44.9	3.3	23.2	0.0	11.5
	3.25	23.4	0.3	24.8	0.0	
	3.50	17.2	2.7	24.0	0.0	
	4.00	12.8	1.2	25.6	0.0	
	5.00	7.8	0.6	22.8	0.0	
	7.00	4.0	0.0	23.6	0.0	
	9.00	2.9	0.0	22.4	0.0	9.5
R-4	0.00	66.3	4.8	24.2	0.0	11.1
	0.25	54.7	4.5	21.2	0.0	
	0.50	54.2	3.9	23.6	0.0	
	1.00	53.6	0.0	22.4	0.0	
	3.00	46.9	1.2	25.6	0.0	11.0
	3.25	30.3	2.1	24.8	0.0	
	3.50	20.4	2.7	24.0	0.0	
	4.00	15.7	3.0	23.6	0.0	
	5.00	10.7	1.5	24.8	0.0	
	7.00	5.6	0.1	21.6	0.0	
	9.00	4.6	0.0	22.4	0.0	9.0

2 Degr	TIME (hours)	SOC (mg/L)	Org.- N (mg/L)	NH3-N (mg/L)	NO2/NO3-N (mg/L)
R-1	0.00	16.5	9.4	25.8	1.4
	0.25	5.8	0.9	29.2	0.7
	0.50	4.7	1.2	28.4	0.6
	1.00	3.8	1.8	29.2	0.0
	3.00	4.5	1.5	28.4	0.0
	3.25	5.0	0.6	22.8	0.0
	3.50	3.2	2.4	30.0	0.0
	4.00	2.8	0.3	30.8	0.4
	5.00	2.5	0.0	32.8	0.8
	7.00	2.9	0.6	29.2	1.1
	9.00	2.7	1.5	34.4	1.3
	11.00	2.3	0.6	39.6	1.5
	14.50	2.7	0.9	23.8	2.3
	17.00	3.0	0.8	23.0	
R-2	0.00	31.9	8.4	28.6	0.0
	0.25	16.4	2.7	34.4	0.0
	0.50	16.2	3.0	35.2	0.0
	1.00	14.2	0.6	36.4	0.0
	3.00	11.5	1.8	34.4	0.0
	3.25	31.5	2.7	24.0	0.0
	3.50	7.5	0.3	39.6	0.0
	4.00	6.0	1.2	37.6	0.0
	5.00	3.5	0.0	44.8	0.0
	7.00	3.2	0.6	44.8	0.0
	9.00	3.2	0.3	39.6	0.0
R-3	0.00	62.8	8.2	26.6	0.0
	0.25	46.5	7.2	23.2	0.0
	0.50	45.3	6.9	23.2	0.0
	1.00	40.6	6.9	27.6	0.0
	3.00	37.1	4.2	26.0	0.0
	3.25	17.9	3.3	24.0	0.0
	3.50	14.2	2.7	27.6	0.0
	4.00	10.4	0.6	26.0	0.0
	5.00	6.2	0.6	28.4	0.0
	7.00	4.4	1.2	27.6	0.0
	9.00	3.7	1.2	28.4	0.0
R-4	0.00	63.4	7.8	27.0	0.0
	0.25	49.0	2.7	23.2	0.0
	0.50	47.5	4.5	25.6	0.0
	1.00	50.3	3.3	27.0	0.0
	3.00	41.1	3.3	19.6	0.0
	3.25	22.4	0.6	24.0	0.0
	3.50	14.4	2.1	26.8	0.0
	4.00	11.2	1.2	27.6	0.0
	5.00	7.0	4.8	29.2	0.0
	7.00	4.1	0.9	26.0	0.0
	9.00	4.3	0.9	30.8	0.0

0.5 C	TIME (hours)	SOC (mg/L)	GLUCOSE (mg/L)	ACETIC A. (mg/L)	Org.- N (mg/L)	NH3-N (mg/L)
R-1	0.00	15.0	15.8	9.7	------	25.8
	0.25	5.8	0.0	0.0	0.3	34.0
	0.50	4.9	0.0	0.0	0.3	30.4
	1.00	3.1		5.0	3.3	20.4
	3.00	2.9		0.0	4.0	26.0
	3.25	3.3		3.2	0.7	30.0
	3.50	3.0		0.0	1.8	28.2
	4.00	3.4		0.0	0.8	30.5
	5.00	2.8		0.0	0.4	30.5
	7.00	2.9		0.0	0.4	31.9
	9.00	2.7		0.0	0.3	30.5
R-2	0.00	32.7	34.6	17.1	------	30.2
	0.25	20.3	23.1	5.2	0.6	36.0
	0.50	17.4	17.0	0.2	0.3	30.4
	1.00	15.3	5.2	0.0	2.0	30.8
	3.00	11.2	0.0	0.0	2.1	28.8
	3.25	9.7		1.8	1.2	30.4
	3.50	8.4		0.0	1.2	31.2
	4.00	6.9		1.0	0.9	31.2
	5.00	4.8		1.4	0.3	32.0
	7.00	4.2		0.8	0.6	32.0
	9.00	4.0		4.4	2.1	33.6
R-3	0.00	49.4	51.3	29.1	------	31.0
	0.25	36.5	45.2	13.6	0.3	22.8
	0.50	34.2	30.0	12.2	2.7	18.8
	1.00	30.8	17.4	9.0	2.1	20.4
	3.00	23.9	0.0	7.4	2.7	22.4
	3.25	13.9		0.0	3.9	20.4
	3.50	11.7		0.0	2.1	21.2
	4.00	9.0		0.0	1.8	22.0
	5.00	6.6		0.0	0.9	22.0
	7.00	5.4		4.2	1.2	21.2
	9.00	5.5		1.2	0.6	20.0
R-4	0.00	50.0	51.3	28.2	------	29.8
	0.25	41.9	45.0	18.2	0.3	22.4
	0.50	37.4	31.2	19.2	4.5	22.0
	1.00	38.6	9.2	16.6	3.9	20.0
	3.00	36.0	0.0	20.8	3.3	20.0
	3.25	22.4		8.6	2.4	21.6
	3.50	16.4		0.0	2.1	19.2
	4.00	11.4		0.0	1.5	21.2
	5.00	8.2		0.0	1.2	20.8
	7.00	5.9		2.8	0.6	19.2
	9.00	6.7		2.6	0.9	20.0

R1

Day No.	pH In	pH Out	TOC (mg/L) In	TOC (mg/L) Out	COD(mg/L) In	COD(mg/L) Out	TKN(mg/L) In	TKN(mg/L) Out	TP-P(mg/L) In	TP-P(mg/L) Out	MLSS (mg/L)	MLVSS (mg/L)	Qw mL	eff. VSS (mg/L)
1	8.9	7.7	109.5	2.4	290.0		40.0		11.0	9.4	1900	1620		73
5	7.8	7.4	113.7	4.2	390.0	90.0	46.4	14.4	11.4	7.8	1970	1750		38
8		7.7	118.8	2.9	310.0	35.0	38.0	9.6	11.2	10.6	2000	1760		36
12		7.5	95.4	3.4	380.0	20.0	38.8	6.4	9.0	8.2	2200	1890		0
15		7.6			360.0	20.0			11.8	7.7	2060	1830	150	19
19		7.5	122.0	2.9	380.0	38.0	37.6	3.6	12.0	9.2	2020	1750	150	13
22		7.6	88.5	5.3	310.0	60.0			11.0	8.8	1160	1030	150	300
27		7.5	131.2	3.5	360.0	17.5	37.2	4.8	12.4	8.7	1240	1110	150	5
28		7.3									1510	1390	150	
30		7.2							12.1	8.1	1460	1250	150	6
33		7.4									1350	1150	150	5
36		7.3	30.0	5.1	180.0	30.0	35.0	1.6	11.2	7.4	1340	1250	150	25
40	7.6	7.5	31.0	8.5	160.0	30.0	38.2	3.0	12.8	9.7	1670	1490	150	13

R2

Day No.	pH In	pH Out	TOC (mg/L) In	TOC (mg/L) Out	COD(mg/L) In	COD(mg/L) Out	TKN(mg/L) In	TKN(mg/L) Out	TP-P(mg/L) In	TP-P(mg/L) Out	MLSS (mg/L)	MLVSS (mg/L)	Qw mL	eff. VSS (mg/L)
1	8.9	7.8	109.5	3.9	290.0		40.0		11.0	11.0	1790	1590		68
5	7.8	7.5	113.7	5.3	390.0	80.0	46.4	13.2	11.4	11.4	1770	1600		44
8		7.8	118.8	3.0	310.0	10.0	38.0	10.4	11.2	10.2	1880	1680		34
12		7.4	95.4	4.1	380.0	20.0	38.8	4.4	9.0	8.4	2130	1790		0
15		7.7			360.0	20.0			11.8	8.1	1960	1750	150	17
19		7.6	122.0	3.5	380.0	40.0	37.6	4.0	12.0	9.5	1900	1670	150	8
22		7.5	88.5	5.7	310.0	50.0			11.0	8.7	1040	930	150	290
27		7.6	131.2	3.3	360.0	17.5	37.2	1.6	12.4	8.9	1150	1030	150	9
28		7.4									1520	1390	150	
30		7.4							12.1	7.7	1480	1250	150	7
33		7.5									1390	1200	150	4
36		7.4	30.0	13.5	180.0	80.0	35.0	6.4	11.2	8.1	1440	1330	150	27
40	7.6	7.4	31.0	9.7	160.0	40.0	38.2	4.4	12.8	10.1	1680	1530	150	11

Supplemental — R1 & R2 — Study 1

	Day No.	pH In	pH Out	TOC (mg/L) In	TOC (mg/L) Out	COD(mg/L) In	COD(mg/L) Out	TKN(mg/L) In	TKN(mg/L) Out	TP-P(mg/L) In	TP-P(mg/L) Out	MLSS (mg/L)	MLVSS (mg/L)	Qw mL	eff. VSS (mg/L)
R3	1	8.9	7.7	109.5	2.7	290.0		40.0		11.0	11.3	1820	1620		54
	5	7.8	7.4	113.7	6.6	390.0	110.0	46.4	12.4	11.4	11.8	1950	1720		38
	8		7.5	118.8	3.7	310.0	8.0	38.0	6.8	11.2	10.4	1970	1860		42
	12		7.5	95.4	5.0	380.0	30.0	38.8	3.6	9.0	8.4	2200	1890		0
	15		7.7			360.0	30.0			11.8	8.1	2120	1930	150	15
	19		7.6	122.0	3.2	380.0	38.0	37.6	3.6	12.0	9.1	1920	1690	150	12
	22		7.5	88.5	4.8	310.0	50.0			11.0	8.5	920	840	150	320
	27		6.9	131.2	4.0	360.0	40.0	37.2	0.4	12.4	8.5	1240	1100	150	13
	28		7.4									1550	1390	150	
	30		7.5							12.1	7.9	1410	1200	150	12
	33		7.5									1400	1190	150	14
	36		7.4	30.0	10.1	180.0	60.0	35.0	5.2	11.2	8.2	1290	1220	150	32
	40	7.6	7.5	31.0	14.2	160.0	80.0	38.2	6.8	12.8	11.0	1450	1290	150	21

	Day No.	pH In	pH Out	TOC (mg/L) In	TOC (mg/L) Out	COD(mg/L) In	COD(mg/L) Out	TKN(mg/L) In	TKN(mg/L) Out	TP-P(mg/L) In	TP-P(mg/L) Out	MLSS (mg/L)	MLVSS (mg/L)	Qw mL	eff. VSS (mg/L)
R4	1	8.9	7.8	109.5	3.3	290.0		40.0		11.0	10.8	1880	1690		64
	5	7.8	7.5	113.7	4.6	390.0	70.0	46.4	12.0	11.4	11.6	1930	1720		48
	8		7.6	118.8	2.9	310.0	10.0	38.0	6.4	11.2	10.4	2040	1790		26
	12		7.6	95.4	3.1	380.0	30.0	38.8	4.4	9.0	8.5	2260	1930		0
	15		7.7			360.0	35.0			11.8	7.9	2000	1800	150	24
	19		7.6	122.0	3.1	380.0	38.0	37.6	2.8	12.0	9.4	1880	1600	150	11
	22		7.6	88.5	5.4	310.0	50.0			11.0	8.9	1090	980	150	310
	27		7.6	131.2	3.1	360.0	25.0	37.2	0.2	12.4	8.8	1050	920	150	9
	28		7.4									1580	1440	150	
	30		7.4							12.1	8.1	1480	1250	150	7
	33		7.4									1420	1230	150	6
	36		7.4	30.0	9.1	180.0	50.0	35.0	4.4	11.2	7.9	1460	1360	150	27
	40	7.6	7.4	31.0	9.0	160.0	12.0	38.2	3.0	12.8	10.4	1690	1480	150	14

Supplemental — R3 & R4 — Study I

Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)
1	65.0		51.2		36.8		1.0					
2		8.9		34.4		27.2	1.0	140	2130	1870	10	56
3									2120	1920	10	
4	58.0	4.1	41.6	23.2	34.4	22.0	1.5	152	2300	2070	10	
5									2170	1880	10	29
8	160.0		80.0									
9									2780	2430	10	
10	52.0	3.0	30.0	27.6	26.0	23.2	1.5	164	2740	2460	10	32
11									2680	2420	10	
12	53.0	3.3	37.6	27.6	26.2	23.2	1.7	176	2650	2370	10	
13									2570	2340	10	8
16									2740	2470	10	
17	54.0	4.2	38.4	28.8	27.6	24.0	2.2	189	2650	2460	10	6
18									2680	2340	10	
19	53.0	6.0	41.6	31.6	26.4	22.0	2.4	165	2620	2240	10	
20									2450	2250	10	14
23									2490	2270	10	
24	56.0	3.2	44.8	24.0	30.8	19.6	3.0	181	2490	2200	10	10
25									2580	1960	10	
26	55.5	3.6	44.8	25.6	30.8	25.6	4.0	204	2620	2420	10	
27									2530	2330	10	30
30									2310	2130	10	
31	60.0	4.0	42.4	29.2	37.2	21.2	3.5	202	2310	2070	10	9
32									2390	2070	10	
33	110.0	4.7	43.6	17.6	28.4	20.8	4.0	181	2390	2140	10	15

Supplemental — RI — Study 4

Day No.	TOC (mg/L) In	TOC (mg/L) Out	TKN-N (mg/L) In	TKN-N (mg/L) Out	NH3-N (mg/L) In	NH3-N (mg/L) Out	NO2/3 (mg/L)	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)
1	65.0		51.2		36.8							
2	65.0	25.2		29.2		28.4	1.0	130.0	2320	1990	10	55
3									2200	2000	10	
4	42.0	23.0	48.4	33.2	37.2	30.4	1.5	149.0	2350	2010	10	
5									2330	1990	10	25
8	160.0		80.0									
9									2660	2360	10	
10	38.0	21.3	35.6	40.0	30.4	31.6	1.0	160.0	2610	2450	10	28
11									2640	2340	10	
12	33.0	21.5	44.4	40.0	36.4	31.6	1.1	145.0	2530	2240	10	
13									2660	2390	10	8
16									2730	2530	10	
17	50.0	19.5	46.4	40.0	30.0	24.0	1.0	149.0	2350	2180	10	9
18									2560	2340	10	
19	37.0	22.5	48.0	42.0	30.8	25.2	1.3	129.0	2580	2230	10	
20									2630	2380	10	17
23									2580	2350	10	
24	50.0	24.0	37.6	36.4	28.4	34.4	1.5	122.0	2600	2320	10	23
25									2600	2270	10	
26	44.0	21.0	40.8	35.6	34.4	34.8	1.5	115.0	2760	2580	10	
27									2390	2190	10	24
30	27.0								2340	2070	10	
31	35.0	18.0	34.8	28.4	27.6	29.6	1.0	121.0	2470	2190	10	24
32									2640	2290	10	
33	28.0	16.8	30.0	27.6	26.8	26.8	1.2	129.0	2330	2040	10	17

Supplemental — R2 — Study 4

Day	TOC (mg/L) In	TOC (mg/L) Out	NO2/3 (mg/L) @3hrs.	NO2/3 (mg/L) @9hrs.	In	TP-P (mg/L) @3hrs.	TP-P (mg/L) @9hrs.	SVI (mL/g)	MLSS (mg/L)	MLVSS (mg/L)	Qw (mL)	VSS (eff) (mg/L)
1				2.5			9.6		1590	1490	290	
2		3.3	0.0	2.5		10.2	8.2	93	1660	1460	240	19
3									1750	1550	400	
4	98.5	2.8	0.5	5.0		21.0	13.5	148	1570	1390	100	
9									2060	1830	610	22
10			0.0	6.2		10.8	8.2	212	1730	1630	430	35
11									1700	1540	280	
12	109.7	3.0	0.0	7.1	9.4	10.6	8.8	202	1650	1500	190	
13									1630	1550	300	18
16									1830	1730	530	
17	123.0	2.3	0.0	11.0		12.8	9.2	227	1540	1470	150	70
18									1650	1470	150	
19	125.0		0.0	13.5	14.5	12.2	10.0	242	1720	1460	130	
20									1540	1440	90	51
23									1700	1630	430	
24	117.0	2.3	0.0	17.5	11.8	13.4	9.0	240	1600	1470	150	31(19)
25									1770	1540	280	
26	119.0		0.0	13.0	11.6	11.6	9.0	245	1630	1570	340	
27									1570	1520	250	55(27)
30									1720	1550	300	
31	120.0	2.6	0.0	16.0	9.8	11.2	8.2	229	1960	1890	500	11
32									1500	1350	120	
33	121.0		0.0	17.5	9.0	11.8	9.0	193	1810	1650	460	24
34									1630	1500	190	
37									1980	1740	600	
38					9.4	10.1	8.3	192	1650	1540	280	
55					10.2		3.8					
60					9.4		3.0					

Supplemental— Study 5 — () Indicates in situ sampling.

APPENDIX II

TOC:COD CORRELATION

	TOC (mg/L)	COD (mg/L)
	112.3	280.0
	91.4	260.0
	109.5	290.0
	113.7	390.0
	118.8	310.0
	95.0	380.0
	122.0	380.0
	88.5	310.0
	131.2	360.0
	30.0	180.0
	31.0	160.0
	112.7	370.0
	71.0	270.0
	36.0	135.0
	71.0	270.0
	140.1	385.0
	82.7	310.0
	32.0	120.0
	110.1	330.0
TOTAL	1699.0	5490.0
AVERAGE	89.4	288.9
CORRELATION COEFFICIENT	0.900	
SLOPE (COD:TOC)	2.186	