

FEASIBILITY OF PRE-DENITRIFICATION IN THE PURE OXYGEN
ACTIVATED SLUDGE SYSTEM

BY

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A Thesis

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

MASTER OF SCIENCE

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ABSTRACT

A high purity oxygen activated sludge operating with low solid retention time (SRT) used at the North End Water Pollution Control Centre (NEWPCC) in Winnipeg produced a final effluent with high ammonia nitrogen concentration. This study documents the method applied to assess the feasibility of nitrification and denitrification of the primary effluent from the NEWPCC and to evaluate the effects of pre-denitrification on nitrification by using a single sludge system (Pre-Den) with a pure oxygen reactor. No study of the Pre-Den process effects on nitrification, using pure oxygen, has been reported to date. Three trains of pilot scale-stirred reactors were installed at NEWPCC, and fed with primary effluent. One of these trains was a combined nitrification system using pure oxygen, and the other two were Pre-Den systems. The system SRT based on volume of reactor was 10 days in the latter system, and 8 days in nitrifying mode. The hydraulic retention times (HRT) based on raw wastewater flow were of 1.5 and 3 h in the anoxic reactors, and of 6.2 and 12 h in the oxygen reactors. Full nitrification was demonstrated and an effluent pH level higher than the expected level was produced. The overall recycle ratio correlated better with the TKN than with the $\text{NH}_3\text{-N}$ concentrations. The Pre-Den showed several advantages over the nitrifying mode; i.e. an alkalinity recovery up to $70 \text{ mgCaCO}_3/\text{L}$; a saving in oxygen consumption of up to 26 %; the highest nitrification rate (up to 4.3 mgN/gVSS.h with a denitrification rate up to 5.4 mgN/gVSS.h); and the lowest sludge production. The TKN removal was up to 95 %, and the total nitrogen removal up to 75 %.

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DEDICATION

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LIST OF ABBREVIATIONS

Alk.: Alkalinity
ASP: Activated Sludge Processes
BOD or BOD₅: Biological Oxygen Demand at 5 days of incubation
C/N: Organic Carbon to Total Nitrogen Ratio
COD: Chemical Oxygen Demand
DN: Denitrification
DNR: Volumetric Denitrification Rate
DO: Dissolved Oxygen
E: Overall Removal Efficiency of Substrate
Ef.A: Effluent from Train A
Ef.B: Effluent from Train B
Ef.C: Effluent from Train C
EVSS: Effluent Volatile Suspended Solid
FE: Final Effluent
F/M: Food to Microorganism Ratio
HOAS: High-purity Oxygen Activated Sludge
HRT: Hydraulic Retention Time
I: Influent
ML: Mixed Liquor
MLE: Modified Ludzac and Ettinger System
MLVSS: Mixed Liquor Volatile Suspended Solid
MMLVSS: Mean Mixed Liquor Volatile Suspended Solid in pre-denitrifying train
MO: Microscope Observation
NEWPCC: North End Water Pollution Control Centre
NH₃Eff: Ammonia Effluent
NH₃-N: Ammonia Nitrogen
NH₃R: Ammonia Removal
NH₃RAW: Raw Wastewater Ammonia
N_{org}: Organic Nitrogen
N_{org}Eff: Effluent Organic Nitrogen
N_{org}RAW: Raw Wastewater Organic Nitrogen
NO₃Eff: Effluent Nitrate

NO_{3RAW}: Raw Wastewater Nitrate
NO_{3-N}: Nitrate Nitrogen
NO_{3R}: Nitrate Reduced
NO_{3R}: Nitrate Removal
NO_x: Oxidized Nitrogen Compounds
NR: Biological Nitrogen Removal
ORP: Oxidation-Reduction Potential
OUR: Oxygen Uptake Rate
PE: Primary Effluent
Pre-Den: Pre-denitrification
Q_{Ef}: Effluent Flow Rate
Q_{RAS}: Return Activated Sludge Flow Rate
Q_{RAW}: Raw Wastewater Flow Rate
Q_{RNO3}: Return Nitrate Flow Rate
Q_{WAS}: Waste Activated Sludge Flow Rate
r: Overall Recycle Ratio
r₁: Return Activated Sludge Recycle Ratio
r₂: Return Nitrate Recycle Ratio
RAS: Return Activated Sludge
RAS-N: Nitrified Return Activated Sludge
RAS-DN: Denitrified Return Activated Sludge
RAW: Raw Wastewater
RNO₃: Recycled Nitrate-rich Mixed Liquor
RI: Reactor I
RII: Reactor II
RIII: Reactor III
RIV: Reactor IV
RV: Reactor V
R²: Squared Error
SBR: Sequencing Batch Reactor
S_{Ef}: Effluent Substrate
SD: Sample Standard Deviation
SDNR: Specific Denitrification Rate
SNR: Specific Nitrification Rate

S_o : Raw Wastewater Biological Oxygen Demand
 SOC_{Ef} : Effluent Soluble Organic Carbon
 $SOCR$: Soluble Organic Carbon Removal
 SOC_{RAW} : Raw Wastewater Soluble Organic Carbon
 $SOUR$: Specific Oxygen Uptake Rate
 SP : Sludge Production
 S_{RAW} : Raw Wastewater Substrate
 SRT : Solid Retention Time
 SS : Suspended Solid
 $SSRT$: System Solid Retention Time
 SVI : Sludge Volume Index
 TKN : Total Kjeldahl Nitrogen
 TKN_{Ef} : Effluent Total Kjeldahl Nitrogen
 TKN_{RAW} : Raw Wastewater Total Kjeldahl Nitrogen
 $TKNR$: Total Kjeldahl Nitrogen Removal
 TN : Total Nitrogen
 TNR : Total Nitrogen Removal
 TP : Total Phosphorous
 U_{DN} : Substrate Utilization Rate in Pre-Den Reactor
 V_C : Volume of Clarifier
 V_{DN} : Volume of Denitrifying Reactor
 V_{DN-N} : Volume of Denitrifying plus Nitrifying Reactors
 V_N : Volume of Nitrifying Reactor
 VIP : Virginia Initiative Plant
 VSS : Volatile Suspended Solid
 WAS : Waste Activated Sludge
 $WVSS$: Waste Activated Sludge Volatile Suspended Solid
 Y_{obs} : Observable Yield

CHAPTER 1: INTRODUCTION

The aim of this chapter is to present a brief explanation of the nitrogen compounds in the environment, biochemical transformations of those compounds in a treatment plant, and nitrogen compounds at north end wastewater treatment plant in Winnipeg, Manitoba, Canada.

1.0 NITROGEN COMPOUNDS IN THE ENVIRONMENT

Soluble forms of nitrogen are harmful to the environment in many ways. In the particular case of effluent from sewage plants, the presence of nitrogen can be detrimental to the aquatic environment. For example, higher summer temperatures in a river can shift nitrogen speciation towards un-ionized ammonia which is directly toxic. The nitrification of ammonia, in addition, causes oxygen depletion. All nitrogen compounds, in fact, are nutrients in the process of eutrophication. Nitrates in water can be directly toxic to infants as evidenced by their production of methaemoglobinaemia (Bailey and Tomas, 1975).

Historically, a greater emphasis has been placed in the removal of phosphates from sewage wastewater. However, more recently, the concern has shifted to nitrogen removal as there is evidence that nitrogen removal from sewage improves phosphate removal (Barnard, 1975, and Morales et al, 1991). In addition, it has been stated that nitrogen removal may be required to maximize the benefits of phosphorous reduction in fresh water areas (Blankenship, 1993).

Denitrification of secondary effluent has been undertaken mostly because of

environmental and health concerns. For example in the cases of the Chesapeake Bay Agreement (U.S.A.) signed in 1987 (Kunihiro et al, 1992), the Alberta Environment's Municipal Standards, Canada (Wilson et al, 1992), and the new permit limits of the Florida Department of Environmental Regulation, U.S.A. (Refling et al, 1992).

However, because of operational objectives, denitrification has also been implemented to:

1. Improve the settling characteristics of the nitrified mixed liquor impairing denitrification in the secondary clarifiers as done in the Hawaii wastewater treatment plant, Honolulu, Hawaii (Gorenflo and Cross, 1992).
2. Overcome deficiency in the raw wastewater alkalinity as implemented in the Moores Creek wastewater treatment plant, Charlottesville, Va., U.S.A. (Judkins and Anderson, 1992).
3. Reduce oxygen consumption as implemented in the Newark, Ohio, wastewater treatment plant (Miskis and Jamesson, 1992).
4. Reduce sludge production as done also in the Newark, Ohio, wastewater treatment plant (Miskis and Jamesson, 1992).
5. Improve the removal of phosphorous in treatment plant in which nitrification is also required (Barnard, 1975; Morales et al, 1991).

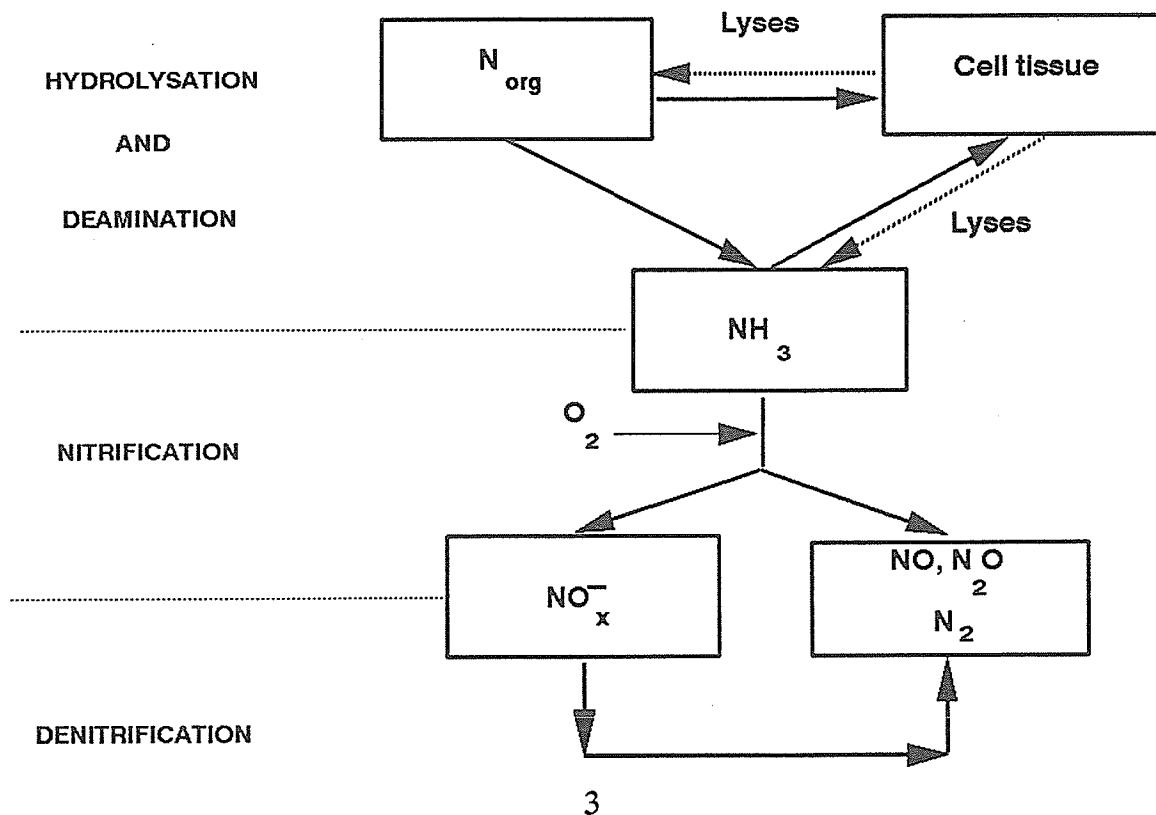
1.1 BIOCHEMICAL TRANSFORMATIONS OF NITROGEN COMPOUNDS

Biological nitrogen removal involves four biochemical steps: hydrolysatation, deamination, nitrification, and denitrification. The first two steps refer to the

conversion of organic nitrogen to ammonia. Hydrolysis is the conversion of the proteins yielding α -amino acids, and deamination is the transformation of amino acids to ammonia and organic acids. Deamination can also produce carbon dioxide (CO_2) according to the involved reactants and to the operational conditions under which the process takes place.

The possible biochemical transformations that nitrogen compounds undergo in a sewage treatment plant are represented in Figure 1.1. In secondary treatment plants, hydrolysis and deamination take place, thus the effluent total nitrogen (TN) concentration is still high as nitrogen is removed mainly by assimilation for production of new cell tissue.

Fig.1.1: Biochemical transformations of nitrogen compounds in a municipal treatment plant



In advanced treatment plants which involve tertiary treatment, either nitrification or denitrification may be included. If the treatment plant involves nitrification, the effluent TN concentration may be slightly lower than the TN concentration of the secondary effluent as denitrification may take place to some extent in the nitrifying reactor and in the secondary clarifier. The biological oxidation of ammonia to the oxidized nitrogen compounds (NO_x^-) is referred to as autotrophic nitrification, while the biological conversion of ammonia into nitrogen gas without intermediary accumulation of nitrite is known as heterotrophic nitrification (Robertson et al, 1988). Nitrogen compounds are further removed when denitrification is one of the step in the advanced treatment plant.

1.2 NITROGEN AT NORTH END TREATMENT PLANT

The North End Water Pollution Control Centre treatment plant (NEWPCC) in the City of Winnipeg provides secondary treatment to 332 MLD (average flow) wastewater and discharges into the Red River. The NEWPCC was designed to treat domestic wastes, and some run-off from rain and melting snow, as about half of Winnipeg is served by combined sewers. Table 1.1 summarizes the wastewater characteristics.

The city's largest plant, NEWPCC, treats the wastewater in seven steps as shown by the flow schematic in Figure 1.2. The main liquid stream is fed to the preliminary treatment through the pumping station of 826 MLD of capacity with the largest pump out of service. The preliminary structure has four treatment trains,

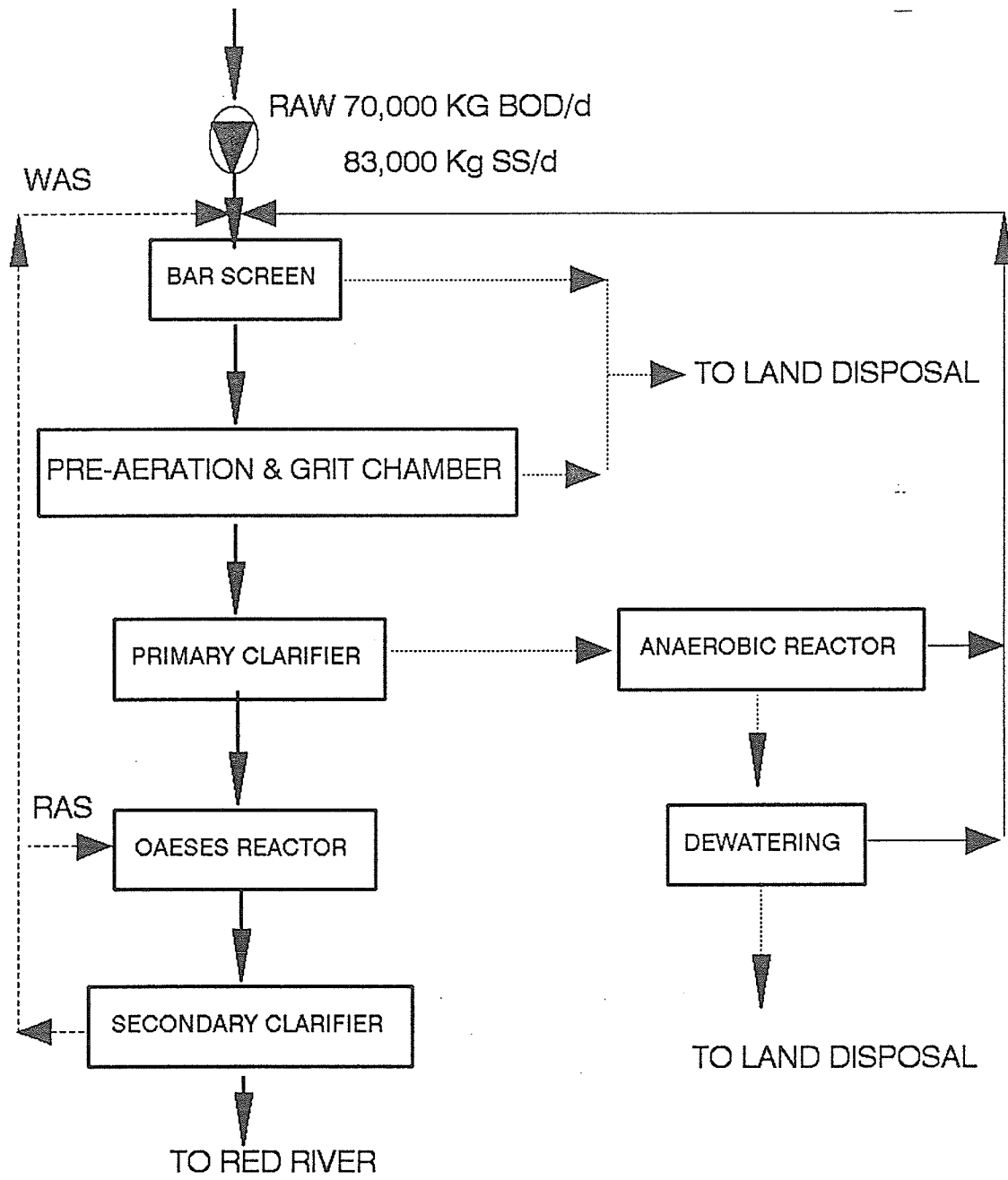
each consisting of a 12 mm bar screen and an aerated grit chamber. The removed solids are taken to landfill disposal. The waste activated sludge (WAS) is discharged to the head of the preliminary treatment. The flow from the preliminary stage is split into five primary clarifiers, three circular and two rectangular. The primary sludge is pumped to six mesophyllic anaerobic digesters. The digested sludge flows to eight holding tanks, then fed to six centrifuges for dewatering, and afterwards is conveyed to two sludge cake bins from which it is taken to land disposal.

Table 1.1: Characteristics of NEWPCC's Influent (I), Primary Effluent (PE), and Final Effluent (FE). Note: From monthly data provided by NEWPCC, for the year 1989.

	I	PE	FE
BOD₅, mg/L	210	137	23
SS, mg/L	250	100	17
TN, mgN/L	36	NA	27.1
TP, mgP/L	5.2	NA	1.7

The main liquid-stream flows from the primary to the secondary treatment. The secondary treatment consists of three parallel pure oxygen reactor systems (OASES), each consisting of two trains with four stages per train. The mixed liquor (ML) flows through ten circular and sixteen rectangular secondary clarifiers. The

Fig.1.2: Flow schematic of NEWPCC's treatment process



clarified effluent with the characteristics reported in Table 1.1 is discharged into the Red River.

The high rate pure oxygen activated sludge system, operated by NEWPCC, successfully achieves carbonaceous BOD, suspended solid, and, to some extent phosphorous but not nitrogen removal. The discharge criterion is reached at a solid retention time of 1.5-2.5 days, without noticeable conversion of the ammonia to nitrates (23.4 of the 27.1 mgN/L in the FE is as ammonia). Since there were some concerns raised about the potential summer toxicity of the un-ionized ammonia in the Red River, the City decided to study the feasibility of attaining nitrification by increasing the solids retention time (SRT) in one of the full scale reactors.

Because of the benefits offered by denitrification, and the awareness of the inhibitory effects of decreased alkalinity and pH level caused by nitrification and dissolution of carbon dioxide in the ML of the OASES reactors, the City has decided to study, in small scale, the performance of a pre-denitrification process (Pre-Den), as one of the methods of maintaining higher alkalinity in the system at NEWPCC.

CHAPTER 2: OBJECTIVES

While in municipal wastewater the biological potential exists for both nitrification and denitrification without supplemental organic carbon sources, the operational conditions usually used in aerobic biological processes produce efficient carbonaceous removal and nitrification but not efficient denitrification (Bishop et al, 1976). On the other hand, the main disadvantage of high rate oxygen processes is that nitrification is unlikely to be accomplished due to short SRT and low pH level (Toms and Booth, 1982, and Blachford et al, 1982). This study has thus been initiated to answer the following questions:

- Is pre-denitrification feasible in conditions of high dissolved oxygen residue in the return liquid streams fed to the pre-denitrification tank?
- Is pre-denitrification capable of reducing the alkalinity consumption caused by nitrification?
- Is complete nitrification feasible in conditions of variable, decreasing pH of the ML?

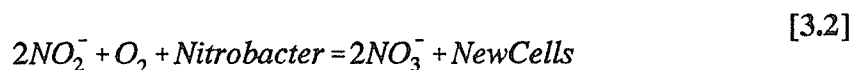
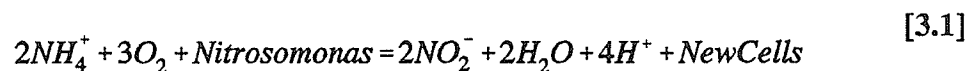
The study is intended as an introductory research into the feasibility of biological nitrification and denitrification processes in pure oxygen systems, and there have been no efforts made to closely duplicate the conditions of the North End Plant.

CHAPTER 3: REVIEW OF THE LITERATURE

The purpose of this literature review is to present an overview of the basic principles and concepts that govern biological nitrification and denitrification. A general discussion about of the developments in biological nitrogen removal (abbreviated NR) by conventional and pure oxygen activated sludge will be also presented.

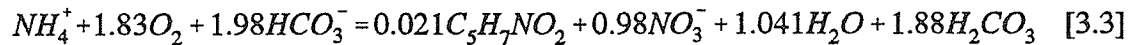
3.0 BIOLOGICAL NITRIFICATION

Biological nitrification or simply nitrification, is a two step biological process in which ammonia is oxidized, first to nitrite (NO_2^-) and later to nitrate (NO_3^-). The nitrifying bacteria responsible of the former conversion belong to the genera *Nitrosomonas*, and *Nitrobacter* are responsible for the latter. The reactions carried out by these microorganisms may be represented as follows



The stoichiometric requirements for carbon and oxygen in nitrification are related to the quantities of ammonia that need to be oxidized, and to the alkalinity

consumed by Equation 3.3, which considers both oxidation and synthesis (U.S.EPA, 1975):



This equation shows that one gram of ammonia nitrogen converted requires 4.18 g of oxygen, and 7.14 g of alkalinity as $CaCO_3$. The nitrifier bacteria that are capable of carrying out the above equations are autotrophic organisms. Most of these bacteria are obligately lithoautotrophic, even though they can assimilate organic compounds to a limited extent (Bock et al, 1989).

As most research into nitrification and denitrification has involved a limited group of bacteria species, there is a strong belief that successful nitrification requires autotrophic nitrifiers whereas denitrification can take place under anaerobic conditions (Robertson et al, 1988). However, some heterotrophic bacteria and fungi can nitrify if they are supplied with a source of energy. Bacteria which are capable of both heterotrophic nitrification and aerobic denitrification have been recently isolated in pure culture (Robertson and Kuenen, 1984; and Robertson et al, 1988). Heterotrophic nitrification is therefore another process which involves the oxidation of reduced nitrogen compounds. Heterotrophic nitrification may be significant in atypical environments with either very alkaline or acidic conditions (Randall et al, 1992).

Nitrification may occur in suspended-growth and attached-growth processes,

and two basic forms may be implemented: **single-stage** (also referred to as combined nitrification) and **separate-stage**. In the single-stage scheme (Fig.3.1), carbon and nitrogen compounds are oxidized in the same reactor, while in the separate-stage scheme (Fig.3.2) one reactor removes carbon in the first stage and ammonia is oxidized to nitrate in a second reactor. The ML clarification of the latter scheme may be performed either in the same or in separate clarifiers, thus the separate-stage configuration may be **single-sludge** or **separate-sludge**. Sutton et al (1975) has compared the efficiency of carbon oxidation and nitrification achieved in three different process configurations under a range of operating temperatures and SRTs at pseudo steady-state conditions.

Both basic process configurations have advantages and disadvantages which makes the choice of one over the other dependent on the specific raw wastewater, site limitations, and economic factors. The two-stage nitrification (separate-stage) system resists the toxic or inhibitory effects of various compounds and of the environmental factors better than the single-stage process (Sutton et al, 1975). Bailey et al (1989) have reported a new means to overcome site limitations, and have presented a generalized comparison of single and two-stage nitrification configurations.

As the autotrophic nitrifiers are more fragile and sensitive to environmental changes and have lower yields and growth rates than the heterotrophic microorganisms, the SRT is an essential parameter in nitrification. The SRT control is therefore a necessary tool to achieve efficient nitrification since it ensures the

Fig.3.1: Single-stage nitrification configuration

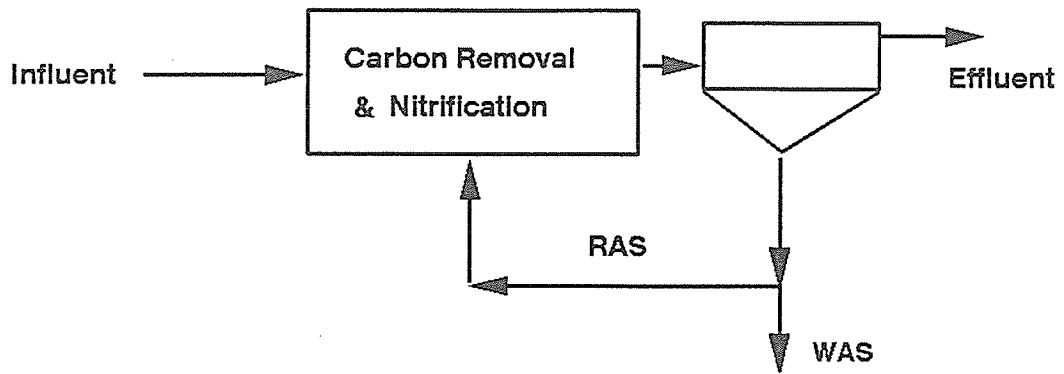
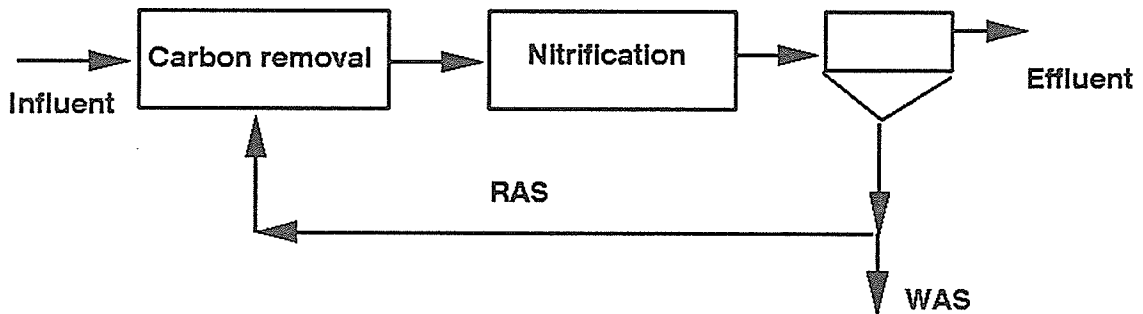
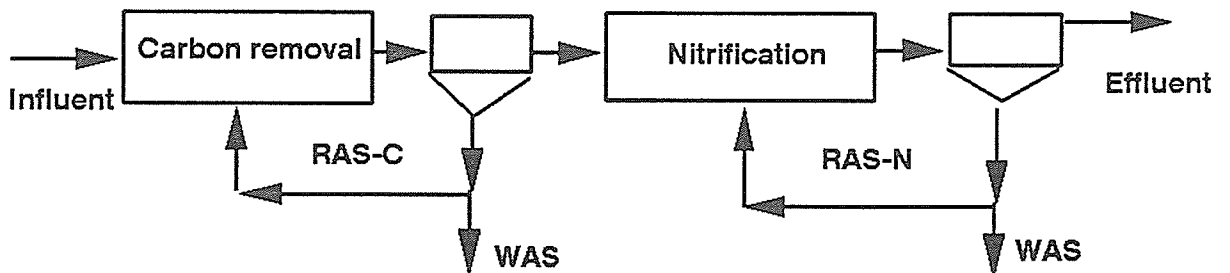


Fig.3.2: Separate-stage nitrification configurations

I) Single-sludge



II) Separate-sludge



growth and accumulation of nitrifiers in the system.

The kinetics of nitrification for activated sludge processes (ASP) have been described by the Monod equation. Several factors affect the nitrification kinetics: BOD₅ to TKN ratio, ammonia and nitrite concentrations, toxic compound concentrations, pH, dissolved oxygen concentrations (DO), alkalinity, temperature, and mixing system in ASP. These factors have been extensively studied. Wild et al (1971) analyzed the effects of pH, temperature and BOD₅ on nitrification in a two-stage configuration. Drtil et al (1993) recently presented a modified respirometric method to determine the kinetic constants of the first stage of nitrification. These researchers have also discussed the role of the substrate concentration and activated sludge ratio on respirometric methods.

Anthonisen et al (1976) have shown that ammonia and nitrite inhibitions of nitrification occur with municipal, industrial, and agricultural wastes and with fertilizers in the soil. However, nitrification patterns may be modified by operating procedures that increase or reduce those inhibitory effects (Anthonisen et al, 1976). A major environmental factor in our system is the pH level in the ML which is relevant to a successful nitrification. Painter and Loveless (1983) have studied the effect of temperature and pH value on the growth-rate constants of nitrifiers in the ASP, and found that nitrification was not possible at a pH of 6 at any temperature. These authors also reported an optimal pH range between 7.5 and 8.5; however, they could not determine a factor representing the effect of pH. Kholdebarin and Oertly (1977) reported an optimum pH of about 8.5 for the biological oxidation of NO₂⁻ to

NO_3^- in fresh water. Haug and McCarty (1972) found full acclimation at pH level of 6 in a submerged filter reactor.

Alkalinity and nitrification relationships in ASP have been also investigated by many researchers. Degyansky (1977) found that neither the amount of alkalinity nor the oxygen requirement for nitrification are constant values due to their dependence on the BOD_5 to NH_4^+ -N ratio, and SRT. Benninger and Sherrard (1978) stated that an increase in the ratio of alkalinity as CaCO_3 destroyed to TKN removed was observed at high SRT (15 d) and low COD to TKN ratio (4.18:1). These authors obtained lower alkalinity values compared to the theoretical value determined by Equation 3.3.

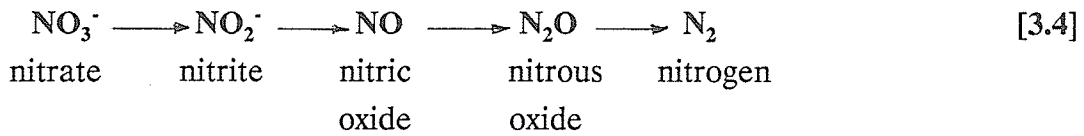
The importance of the DO on nitrification was demonstrated by several investigators (Degyansky, 1977; Stenstrom and Poduzka, 1980; and Stenstrom and Song, 1991). The relationship between nitrification, mixing intensity of the reactor, and DO concentrations was shown by Stenstrom and Song (1991). Figueroa and Silverstein (1992) investigated the relationship between DO, nitrification, and soluble and particulate BOD in biofilm processes.

3.1 BIOLOGICAL DENITRIFICATION

Biological denitrification, referred to as denitrification, is the dissimilation pathway in which nitrates are biologically reduced to gaseous nitrogen-oxides (NO or N_2O) and /or nitrogen gas (N_2) according to the following pathway proposed by Payne (1973) (from Casey et al, 1992)

Oxidation

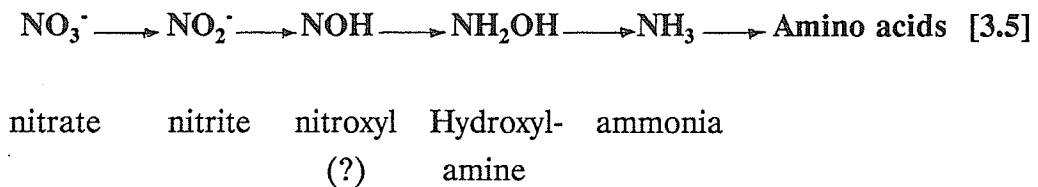
State +5 +3 +2 +1 0



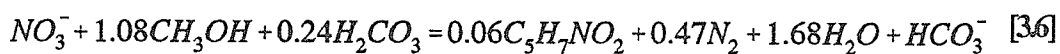
Another biochemical transformation that can remove nitrogen by nitrate reduction is the assimilation pathway in which nitrate is reduced to ammonia for satisfying anabolic needs of the microorganisms. This pathway can be represented by the following equation adapted from Grabinska-Łoniewska, (1991)

Oxidation

State +5 +3 +1 -1 -3

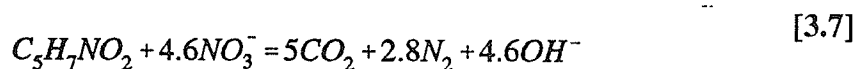


In Figure 1.1 nitrate assimilation was not included because: 1) it rarely occurs in wastewater treatment plant since the intensity of assimilation pathway is rather low (Grabinska-Łoniewska,1991); 2) it occurs when ammonia is not available (Randall et al, 1992); and 3) it occurs at high NO_3^- concentrations (Manahan, 1984) which is relatively low in municipal wastewater treatment plants. Hence, denitrification is the widespread biological method used in the NR. The biochemical equation that involves cell synthesis has been presented also in U.S.EPA Manual (1975) as follows



which indicates that one gram of nitrate-nitrogen that is reduced to N_2 requires 0.93 g of organic carbon, and 0.21 g of inorganic carbon. On the other hand, each gram of reduced nitrate-nitrogen produces: 0.48 g of new cell tissue, 0.94 g of nitrogen, 2.16 g of water, and 3.57 g of alkalinity as $CaCO_3$.

Nitrates may replace oxygen during endogenous respiration. The proposed reaction (from Sedlak, 1991) is



This biochemical expression also indicates that for one gram of reduced nitrate-nitrogen 3.57 g of alkalinity as $CaCO_3$ is produced. However, if endogenous nitrate respiration takes place, a depressing effect of the system on pH level may occur due to the 3.42 g of CO_2 produced for each gram of nitrate-nitrogen reduced, and the net alkalinity generated would drop.

As discussed previously, it was once thought that denitrification could only occur in absence of oxygen; however, Bremner and Blackmer (1978) have demonstrated that nitrification of ammonium ion and urea results in the production of N_2O by the action of many types of bacteria, including *Nitrosomonas europaea* (from Manahan, 1984). The production of nitrous and nitric oxides may be of some concern due to their participation in atmospheric chemical process which may

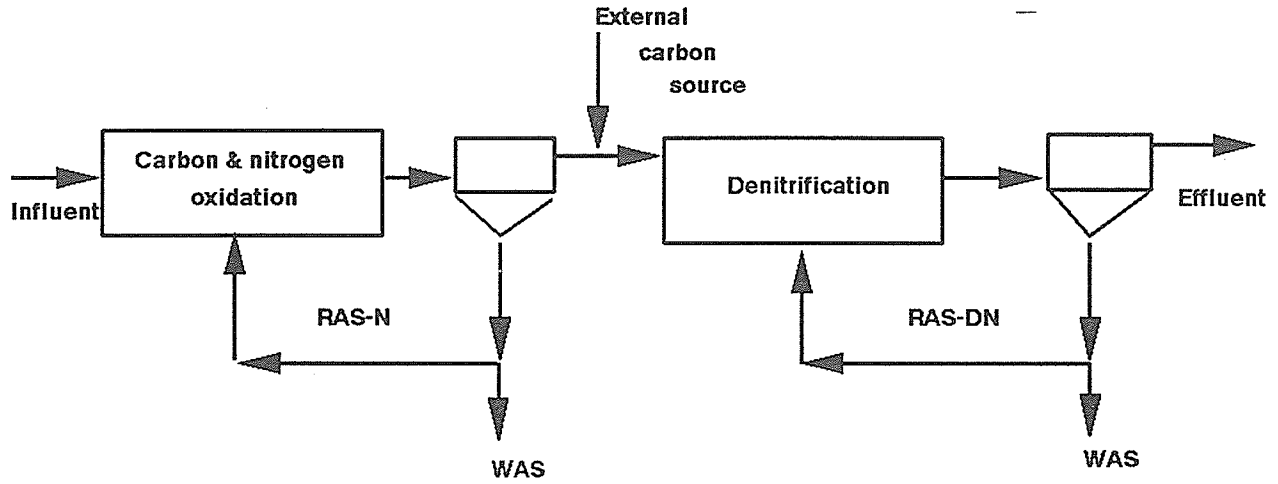
produce a depletion of the ozone layer (Manahan,1984).

As shown in equation 3.6, an organic source of carbon is required by the denitrifier bacteria. This source of carbon may be external i.e. methanol, or internal i.e. sewage. The presence of oxidized nitrogen is essential in denitrification, thus the denitrification process is always coupled with nitrification. In general, denitrification may be classified as a **single-sludge** or **two-sludge** system. The former system includes more than one stage and involves only one secondary clarifier, thus the settled biomass must recycle through all the stages. The carbon source in this scheme may be internal and external, while the two-sludge system requires an external source of carbon (Fig.3.3-I). The most common configurations of the single-sludge systems are the modified Ludzac and Ettinger (MLE), and the Bardenpho or four-stage biological nitrogen removal systems (Fig.3.3.II A and B). Like nitrification, pre-denitrification may be implemented in suspended-growth or attached-growth reactors, so that several configurations are used to remove nitrogen.

The biological kinetics of denitrification have been studied by many investigators. Some of their findings appear to be in contrast with each other. In the literature, the denitrification rate has been reported as a zero order reaction (Stensel et al, 1973; Bishop et al, 1976; Beccari et al, 1983; and Sedlak, 1991). However, Tam et al (1992) have demonstrated a substrate-dependence of the reduction of $\text{NO}_3\text{-N}$ using different carbon exogenous sources. According to a graph presented by these researchers, the denitrification rate was a zero order reaction only when methanol was the exogenous carbon source. On the other hand, when an internal carbon

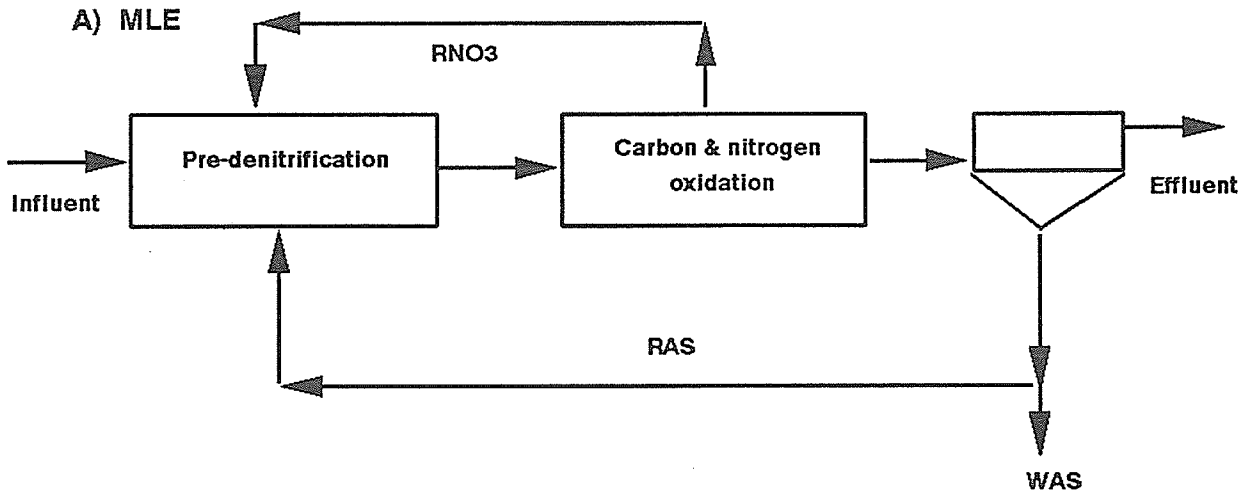
Fig.3.3: Denitrification systems

I) Two-sludge configuration

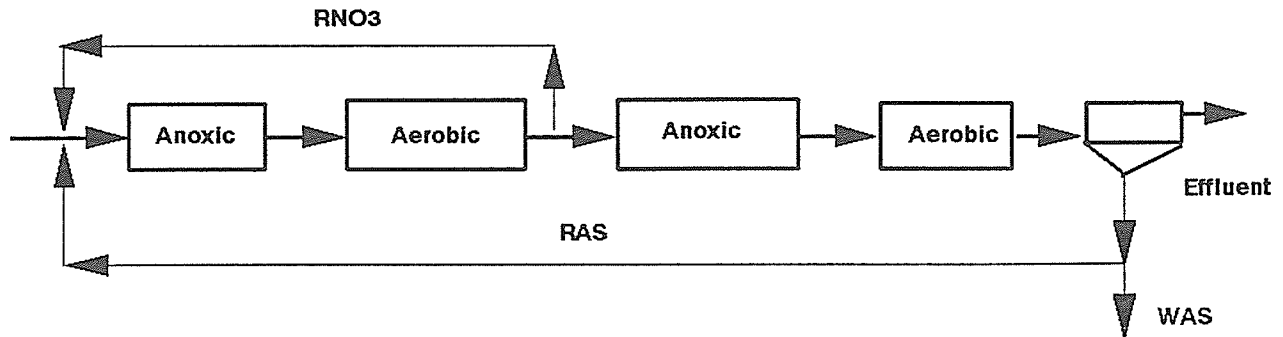


II) Single-sludge configuration

A) MLE



B) Bardenpho



source is used, the reaction is of an order other than zero, and the nitrification reaction rate depends on the easily degradable carbon concentration (Barnard, 1975; Sikora and Keeney, 1976; Argaman and Brenner, 1986; McCartney and Oleszkiewicz, 1990; and Wentzel et al, 1990).

Several environmental and operational factors affect the denitrification process such as pH, temperature, characteristics of the raw wastewater, HRT and SRT. The raw wastewater characteristics are important not only for the substrate and nutrient concentrations but also for the biomass present in the raw wastewater. Henze (1986) reported that the denitrifying activity varies considerably from one type of wastewater to another type, and from one type of activated sludge to another. Stensel et al (1973) stated that denitrifiers would be washed out of the system at SRT values of approximately 0.5 d at 20° and 30°C, and at an SRT value of about 2 d at 10°C. These investigators also noted that denitrification was affected slightly when the temperature decreased from 30° to 20°C; however, the biological activity decreased significantly when the temperature decreased to 10°C.

3.1.1 TWO-STAGE SINGLE-SLUDGE PRE-DENITRIFICATION (MLE)

A pre-denitrification system as that shown in Figure 3.4.II.A, consists of an anoxic reactor receiving primary effluent as carbon source, recycled sludge (biomass-RAS) and nitrified mixed liquor (electron acceptor). The pre-denitrification reactor is immediately followed by an aerobic reactor where the process of nitrification and carbon oxidation occur simultaneously. The characteristic features of the pre-

denitrification mode treatment are:

- Removal of raw wastewater BOD utilizing the oxygen bound in nitrates, thus decreasing the volume of oxygen required for subsequent carbonaceous and nitrogenous BOD removal.
- Production of alkalinity, thus increasing the buffering capacity of waste fed to the aerobic reactors.
- Decrease of the C/N ratio, thus improving nitrification and perhaps controlling filamentous organisms.
- Rates of denitrification lower than in the two-sludge systems.

The economics of nitrogen removal in a pre-denitrification mode were analyzed by Randall (1987) and by Brannan and Randall (1987). This researchers stated that by selecting the MLE system instead of a system achieving nitrification only, a big advantage from an economic point of view is gained. Ekama and Marais (1984) pointed out that a MLE system should be selected instead of a Bardenpho system when COD/TKN ratio is lower than 9.5 (From Brannan and Randall, 1987).

Jones et al (1980) studied the effect of the system solid retention time (SSRT or sludge age) on nitrogen removal using a MLE configuration. The aerobic-hydraulic retention time (HRT) was 5 h, and the anoxic HRT 2 h. They have assumed a zero order reaction for both nitrification and denitrification, and found that the nitrogen removal increased at higher SSRT at constant temperature. Henze (1987) reported that the fraction of denitrifiers is a function of three factors: 1) the

potential inlet fraction of denitrifiers, 2) the anoxic SRT, and 3) the SSRT. Casey et al (1992) proposed an hypothesis to explain the small growth of the low F/M filaments in the fully aerobic and fully anoxic conditions. Henze et al (1993) analyzed the effect of nitrate concentration and temperature on rising sludge episodes in the secondary clarifier.

There is evidence that single-sludge denitrification systems can achieve substantial reductions in oxygen requirements and high NR at nitrate recycle ratios ranging from 0 to 1 (Brannan and Randall, 1987). The effect of activated sludge recycle ratio on denitrification of a high ammonia concentration leachate has been study by Elefsiniotis et al (1989).

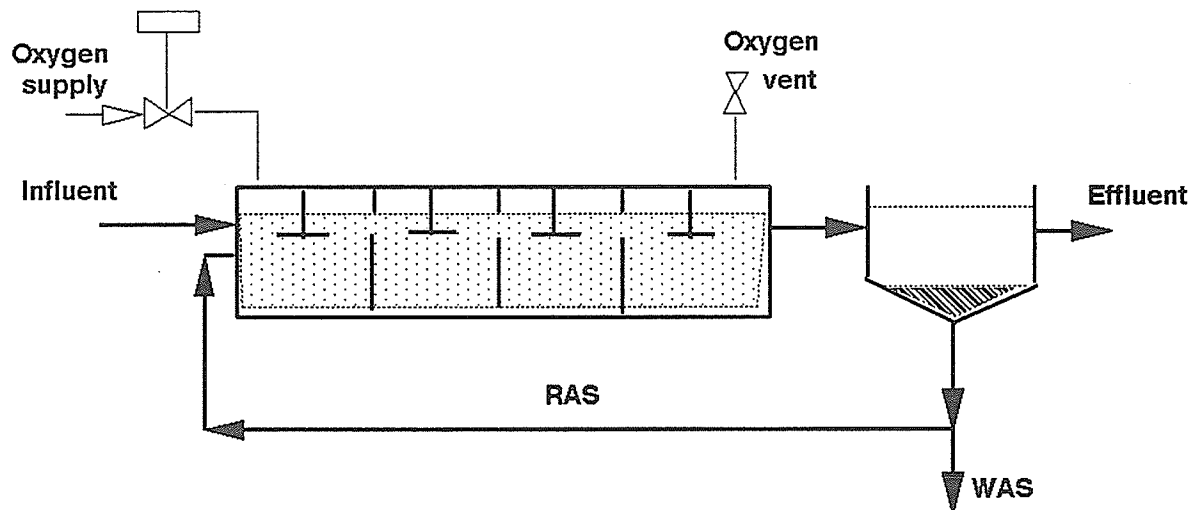
3.2 HIGH-PURITY OXYGEN ACTIVATED SLUDGE

High-purity oxygen activated sludge system (HOAS) uses high purity oxygen (90+ percent purity) in place of air to achieve biochemical oxidations. This system typically consists of covered and staged reactors as shown in Figure 3.4. HOAS operates at a lower pH level than conventionally aerated systems because the O₂ that enters the first stage is reused in the subsequent stages, resulting in the buildup of CO₂ released due to biological activity. Model predictions indicate a pH drop in the fourth stage of HOAS from approximately 6.5 to below 6.0 when the influent bicarbonate alkalinity decreases from 400 to 100 mg/L, and the influent pH is maintained constant at 7.2 (Cliff and Andrews, 1986).

Several studies compared the efficiency of carbonaceous BOD removal and

performance of the ASP and HOAS since the Union Carbide Corporation (UCC) developed the high-rate HOAS called UNOX in the late 1960's. The benefits of such systems compared to conventional ASP have been extensively discussed elsewhere (Kalinske, 1976; Chapman et al, 1976; Parker and Merrill, 1976; Blachford et al 1982; and Nelson and Puntteney, 1983).

Fig.3.4: High-purity oxygen activated sludge



The decrease in pH in the HOAS appears to be a disadvantage of this process, mainly if nitrification needs to be implemented. Nitrification in HOAS has been investigated by Stankewich (1972), Heidman (1975), Braunscheidel and Gyger (1976), and Toms et al (1982).

Stankewich (1972) analyzed single and two-stage carbon oxidation and nitrification systems using high purity oxygen as the aerating gas. In the single-stage system, complete and consistent nitrification was achieved at pH of 5.8 - 6.0 with SRT of 6 d; pH acclimation was noted in both systems. Heidman (1975) investigated the effect of low pH on nitrification in a separate stage process using HOAS with and without pH control, and separate stage nitrification with ASP and HOAS controlled at pH level of 7, at Blue Plains treatment plant (from U.S.EPA, 1975). This work demonstrated that the pH of the nitrification could drop as low as 6.0 with attainment of complete nitrification.

Braunscheidel and Gyger (1976) reported that the single-stage nitrification HOAS operating at HRT from 2.5 to 3.5 h at Pensacola, Florida, produced an effluent with an average ammonia concentration of 2 mg/L. The authors recommended the single-stage nitrification HOAS for low strength wastewater which is relatively free of toxic materia.

Toms and Booth (1982) have investigated whether nitrification could be achieved by raising the pH value in the oxygen reactor. They added sodium hydroxide to the recycle sludge to increase the pH value above 8.0. Results demonstrated that it was possible to achieve complete nitrification even at SRT of only 3.5 to 5 d with a BOD loading of approximately 0.5 Kg/Kg.d.

The potential benefits of pre-denitrification using a single-stage HOAS nitrification has, to my knowledge, not been reported. However, pre-denitrification may be an essential tool to ensure nitrification. Moreover, pre-denitrification would

be an advantageous choice for retrofit HOAS processes when NR is required. In a nitrifying-denitrifying activated sludge, whether the raw wastewater enters a tank which is under aerobic or anoxic conditions is important since it is reasonable to assume that if the easily degradable carbon is removed under anoxic conditions, the result would be a good production of denitrifying biomass (Henze, 1986). On the other hand, the denitrification activity to the oxygen activity in pure oxygen plant was found to be relatively low by Henze (1986). Consequently, it may be assumed that denitrification of a ML from two-stage HOAS nitrification would be difficult to attain.

CHAPTER 4: MATERIALS AND METHODS: PROCESS OPERATION AND CONTROL

The aims of this chapter are to describe the operations and process controls applied to promote the growth of the bacterial populations responsible for assimilating, oxidizing and stabilizing the carbonaceous and nitrogenous organic matter as well as the inorganic compounds of NEWPCC's primary effluent (PE).

This chapter presents the background data, the characteristics of PE and mixed liquor (ML) and the experimental approach. The bulk of the raw data used for the graphs and tables presented in this chapter is enclosed in Appendix A.

4.0 EXPERIMENTAL DESIGN

The study was carried out at the site of NEWPCC's final clarifiers, where the plant personnel provided all hookups, including the supply of PE and pure oxygen. The PE, i.e. the raw wastewater of the pilot plant, was fed into a stirred equalization tank in an attempt to even out the hourly quality fluctuations. Figure 4.1 shows a general photograph of the whole arrangement, while figures 4.2 through 4.4 show the individual arrangement of the treatment trains. Three parallel treatment trains were installed: Train A, Train B, and Train C. Trains A and C were designed in the modified Ludzac-Ettinger mode (MLE), herein named Pre-Den because the aerobic zone is created by applying pure oxygen rather than air.

The hydraulic retention time (HRT), solid retention time (SRT), and the recycle ratio (defined as returned activated sludge plus returned nitrified ML divided

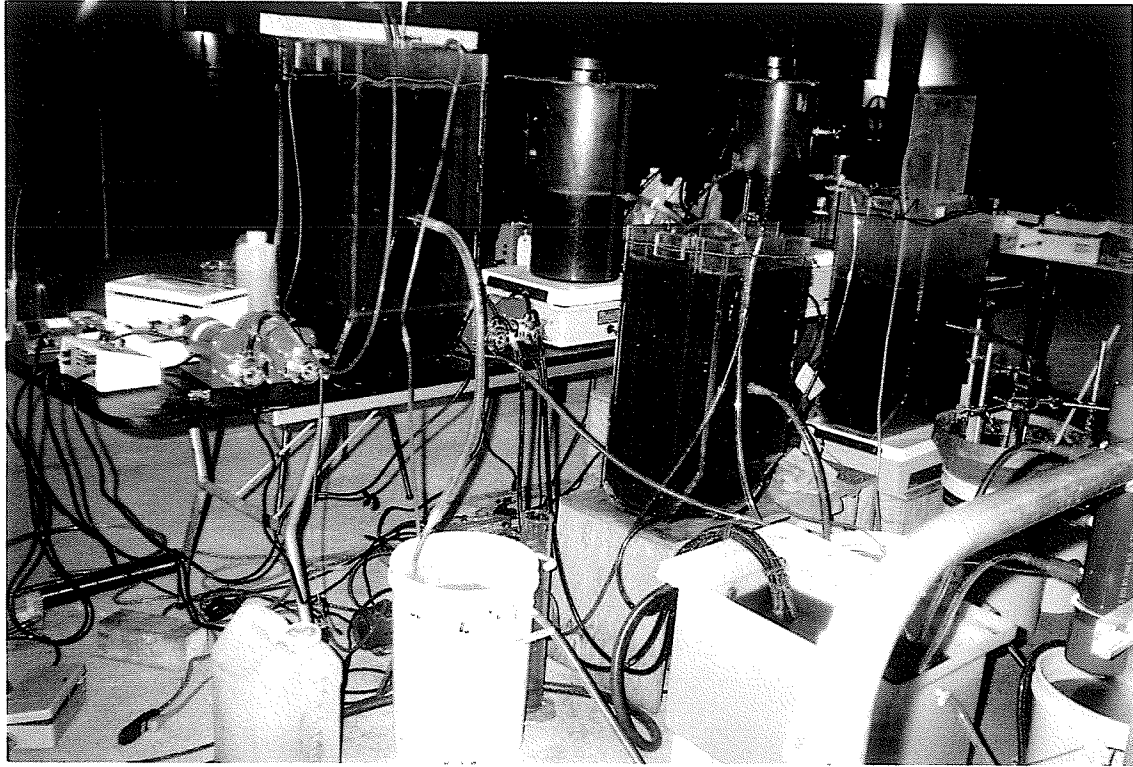


Fig.4.1 Photographs of the pilot plant at NEWPCC. Trains A, B, and C

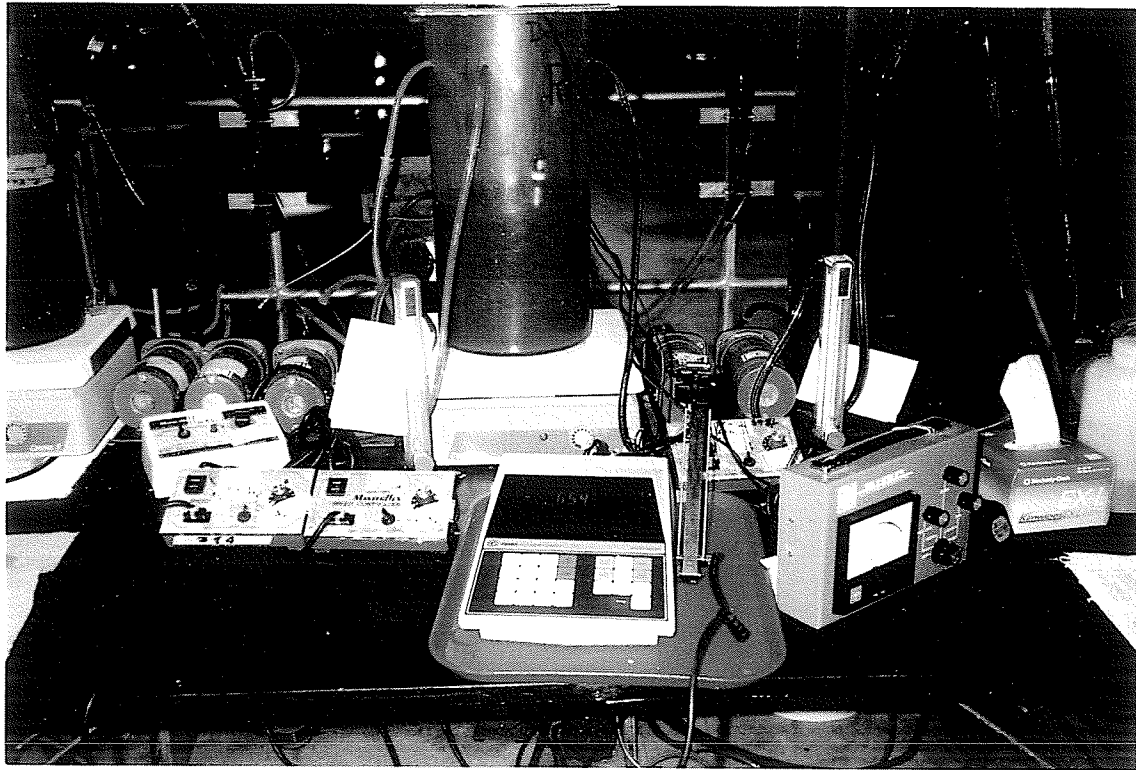


Fig. 4.2 PRE-DEN TRAIN A SCHEMATIC

$Q_{RAW} = 56 \text{ L/d}$

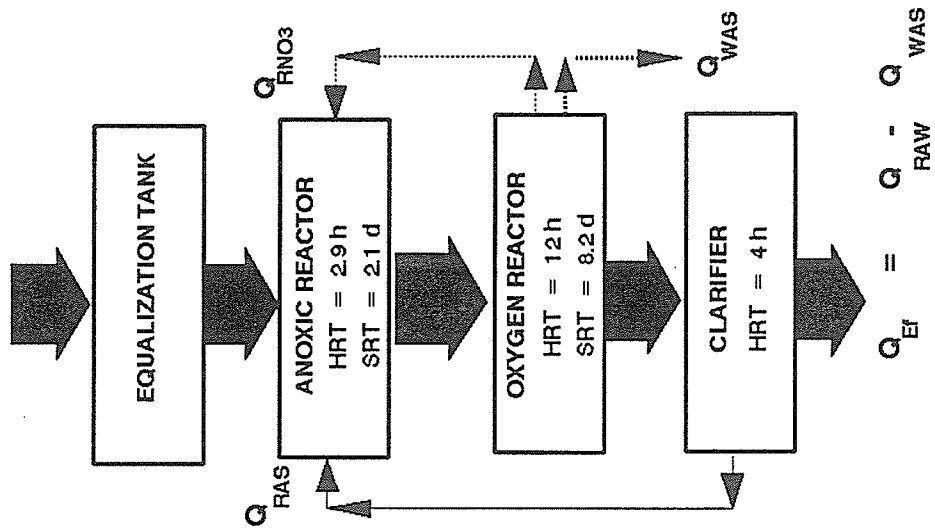
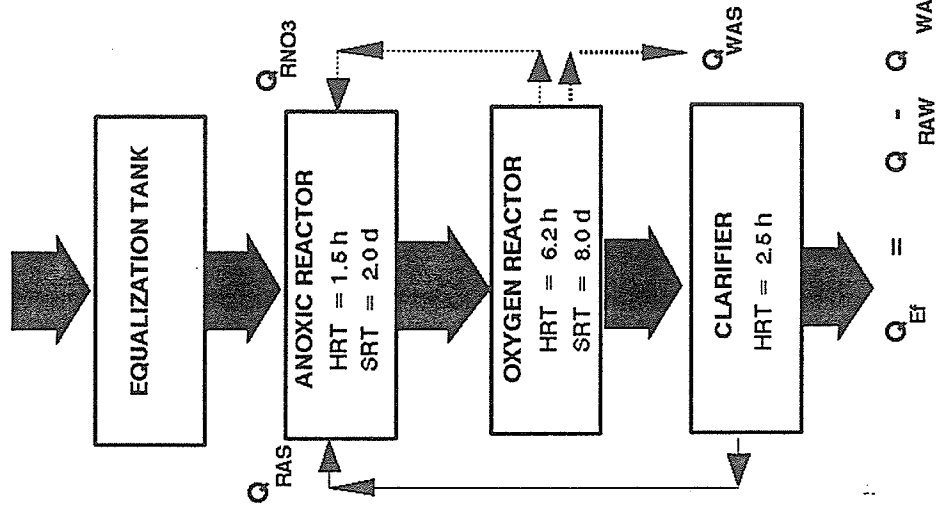


Fig. 4.3 PRE-DEN TRAIN C SCHEMATIC

$Q_{RAW} = 108 \text{ L/d}$

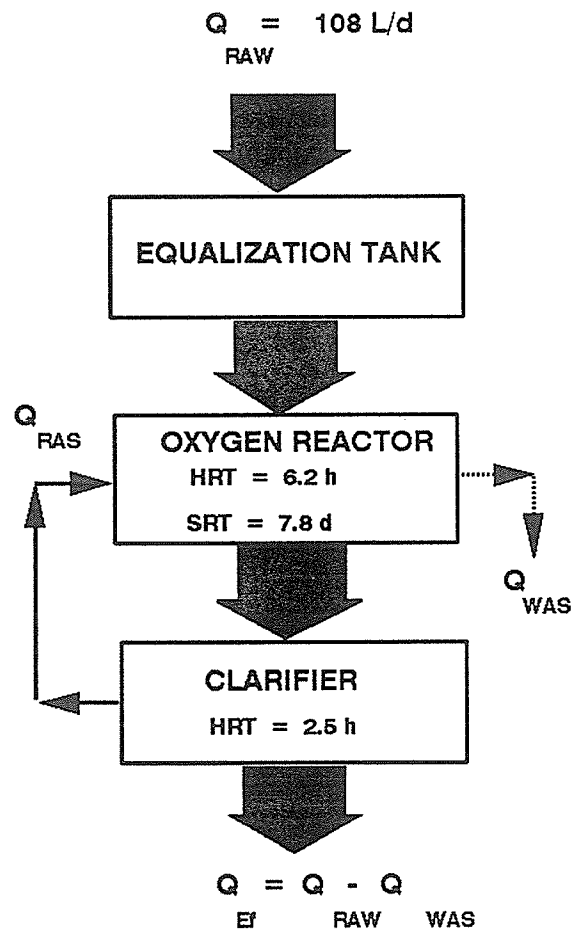


by Q_{Raw}) were determined using the kinetic coefficients from the literature and the characteristics of the NEWPCC's PE. The process design procedure applied in this study followed that of Metcalf and Eddy (1990) for combined nitrification-denitrification system. The parameters for the pre-denitrifying reactors were verified using the method described by De Renzo (1978).

The experimental design initially called for a comparison of Trains A and B: i.e., Pre-Den Train A and nitrifying Train B. The comparison was run at a SRT expected to effect complete nitrification (approx. 8 d) and at a prolonged HRT. Unfortunately, the oxygen HRT of the Pre-Den Train was twice the HRT of Train B because the HRT of former was referred by mistake to the total influent flow entering the oxygen reactor (RII) instead of to the Q_{RAW} entering the Train A, as is customary (Metcalf and Eddy, 1990). However, we decided to maintain those conditions in Train A, to prevent bacterial washout. The third Train C, Pre-Den, with the same SSRT as Train A but with half the HRT (in both biological reactors) was thus installed. The decision taken was based on the fact that nitrification appears to depend not only on the SRT but also on the HRT. Braunscheidel and Gyger (1976) have reported that a single step nitrification in oxygen-activated sludge, operated at low organic loadings, resulted in relatively long HRT compared to the conventional carbonaceous removal process.

Poduzka and Andrews (1975) have operated a single-stage nitrification at SRT of 10 d and HRT of 11 h based on raw wastewater plus the base (NaOH) used for pH control. Qasim et al (1990) have operated the nitrification reactor of a three-

Fig. 4.4 NITRIFICATION TRAIN B SCHEMATIC



stage treatment system at HRTs range between 4.9 and 6.3 h based on Q_{RAW} .

4.0.1 PILOT TREATMENT TRAIN OPERATION

The raw wastewater from the equalization tank was lifted by three parallel peristaltic pumps into Trains A, B, and C. The Pre-Den Trains (Fig. 4.2 and 4.3) consisted of an anoxic denitrifying reactor (RI, Train A or RIV, Train C) followed by the nitrifying reactor (RII, Train A or RV, Train C). The denitrifying reactors were magnetically stirred and covered with a solid cover which, although not fully air tight, eliminated air entrainment due to stirring. The reactors RI and RIV each received PE and recycled activated sludge (RAS) as well as recycled nitrate-rich ML (RNO_3) from the respective nitrifying RII or RV. The nitrifying Train B (Fig. 4.4) consisted of a plexiglass reactor in which the reaction zone (RIII) was separated from the clarifier by a baffle. The three oxygen reactors were unified reactors at first.

There were essentially three operational periods: the first period from days 0 to 47, when only two Trains A and B were operating, and the following two periods when all three trains were operated according to the schedule outlined in tables 4.1, 4.2, 4.3. The second period ran from day 48 to day 86, and the last one ran from day 87 to day 122 (Tables 4.2, 4.3).

Train C was initiated on day 40, and operated for 83 days. Therefore, day 0 for Train C corresponds to day 40 for Trains A and B, and day 83 corresponds to day 122. Trains A and B were started simultaneously, and were run for 122 days. They were seeded with sludge from the full scale control reactor rather than from the

Table 4.1: Design parameters for the First Period (From day 0 to 47).

	TRAIN A		TRAIN B
	RI	RII	RIII
HRT (h)	3.0	12.0	6.2
Q_{RAW} (L/d)	56.2	NA	108.0
Q_{RAS} (L/d)	$0.6Q_{RAW}$	NA	$0.6Q_{RAW}$
Q_{RNO3} (L/d)	$1.5Q_{RAW}$	NA	NA
Temperature °C	15	15	15

Table 4.2: Design parameters for the Second Period. (Day 48-86)

	TRAIN A		TRAIN B	TRAIN C	
	RI	RII	RIII	RIV	RV
HRT (h)	3.0	12.0	6.2	1.5	6.2
Q_{RAW} (L/d)	56.2	NA	108.0	108.0	NA
Q_{RAS} (L/d)	$0.8Q_{RAW}$	NA	$1.1Q_{RAW}$	$1.1Q_{RAW}$	NA
Q_{RNO3} (L/d)	$0.7Q_{RAW}$	NA	NA	$1.1Q_{RAW}$	NA
Temp.°C	15	15	15	15	15

nitrifying reactor. Tables 4.4, 4.5, and 4.6 describe the means of the operational parameters that were determined daily with the exceptions of SRT and sludge volume index (SVI). After the initial period with HRT (based on Q_{raw}) of 12 h in RII, Train C was started with a decreased HRT of 6.2 h. The concern here was to test alternative conditions for the Pre-Den process and not necessarily to duplicate the conditions existing at NEWPCC.

Table 4.3: Design parameters for the third period. Note: the HRT and Q_{RAW} are the same as those of the other periods).

	TRAIN A		TRAIN B	TRAIN C	
	RI	RII	RIII	RIV	RV
Q_{RAS} (L/d)	$0.4Q_{RAW}$	NA	$1.1Q_{RAW}$	$1.0Q_{RAW}$	NA
Q_{RNO3} (L/d)	$0.5Q_{RAW}$	NA	NA	$0.7Q_{RAW}$	NA
Temp.°C	15	15	15	15	15

4.0.2 PROCESS CONTROL

The process control was implemented in order to accomplish high levels of treatment performance: complete nitrification in RII, RIII, and RV, and complete denitrification in RI and RIV. The main factors controlled throughout the experiment were:

- 1) Waste Activated Sludge (WAS),

2) pH, and

3) Dissolved Oxygen (DO).

Table 4.4: Operational parameters in the nitrifying Train B.

PERIOD #	SRT d	SVI ml/g	HRT d	Q_{RAW} L/d	Q_{RAS} L/d
I (±SD)	6.08 (1.31)	217.06 (82.60)	0.26 (0.003)	107.97 (1.22)	68.39 (21.37)
II (±SD)	8.80 (1.77)	80.95 (38.59)	0.26 (0.005)	107.37 (1.89)	120.64 (7.88)
III (±SD)	8.61 (1.23)	64.29 (19.02)	0.26 (0.003)	108.17 (1.12)	104.41 (6.60)

4.0.2.1 WAS Control

The aim of the WAS control was to achieve the design nitrifying SRT of 8 d, and, indirectly, to maintain an appropriate settling characteristic of the sludge as described by the SVI of lower than 150 mL/g. Randall et al (1992) have stated that a typical SVI for a well-operated biological phosphorous removal system is 50 mL/g, and that the addition of nitrogen removal will typically increase the SVI to about 120 mL/g. Initially, the hydraulic control of sludge age proposed by Garret (1958), and modified by Burchett and Tchobanoglous (1974) was applied. According to Benefield et al (1975), Burchett and Tchobanoglous (1974) introduced the volume

Table 4.5: Controlled operational parameters Pre-Den Train A.

PE RI OD #	SRT (d)		SVI (mL/g)		HRT (h)		Q RAW (L/d)	Q RAS (L/d)	Q RNO ₃ (L/d)
	RI	RII	RI	RII	RI	RII			
I mean ±SD	1.64	6.57	121	136	3.02	12.15	55.3	32.5	79.6
	0.40	1.62	26	54	0.06	0.25	1.1	4.0	12.5
II mean ±SD	2.23	8.91	92	84	2.99	11.97	56.2	63.0	50.6
	0.34	1.37	21	18	0.03	0.13	0.6	10.7	12.6
III mean ±SD	2.05	8.19	109	88	2.98	11.92	56.4	63.7	41.4
	0.33	1.30	32	20	0.03	0.14	0.7	20.1	19.7

Table 4.6: Controlled operational parameters Pre-Den Train C.

PE RI OD #	SRT (d)		SVI (mL/g)		HRT (h)		Q RAW (L/d)	Q RAS (L/d)	Q RNO ₃ (L/d)
	RIV	RV	RIV	RV	RIV	RV			
II mean ±SD	1.95	7.79	65	69	1.50	6.17	109.0	109.6	117.6
	0.15	0.61	13	32	0.06	0.10	1.7	28.7	26.2
III mean ±SD	2.06	8.24	53	53	1.54	6.21	108.3	113.2	70.6
	0.19	0.76	9.61	5	0.03	0.04	0.76	8.4	9.3

of clarifier in the determination of SRT using the Garret's equation. The hydraulic control of SRT is one of the two forms of static control in which the SRT and F/M are controlled by flow of WAS (Vaccari and Christodoulatos, 1989). As the SRT and SSRT were controlled by wasting the mixed liquor suspended solids (MLSS) directly from reactors II, III, and V into volumetric containers, the WAS flow in the nitrifying Train B was determined from day 10 until day 30 as:

$$Q_{WAS} = \frac{V_N + V_C}{SRT} \quad [4.1]$$

in which the solids lost in the effluent are neglected, and

Q_{WAS} = Flow of wasted activated sludge, L/d

V_N = Volume of nitrifying reactor RIII, L

V_C = Volume of clarifier, L

SRT = Solid retention time of Train B, d

For the Pre-Den Train the following equation was used

$$Q_{WAS} = \frac{V_{DN} + V_N + V_C}{SSRT} \quad [4.2]$$

in which the effluent VSS was also neglected and

V_{DN} = Volume of denitrifying RI (Train A), L

V_N = Volume of nitrifying RII (Train A), L

SSRT = System solid retention time of Train A, d

The SSRT represents the addition of the SRT in RI plus the SRT in RII. The SRT was split in proportion to the volume of the respective reactor, according to Jones et al (1980). The formula applied for its determination was

$$SSRT = \frac{MMLVSS * V_{DN-N}}{WVSS * Q_{WAS} + EVSS * Q_{Ef}} \quad [4.3]$$

in which

MMLVSS = mean VSS in the predenitrifying train, mg/L

V_{DN-N} = Denitrifying-reactor volume plus nitrifying-reactor volume, L

WVSS = VSS concentration in the WAS that, in this case, is equal to MLVSS concentration in the nitrifying reactor, mg/L

EVSS = VSS concentration in the effluent

Q_{Ef} = effluent flow rate = $Q_{RAW} - Q_{WAS}$

If $EVSS * Q_{Ef}$ is neglected equation 4.3 becomes

$$SSRT = \frac{MMLVSS * V_{DN-N}}{WVSS * Q_{WAS}} \quad [4.4]$$

In equations 4.3 and 4.4, the volume of clarifier was not considered, following the proposals of Stern and Marais (1974), and Jones et al (1980) that nitrification

does not take place in the clarifier. Equations 4.3 and 4.4 differ from those proposed by these researchers in the following ways:

- 1) Equation 4.3 and 4.4 considered volatile suspended solids instead of SS
- 2) Equation 4.4 neglects the solid lost in effluent, and
- 3) The WVSS is assumed to be equal to MLVSS of the nitrifying reactor since the sludge is wasted from it. This assumption was validated by determining the VSS not only in the ML but also in the WAS.

On day 31, in order to unify criteria, we decided to consider only the volume of the nitrifying reactor, and the SRT in the nitrifying Train was determined by

$$SRT = \frac{MLVSS * V_N}{MLVSS_N * Q_{WAS} + EVSS * Q_{Ef}} \quad [4.5]$$

in which

MLVSS = VSS in the nitrifying reactor, mg/L.

and the SSRT in the Pre-Den trains was determined by

$$SSRT = \frac{MMLVSS * V_{DN-N}}{MLVSS_N * Q_{WAS} + EVSS * Q_{Ef}} \quad [4.6]$$

These equations were applied from day 31 and until the end of the experiment. If the SRT or SSRT had not been equal to the values expected to produce complete nitrification (SRT = 8d, SSRT = 10d), the equations were solved for the Q_{WAS} to correct it afterwards. The solids control operations were done three times a week.

4.0.2.2 pH CONTROL

Since one of the objectives of this study was to demonstrate the feasibility of Pre-Den process to alleviate the expected problems with pH decrease due to H^+ production and alkalinity decrease in the process of nitrification, pH in the Pre-Den Trains A and C was recorded, not modified. However, the pH level in the control nitrifying reactor RIII was manually maintained at 6.6.

4.0.2.3 DO CONTROL

To assess the feasibility of attaining pre-denitrification under conditions of high oxygen levels in the aeration tank and of high DO in the return liquid streams (RNO_3) fed to the Pre-Den reactor, we tested alternative conditions for the Pre-Den process by decreasing the RNO_3 in the last two operational periods as shown in Tables 4.1, 4.2, and 4.3. Since the flow of pure oxygen was adjusted to maintain a DO level of 4 mg/L as the lowest level in the ML of RII, RIII, and RV, no limitation of the nitrification process due to DO concentration and reactor mixing intensity was expected. However, limitation of the denitrification process could occur as oxygen respiration prevails when oxygen and nitrate are present.

4.1 DAILY OPERATION AND SAMPLING PROGRAM

At the start of the investigation, the pilot treatment Trains were monitored and sampled once a day, 7 days a week (except for the first week when it was measured 6 days a week). The on-site daily monitoring included temperature, DO,

pH, and influent, effluent, recycle, and WAS flow rates. Other parameters analyzed daily on the raw wastewater (RAW or PE) and on the effluent samples such as soluble organic carbon (SOC), nitrogen species and phosphorous were performed in the laboratory of the U of M. The samples were preserved and stored in accordance with recommendations of the Standard Methods for the Examination of Water and Wastewater, 1989 (APHA or Standard Methods). PE suspended solid (PESS), PE volatile suspended solid (PEVSS), MLSS, MLVSS, ESS, EVSS concentrations, and SVI were determined several times a week, sometimes at the NEWPCC and sometimes at the University laboratory.

When complete nitrification was achieved for more than ten consecutive days, some of the chemical and biological parameters were monitored according to Table 4.7, which is a summary of the sampling program and analyses performed. The on-site daily monitoring was maintained throughout the experiment. Biological oxygen demand (BOD_5), and alkalinity were tested on the raw wastewater sample and on the effluent samples from day 19. At the beginning both analyses were performed once a week; however, alkalinity started to be tested three times a week on day 75. On day 22, SOC, nitrogen species, and phosphorous, were also tested in samples of influent to Pre-Den reactors and in effluent from these reactors three times a week in accordance with the schedule of Table 4.7. RAS suspended solid and volatile suspended solid concentrations as well as those of WAS were also determined on that date.

Measurements of oxidation-reduction potential (ORP) were started almost at

Table 4.7: Sampling and analysis schedule.

Parameters	Sun	Mon	Tues	Wed	Thu	Fri	Sat
SS & VSS*	+	x	+	x	+	x	+
SVI**	+	x		x		x	+
MO**	+	x	+	x	+	x	+
SOC		x		x		x	
TKN		x		x		x	
NH ₃ -N		x		x		x	
NO _x -N		x		x		x	
PO ₄ -P		+		+		+	
BOD ₅ *				x			
Alk.		+		x		+	
OUR**			+		+		
ORP**	+	+	+	+	+	+	+

x: sampling schedule throughout whole experiment.

+: sampling schedule during the first, second, and / or third operational period.

*: analyses performed on the same day of sampling.

** : analyses performed at NEWPCC on the same day of sampling.

the end of the second period on day 72. Initially, the measurements were done on grab samples and on reactor, once a day. After that, the ORPs were analyzed only on reactor for long period of time, and finally, they were recorded continuously on

RI and RIV for several days, and for a couple of days in the oxygen reactors RII and RV. Towards the end of the study, oxygen uptake rates (OUR) on RII, RIII, and RV as well as the denitrification rates and SOC rates on the Pre-Den reactors were assessed in batch experiments.

4.2 ANALYSES

All samples of PE, influent, and effluent drawn for determination of SOC, BOD₅, phosphorous, and full nitrogen spectrum with the exception of the TKN samples were vacuum filtered through a 0.45 μm glass microfibre filter (Whatman 934-AH) to remove particulate matter. Those samples were analyzed in accordance with the following analytical techniques:

The SOC were measured using a Dohrmann DC-80 Total Organic Carbon Analyzer equipped with an ultraviolet detector according to technique 5310 C (Standard Methods, 1989);

The BOD₅ analyses were performed by using the technique described in Standard Methods under number 5210 B;

The orthophosphate determinations were conducted according to technique 4500-P D of APHA (1989);

The TKN and NH₃ concentrations were monitored using an Tecator DS 20-1015 Digester, Kjeltac Auto Analyzer, and Exhaust System Scrubber following the revised TKN and NH₃ analysis. These procedures are based on the standard methods 4500-Norg, and on the titrimetric method described under technique 4500-

NH₃ in APHA (1989);

The oxidized nitrogen (nitrite plus nitrate) was tested according to the automated cadmium reduction technique 4500-NO₃ F using a Technicon Auto Analyzer II; and

Suspended solids and volatile suspended solids concentrations were assessed in accordance with the gravimetric analyses described in the Standard Methods under number 2540 D and 2540 E, respectively.

pH and temperature of the reactors contents were monitored using a glass electrode, and a mercury bulb thermometer in accordance with APHA.

The dissolved oxygen (DO), oxygen uptake rate (OUR), and specific oxygen uptake rate (SOUR) were assessed using a probe with an oxygen-sensitive electrode as specified in Standard Methods (1991).

The microscopic observation (MO) number, a subjective parameter that enumerates the filament abundance in the floc structure, was performed according to the examination procedure described in the summary report prepared for U.S. Environmental Protection Agency (U.S. EPA, 1987). Using a phase contrast or normal light microscope at 100x magnification, the floc is viewed to determine the MO number (Marstaller, 1992).

The sludge volume index (SVI) was assessed from sludge volume after 30 min of settling (SV) on ML volumes of 100 mL (King and Forster, 1990; Marstaller, 1992; and Urbain et al, 1993). As the term SVI has many different meanings (Randall et al, 1992), it should be noticed that in this study SVI in mL/g refers to

the ratio between SV and the dry matter content (MLSS) of the sludge. Randall, et al (1992) presented a brief and excellent argument about the need to standardize the SVI procedure. Lee et al (1983) and Koopman and Cadee, (1983) discuss further this important parameter, but a detailed discussion of their work is beyond the scope of this study.

The ORP was monitored using a platinum combination electrode manufactured by Fisher Scientific. The metallic electrodes were calibrated in accordance with the proposed technique 2580 of APHA (1991).

4.3 NEWPCC'S PRIMARY EFFLUENT: Raw wastewater fed to the pilot plant

The process operation, control, and performance of the treatment Trains investigated were dependent upon the fluctuations of the composition, concentration, and stream flows entering and leaving the reactors. As mentioned previously, the use of peristaltic pumps and equalization tank prevented the raw wastewater flow rate (Q_{RAW}) variations, so that a nearly constant Q_{RAW} was achieved in every one of the treatment trains as shown in Tables 4.4, 4.5, and 4.6. However, the constituent concentration dampings were not accomplished due to failure of the equalization tank. Therefore, the pilot plant's raw wastewater composition and concentration variations reflected the dynamic fluctuations of NEWPCC's PE in the real field.

A summary of the statistical characteristics for PE is provided in Table 4.8, and 4.9. The statistical analyses were determined using the procedure illustrated by Metcalf and Eddy (1990) and using the sample-statistic functions of Quatro Pro 3.0

Table 4.8: Raw wastewater characteristics

mg/L*	First period		Second period		Third period	
	Median	Range	Median	Range	Median	Range
NH ₃ -N	20	7-38	22	9-39	23	11-39
TKN	32	11-63	32	15-54	32	18-54
TN	32	11-63	32	15-54	32	18-54
SOC	63	24-112	76	50-100	78	49-110
BOD ₅	93	90-100	92	50-120	122	120-130
Alk.	260	210-310	229	190-280	264	120-340

*: All the nitrogen species are expressed as mgN/L, and alkalinity (Alk.) as mgCaCO₃/L.

which were used in all statistical analyses (ie.: Tables 4.4, 4.5, and 4.6). Figures 4.5, and 4.6 are closed examples of probability graphs plotted for the constituents of PE in each operational period to determine the median value of 36 observations in the first period, 15 observations in the second period, and 16 observations in the last one. BOD values are the result of 5 observations in each of the three periods. Alkalinity data are average values of 5 observations in the first period, seven in the second period, and 16 in the last one. The complete data for NH₃-N, TKN, SOC, and the

Fig.4.5 Probability plot of NH3 in PE
First operational period

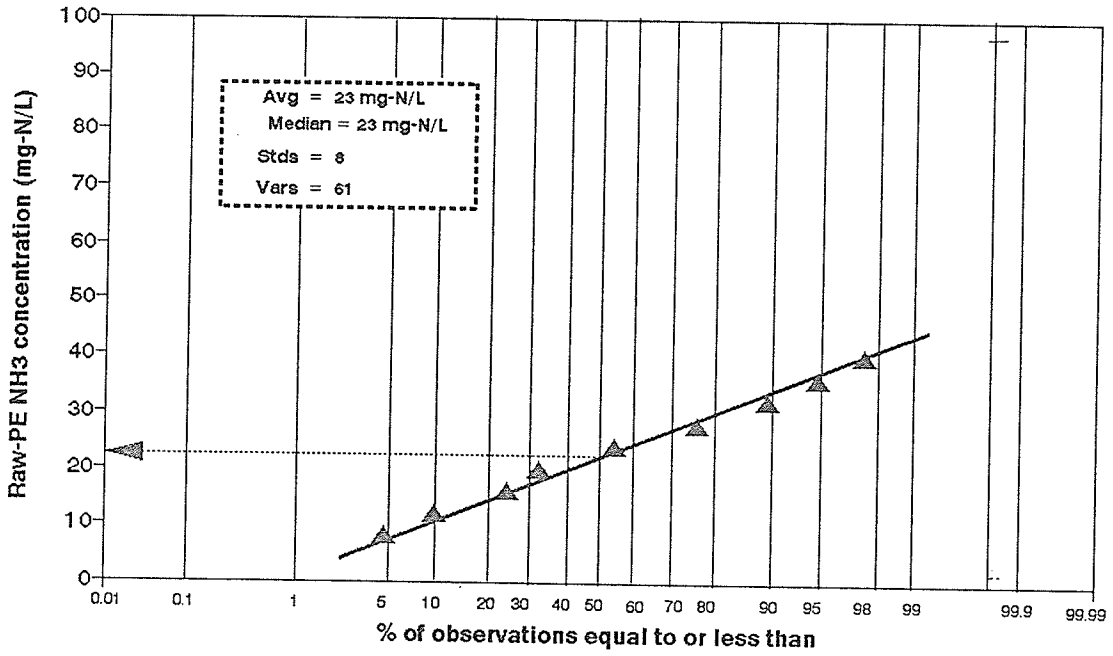
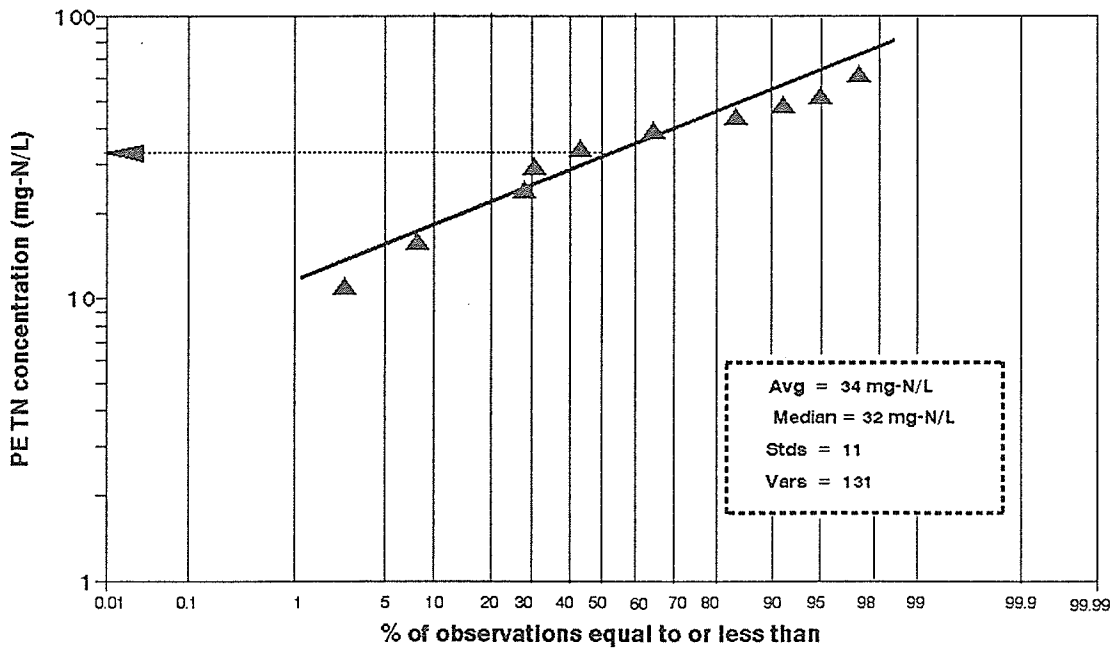


Fig.4.6 Probability plot of TN in PE
First operational period



relationships between organic carbon and total nitrogen (C/N) can be found in Tables A.7, A.8, and A.9, in appendix A. A correlation factor between BOD₅ and SOC was derived from BOD₅ and SOC analyses of the PE. The correlation coefficients found were 1.31, 1.18, and 1.42 for the first, second, and third period, respectively. The value of C/N based on BOD₅ was then obtained, and is reported in Table 4.9.

Table 4.9: C/N, pH, and temperature of NEWPCC'S PE (PE)

		First period		Second period		Third period	
		Mean	Range	Mean	Range	Mean	Range
C/N	SOC	2.00	1.13 - 3.45	2.62	1.37 - 5.89	2.18	1.65 - 2.56
	BOD	2.62	1.48 - 4.5	3.07	1.62 - 6.95	3.09	2.34 - 3.64
pH		NA	7-7.9	NA	7-7.6	NA	7.2-7.7
Temp.°C		NA	15-19	NA	17-21	NA	16-22

The low value of C/N was thought to be potentially significant in both processes: nitrification and denitrification since low concentration of carbonaceous organic matter enables the growth of nitrifying bacteria, (Hutton and La Rocca, 1975; Metcalf and Eddy, 1990). On the other hand, low concentrations of carbonaceous

organic matter hinders the denitrification rate. Randall et al (1992) stated that for successful biological nitrogen removal, the influent BOD_5/N ratio should be well above 4.0 to ensure that there is sufficient oxygen demand from the carbonaceous material to utilize the nitrate produced.

The stoichiometric requirement for carbon in denitrification is related to the quantity of nitrates to be reduced with the use of the sequestered electrons from the organic carbon present in raw wastewater (in this study PE). Using the analogy for methanol-supported denitrification in the two-sludge system the need, for the energy (catabolic), and cell synthesis (anabolic), is given by equation 3.6 which shows a minimum requirement of 0.93 gram of organic carbon, and 0.24 gram of inorganic carbon for one gram of nitrate-nitrogen removed.

The endogenous respiration-reaction (equation 3.7) also shows that for one gram of NO_3-N reduced 0.93 gram of organic C is required. It could be assumed therefore that 0.93 gSOC/g NO_3-N is the minimum requirement of organic carbon. Tables B.1 and B.2 (in appendix B) prove that SOC/ NO_3-N values in influent to RI and RIV, Pre-Den reactors, were above of the stoichiometric C/N based on SOC and nitrate but several times they were below of BOD_5/N suggested by Randall et al. (1992).

The mass loadings entering the treatment Trains in all three periods are summarized in table 4.10. They were determined based on the median value concentrations of specific constituents and the mean Q_{RAW} values reported in Tables 4.4, 4.5, and 4.6 since Q_{RAW} was nearly constant. The flow-weighted average

suggested by Metcalf and Eddy (1990) was used to determine the organic mass loading expressed in $\text{gBOD}_5/\text{gVSS}\cdot\text{d}$ to determine the sludge production afterwards, the average of BOD_5 mass loading was compared to the flow-weighted average. It was found that the former average was 8%, and 2% higher than the flow-weighted values in the first and second period, respectively, and no difference between both averages was found in the third operational period which validates the values reported in Table 4.10.

Table 4.10: Mass loading to the Pilot Treatment Plant

Mass loading g/d	First period		Second period			Third period		
	A	B	A	B	C	A	B	C
TN	1.77	3.46	1.80	3.44	3.49	1.80	3.46	3.47
SOC	3.48	6.80	4.27	8.16	8.28	4.40	8.44	8.45
BOD_5	5.14	10.04	5.17	9.88	10.03	6.88	13.20	13.21

CHAPTER 5: PROCESS PERFORMANCE, RESULTS, AND DISCUSSION

The following discussion intends to describe the process performance, and to present a summary of the experimental results and findings on which the stated conclusions are based. All of the original experimental data could not be attached because of space constraints; however, the most important to the discussion are contained in appendices A, B, C, and in the previous chapter.

5.0 PROCESS PERFORMANCE

Effluent quality, process efficiency, and ML characteristics will be used to illustrate the performance of the process in all three treatment Trains. Tables 5.1 through 5.3 present a summary of the composition and concentration of final effluents (Ef.A, Ef.B, and Ef.C, for Trains A, B, and C, respectively). Effluent BOD₅, SOC, NH₃, TKN, and alkalinity exhibited normal distribution, while NO₃, and total nitrogen (TN) fitted to a log-normal distribution. Figures 5.1 and 5.2 are examples of probability plots of the experimental results obtained in this experiment. Tables B.1 through B.9 report the effluent concentrations as well as the removal efficiencies measured in this study. Figure 5.3 shows a histogram of the performance of all three Trains. The TN entering the pilot plant was composed by organic nitrogen (N_{org}) and NH₃-N; their percentage in PE was variable. NH₃-N ranged from 45% to 85% of TKN. The high variations were caused by the wet summer with relatively low temperatures.

Table 5.1: Quality of the Predenitrified effluent from Train A. (Ef.A).

mg/L ¹	First Period		Second Period		Third Period	
	M	Range	M	Range	M	Range
NO ₃ -N	16	5-25	13	6-29	12	5-25
TKN	5	2-15	2	1-5	3	2-6
TN	21	12-36	16	8-34	18	9-28
SOC	20	14-29	22	18-26	20	17-26
BOD ₅	3	2-5	3	1-5	5	3-6
Alk.	110	80-180	110	90-150	140	100-200
pH	NA	7.2-8.1	NA	7.3-7.9	NA	7.5-7.9

Table 5.2: Quality of the Nitrified Effluent from Train B. (Ef.B).

mg/L ¹	First Period		Second Period		Third Period	
	M	Range	M	Range	M	Range
NO ₃ -N	20	7-40	25	13-39	25	15-39
TKN	4	2-15	2	1-6	3	2-5
TN	25	6-52	28	15-45	31	18-43
SOC	21	17-27	22	19-25	22	15-28
BOD ₅	3	3-7	3	3-5	4	3-10
Alk.	70	50-110	70	60-100	90	40-160
pH	NA	6.9-7.8	NA	6.8-7.8	NA	6.8-7.6

Table 5.3: Quality of the Predenitrified effluent from Train C. (Ef.C).

mg/L ¹	First Period		Second period	
	M	Range	M	Range
NO ₃ -N	14	3-29	12	9-24
TKN	3	1-6	3	2-4
TN	16	9-34	18	11-27
SOC	23	19-27	21	16-27
BOD ₅	4	2-7	5	3-7
Alk.	100	80-140	130	80-220
pH	NA	7.1-7.8	NA	7.3-7.8

1: All chemical parameters with the exception of pH are expressed in mg/L, the nitrogen species as mgN/L, and alkalinity (Alk.) as mgCaCO₃/L. M is the median value determined for that period.

The initial increase in ammonia in Trains A and B (seeded with non-nitrified ML) was probably caused by a combination of a predominance of organic nitrogen hydrolysis over NH₃ oxidation and a biological time lag during which a shift of microbial populations must have occurred due to longer sludge age (low food to microorganisms). This period of acclimatization for both Trains was ten days, after which the decrease of the ammonia nitrogen content produced in the effluents by ammonia oxidation to nitrate was substantial. This decrease in NH₃ coincided with a drop in effluent pH (Figures 5.21, and 5.24). In Train C, the biological time lag

Fig.5.1 Probability plot of SOC in Ef.C
 Second operational period

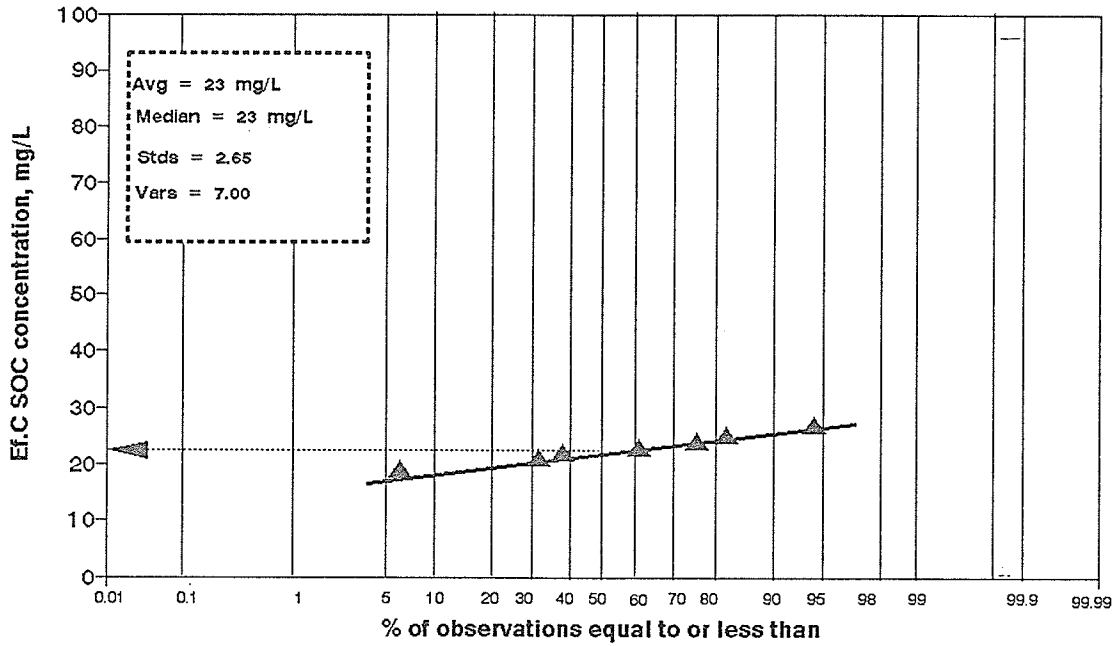
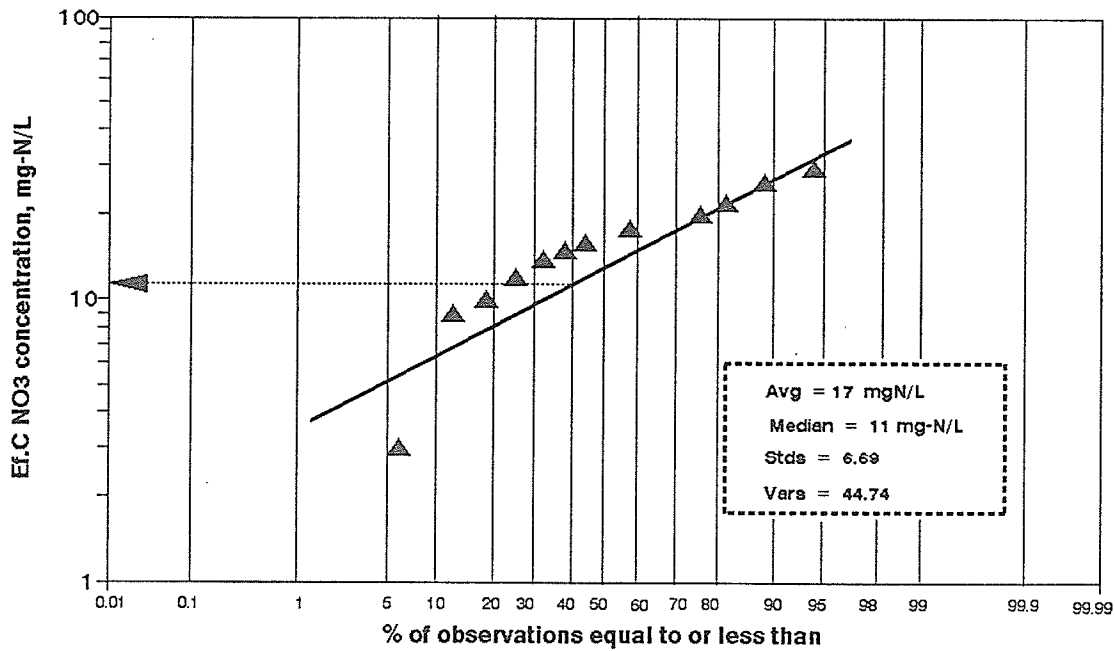


Fig.5.2 Probability plot of NO3 in Ef.C
 Second operational period



was as short as two days for nitrification because it was seeded with WAS from the other Trains which must already have had a good population of nitrifiers, and, to some extent denitrifiers. As Figures 5.3, 5.4, 5.5, and 5.6 show, a high level of treatment was achieved in terms of TKN, NH₃, SOC but not TN removal. A low TN efficiency in Train B was expected since it was the nitrifying Train where nitrogen conversion mainly took place, and nitrogen removal would have occurred by microbial assimilation in the excess biomass produced (12% normal presence of nitrogen in the live cell Eckenfelder et al, 1976) and, to some extent, by denitrification in the clarifier (15% according to Randall et al, 1992).

5.0.1 EFFICIENCY OF PILOT TREATMENT TRAINS

Overall removal efficiencies were calculated taking into account the simplified mass balance which results in the following general expression

$$E = \frac{S_{RAW} - S_{Ef}}{S_{RAW}} * 100 \quad [5.1]$$

where

E = overall removal efficiency of substrate (S), %

S_{RAW} = initial concentration of S, mg/L

S_{Ef} = substrate-effluent concentration, mg/L

The overall nitrification and denitrification efficiencies are discussed next because of their importance in this chapter.

Fig.5.3 Histogram of NH3 in all trains

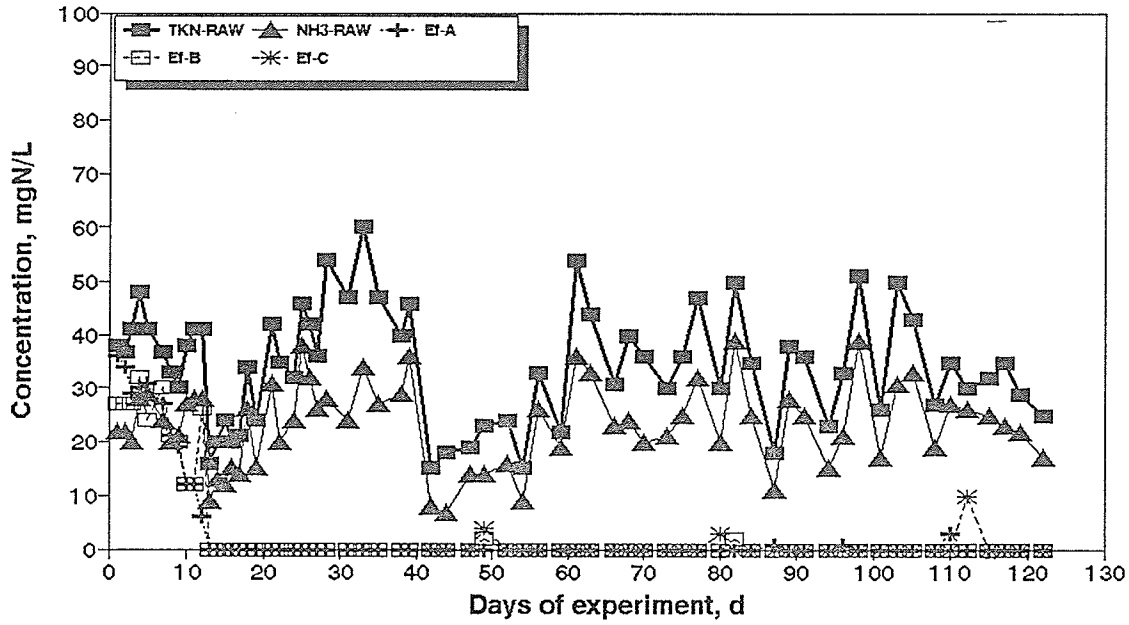
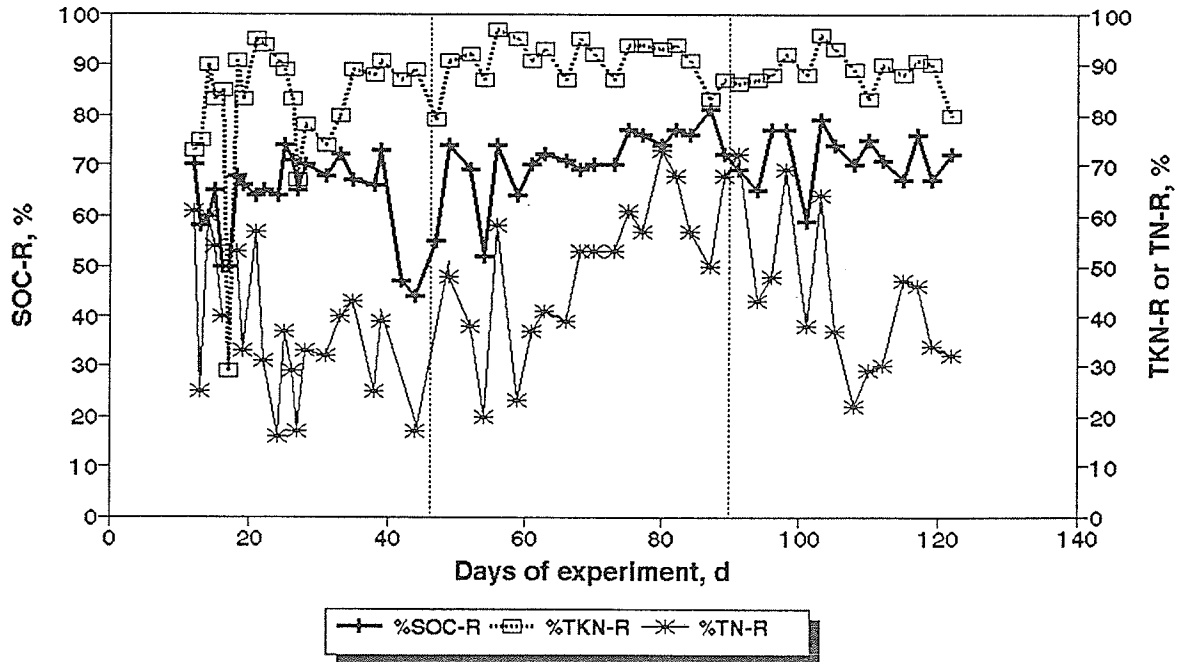
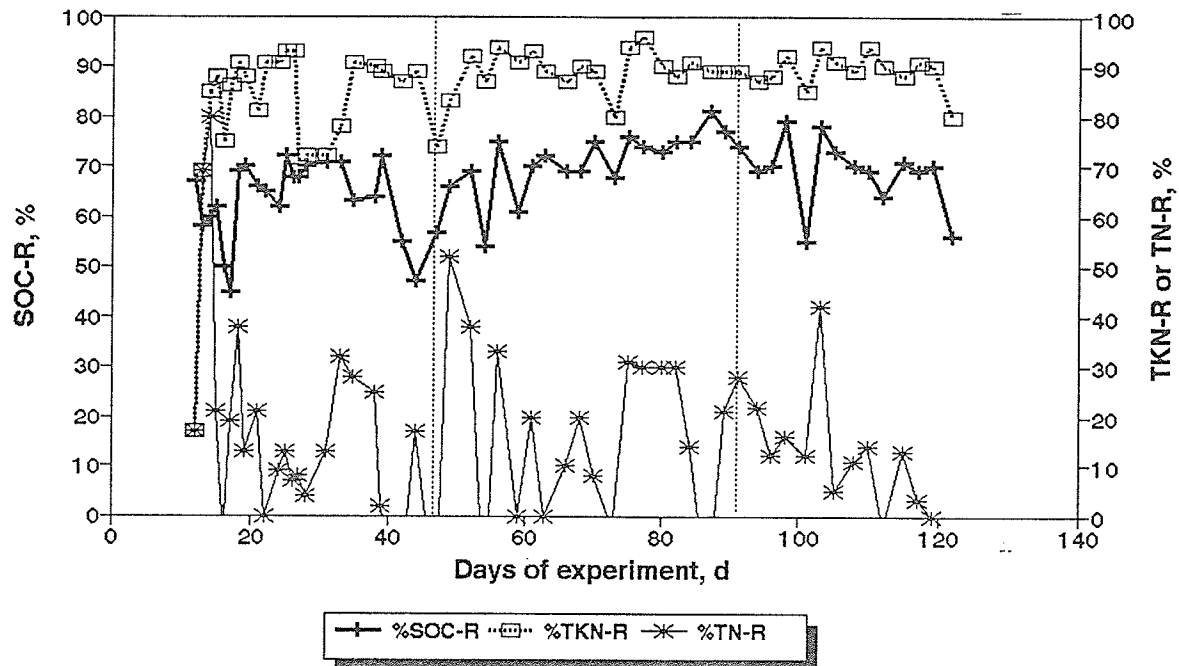


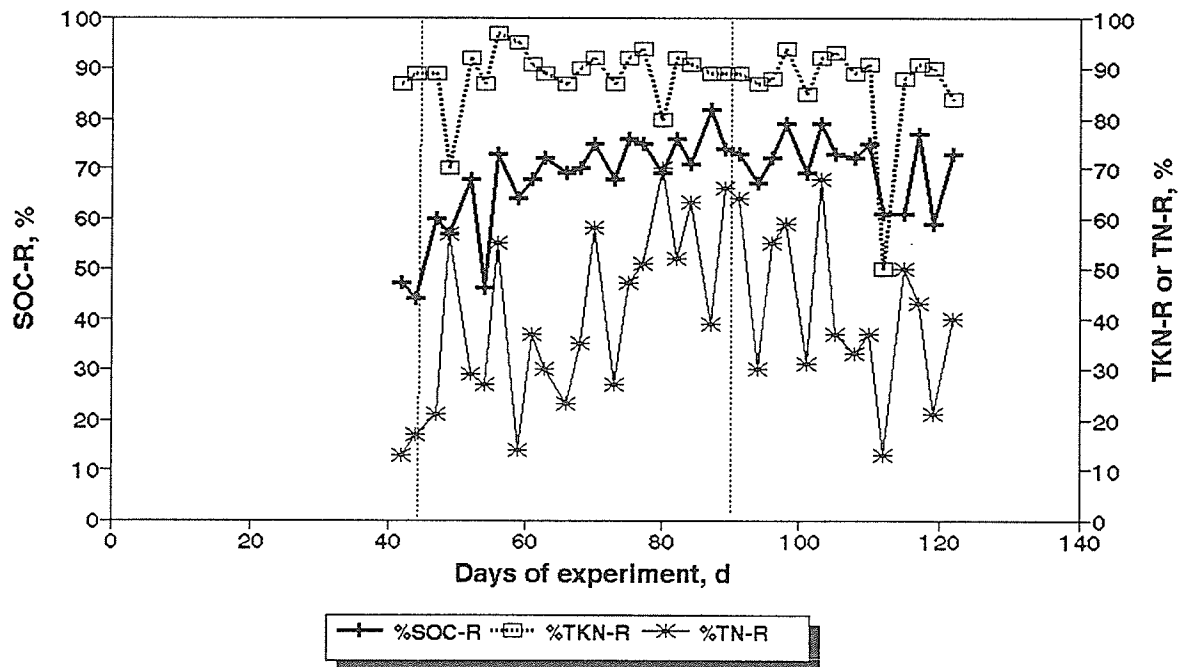
Fig.5.4 Removal Histogram In Pre-Den Train A



**Fig.5.5 Removal Histogram
In Nitrifying Train B**



**Fig.5.6 Removal Histogram
In Pre-Den Train C**



5.0.1.1 NITRIFICATION EFFICIENCY

Ammonia removal, an indicator of biological nitrification, not only includes $\text{NH}_3\text{-N}$ conversion to NO_3 , but also nitrogen incorporation into biomass during both anabolic and catabolic cell needs. In addition, organic nitrogen (N_{org}) and $\text{NH}_3\text{-N}$ realized during decay are considered. An example of the nitrogen mass balance considered is given in Figure 5.7 which was adapted from Oleszkiewicz and Berquist (1988). The N_{org} contained in the raw wastewater was mainly hydrolysed to NH_3 , increasing the ammonia entering the pilot treatment plant that needed to be oxidized. On the other hand, ammonia is a product of a biological process itself so that the initial concentration of NH_3 equal to TKN in the raw wastewater minus N_{org} in the effluent was considered such that equation 5.1 for ammonia removal efficiency (NH_3R) becomes

$$\text{NH}_3\text{R} = \frac{\text{TKN}_{\text{RAW}} - N_{\text{orgE}f} - \text{NH}_{3\text{E}f}}{\text{TKN}_{\text{RAW}} - N_{\text{orgE}f}} * 100 \quad [5.2]$$

where

TKN_{RAW} = TKN in raw wastewater, mgN/L

$N_{\text{orgE}f}$ = N_{org} in effluent equal to $\text{TKN}_{\text{E}f} - \text{NH}_{3\text{E}f}$, mgN/L

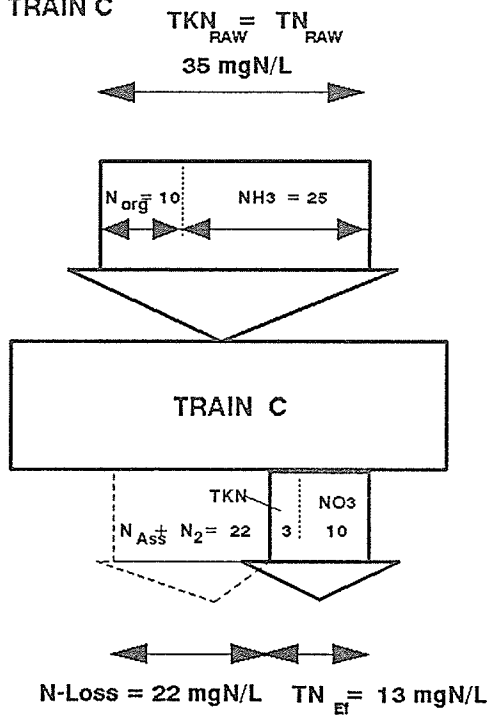
$\text{TKN}_{\text{E}f}$ = TKN in effluent, mgN/L

$\text{NH}_{3\text{E}f}$ = NH_3 in effluent, mgN/L

If organic nitrogen is replaced in equation 5.2, the following expression results

Fig. 5.7 Mass balance on day 84

I) TRAIN C

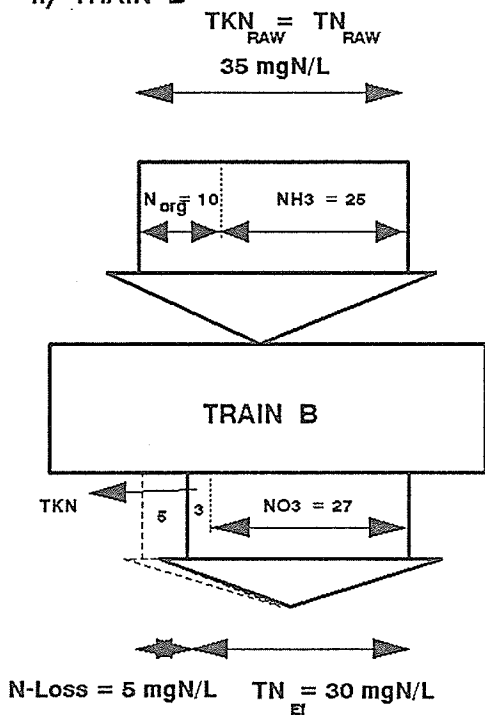


$$NH_3R = \frac{35 - 3 - 0}{35 - 3} * 100 = 100\%$$

$$NO_3R = \frac{35 - 3 + 0 - 10}{35 - 3 + 0} * 100 = 69\%$$

$$TNR = \frac{35 - 3 - 10}{35} * 100 = 63\%$$

II) TRAIN B



$$NH_3R = \frac{35 - 3 - 0}{35 - 3} * 100 = 100\%$$

$$NO_3R = \frac{35 - 3 + 0 - 27}{35 - 3 + 0} * 100 = 16\%$$

$$TNR = \frac{35 - 3 - 27}{35} * 100 = 14\%$$

$$NH_3R = \frac{TKN_{RAW} - TKN_{Ef}}{TKN_{RAW} - TKN_{Ef} + NH_{3Ef}} * 100 \quad [5.3]$$

Nitrification efficiency could also be defined based on TKN removal efficiency (TKNR); however, when complete nitrification (as was obtained in this experiment) is attained, NH_3R is underestimated because TKN includes both the biodegradable and the non-biodegradable nitrogenous organic fractions. Hence, TKNR is a better indicator of N_{org} removal.

5.0.1.2 DENITRIFICATION EFFICIENCY

Biological denitrification efficiency can be determined based on the compound that removes (nitrate) only or considering both the nitrate removed and the non-biodegradable fraction of N_{org} through TN removed. Since the goal of denitrification in wastewater treatment is to reduce nitrogen content, TN removal efficiency (TNR) appears to be more representative than nitrate removal efficiency (NO_3R). On the other hand, it should be noted that a high NO_3R does not always mean a high TNR. Nitrate conversion to N_2 is a multiple step reaction, and nitrogen removal through it is accomplished only when NO_3^- is reduced either to gaseous nitrogen-oxides (NO and N_2O) or N_2 . Nevertheless, NO_3R was also determined because of TNR dependence on nitrate fed to the anoxic reactor. If both complete nitrification and complete denitrification occur, the nitrate in the effluent of the nitrifying reactor can be obtained from a mass balance around the Pre-Den reactor (Randall et al, 1992)

$$N_n * Q = N_i * (Q_{RAS} + Q_{RNO_3} + Q) \quad [5.4]$$

where

N_n = nitrogen that will be denitrified in the Pre-Den reactor, in our case is

TKN_{RAW} , mgN/L

N_i = nitrate in effluent, NO_{3Ef} mgN/L

$Q_{RAS} = r_1 Q$

r_1 = RAS recycle ratio

$Q_{RNO_3} = r_2 Q$

r_2 = RNO_3 recycle ratio

Solving for NO_{3Ef} and considering $r_1 + r_2 = r$, the equation 5.3 becomes

$$NO_{3Ef} = \frac{TKN_{RAW}}{r + 1} \quad [5.5]$$

Therefore, equation 5.1 can be rewritten for nitrate as:

$$NO_3R = \frac{r}{1 + r} * 100 \quad [5.6]$$

Considering the N_{orgEf} that is not hydrolyzed, and according to the simplified mass balance in Figure 5.7, the nitrogen that must be oxidized is given by TKN_{RAW} minus N_{orgEf} . The following expression was therefore used to calculate the experimental or measured NO_3 -N:

$$NO_{3R} = \frac{TKN_{RAW} - TKN_{Ef} + NH_{3Ef} - NO_{3Ef}}{TKN_{RAW} - TKN_{Ef} + NH_{3Ef}} * 100 \quad [5.7]$$

The theoretical TNR was derived making the same assumptions as those made for NO_{3R} , and considering that: 1) $TN_{Ef} = TKN_{Ef} + NO_{3Ef}$, 2) $TN_{RAW} = TKN_{RAW}$, and 3)

$$TNR = \frac{TKN_{RAW} - TKN_{Ef} - NO_{3Ef}}{TKN_{RAW}} * 100 \quad [5.8]$$

which represents the observed TNR. If equation 5.5 replaces NO_{3Ef} , the calculated TNR can be determined by

$$TNR = \frac{\frac{r}{1+r} TKN_{RAW} - TKN_{Ef}}{TKN_{RAW}} * 100 \quad [5.9]$$

Equation 5.9 shows the relationship between the TNR and the overall recycle ratio, and it was validated by plotting TNR versus $(TKN_{Ef}/TKN_{RAW}) * 100$; i.e. Figures 5.8 and 5.9 (The other periods are attached in appendix B). From this equation, r can be determined as a function of TKN concentrations in the raw wastewater and in the final effluent. Solving it for r , the following equation is obtained

$$r = \frac{\frac{TNR}{100} * TKN_{RAW} + TKN_{Ef}}{(1 - \frac{TNR}{100}) * TKN_{RAW} - TKN_{Ef}} \quad [5.10]$$

Equation 5.10 differs from that used to determine the parameters reported in Tables 4.1, 4.2, and 4.3. As was mentioned in chapter 4, r was determined by using the equation given by Metcalf and Eddy (1990), which is

$$r = \frac{NH_{3RAW} - NH_{3Ef}}{NO_{3Ef}} - 1 \quad [5.11]$$

In both equations, complete denitrification in the anoxic stage was assumed and neglected the nitrogen assimilation. The r must thus become equal to 2.2 for a wastewater similar to NEWPCC's PE with 25 mgNH₃-N/L, 36mgN/L of TKN, and assuming 90% of nitrification and 7 mgNO₃-N/L in the effluent using equation 5.11. However, r is 9 if equation 5.10, based on TKN, is applied for 80% of TNR (0.8*36+3.6 / 0.2*36-3.6). Hence, r was calculated for each operational period using equation 5.10. It was found that r should have ranged from 29 to 4.6 for 80% of TNR, and from 6.5 to 2.9 for 70% of TNR for the first period in which the PE was the weakest and exhibited high variability in its composition. This finding shows that the characteristics and wide range of substrate concentrations of PE were dictated higher r than those applied to our systems if we wanted TNR about 60 to 80%. It should be mentioned that r greater than 9 is out of consideration from an economic point of view due to pumping costs. Brannan and Randall (1989) stated that the operation of a MLE system at RNO₃ ratio (r_2) higher than about 2 to 3 appears to be economically unwarranted unless effluent limitations justify.

Another insight into the denitrification efficiency dependence on TKN is

Fig.5.8 TN-R Vs TKN-Ef/TKN-RAW
In Pre-Den Train A-Second period

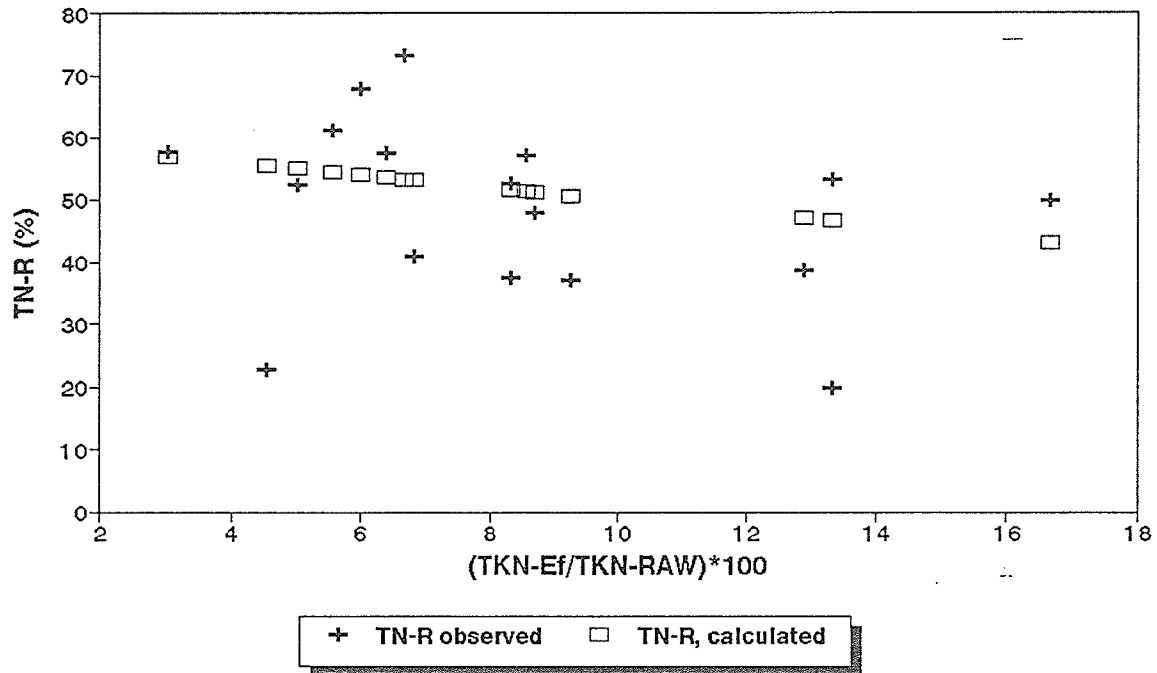
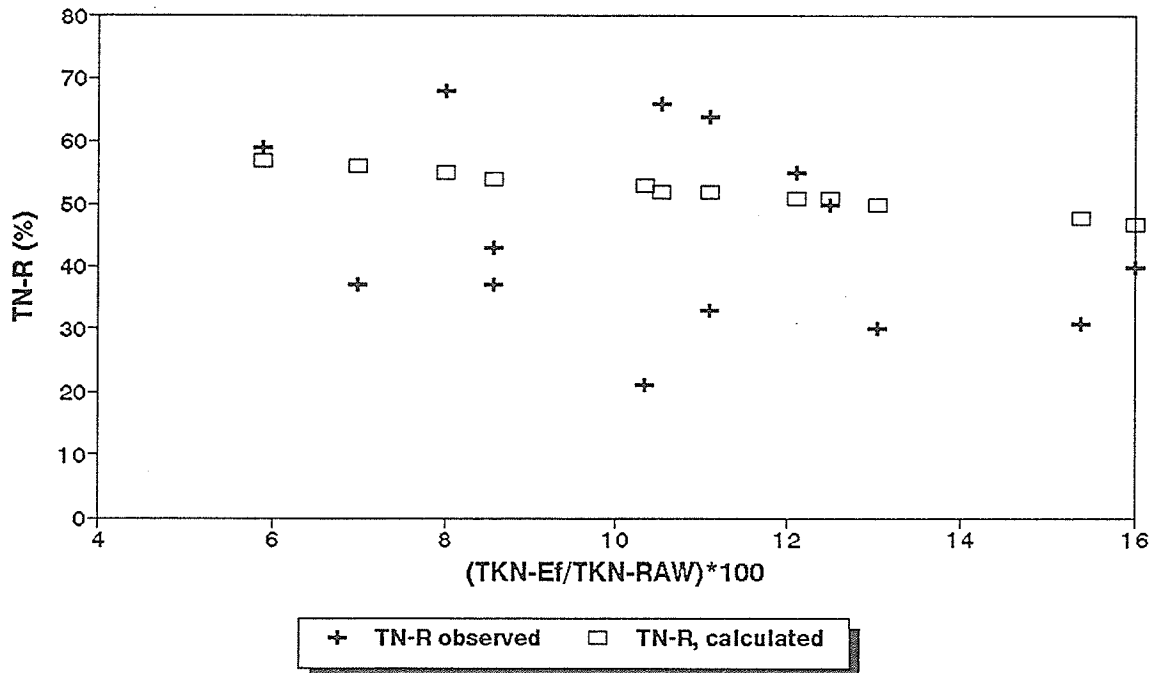


Fig.5.9 TN-R Vs TKN-Ef/TKN-RAW
In Pre-Den Train C-Third period



presented in Figures 5.8 and 5.9 which correlates the measured and calculated TN-R with TKN concentrations for the constant r reported in the previous chapter. A measured TNR greater than 10 mgN/L from the calculated TNR occurred several times on days when SOC_{RAW} was higher than 75 mg/L. On the other hand, the measured TNR lower than the calculated TNR were obtained for SOC_{RAW} below of 65 mg/L such as in the case of measured TNR of 20% and 23% on days 54 and 59 (Fig.5.8 and Tables B.5 and B.9).

The lowest TNR of Train C on day 112 (Fig.5.6) was caused by a failure of the mixing system of RIV for more than six hours so that this value was not considered either in the statistical analyses or in Figure 5.9. No linear correlation was found between TNR and SOC/TKN in the PE, a moderate linear correlation (Squared error, R^2 , ranging from 0.4 to 0.55) between TNR and TKN_{RAW} and SOC_{RAW} in the second and third period in Pre-Den Train A, and for the other Pre-Den Train, the correlation was similar to that of Train A for SOC_{RAW} but not for TKN_{RAW} whose correlation was moderate in the third period only. The fact that the R^2 for the correlation between TNR and SOC/TKN in PE ranged from 0.00 to 0.09 can be explained by the high TKN_{RAW} content which coincided with the high SOC_{RAW} most of the time, except on days 13, 56, and 87. As Figures 5.8 and 5.9 as well as Table 5.4 show, the median TNRs attained in the pilot treatment Trains were in the expected range (calculated range).

The low TNR obtained could thus be caused by the constant and low r applied to our systems, and by the wide range in substrate concentrations. Moreover,

in periods of low nitrogen concentrations (Fig. 5.8 and 5.9) that require higher r to achieve the desired TKN and $\text{NO}_3\text{-N}$ effluent concentrations and to maintain a steady TNR. Those effects do not exclude some inhibition of denitrification which is understood as a decrease in the rate of NO_3 oxidation due to external and internal reasons such as low C/N ratio, lack of optimization of the RAS concentration, or NH_3 accumulation by dissimilatory $\text{NO}_3\text{-NH}_3$ that depends on the nature of the carbon substrate present in the medium (Akunna et al, 1993).

As Figures 5.4 and 5.6 show, and considering Tables 4.1 through 4.6, an overall recycle ratio, r , less than 1 appears to be inappropriate for Train A since the medium value of TNR dropped from 53% to 43% when r was reduced from 1.5 to 0.9. The critical r for Train C seems to be 1.5. Those r s (0.9 in Train A and 1.5 Train C) meant RNO_3 ratios, r_2 , of 0.5 and 0.7. Others (Brannan, and Randall, 1989) have suggested that a r_2 of 0 to 1 provides adequate TNR (60% to 80%) and oxygen requirement savings minimizing costs associated with RNO_3 flows. Argaman and Brenner (1986) have found that the minimum attainable effluent nitrate is inversely proportional to the overall recycle ratio ;however, they also observed that effluent nitrate did not always decreased with r due to poor denitrification kinetics associated with low chemical oxygen demand. The later authors operated four pre-denitrification units at r between 14.9 and 2.9.

The different r s found for Trains A and C may be explained by the different anoxic HRT at which these Trains were operated. Those differences may thus imply that lower HRT needs higher r to achieve the same TNR. However, further

investigations, in which equation 5.10 should be applied, are required to confirm that inverse relationship between HRT and r. The low TNR obtained in the first period in Train A as well as the low TNR in Train C could be explained by the short time of operation and lack of steady state in terms of TNR, specially, if we consider that the Virginia Initiative Plant (VIP) pilot study has required two months to reach TNRs averaged approximately 70% (Brannan and Randall, 1989).

Table 5.4: Comparison of the expected and measured TN Removals in Pre-Den Trains.

	TRAIN A			TRAIN C	
	I	II	III	II	III
Range of the calculated TNR, %	35-63	43-57	27-43	33-60	47-58
Range of the measured TNR, %	11-43	20-73	22-72	14-70	16-68
Median measured TNR, %	31	53	43	43	40

The TNR in the nitrifying Train B was highly variable (Fig.5.5) with a medium value of 9%, 15% and 14% for the first, second and third period, respectively. It

should be noticed that, at times, the TNR was higher than 27% (value equal to the sum of TNR by assimilation and TNR by denitrification in the clarifier). This fact means that denitrification took place to some extent in RIII (oxygen reactor) supporting the idea of denitrification occurring in both anoxic and aerobic processes (Bishop et al, 1978; Daigger et al, 1987).

The high and steady TKNR, BODR, SOCR, and NH_3R accomplished in all treatment trains throughout the experiment (Fig.5.3 to 5.6), prove that the variation in the raw wastewater organics and ammonia concentrations did not affect these efficiencies in the conditions under which the experiment was carried out.

Complete nitrification began on day 14 of the pilot study in Trains A and B. The NH_3R was maintained at near 100% level throughout the experiment in these Trains, with the exception of the two days in Train B and for three days in Train A (Fig.5.3). In Train C, started latter, there were three days of incomplete NH_3R . The incomplete nitrification on those days is explained by a small aberration in the quality of the PE and by problems with the oxygenation system which at times has provided less than ideal DO (ideal was assumed to be 4mg/L) levels in the nitrification reactors. The 91% NH_3R in Train A on day 110 and 60% in Train C on day 112 (reported in Tables B.9), were due to the mixing interruption in the denitrification reactors which resulted in the decreased MLSS levels in the subsequent nitrification reactors II and V.

The TKN and SOC removals were incomplete in all Trains because of incomplete conversion of the organic nitrogen and organic carbon to NH_3 and CO_2 ,

respectively, as well as the presence of the organics in the final effluent solids. Since all ammonia was removed in all Trains there was no blocking of the nitrification process. However, as complete organic degradation appears to be impossible in a biological process, the complete removal of ammonia in all Trains meant that there was room for optimization of the system, i.e. a decrease of the HRT or a decrease of the SSRT, or both. Optimization was not attempted as it was not within the time-frame of the study.

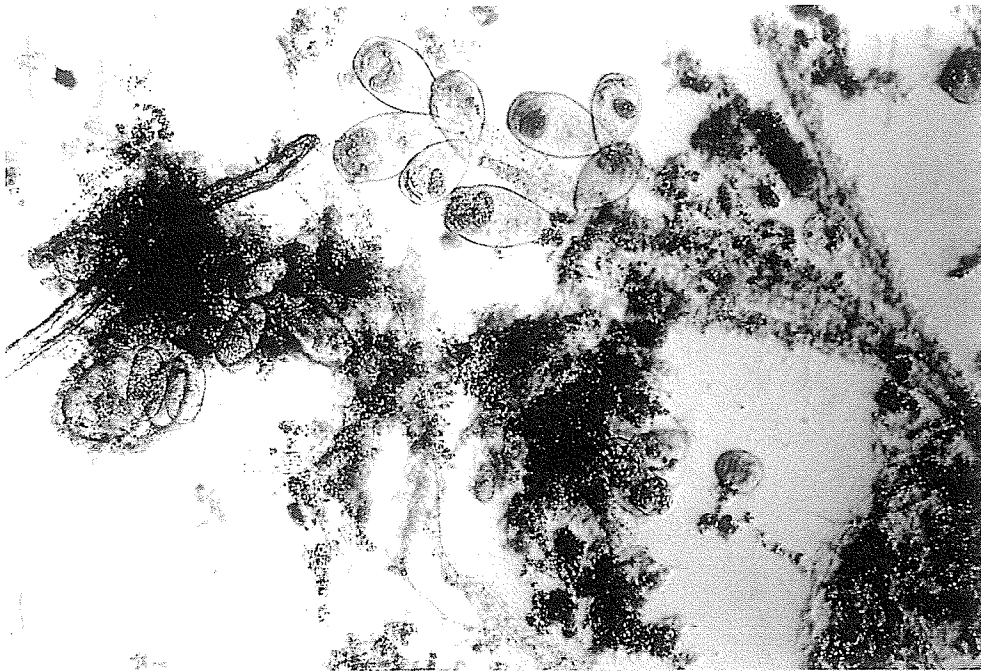
5.0.2 MIXED LIQUOR AND BIOMASS CHARACTERISTICS

The heterogenous microbial populations cultured in the pilot treatment plant are exhibited in Figures 5.10 through 5.12, in which microphotographs of typical floc from ML of each reactors are presented. Since the reactors of Trains A and B were seeded with sludge from the full scale treatment plant, a healthy sludge in which ciliates were the predominant microorganisms was observed from the start up of the pilot plant.

In the RIII, a typical branching stalk of protozoa i.e. *Vorticella* or *Epistyles* as well as small protozoa resembling the genus *Aspidisca*, *Colpoda*, *Euplotes*, and *Pleuronema* were noticed apparently in the same proportion at first. On day 12, a substantial shift to colonial stalked ciliated protozoa was observed. Nematodes and roundworms were found on day 7. The presence of rotifers such as *Philodina* and *Proales* like were observed on day 35. The last microorganism observed in RIII, not only by microscopic observations but also by macroscopic observations of the sludge

Figure 5.10: Photomicrograph of typical activated sludge floc from nitrification reactors on day 117. I) RIII, SVI = 80 mL/g, MO = 1-2; II) RV, SVI = 50 mL/g, MO = 1-2. (400x, light microscope)

I)



II)

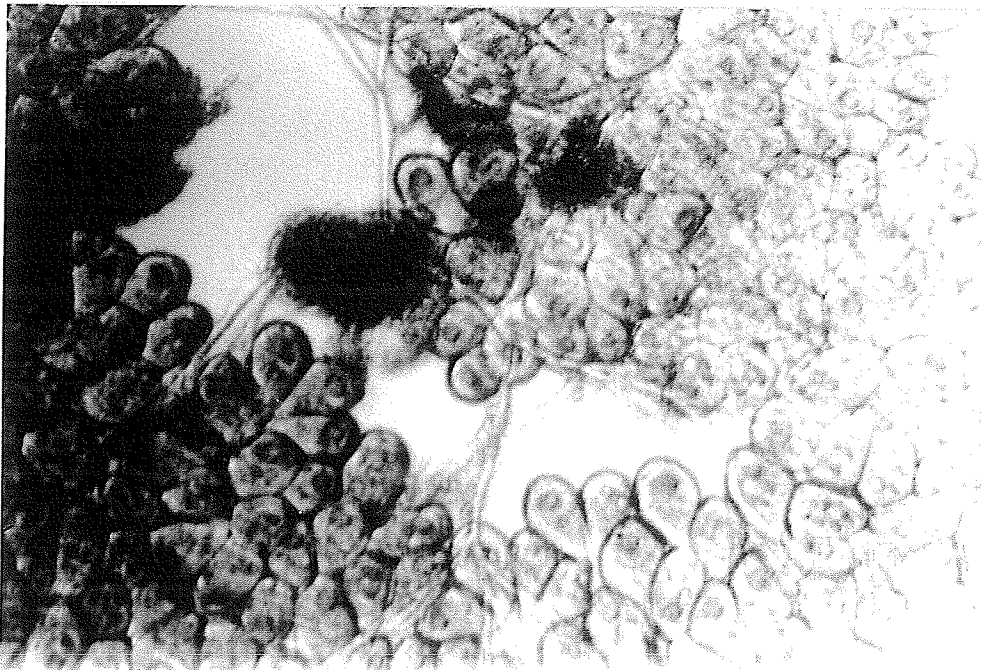
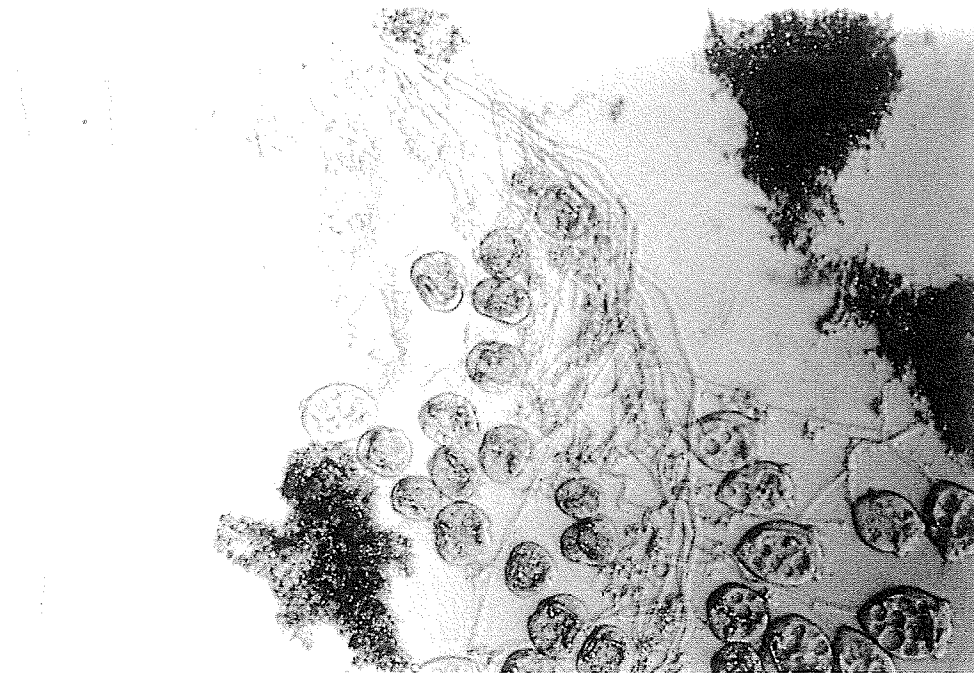
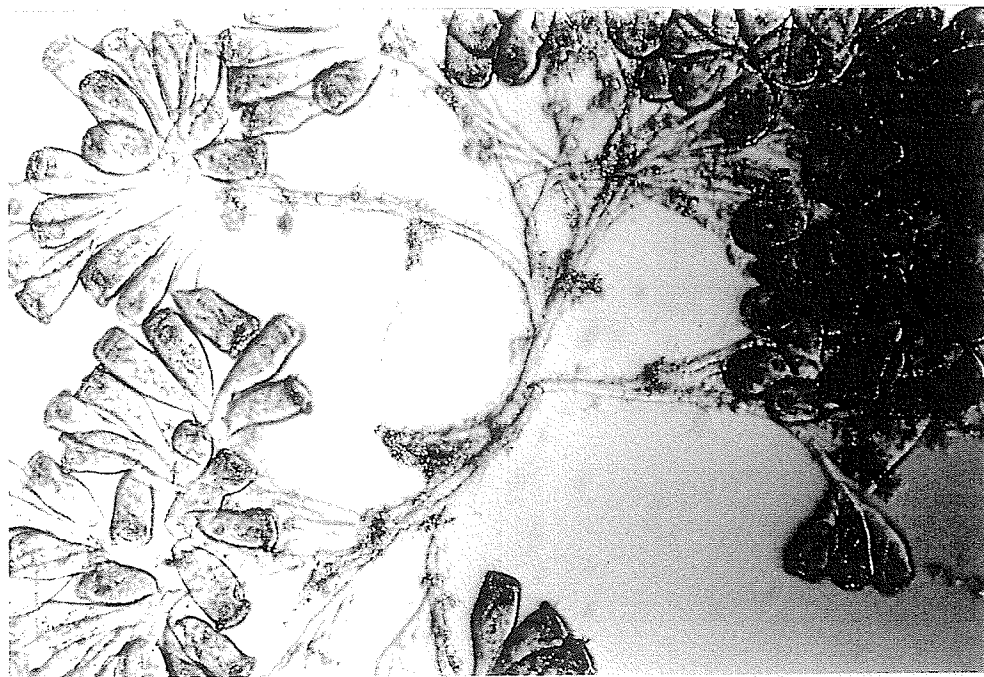


Figure 5.11: ML from Pre-Den Trains on day 117. I) Anoxic Reactor I, SVI = 90 mL/g, MO = 1. II) Anoxic Reactor IV, SVI = 50 mL/g, MO = 1 (400x, light microscope).

I)



II)

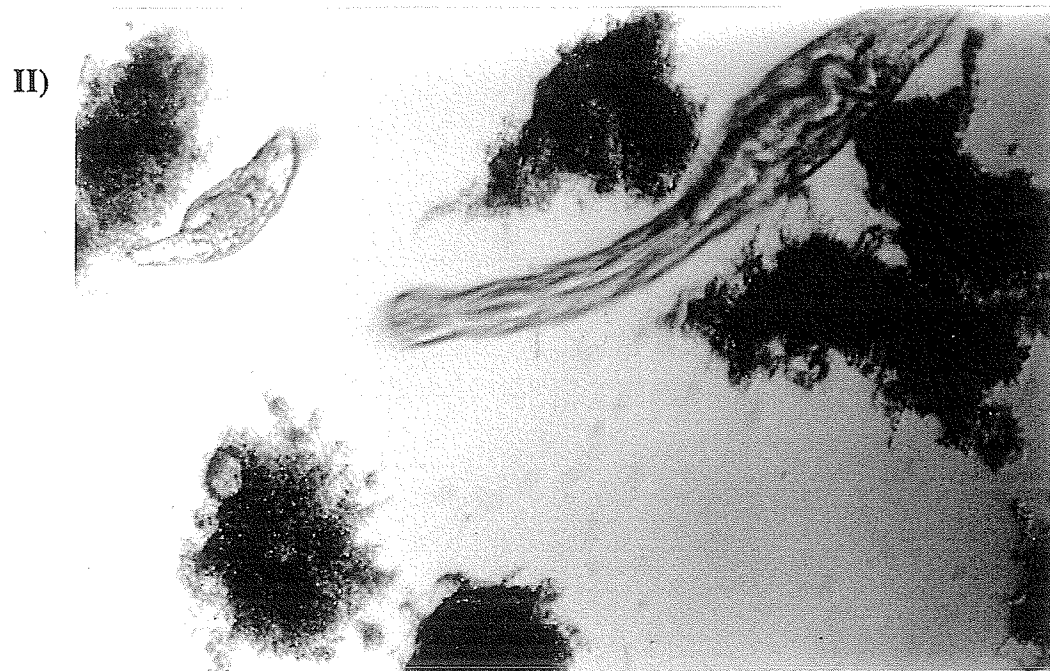
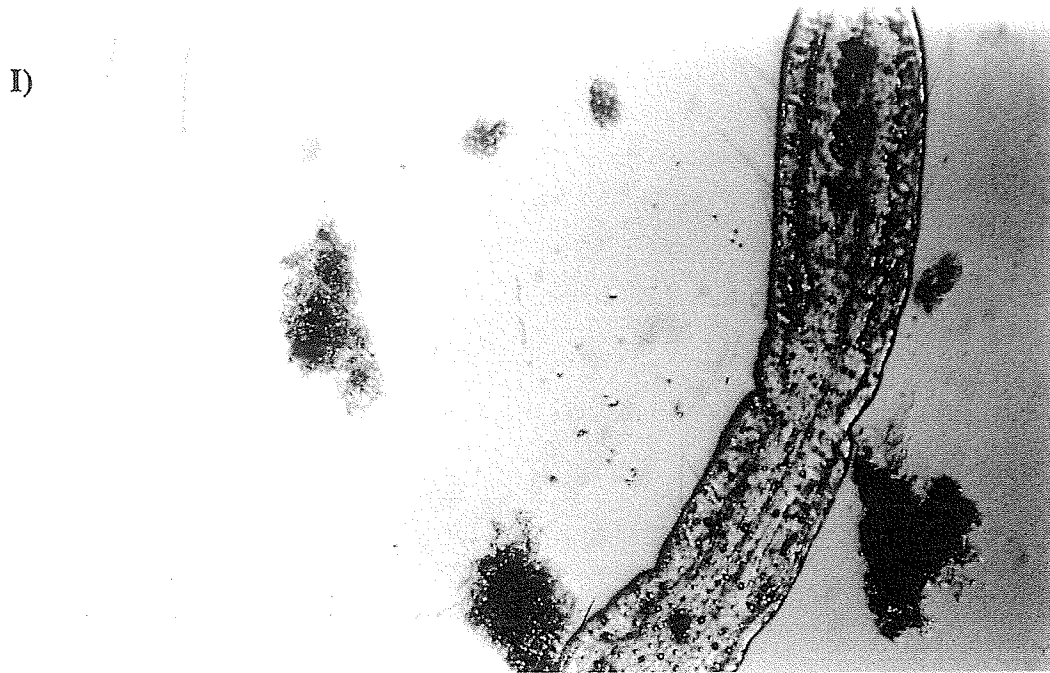


due to its reddish spots, was the flatworm. Actually, the flatworms were observed in the ML of RV (nitrification reactor of the Pre-Den Train C) on day 68 by microscopic observation; however, we thought that they must have been in the ML of the RV since or before day 65 when a small reddish aura was observed at the upper layer of the sludge blanket in the clarifier of Train C. The flatworm observed in Figure 5.12.I resembles an *Aelosoma* sp. which was described by Fox et al (1981) as having burnt orange spots over its surface.

The ML of RII (Pre-Den Train A) differed from ML-RIII in that the big branches of stalked ciliates, as those shown in Figures 5.10 and 5.11 were not observed until day 12. This fact, as well as the later shift of the small protozoa to the bigger ones in the reactors of Train A, must have been caused by the anoxic stage at which the populations of microorganisms of NEWPCC's activated sludge needed to acclimate. The nematodes in Train A were found first in the anoxic reactor I (day 12) and later on day 51 in the oxygen RII.

The population observed in the ML from the third nitrification reactor RV (Fig.5.10.II) were as heterogeneous as the others, and only differed from RII in the greater abundance of colonial stalked ciliated protozoa due to higher mass loading (see Table 4.10). The effect of higher mass loadings was also observed in the anoxic reactors RI (Train A) and RIV (Train C). Figure 5.11 compares the activated sludge of both these reactors. As observed in this Figure, branching stalked ciliates in RIV, which received a double mass loading, were more voluminous than that in RI shown at the upper microphotograph of Figure 5.11. It should be mentioned that the shift

Figure 5.12: Rotifers and Flatworms in the Pilot Treatment Plant on day 117. I)
Nitrification Reactor II-Train A, SVI = 90 mL/g, MO = 1. II)
Anoxic Reactor IV-Train C.(400x, light microscope).



of small protozoa to bigger ones was not observed in RI until day 59. The flatworms were found on day 93 on both the reactors of Train A.

The microphotograph of RIV in Figure 5.12.II was chosen to show the presence of rotifers in the anoxic stage, although they are expected in ML with long aeration HRTs or with SRTs longer than 10 days according to MOP 11 Task Force (WPCF, 1990). The MLs of Pre-Den Train C seeded with WAS from the other Trains appeared to comprise a great abundance of colonial stalked ciliated protozoa and rotifers. The fact that the pilot plant WAS was used as seed to initiate Train C ML comprised always a healthy biomass, allowed to shorten the acclimatization period in Train C.

In general, the pilot plant produced a well-flocculated ML in which a heterogenous microbiological community was cultivated. The high removal of organic matter suggests the presence of heterotrophic and autotrophic bacteria that play a significant role consuming the organic matter in wastewater.

5.0.2.1 SETTLING CHARACTERISTICS AND SLUDGE AGE

The SVI and SRT histograms of both Pre-Den trains (Fig. 5.13 through 5.16) showed that the fluctuations of SVI and SRT in Trains A and C were lower than those observed in the nitrifying Train B (Fig.5.17). In the first period, as reported in Tables 4.4 and 4.5, the mean SVI of the nitrifying train B (Table 4.4) was 217 mL/g with a sample standard deviation (SD) of 82, while the mean SVI for RII (Pre-Den train A) was 136 mL/g with a SD of 54. Initially, it was thought that the lower SVI fluctuations in the Pre-Den process was produced by the anoxic zone ahead of

Fig.5.13 Histogram of SVI
Pre-Den Train A

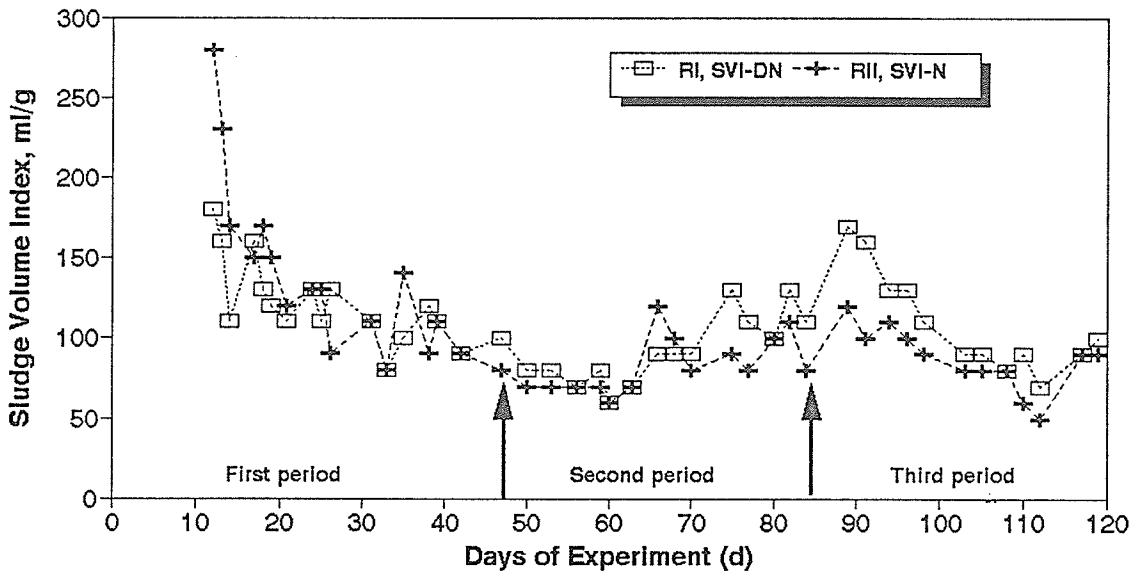
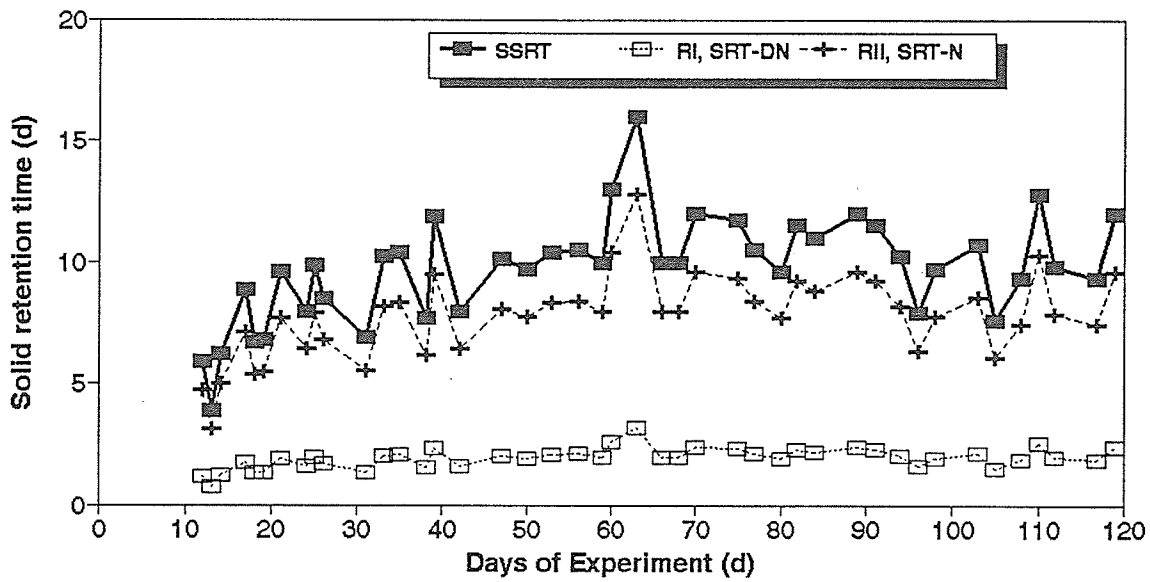
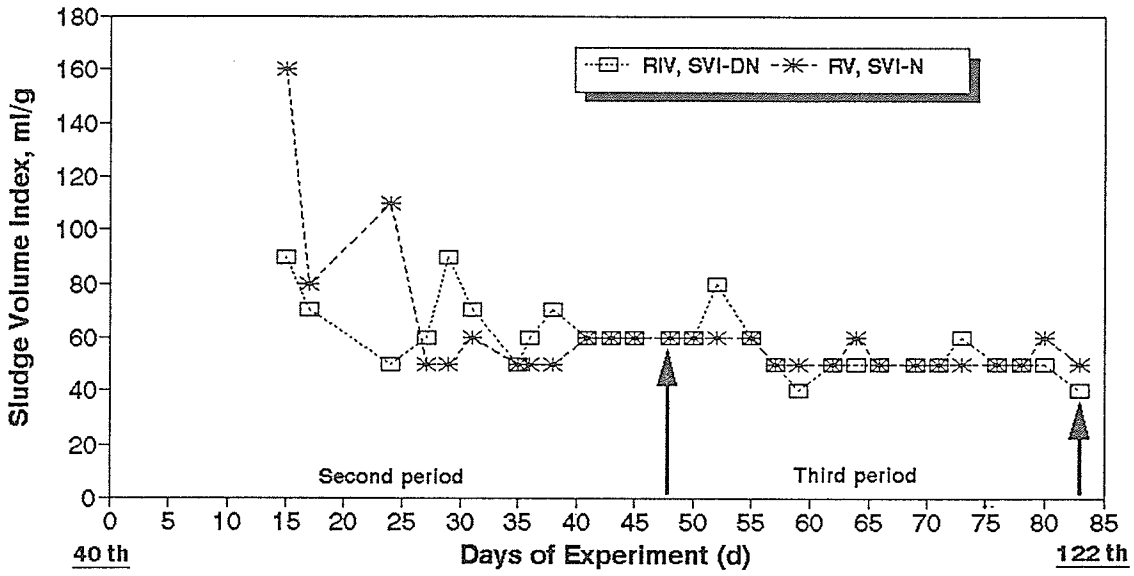


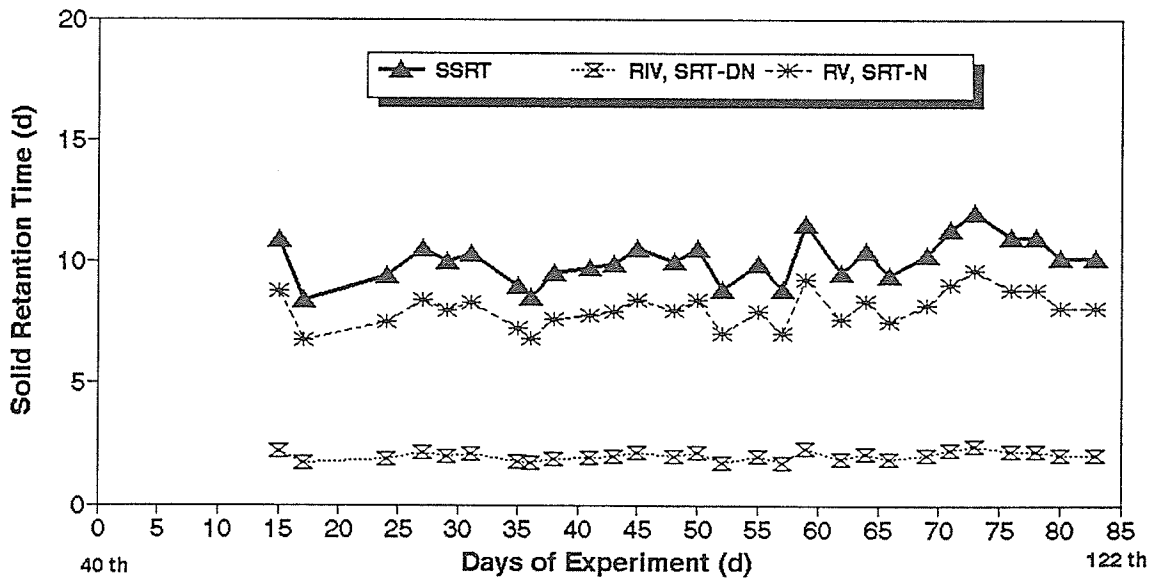
Fig.5.14 Histogram of SRT
Pre-Den Train A



**Fig.5.15 Histogram of SVI
Pre-Den Train C**



**Fig.5.16 Histogram of SRT
Pre-Den Train C**



the oxygen reactor. The fact that SVI in the nitrifying and Pre-Den systems was lower than that reported by Randall et al (1992) was explained by the use of pure oxygen instead of air according to the findings reported elsewhere (Chapman et al, 1976; Nelson and Punttenney, 1983). However, comparing equations 4.1 to 4.2, it can be noticed that there is one other difference besides V_{DN} , and use of oxygen. This difference is in the SSRT calculation. The SVI fluctuations decreased substantially in the last two periods when the WAS control was based on equations 4.5 and 4.6; furthermore, the SVI in both reactors of train C was practically constant after day 35. The value of 80 mL/g in RIV was measured on a day when the DO was well high 10.8 mg/L, thus the RNO_3 may have affected the denitrifying reactor RIV. On the same day, the nitrate removal in RIV decreased from 100% to 57% and the total nitrogen removal from 48% to 29%. The mean SVI value for RV was 65 and 53 mL/g for the second and third period respectively. Table 4.6 summarizes the SVI, SRT, and SSRT; the complete sample of data used to make the histograms is enclosed in appendix A.

In Pre-Den Train A, the SVI variation was slightly higher than that observed in Train C, mainly in the third period. The higher SVI fluctuation in that operational period is explained by the reduction of RAS from 0.8 to 0.4 (see Table 4.2 and 4.3), and by the change of the unified reactor RII in order to improve the VSS concentration in RAS. On day 61, the clarifier of train A was completely separated from RII by installing a circular final clarifier and installing a pumped recycle from the hopper. The clarifier worked well for a week and then developed problems in

the thickening zone, resulting in a recycle concentration which remained as weak as it had been before the modification. The inability to properly concentrate sludge is a typical shortcoming of the small scale pilot studies (Oleszkiewicz and Caponetto, 1992).

The MO varied from 3 to 4 in the five first days and dropped to 0-2, afterwards; however, the SVIs in those five first days were 80 and 90 mL/g as Figure 5.13 and Tables A.1 and A.2 report proving that no bulking episodes were developed due either to filamentous or non-filamentous growth. On the other hand, the small growth of filamentous bacteria supports the idea that the high SVIs measured at the start up of the experiment was associated with the type of WAS control applied at the beginning of the first operational period. At this point, it should be also mentioned that high EVSS (higher than about 10 to 15 mg/L) was related to episodes of rising sludge due to high $\text{NO}_3\text{-N}$ concentrations and lack of squeegees in the thickening zone of the clarifier. The former cause was solved by increasing RAS from 0.6 to 1.1 in Trains B and C at the end of the first period, and the latter by simulating manually the functions of the squeegees twice a day from day 72 in the three clarifiers.

Figures 5.18, 5.19, and 5.20 show a decreased fluctuation of SRT as well as of MLVSS. This appeared to be in contrast to the work of Christodoulatos and Vaccari, (1993) which suggested that the MLVSS variability increased when mean cell residence time (SRT) was controlled, and controlling MLVSS increased the variability in SRT.

Fig.5.17 Histogram of SRT and SVI
Nitrifying, Train B

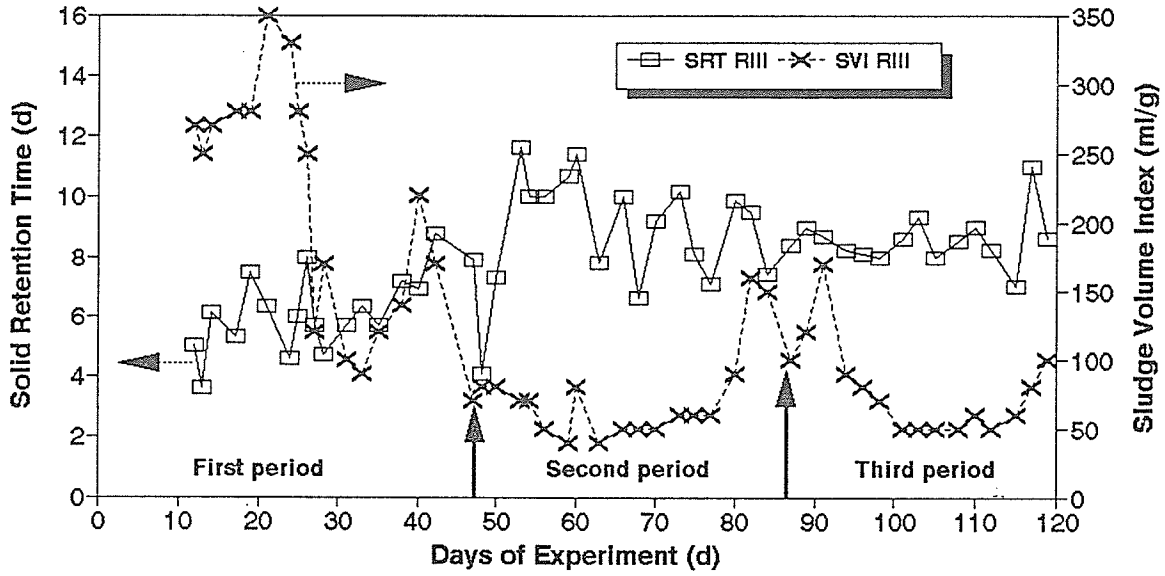


Fig.5.18 Histogram of MLVSS & SSRT
Pre-Den Train A

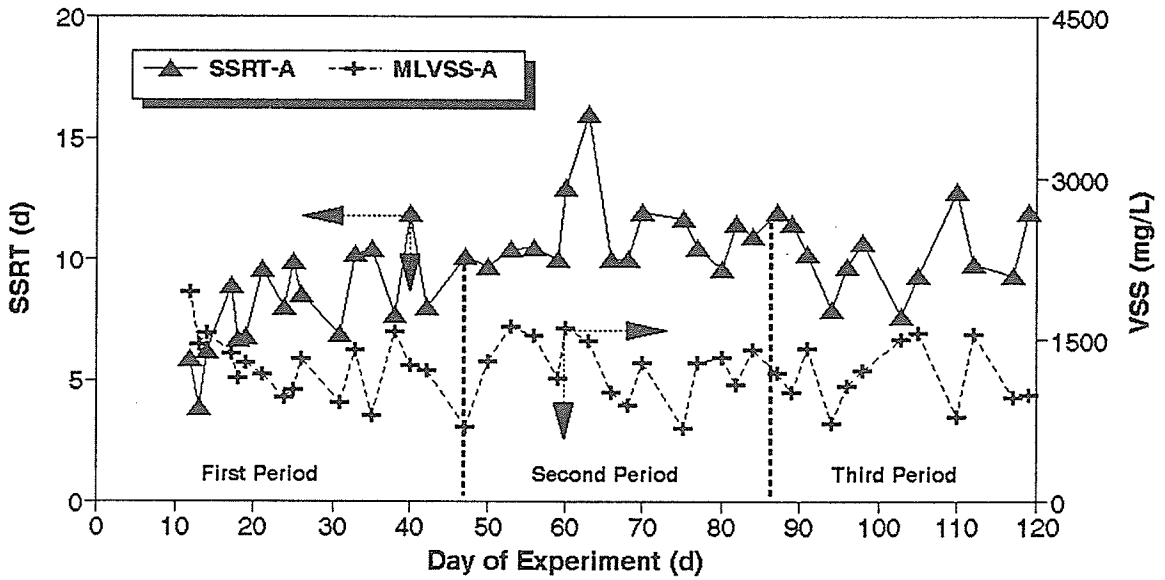


Fig.5.19 Histogram of MLVSS & SSRT
Nitrifying Train B

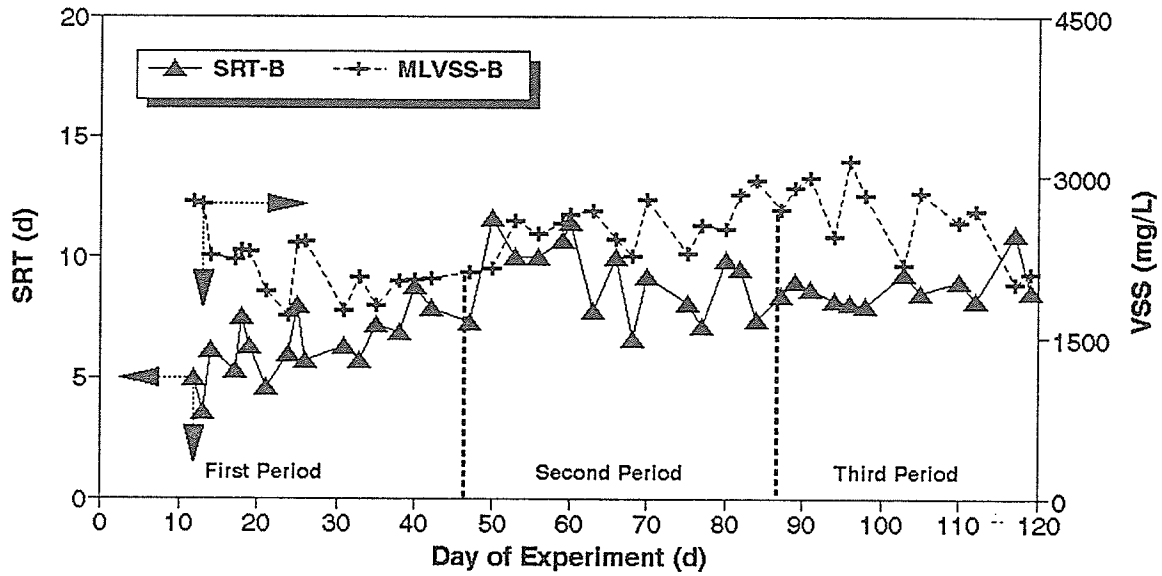
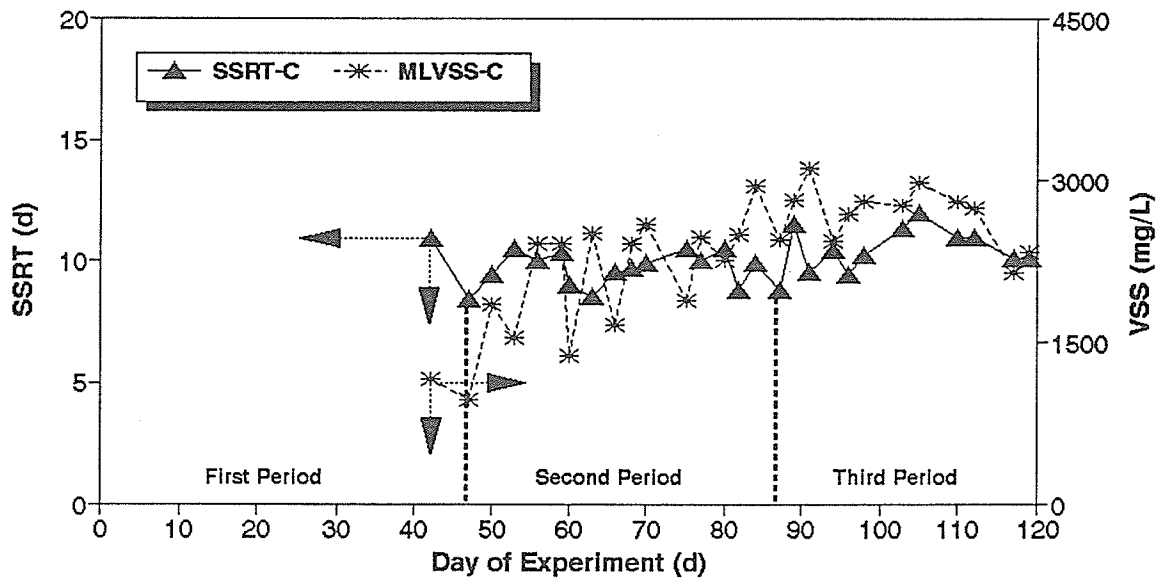


Fig.5.20 Histogram of MLVSS & SSRT
Pre-Den Train C



5.0.2.2 MIXED LIQUOR DO CONCENTRATION

The DO ML-concentrations were measured more than twice a day in all reactors throughout the experiment. Table 5.5 summarizes the ranges of temperature, DO, and pH in each reactor. Although the DO value of 4 mg/L was not always reached in RIII and RV, the NH₃ removal was 100%. That value was chosen based on the findings of Stenstrom and Song (1992) in their investigation of the effects of oxygen transport limitation on nitrification using soluble substrate in the ASP. It should be mentioned that higher values of DO measured in the reactors were usually early in the morning, and the lower values were registered in the afternoon due to higher organic oxygen demand at of the NEWPCC's PE.

Table 5.5: Range of the environmental parameters for the three Trains.

	Train A		Train B	Train C	
	RI	RII	RIII	RIV	RV
Temp.°C	15-24	14.5-23	15.5-23	15.5-24	15-24
DO (mg/L)	0-0.3	4-12	3-12	0-0.2	3-12
pH	7.2-7.8	7.2-8.4	6.7-7.4	7.1-7.7	7-7.6

The higher RNO₃ applied (to analyze the effect of DO) in Train A during the second period did not affect the capacity of Pre-Den reactor RI to denitrify as the TNR in this Train was higher in the second (53 %) than the TNR of 43 % in the

third operational period. However, the start up of the denitrification process appeared to be hindered by the high RNO_3 since the lowest TNR for Train A was achieved in the first period when the RNO_3 was the highest ($1.5Q_{RAW}$). The slight difference of TNR for Train C between that achieved in the second and that TNR achieved in the third period may also indicate that the start up of denitrification was affected by the DO concentration in RNO_3 , so that it could be concluded that the start up of Pre-Den processes should have been done at very low RNO_3 (if none) or at a variable RNO_3 based on equation 5.10. Hence, to confirm these facts further research should be performed.

5.1 EFFECT OF pH CONTROL ON THE PROCESS

According to Sedlak, (1991) the effect of pH on nitrification rate is negligible in the range of pH 7.0 to 8.0 which is that of municipal wastewater. However, Sedlak points out that it is essential that there be sufficient alkalinity in the wastewater to react with the acid produced by nitrification or else alterations in pH might have an adverse effect on nitrification. Furthermore, if the CO_2 is not stripped from the liquid, as can occur in high purity oxygen systems, the alkalinity may have to be as much as 10 times greater than the amount of ammonia nitrified (Sedlak, 1991). Nitrification can be impaired if the pH drop is too great and chemical addition may be required to maintain pH levels (Brannan and Randall, 1987).

Several researchers agree that pH should be maintained within a range acceptable for nitrifying microorganisms (Anthonisen et al, 1976; Braunscheidel and

Gyger, 1976; Verstraete et al, 1976; Kholdebarin and Ortli, 1977; Reinhart, 1979; Scarce, 1980; Brannan and Randall, 1987; Metcalf and Eddy, 1990; Sedlak, 1991; Judkins and Anderson, 1992). However, the range of pH established by them is different which reflects the versatility of biological nitrification that takes place in conditions of variable pH. Differences among the optimal pH ranges are also reported in denitrification. Gaudy & Gaudy (1980) reported an optimal range of 7 to 7.5. Benefield and Randall (1980) mentioned 6.5 to 7.5 as suggested by Metcalf and Eddy (1973). pH range between 6.5 and 7 is reported as design parameters for a two-stage nitrification in Metcalf and Eddy (1991). Recently, Cook et al (1993) investigated the effect of pH on the denitrification of a high-nitrate wastewater using sequencing batch reactors (SBR). They obtained the most efficient and stable rate of denitrification when SBR pH was maintained between 7.4 and 8.0 with HCl.

The fact that pH not only affects the chemical reactions but also the microbial growth, can explain the variability of the optimal pH range reported either in biological nitrification or in biological denitrification processes.

pH affects the state of the chemical species, and determines the direction of chemical reactions associated with the formation, alteration, and dissolution of minerals in an aqueous system (Stumm and Morgan, 1981; Benefield, et al. 1982). On the other hand, biological activities such as respiration and decay, and physical processes such as aeration and stripping influence pH by their ability to decrease or increase the carbon dioxide concentration. Other biochemical reactions such as oxidation of ammonia, reduction of sulphate and nitrate vary the hydrogen ion

concentration. These biochemical reactions may also decrease or increase alkalinity changing the buffering capacity of the system. Hence, as stated by Okey (1978) for waste generation, waste conveyance, or storage systems, that the presence of buffer systems is often an incidental property of a system, could be also stated for an activated sludge process (ASP).

Due to these reasons and due to the relationships among pH, alkalinity, acidity, and carbon dioxide, the increase or decrease of pH can be expected to depend to a great extent on the particular wastewater and the treatment system under investigation. We decided to maintain the pH above 6.6 in the nitrifying reactor (reference RIII, or Train B) by the manual addition of 10 to 40 mL of 1 M sodium carbonate to the ML of RIII on several occasions: ten times during the duration of the experiment (eight times in the second operational period and two times in the third one) as Figure 5.21 shows. The pH patterns of these Trains are shown in figure 5.22 and 5.23. Figure 5.24 is a comparison of the pH in all final effluents.

An atypical ML-pH pattern was observed in Pre-Den Train A (Fig.5.22). Although autotrophic denitrification produces H^+ (Batchelor and Lawrence, 1978), we expected that the pH of the denitrified ML would be higher than that of the nitrified ML as occurred in Train C (Fig.5.23) since nitrification itself decreases the pH of the medium due to production of H^+ , and denitrification increases pH due to production of OH^- . However, the pH in RI (Anoxic reactor) was lower than that of the nitrification reactor RII. This atypical pattern can be explained if a fast

Fig.5.21 Histogram of pH in Train B

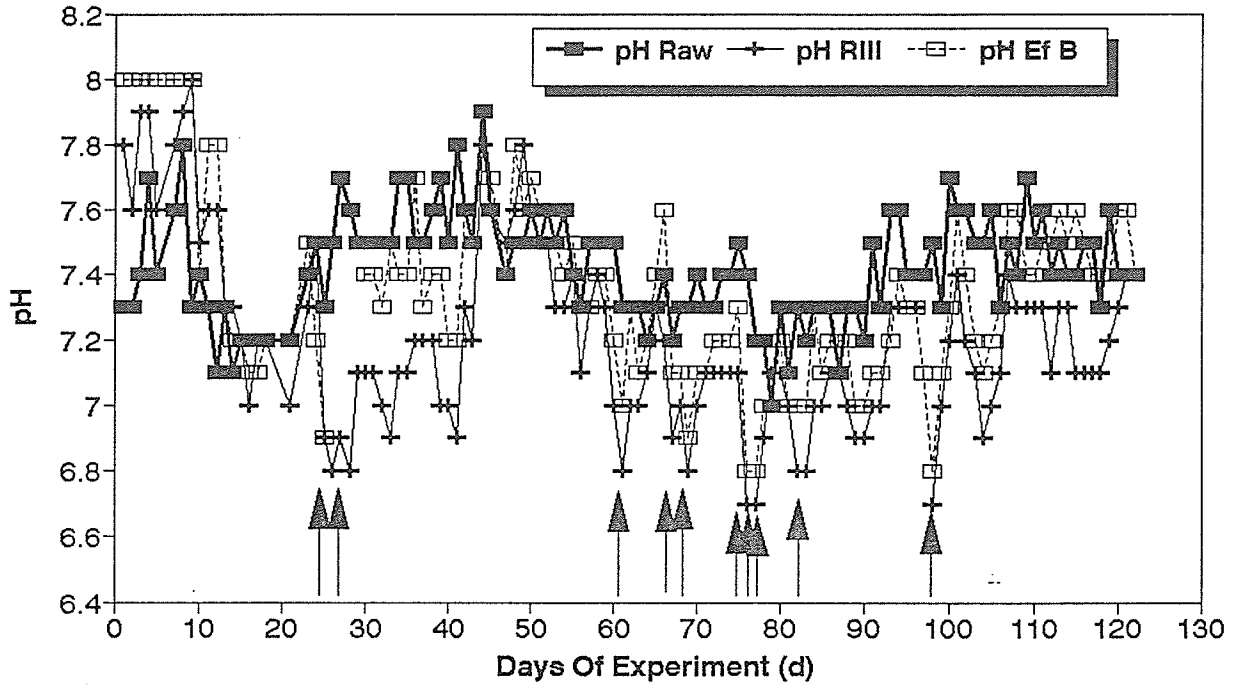


Fig.5.22 Histogram of pH in Train A

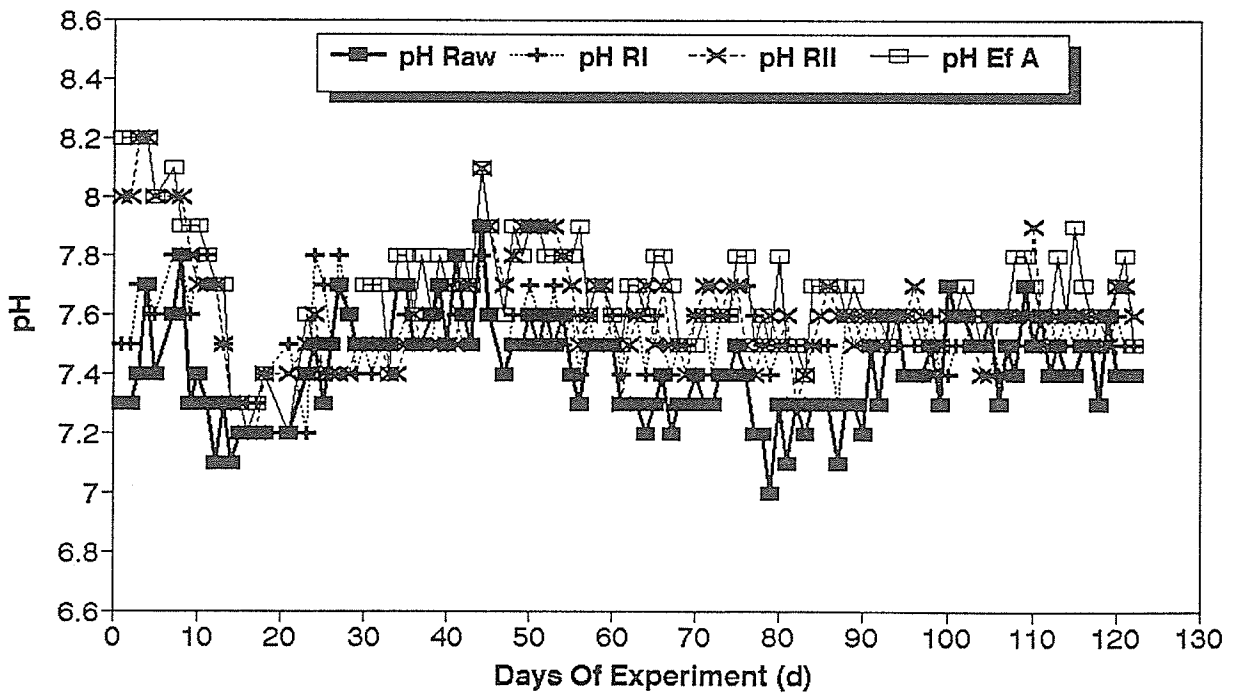


Fig.5.23 Histogram of pH in Train C

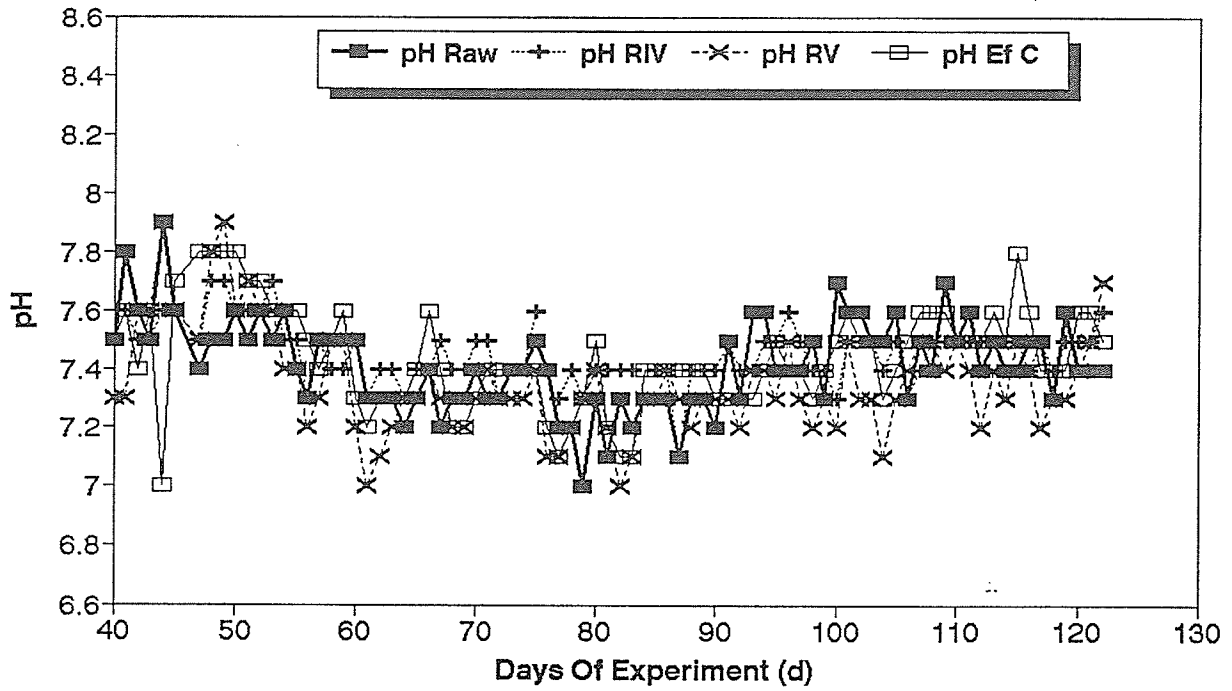
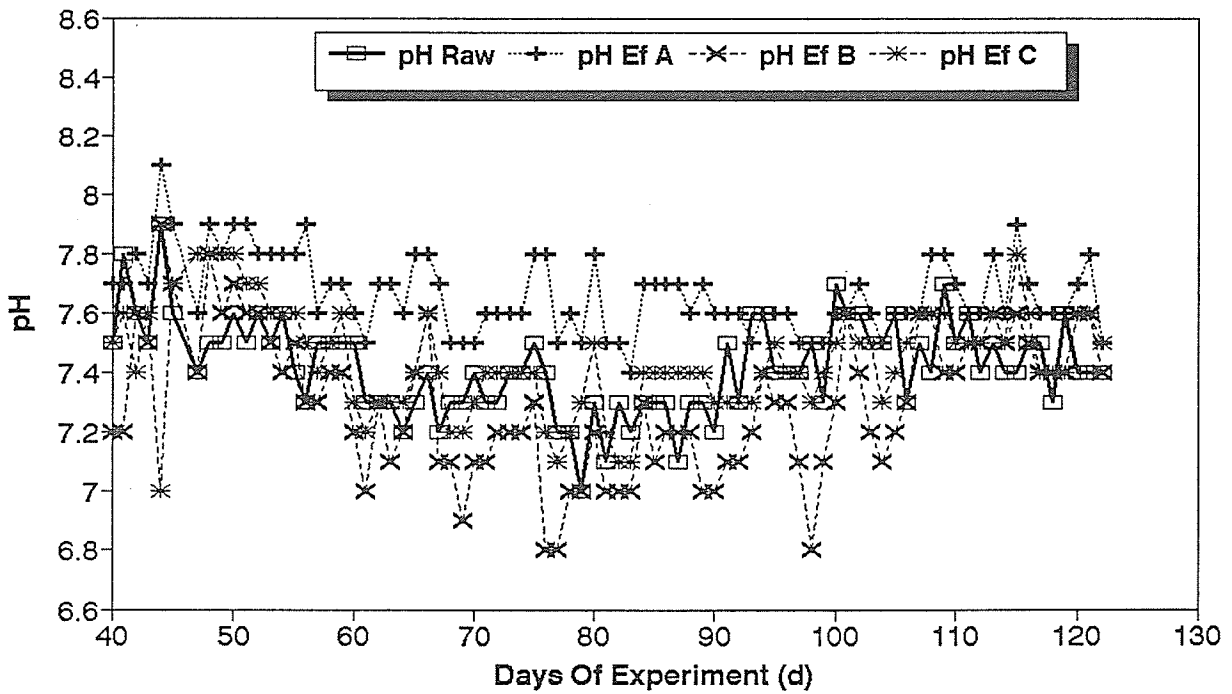


Fig.5.24 Histogram of pH in all trains



consumption of CO_2 by an autotrophic population in RII had taken place and raised the pH of the ML RII. Consequently, a greater production of biomass should have occurred in RII than in RV. This possibility is supported by the greater observable yield (Y_{obs}), i.e. 1.6 g/g.d in Train A and 0.6 g/g.d in Train C, obtained in Train A which was operated at double HRT which must have allowed a higher growth of autotrophic bacteria (Fig.6.13).

The effect of increasing pH due to CO_2 assimilation also depends on the initial alkalinity in the system (Manahan, 1984). The higher pH in RII coincided with lower alkalinity consumption in Train A and indicates that the inorganic carbon consumed by autotrophic microorganisms was CO_2 dissolved in the ML rather than HCO_3^- . This finding could be of great relevance for wastewater treatment plants which like NEWPCC operate high purity-oxygen activated sludge systems, as their main disadvantage for nitrification is the accumulation of CO_2 in its covered-head space. Hence, the addition of an anoxic tank prior to the oxygen reactor would produce not only an increase of the buffer capacity of the ML entering the oxygen reactor but also a decrease of the depressing effect on ML pH caused by CO_2 accumulation in the reactor head-space. Higher pH levels in the nitrified-ML than in the denitrified-ML have not, to our knowledge, been reported in the published literature.

Barth and Ryan (1978) reported a slightly higher pH in the nitrified effluent than in the denitrified effluent by large media denitrification towers with addition of methyl alcohol in the period of November, 1974. Brannan and Randall (1987)

reported 7.5 as a typical pH of a VIP pilot plant effluent for an influent pH of 7.3 and 82 mgCaCO₃/L of alkalinity drop. In both these studies, phosphorous was also removed by chemical precipitation in primary clarifiers in the former study, and by the addition of an anaerobic stage prior to the anoxic in the VIP pilot plant. Judkins and Anderson (1992) also reported that the effluent pH level at times, was higher than influent pHs using a pre-denitrification mode in which the anoxic zone took place in the same basin as the aerobic one. According to these authors, the Moores Creek Wastewater Treatment Plant in Charlottesville, Va., U.S.A., achieved complete nitrification throughout the summer and fall of 1987, and 50 % of the pH effluent data reported by them was lower than the pH influent entering the pre-denitrification zone, for example an influent pH of 6.7 and an effluent pH of 7.2 with an alkalinity consumption of 77 mg CaCO₃/L on July 19, 1987. It should be noticed that the influent alkalinity at the Moores Creek treatment plant was relatively low ranging from 89 to 140 mgCaCO₃/L in July, 1987.

Both Pre-Den treatment Trains A and C produced completely nitrified effluents with pHs higher than those of the NEWPCC's PE pH most of the time (Figures 5.22 through 5.24). Figure 5.24 shows that the lowest effluent pH was always produced by Train B, the nitrifying Train; however, its nitrified effluent pH was always greater than ML pH (Fig.5.21) proving that denitrification also occurred in RIII and the clarifier. The alkalinity consumption in the pilot treatment Trains is further discussed later in the following chapter.

CHAPTER 6: COMPARISON OF THE PRE-DEN TRAINS WITH NITRIFICATION TRAIN

In this section, the Pre-Den mode process of the systems operated in the pilot plant will be compared to the nitrifying mode process applied in Train B in terms of sludge production, oxygen requirement, and alkalinity consumption. The observed sludge production, oxygen and alkalinity consumptions in the nitrifying Train B were greater than those observed in the Pre-Den Trains A and C.

6.0 SLUDGE PRODUCTION

Sludge production (SP) was determined in each of the treatment trains for each operational period using the equation 6.1 given by Metcalf and Eddy (1991)

$$SP = Y_{obs} * (S_o - S) * Q_{RAW} \quad [6.1]$$

where

SP = sludge production, g/d,

Y_{obs} = observable yield, gVSS/gBOD,

S_o = Raw wastewater BOD₅, mg/L (g/m³),

S = Effluent BOD₅, mg/L (g/m³), and

Q_{RAW} = as defined in chapter 4

The Y_{obs} s were obtained by using the following equation

$$Y_{obs} = \frac{Q_w * MLVSS + Q_{Ef} * EVSS}{Q_{RAW} * (S_o - S)} \quad [6.2]$$

where

MLVSS = VSS concentration, mg/L (g/m³); equal to MLVSS RIII for Train B, and to mean VSS concentration in the Pre-Den Trains considering the volume of both reactors.

S_o, S = as defined previously, and

Q_w, Q_{Ef}, EVSS = as defined in chapter 4.

The food to microorganism ratio (F/M) was calculated by the following equation

$$F/M = \frac{S_o}{HRT * MLVSS} \quad [6.3]$$

where

F/M = Food to microorganism, gBOD/gVSS.d,

HRT = hydraulic retention time, d; equal to HRT of oxygen reactor for Train B, and to the sum of anoxic HRT and oxygen HRT for the Pre-Den Trains, and

MLVSS = as defined in previously.

The mean values of F/M, Y_{obs}, and SP are summarized in Table 6.1 The histograms of these parameters are enclosed in Appendix C. The comparisons of

the values of Y_{obs} and values of SP in each Trains are depicted in Figures 6.1 and 6.2, in which a decreasing trend of both Y_{obs} and SP with time can be observed for Train B. The decreasing trends of Y_{obs} and SP during the experiment can be explained by a better performance of Train B achieved (Fig.5.17 and 5.5) due to the increase of RAS recycle ratio (r_1) from 0.6 to 1.1, and to a better control of SRT in the last periods. On the other hand, the trend followed by Y_{obs} and SP in the Pre-Den Trains were opposite to each other. Y_{obs} followed an decreasing trend while SP followed an increasing pattern which can be related to the decrease of r in the third period.

The higher Y_{obs} of a low loaded system, as occurred in our Train A, may imply an increase of nitrification rate in the system due to fixation of inorganic carbon in cell synthesis by the autotrophic nitrifying bacteria (Silverstein and Schroeder, 1983). The specific nitrification rate (SNR) was calculated, and compared to Y_{obs} (Fig.C.21) showing a decreasing trend of SNR with the decrease of Y_{obs} . The SNR in the Pre-Den trains was higher than in Train B.

The SP in the Pre-Den systems was lower than in the nitrifying Train B (Fig.6.2 and C.4), and the difference between them is higher when r is high. This fact may be explained by: 1) high r which implies a longer stay of the biomass in the system resulting in larger microbial auto-oxidation and leading to lower net Y_{obs} , and 2) high r also implies larger fraction of aerobic biomass which is exposed to anoxic period that may also increase the auto-oxidation with lower Y_{obs} . The lower SPs in the systems achieving nitrogen removal (Trains A and C) is consistent with those

Fig.6.1 Comparison of mean Yobs Throughout the experiment

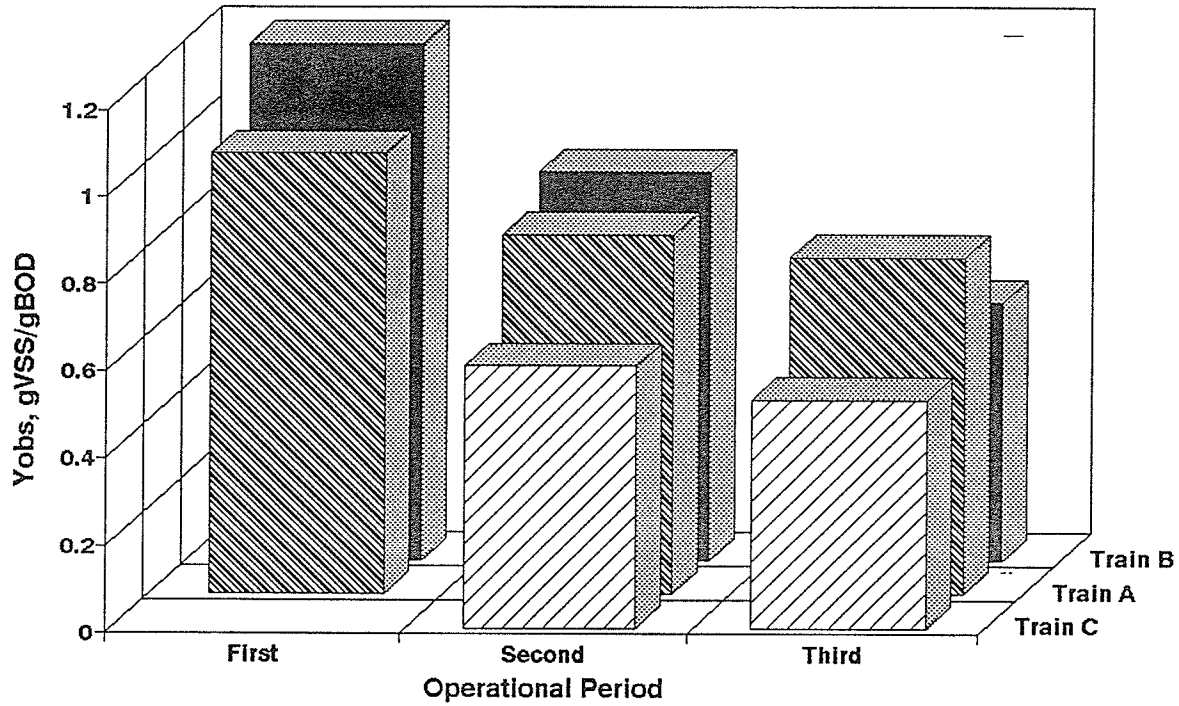
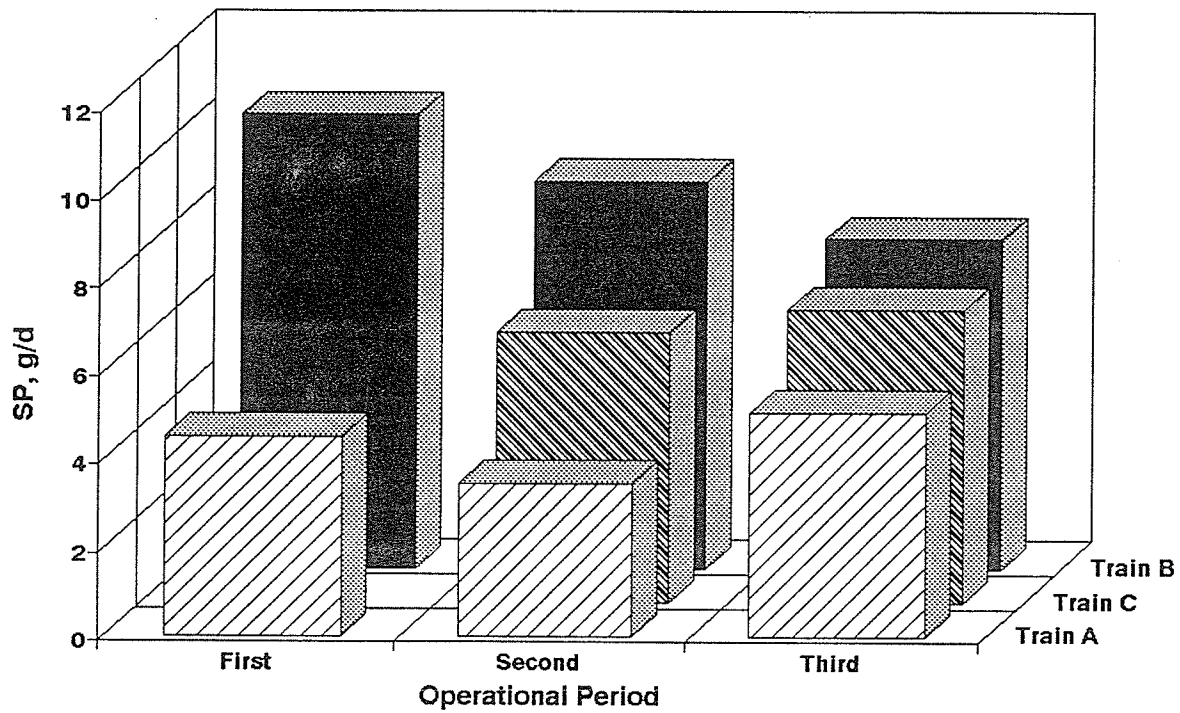


Fig.6.2 Comparison of mean SP Throughout the experiment



reported in the literature. The F/M in each treatment trains was almost constant. The F/M values were close between each other, as shown in Table 6.1, and Figures C.1 through C.3.

Table 6.1: Mean values of F/M, Y_{obs} , and SP. (Values in brackets are standard deviations)

	Train A			Train B			Train C	
	I	II	III	I	II	III	II	III
F/M g/g.d	0.11 (0.01)	0.14 (0.04)	0.16 (0.04)	0.15 (0.03)	0.15 (0.03)	0.19 (0.04)	0.17 (0.05)	0.16 (0.02)
Y_{obs} g/g.d	1.01 (0.22)	0.82 (0.19)	0.77 (0.13)	1.18 (0.28)	0.89 (0.19)	0.59 (0.11)	0.6 (0.19)	0.52 (0.05)
SP g/d	4.51 (1.32)	3.47 (0.90)	5.09 (0.76)	10.26 (2.41)	8.77 (2.26)	7.48 (1.77)	6.08 (1.26)	6.64 (0.74)

6.1 SAVINGS ON OXYGEN CONSUMPTION DUE TO PRE-DENITRIFICATION

The anoxic use of carbon in the Pre-Den reactor can be a source of savings in the oxygen required for subsequent carbon and nitrogen oxidation. Assuming the characteristics of the PE of the third operational period (Table A.9) with mean concentrations of 34 mgN/L and 74 mgSOC/L, and considering that the nitrogenous oxygen demand is 4.2 mgO₂/mgN while carbonaceous oxygen demand is 2.7

mgO₂/mgC, the total theoretical use of oxygen for combined nitrification and carbon removal for 90% removal efficiency, is

$$(34 * 4.2 + 74 * 2.7) * 0.9 = 309 \text{ mgO}_2/\text{L}$$

The combined process that includes nitrification, pre-denitrification, and carbon removal claims 1 mgSOC/mgN in the pre-denitrification reactor, therefore the oxygen requirement is

$$[34 * 4.2 + (74 - 34) * 2.7] * 0.9 = 226 \text{ mgO}_2/\text{L}$$

The difference between the two values (83 mg/L) is the saving in the theoretical oxygen required for complete (90%) nitrification and carbonaceous BOD satisfaction in the third period. The difference represents the savings of approx. 27% when compared to straight SOC and NH₃-N oxidation, without pre-denitrification.

The specific oxygen up-take rate (SOUR) measured in accordance with the Standard Methods gives erroneous results when it is used to quantify SOUR in pilot plant studies (Randall et al, 1992). However, the SOUR measured in the third operational period will be used only to compare the oxygen consumption in the nitrification reactors II, III, and V. In our case, the measured SOUR may be lower than that of the nitrification reactors (RII, RIII, and RV) since SOC and NH₃-N were no longer supplied during the time the tests were performed. As the DO

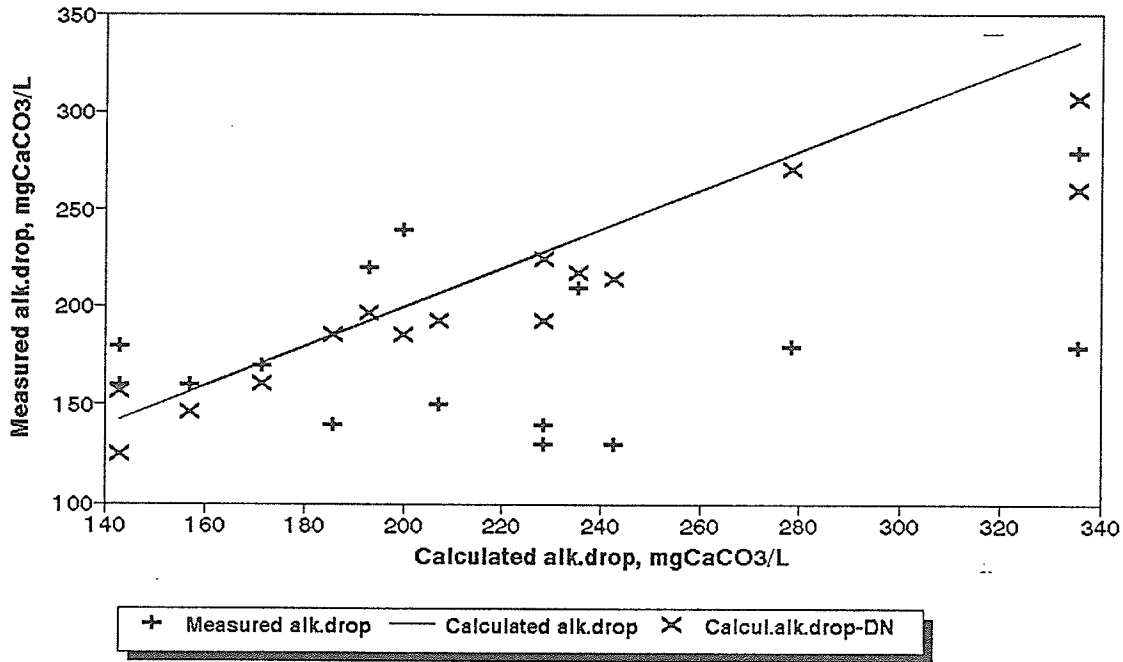
concentrations in those reactors were always over 3 mgO₂/L, no measurement higher than the SOUR of R II, III, and V would be expected. The SOUR average values of three duplicate nitrified-ML samples were 8.6, 11.6, and 9 mgO₂/L for Trains A, B, and C, respectively. Those averaged values mean an observed savings of about 26% and 22% for Pre-Den Trains A and C, respectively when compared with Train B, which was operated in the nitrification mode. The higher savings in oxygen consumption correspond to the Pre-Den Train A which had a better denitrification efficiency.

6.2 EFFECT OF PRE-DEN ON ALKALINITY CONSUMPTION

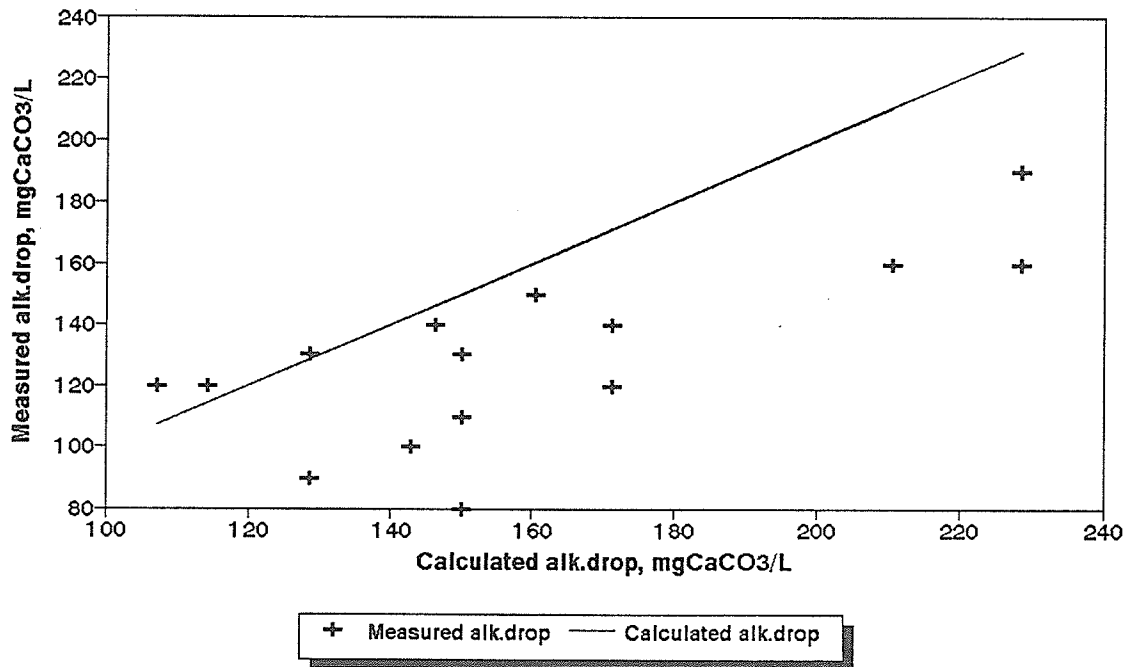
The process of nitrification destroys alkalinity in proportion to the amount of ammonia oxidized. The theoretical relationship for both catabolic and anabolic needs is given by equation 3.3. The theoretical alkalinity consumption can thus be calculated by using the stoichiometric factor of 7.14 gCaCO₃/gNH₃-N. Figure 6.3 correlates the measured alkalinity consumption with the calculated one for the Nitrifying Train B during the third operational period. The straight line represents the stoichiometric requirement of alkalinity based on nitrogen mass balance. It can be seen that the measured consumption of alkalinity due to nitrification is lower than that determined stoichiometrically confirming that denitrification has taken place in both the reactor and clarifier of Train B.

The denitrification could have occurred in the oxygen reactor because of the lack of O₂ into the biological floc, and in the clarifier because of the high NO₃-N

**Fig.6.3 Alkalinity consumption
Nitrifying Train B- Third period**



**Fig.6.4 Alkalinity consumption
Pre-Den Train A- Third period**



concentration as well as the lack of O_2 in the sludge blanket. This finding could also be explained by heterotrophic nitrification which may be favoured due to low pH or low pO_2 (from Robertson et al,1988). In light of this finding, the theoretical alkalinity requirement was calculated based on the effect of the denitrification process which produced alkalinity proportional to the amount of NO_3^- reduced (NO_{3R}). The stoichiometric factor of $3.57 \text{ gCaCO}_3/\text{gNO}_{3R}$ from equation 3.6 was used.

The calculated alkalinity consumption (calculated alk.-DN) values based on the nitrogen mass balance and considering both oxidized $NH_3\text{-N}$ and reduced $NO_3\text{-N}$ are also depicted in Figure 6.3, and still shows a difference with the measured consumption of alkalinity. The low measured consumption of alkalinity supports the idea that both CO_2 and HCO_3^- were the source of inorganic carbon to the autotrophic microorganisms, since CO_3^{2-} may not have been in the ML of RIII due to the low pH.

The fact that the 7.14 gCaCO_3 of alkalinity consumed per $\text{gNH}_3\text{-N}$ oxidized was not achieved agrees with those values reported in the U.S.EPA Nitrogen Control Manual (1975) and Benniger and Sherrad (1978). These researchers have reported that a value of alkalinity destruction lower than 7.14 was obtained when nitrification of a prepared feed solution with COD/TKN higher than 4 was performed in a conventional continuous-flow activated sludge. However, they explained the difference of alkalinity destruction by a) shifts in predominance of microbial species, b) a change in microbial chemical consumption, and/or c) loss of nitrogen via

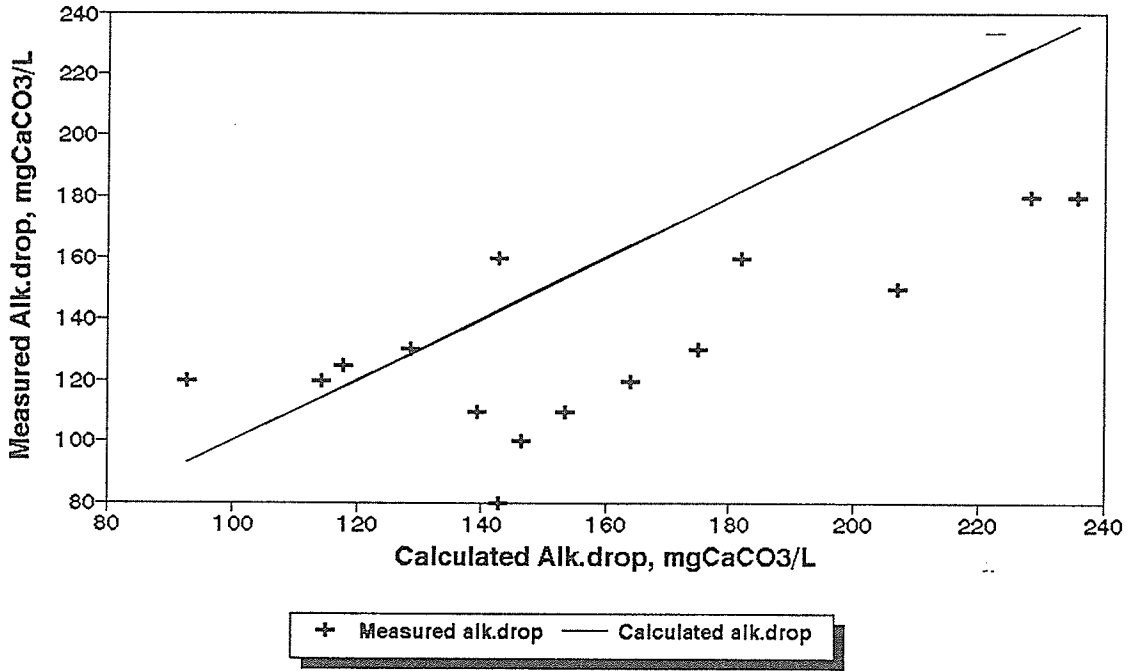
denitrification in the sedimentation basin. In our case, we also considered denitrification in the nitrification reactor, and a possible consumption of the dissolved CO_2 (see item 5.1).

The measured alkalinity in the Pre-Den Trains A and C were also below the calculated alkalinity consumption as shown in Figures 6.4 and 6.5. The measured consumption of alkalinity was compared with TNR and NO_3R for the Trains A and C. Figure 6.6 is an example of those comparisons, and illustrates that the low loss of alkalinity not always coincided with high TNR, proving that the increase of pH in the ML of RII could be produced by the utilization of CO_2 .

Figure 6.6 also shows no blocking of NO_3 reduction to N_2O and N_2 , since NO_3R and TNR follow the same pattern and their values are slightly different, with the exception of those values on day 112, when there was a failure of the mixing system of RIV. This mixing failure apparently impaired complete conversion of $\text{NO}_3\text{-N}$ to the lowest reduced state of N; however, the $\text{NO}_3\text{-N}$ content decreased due to the anoxic conditions in RIV.

The effect of accomplishing denitrification ahead of the oxygen reactor is illustrated in Figures 6.7 and 6.8. The former Figure depicts the medium alkalinity in the raw PE and in the final effluents from the pilot plant during each period, and shows higher alkalinity in the effluents from the Pre-Den Trains A and C. The effluent that had a greater denitrification efficiency also had the higher alkalinity in the final effluent. The highest effluent alkalinity in all three Trains coincided with the highest RAW alkalinity for the third period.

**Fig.6.5 Alkalinity consumption
Pre-Den Train C- Third period**



**Fig.6.6 Histogram of alk.consumption
Pre-Den Train C- Third period**

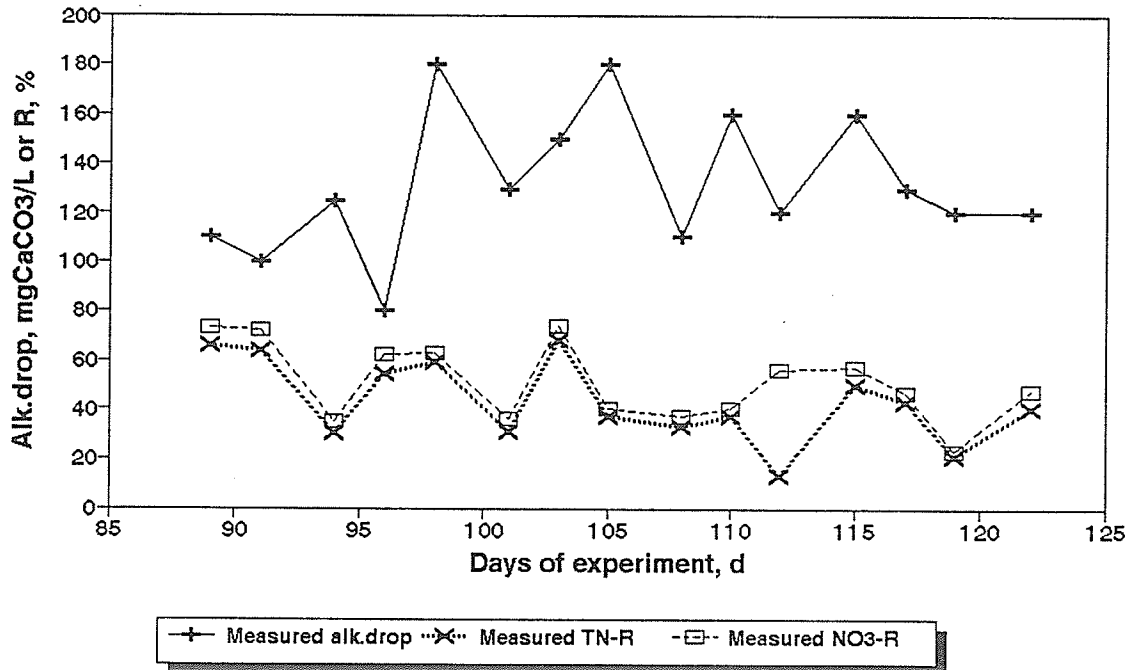


Fig.6.7 Comparison of Effluent Alk. Throughout the experiment

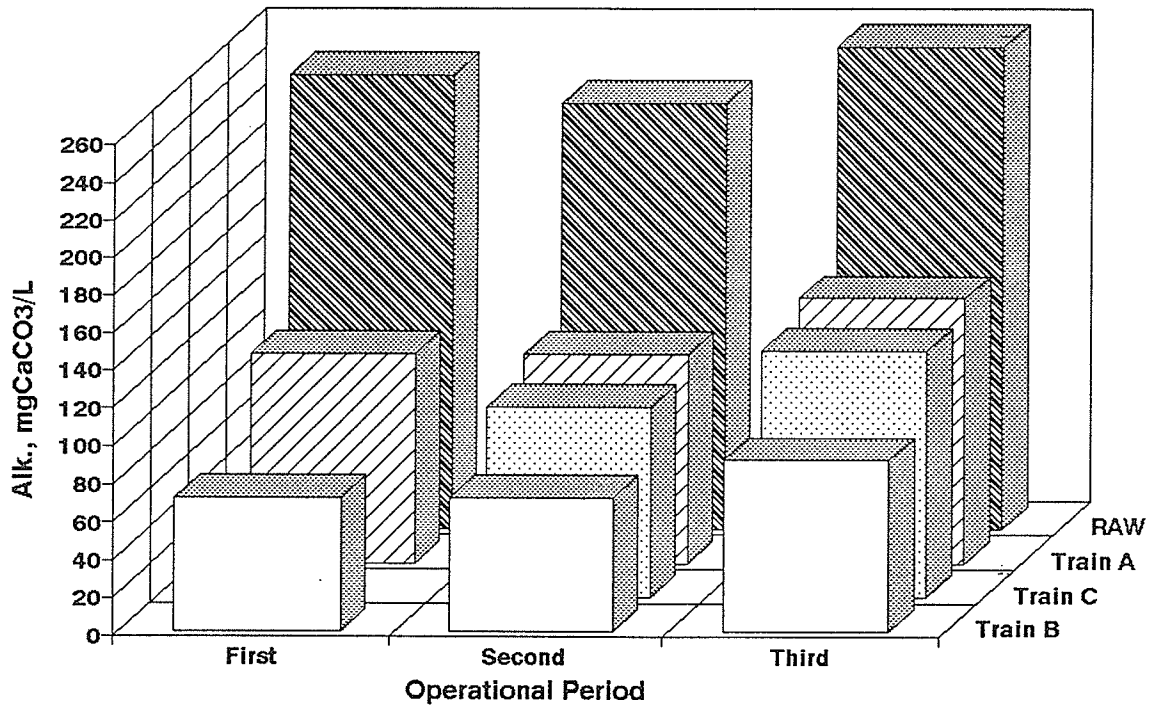


Fig.6.8 Comparison of Alk.Gained by DN Throughout the experiment

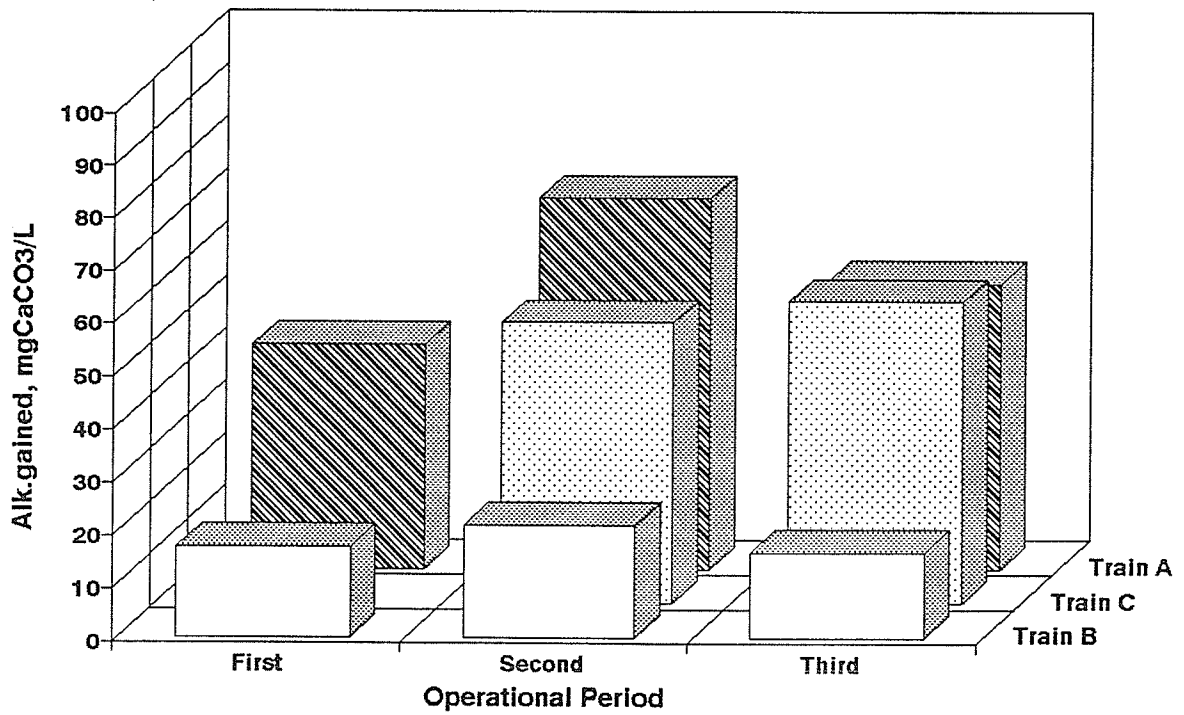


Figure 6.8 compares the alkalinity gained due to Pre-Den, and allows to correlate the effect of Pre-Den to the RNO_3 (r_2) and the overall recycle ratio (r). The averaged alkalinity gained in the second period was 21, 53, and 70 mgCaCO₃/L for Trains B, C, and A, respectively. Despite the lowest PE alkalinity in the second period, Train A achieved the greatest recovery of alkalinity due to denitrification when r was 1.5. The lower alkalinity gained for this Train in the first period can be explained by 1) the high variability of PE composition, 2) the lowest C/N ratio of PE, and 3) the highest r_2 (1.5, see Tables 4.1 through 4.3) that could have delayed the acclimatization of denitrifiers due to inhibition of denitrification caused by the oxygen concentration in r_2 . On the other hand, when r was decreased to 0.9 with r_2 of 0.5, the denitrification efficiency of Train A diminished, so that the alkalinity gained in the third period was lower, despite of the highest PE alkalinity.

The slight difference between the alkalinity gained in the second period and that gained in the third period for Train C (when r_2 was decreased from 1.1 to 0.7) and the low TNR in the first period for Train A may indicate that denitrification required a longer period of acclimatization, therefore the change of the operational r_2 should have been practice later.

The low loss of alkalinity achieved in the pilot treatment Trains may be significant since there is an additional loss of alkalinity (on top of that due to nitrification) due to carbonaceous oxidation and due to slightly higher than atmospheric CO₂ content in the head space of the experimental reactors. Although not comparable to the full scale system the head space has been covered, however

the gas was not recycled. Perhaps, the higher CO₂ dissolved due to the higher partial pressure could be one reason why the finding in our experiment differs from that of Daigger, et al (1986), in which the measured alkalinity consumption compared very well with that calculated based on the same stoichiometric factors. On the other hand, the lower measured alkalinity consumption than the calculated drop of alkalinity, attained in our experiment, agrees with works of Degyansky (1977) and Benninger and Sherrard (1978).

The histograms of effluent alkalinity and of alkalinity consumption as well as the comparisons of measured and calculated alkalinities for all three Trains throughout the experiment, are enclosed in Appendix C.

6.3 COMPARISON OF THE PRE-DEN TRAINS

Even though Pre-Den Train A was compared to Pre-Den Train C during the previous discussion, this section intends to analyze the oxidation-reduction potential (ORP) effects on the denitrification process, and the specific denitrification rate (SDNR) in the Pre-Den Trains.

6.3.1 OXIDATION-REDUCTION POTENTIAL

In the second operational period, the measurements of ORP were started twice a week by monitoring the ORP directly in RI and RIV for long intervals. Figures 6.9 and 6.10 are examples of the ORP readings done for an interval longer than five hours. Due to the pattern followed by the ORPs through the day in both

Fig.6.9 ORP in RI, Pre-Den TRAIN A
On day 77

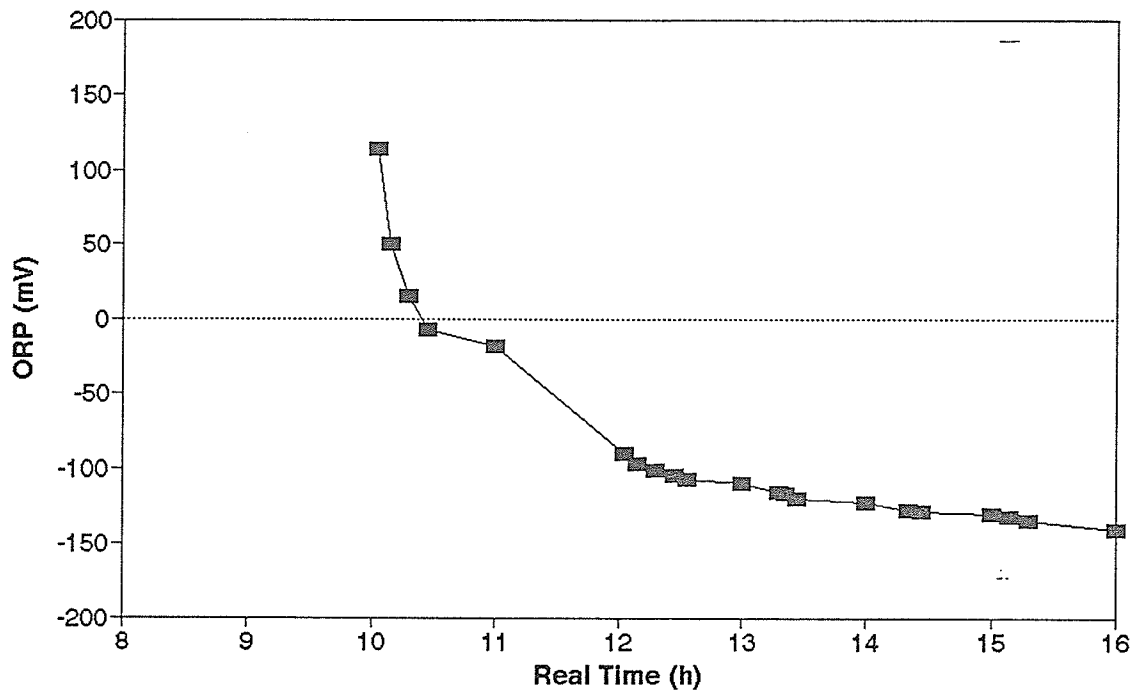
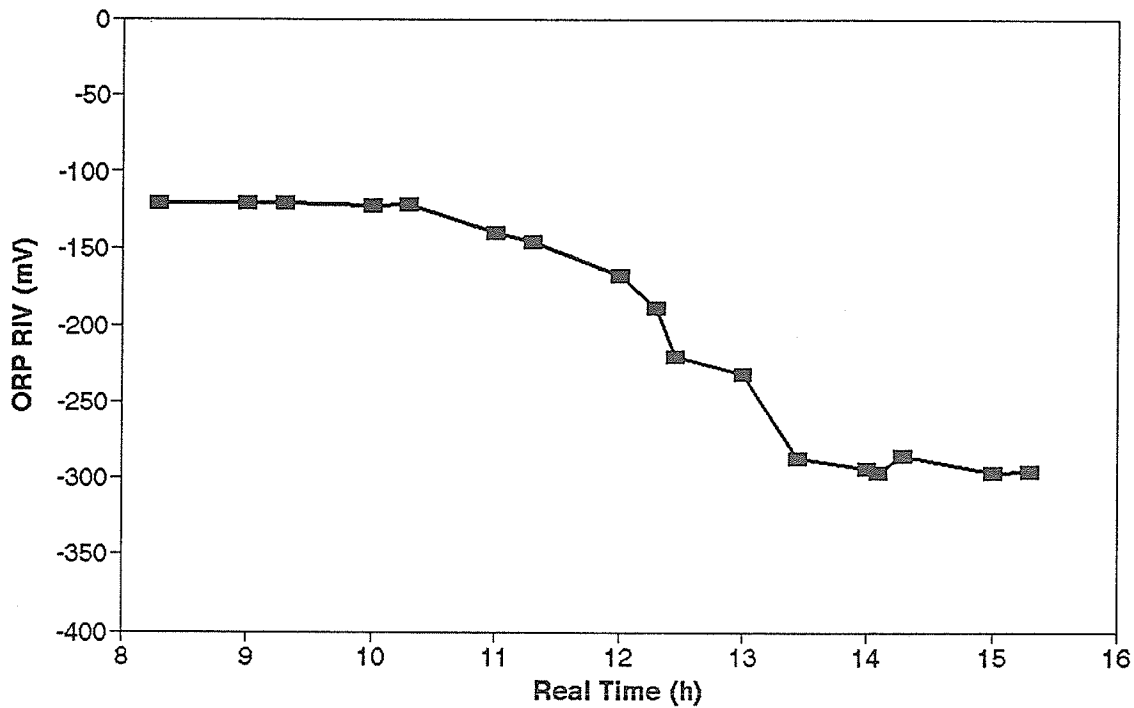


Fig.6.10 ORP in RIV, Pre-Den TRAIN C
On day 87

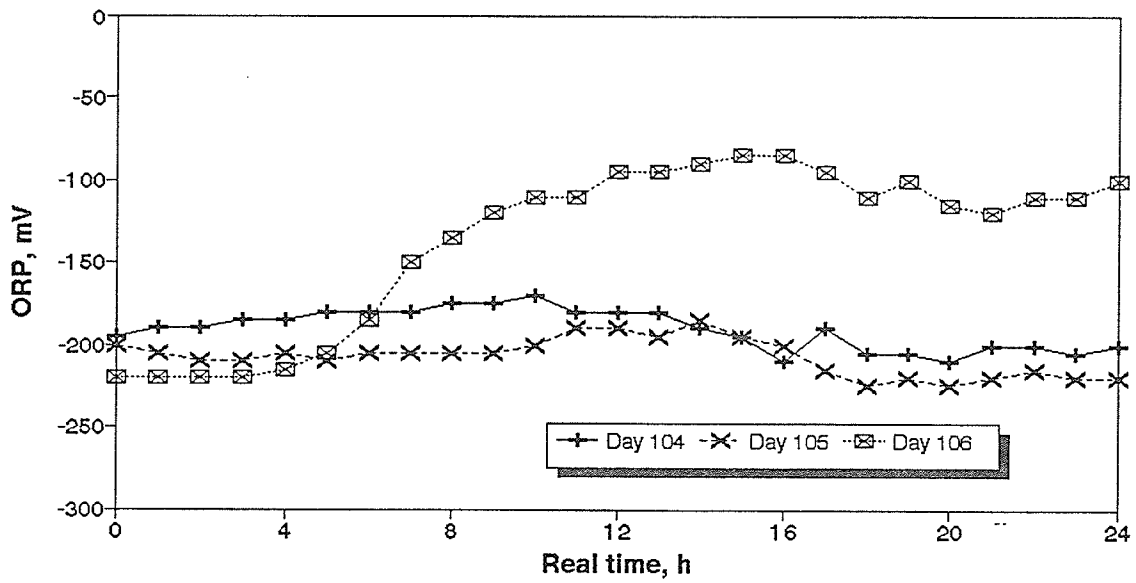


reactors, it was thought that they may exhibit diurnal variation as did the composition of the raw wastewater. To prove or disprove this hypothesis the ORPs were recorded continuously from day 103 in RI (Train A) and from day 105 in RIV (Train C).

The hourly ORPs recorded were loaded to a PC computer for processing by the spreadsheet program of Quattropro 3.0. The diurnal variation of ORP was discharged since the ORPs in both anoxic reactors exhibited slight variation for several days (approx. 12 out of 17 days recorded). Figure 6.11 shows the typical pattern of ML ORPs in RI. The ML ORPs in RIV followed a similar pattern to those of ML RI but the values were approximately 100 mV higher in RIV as shown in Figure 6.12.

The variations of ORP observed at first (Fig. 6.9 and 6.10) may be caused by the composition of PE as shown in Figure 6.13, in which the ORPs decreased substantially at time. Moreover, positive ORPs were recorded. This decrease of ORP appears to be related to a shift of chemical and microbiological activities in the raw wastewater since the range of those variations was most of the time the same for both reactors RI and RIV, as Figure 6.13 depicts. Figure 6.14 was included to show the failure of the RIV mixing system, marked with the arrows on day 112, supporting the explanation of the difference between $\text{NO}_3\text{-N}$ and TNR depicted in Figure 6.6. The low ORP, which reached -300 mV, may account for the absence of $\text{NO}_3\text{-N}$ in the ML of RIV and the low TNR, since the reduction of NO_3^- to NH_4^+ is enhanced at that ORP (Charpentier et al., 1987). The hourly ORPs were averaged, and the ranges found were -210 to -150 mV for RI, and -190 to -70 mV for RIV.

**Fig.6.11 ORP in RI, Pre-Den Train A
on days 104,105,and 106**



**Fig.6.12 Comparison of RI ORP & RIV ORP
on day 106**

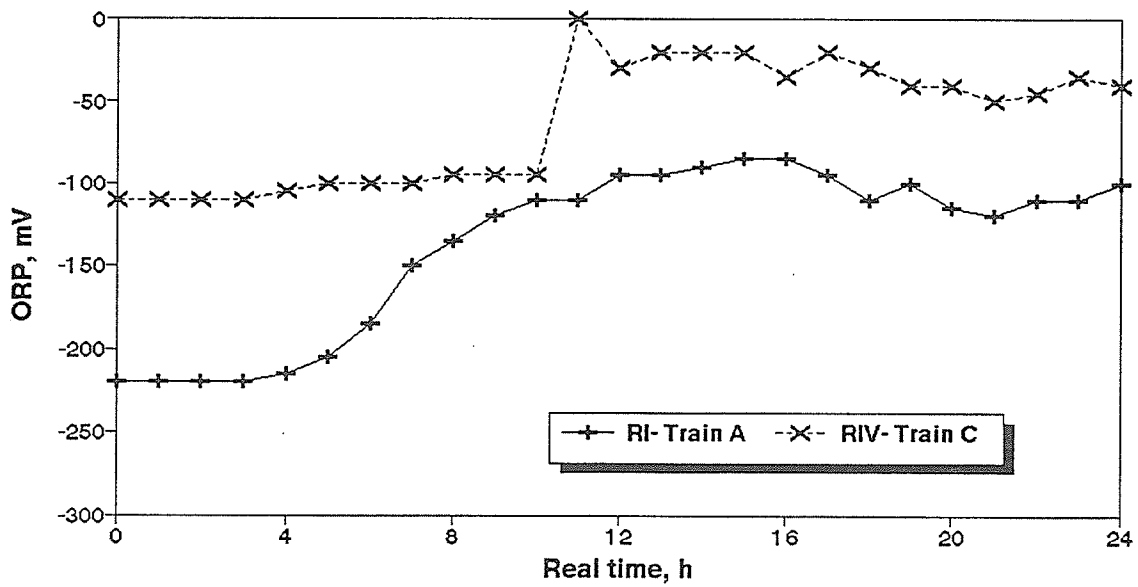


Fig.6.13 Comparison of RI ORP & RIV ORP on day 107

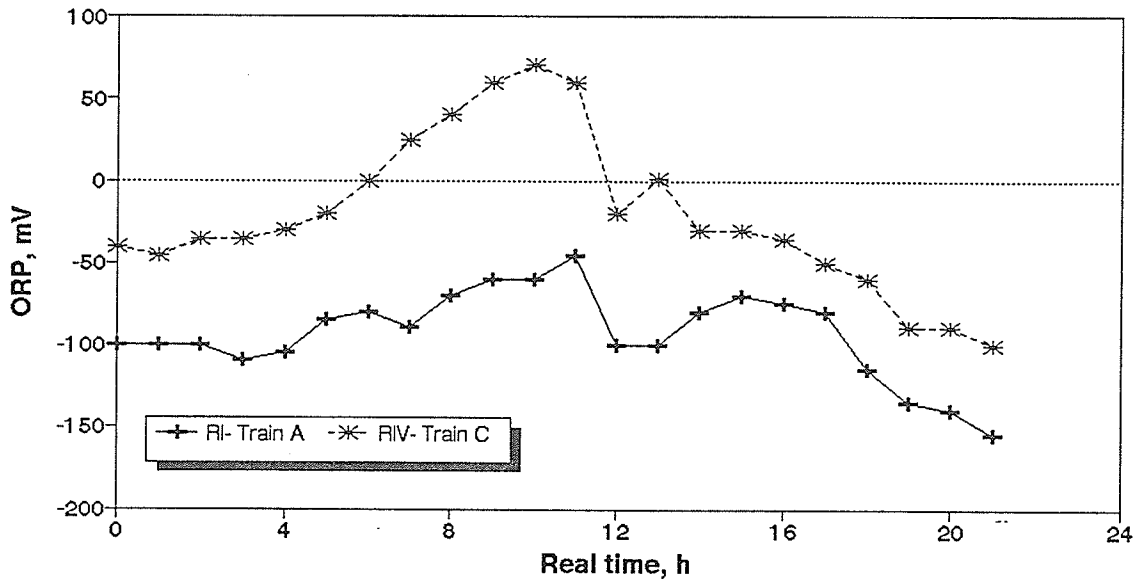
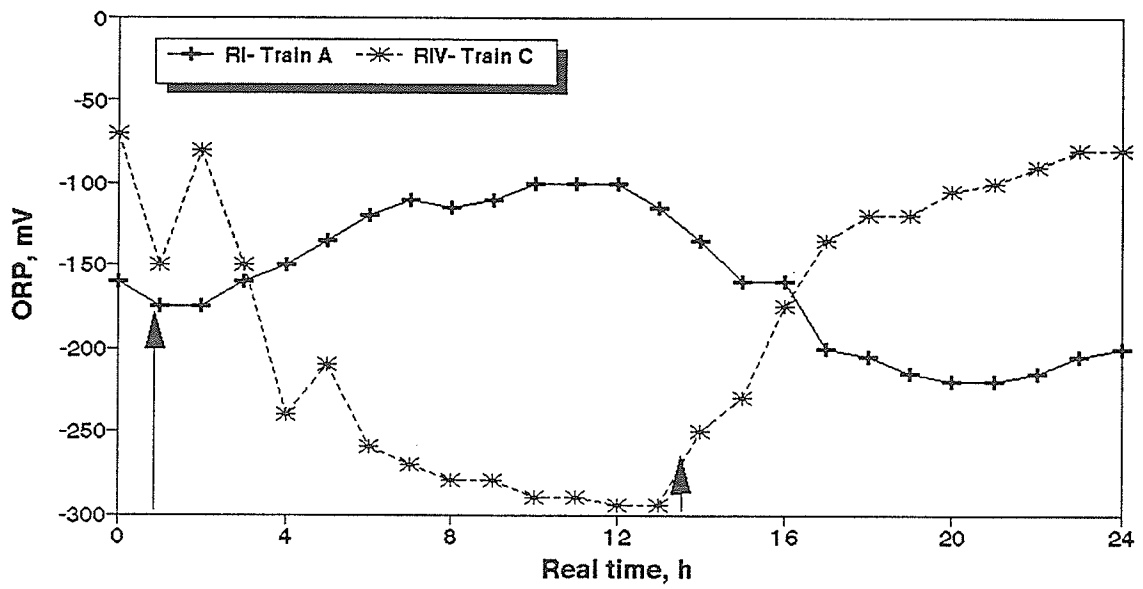


Fig.6.14 Comparison of RI ORP & RIV ORP on day 112



6.3.2 DENITRIFICATION RATE

The SDNRs for the anoxic reactors were determined by equation 5.15

$$SDNR = \frac{NO_{3If} - NO_{3DNEf}}{MLVSS_{DN} * HRT_{DN}} \quad [6.4]$$

where

SDNR = specific denitrification rate, mgNO₃-N/gVSS.h,

NO_{3If}, NO_{3Ef} = nitrate concentration in the influent to the anoxic reactor, and
the denitrified effluent from the anoxic reactor, mgNO₃-N/L,

MLVSS_{DN} = VSS concentration of the anoxic ML, g/L, and

HRT_{DN} = hydraulic retention of the anoxic reactor based on Q_{RAW}.

The SDNR was correlated to the substrate utilization rate (U_{DN}) in the denitrifying reactor. The U_{DN} was calculated using the following equation

$$U_{DN} = \frac{SOC_{If} - SOC_{DNEf}}{MLVSS_{DN} * HRT_{DN}} \quad [6.5]$$

where

U_{DN} = specific utilization rate, gSOC/gVSS.d,

SOC_{If}, SOC_{Ef} = SOC concentration in the influent to the anoxic reactor, in
denitrified effluent from the anoxic reactor, mg/L (g/m³),

MLVSS_{DN} = VSS concentration of the anoxic ML, mg/L (g/m³), and

HRT_{DN} = Anoxic hydraulic retention time, d.

The correlation between the SDNR of Pre-Den Train A and the U_{DN} was strong ($r^2 = 0.87$) and ($r^2 = 0.84$) in the second and third period, respectively ; however, the SDNRs of Train C showed a weaker correlation to U_{DN} ($r^2 = 0.4$). The equation for the correlation lines for Train A depicted in Figures 6.15 and 6.16, are:

a)

$$SDNR_2 = 0.28 + 11.58 * U_{DN} \quad [6.6]$$

b)

$$SDNR_3 = 0.05 + 10.21 * U_{DN} \quad [6.7]$$

where

$SDNR_2$, $SDNR_3$ = SDNR for RI in the second and third period, $mgNO_3^-$
N/gVSS.h, and

U_{DN} = as defined previously.

The lower values of SDNR coincided with low NO_3^- -N (≤ 7 mg/L) and/or low SOC (≤ 30 mg/L) in the influent; however the most important factor appeared to be the availability of carbon (Caponetto et al, 1992). To establish the effect of availability of carbon on denitrification, batch works were performed by taking a

Fig.6.15 SDNR Vs Udn - TRAIN A
Second Period

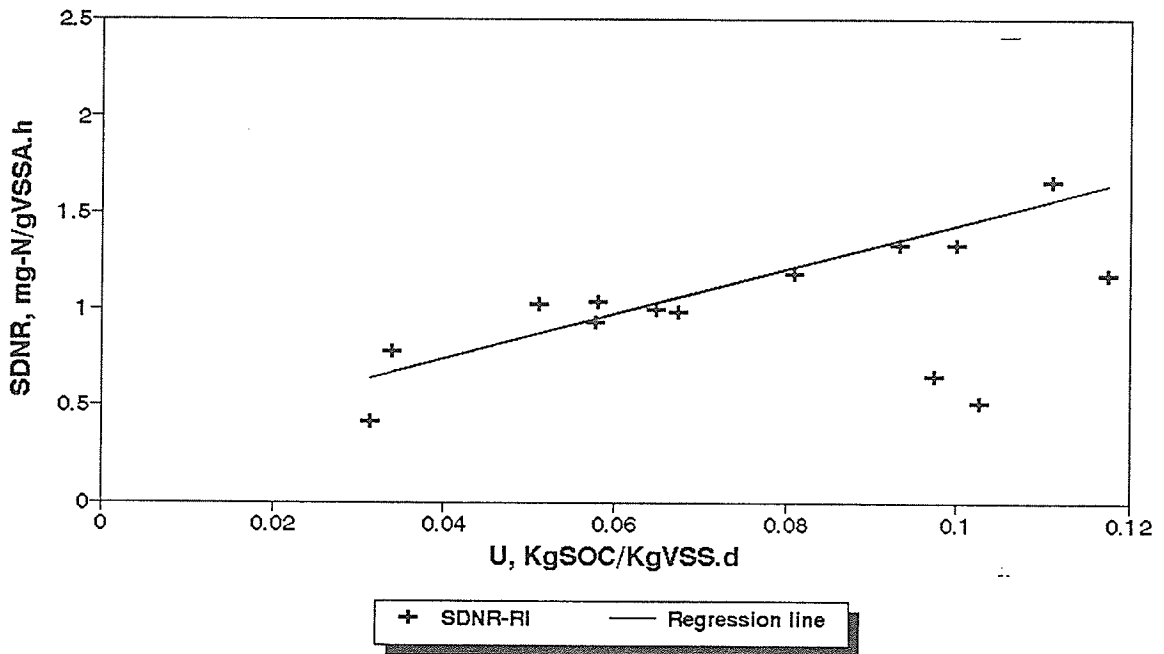
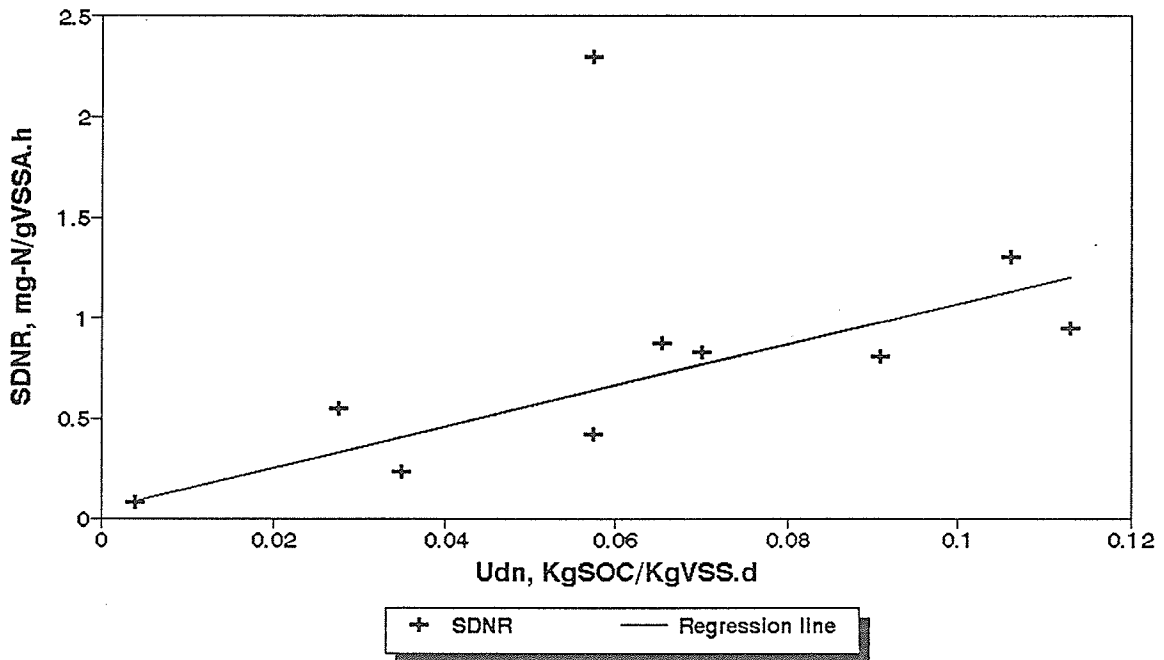


Fig.6.16 SDNR Vs Udn - TRAIN A
Third Period



sample of ML from the denitrifying reactors I and IV, and stirring it under anoxic conditions, while manually collecting samples every 30 minutes. The volumetric rate (DNR in $\text{mgNO}_3\text{-N/L.h}$) of removal of nitrates, that is the rate of denitrification, was thus found by plotting the NO_3 concentrations versus time, and by determining the slope of the line. Figures 6.17 and 6.18 show the results of the batch studies on day 117 and 122 on RI. The plots for RIV as well as those performed after day 122 are attached in Appendix C. During the two days chosen for Figures 6.17 and 6.18 there were similar levels of solids in both experiments, thus making it possible to compare the SDNR expressed in $\text{mgNO}_3/\text{gVSS.h}$. These rates were 2.4 and 1.2 for RI and 2.5 and 1.0 for RIV, on day 117 and 122, respectively. It should be mentioned that the SDNRs determined by equation 6.4 were 2.30 and 1.30 for RI, and for RIV, 3.0 and 1.49 for those days, which validates the use of that equation.

The above SDNR were determined on days of low SOC and relatively low NO_3 . The rates for high SOC and high NO_3 were determined after day 122, and in those occasions the MLVSS was also higher, mainly in RIV. The DNR was proportional to the amount of sludge present, increasing with the increase of MLVSS and with the concentrations of SOC. The SDNR was $3.8 \text{ mgNO}_3\text{-N/gVSS.h}$ for Train A (Fig.6.19). Figure 6.20 illustrates the variations of SOC and NO_3 , and shows that the DNR can be described by two distinct lines. The values of SDNR are 5.4 for the higher DNR and 2.4 for the lower one.

The graphs in figures 6.17 through 6.20 demonstrate another characteristic of denitrification in the Pre-Den mode. At low SOC the decrease is linear, that is the

Fig.6.17 Pre-denitrification Rate- RI on day 117 with low carbon content.

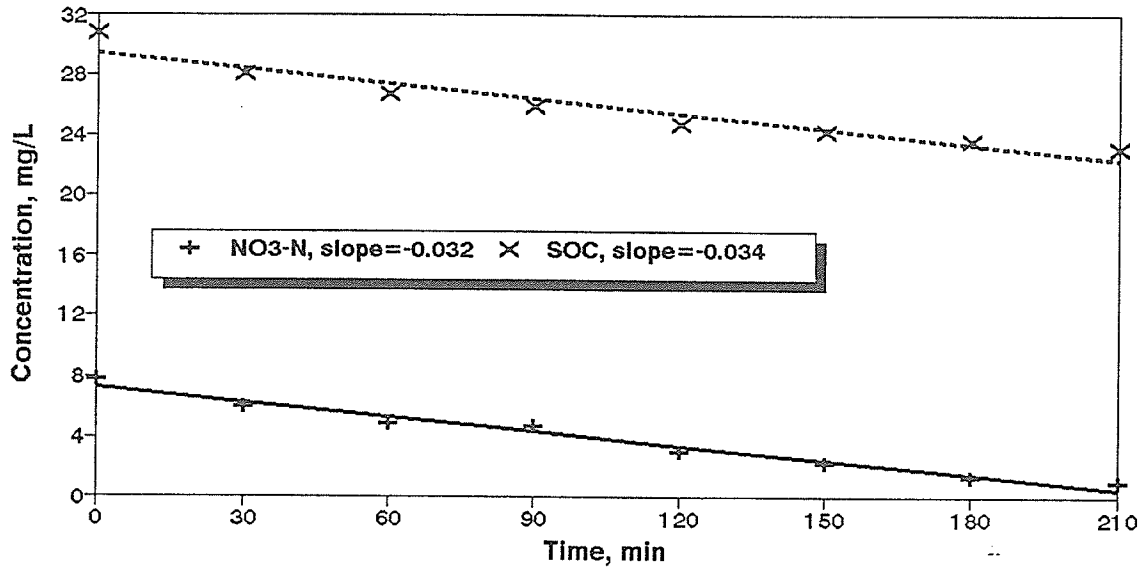
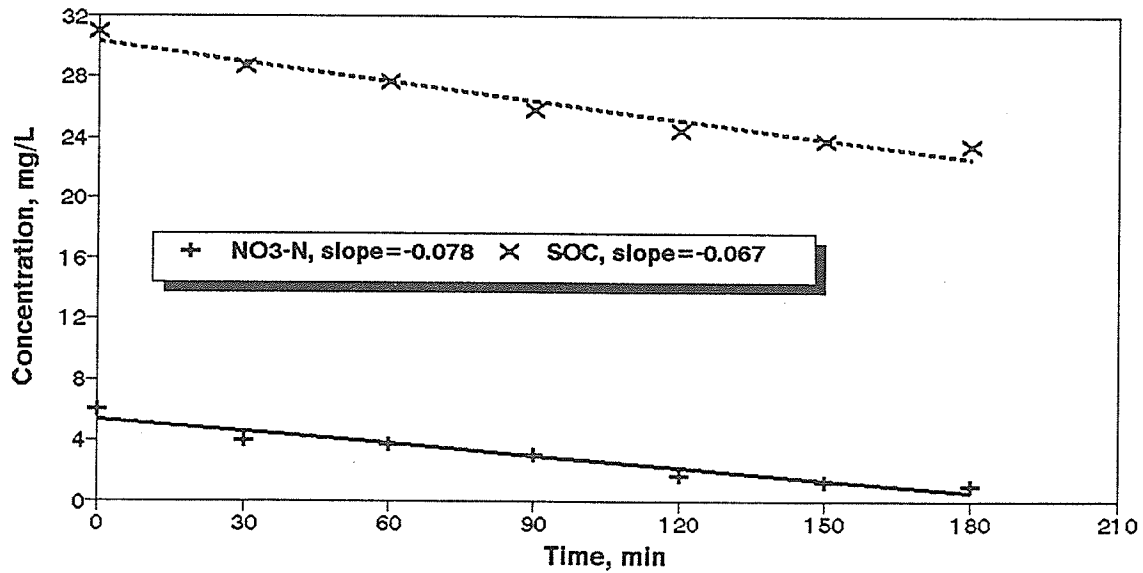
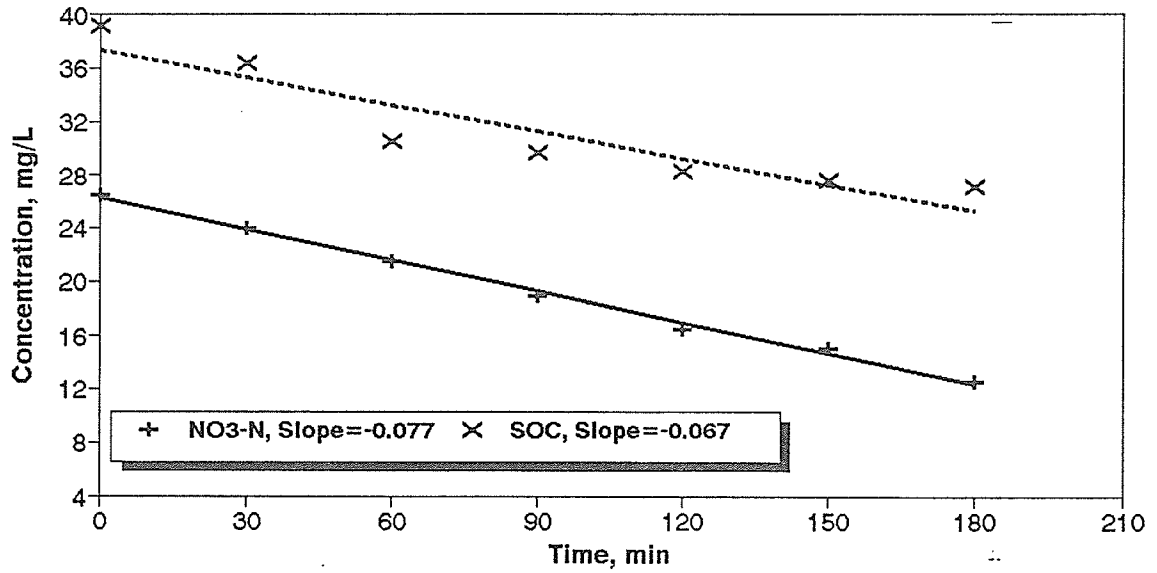


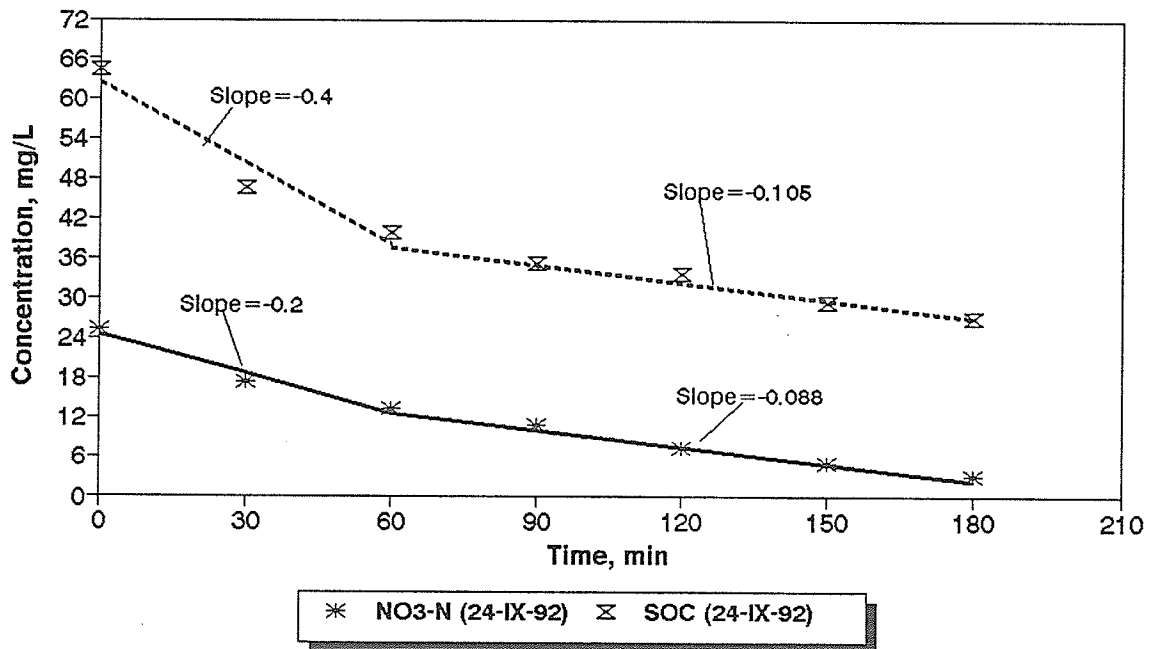
Fig.6.18 Pre-denitrification Rate- RI on day 122 with low carbon content.



**Fig.6.19 Pre-denitrification Rate-RI
on a day with high carbon content,24-IX**



**Fig.6.20 Pre-denitrification Rate-RIV
on a day with high carbon content,24-IX**



reaction is zero order. This means that the rate of denitrification is independent of the concentration of the species remaining (SOC or NO_3). With the stronger primary effluent, and high-loaded Train C, the reaction becomes concentration-dependent, that is of an order other than zero. The reaction rate was concentration-dependent for both Pre-Den Trains when the SOC was even higher (ie. on October 1, see graphs in Appendix C). This finding appears to be in contrast to the literature which suggests that denitrification is a zero order reaction down to very low concentrations of nitrate (Beccari et al, 1983). However, it is consistent with the works of Barnard et al (1975), Sikora and Keeney (1976), and Aragman and Bernner (1986).

The SDNR values obtained are similar to those in the literature (Metcalf and Eddy, 1991; and Randall et al, 1992). There were only eight measurements made of the denitrification rate, and the average ratio of carbon used to nitrogen reduced was 1.09 gSOC/gN reduced. A somewhat higher than the prior theoretical calculation of 0.93 can be explained by the adsorption of the soluble and supra-colloidal SOC on the flocs of the biomass, thus moving from the liquid to the solid phase; however, a simple error due to small number of samples cannot be excluded.

6.3.3 RELATIONSHIPS AMONG ORPs, RAW WASTEWATER, AND PRE-DEN PROCESS EFFICIENCY

The averaged ORPs in the nitrifying reactors RII and RV are compared with their respective anoxic ORPs in Figures 6.21 (Train A) and 6.22 (Train C). The oxic ORP appears to be slightly more steady than the ORP of the anoxic reactors, and

Fig.6.21 ORP in Pre-Den Train A
On day 120

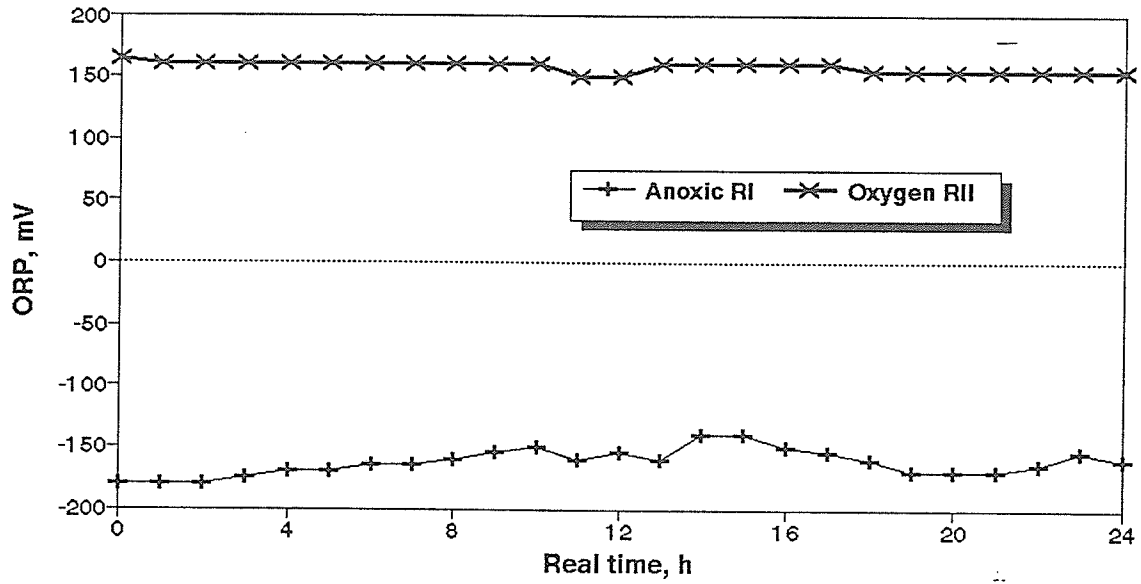
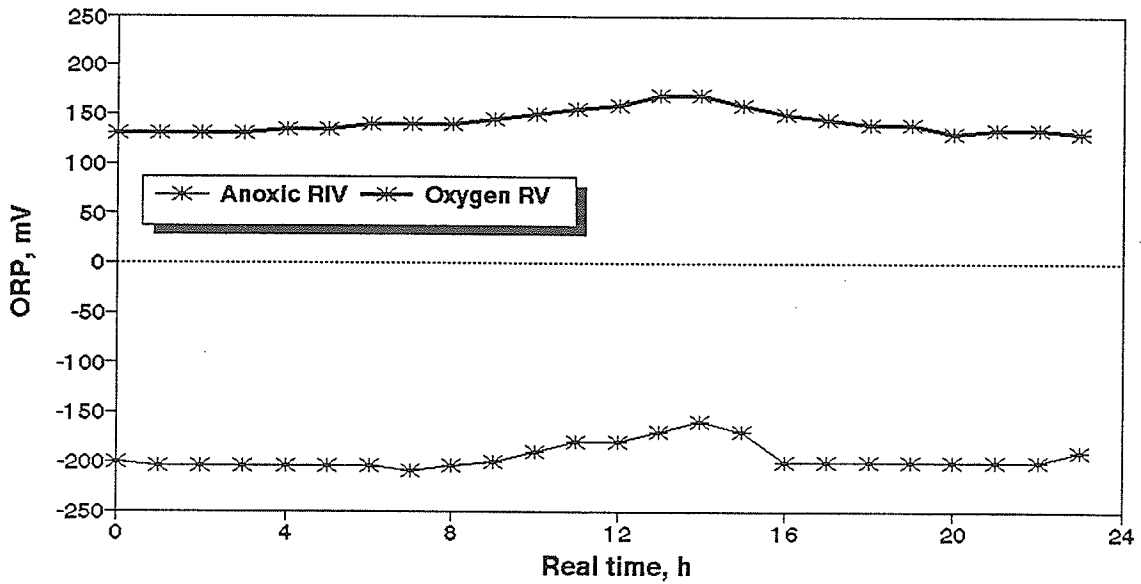


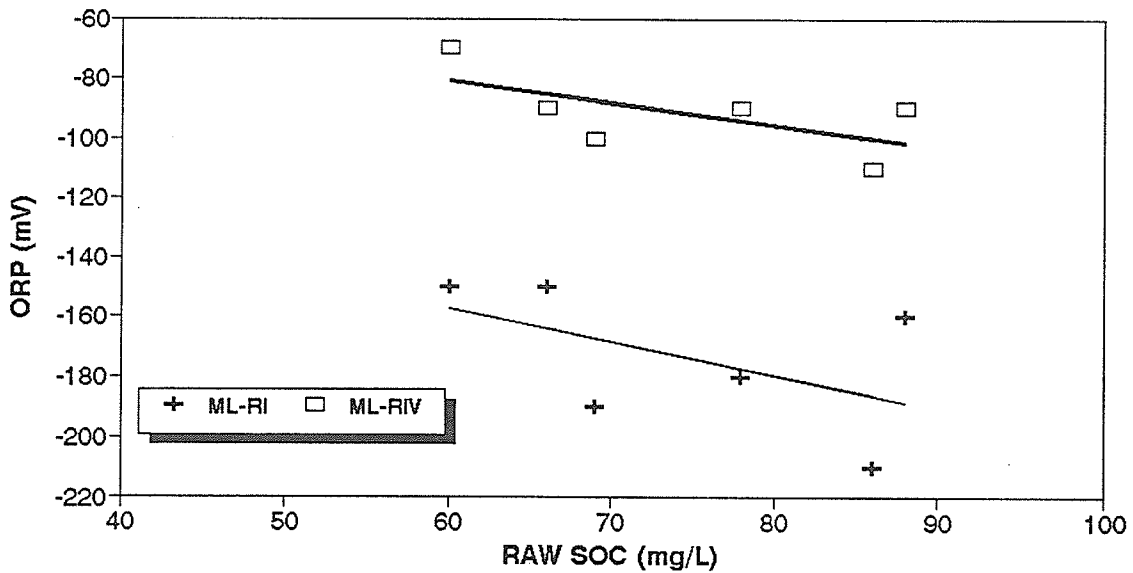
Fig.6.22 ORP in Pre-Den Train C
On day 122



follows a similar pattern to those of RI and RIV, but, as expected, in the positive range. The ORP of RII was 160 mV, slightly higher than that of RIV (140 mV). The highest nitrification ORP was measured in RIII of the nitrifying mode Train B and was about 190 mV.

The averaged anoxic ORPs were correlated with the raw wastewater SOC concentration for the third operational period. Figure 6.23 depicts that correlation and shows more negative ORP values in the ML of RI and RIV for the stronger PE, supporting the discussion of the previous section.

Fig.6.23 Correlation of ORP to PE-SOC in the third period



The highest denitrification efficiency measured has coincided with an ORP of -200 mV in Train A and -100 mV in Train C. It should be mentioned that for days 117 and 122, when the SDNR were measured, the higher SDNR and TNR were on

day 117 with lower ORP, in Pre-Den Train A; however, for the other Pre-Den Train, the higher SDNR and TNR were for the higher ORP, as summarized in Table 6.2. This fact may indicate that the optimal ORP for denitrification is variable and depends on the operational parameters applied to a specific treatment. The optimal ORP appeared to range between -180 and -200 mV for Train A and between -90 and -100 for Train C. However, further studies are required to confirm the ORP that could optimally favour the denitrification process.

Table 6.2 Comparison of SDNR, ORP, and TN-R in the Pre-Den Trains

		Train A		Train C	
		Day 117	Day 122	Day 117	Day 122
Anoxic ORP, mV		-180	-160	-90	-200
SDNR mgNO ₃ -N/L	Measured	2.4	1.2	2.5	1.0
	Calculated	2.3	1.3	3.0	1.5
TN-R, %		46	36	43	40

CHAPTER 7: SUMMARY AND CONCLUSIONS

A pilot study was commenced to demonstrate the feasibility of pre-denitrification in offsetting the negative effects of alkalinity destruction caused by nitrification, and in decreasing the oxygen consumption produced by anoxic removal of SOC. The study, carried out at anoxic HRTs of 1.5 and 3 h and oxygen HRTs of 6.2 to 12 h, based on Q_{RAW} , has contributed to the knowledge of the conditions governing nitrogen removal in **pure oxygen systems**, and attempted to determine the potential for complete nitrification of the NEWPCC's **primary effluent**. It has also been demonstrated that the overall recycle ratio correlates better with the TKN influent and effluent concentrations than with the NH_3-N concentrations; therefore, a new equation based on TKN has been proposed. The following conclusions have been reached:

1. Complete ammonia removal from the NEWPCC's primary effluent through nitrification is feasible. Nitrification, carried at SRT of 6.1 to 8.9 d and HRT of 6.1 h and 12 h appeared independent of the influent fluctuations.

2. The effluent pHs were above the level expected because denitrification has taken place in the oxygen reactor and clarifier, and, probably because dissolved CO_2 must have been an important source of inorganic carbon to the autotrophic microorganisms.

3. The effect of rising pH is greater when denitrification is controlled and applied ahead of the nitrification process. The pH level was well above the level expected from OH^- produced by denitrification at anoxic HRT of 3 h based on raw

wastewater flow.

4. An increase of the nitrified mixed liquor pH was observed, due to a greater utilization of dissolved CO_2 in the Pre-Den mode, when it was operated at HRT of 3 h, and due to the initial alkalinity of the influent to the nitrification reactor.

5. The process efficiencies in terms of BOD, SOC, NH_3 , and TKN were independent of the raw wastewater variability.

6. The denitrification efficiency in terms of $\text{NO}_3\text{-N}$ or TN was highly dependent on influent composition and concentration, and on the overall recycle ratio. It appeared to depend also on the applied process control.

7. Biological denitrification in the pre-denitrifying reactors I and IV at times produced a fully denitrified effluent. The denitrification **around the anoxic reactors** was well correlated to the specific utilization rate based on SOC and raw wastewater flow.

8. The averaged denitrification **around the whole treatment Trains A and C** was 31 to 53%, with periods of 55 to 75 % lasting one to three weeks. The difference between the whole Train efficiency and the Pre-Den reactor efficiency is due to lack of optimization of the return mixed liquor from the aeration compartment matched with the return activated sludge.

9. The higher denitrification efficiency was attained for an overall recycle ratio of 1.5 for Train A and 2.2 for Train C suggesting an inverse relationship between r and HRT.

10. The overall recycle ratio correlated well with the TKN influent and effluent concentrations. Hence, the following equation is proposed for the determination of the overall recycle ratio:

$$r = \frac{\frac{TKN_{RAW}}{100} * TKN_{RAW} + TKN_{Ef}}{(1 - \frac{TKN_{RAW}}{100}) * TKN_{RAW} - TKN_{Ef}}$$

11. Whereas, once initiated, the denitrification process was not hindered by the residual oxygen concentration in the return nitrified-mixed liquor. Denitrification startup appeared hindered by the residual oxygen concentration in the return nitrified-mixed liquor.

12. The pre-denitrification reactors have contributed to the removal of soluble organic carbon at a ratio of 1.09 gSOC removed per g of N reduced. This meant an observed saving in oxygen consumption of 26 % for Train A and 22 % for Train C. These values are close to the 27 % decrease in theoretical oxygen demand at 34 mgN/L and 74 mgSOC/L in the primary effluent, if 90 % nitrification is implemented.

13. The alkalinity gained by Pre-Den mode was 70 mgCaCO₃/L for Train A and 54 mgCaCO₃/L for Train C in the best operational period. In the nitrifying mode, a recovery of alkalinity due to denitrification inside of the mixed liquor bio-flocs and in the sludge blanket of the clarifier has also been observed. The averaged value was 21 mgCaCO₃/L for the same operational period reported

above.

14. The observed consumption of alkalinity was lower than the theoretical calculated value based on nitrogen mass balance and considering denitrification in both treatment mode investigated.

15. Measurements of the oxidation-reduction potential in the Pre-Den reactors suggested that specific denitrification rates and denitrification efficiency in the high-loaded Train C decreased at lower ORP, suggesting that there is an optimal ORP for denitrification.

16. Denitrification appeared to be faster at a range of ORP between -180 and -200 mV in the Pre-Den mode operated at anoxic HRT of 3 h, and between -90 and -100 mV in the mode operated at anoxic HRT of 1.5 h.

17. There was a strong correlation between the lack of easily available carbon in the weak primary effluent and decreased denitrification. Denitrification rate was up to 5.4 mgNO_{3R}-N/gVSS.h at high SOC concentration in the primary effluent. The denitrification rates were comparable to those reported in literature.

18. Complete nitrification has been achieved at an ORP range from 140 to 210 mV. The nitrification rate was up to 4.34 mgN/gVSS.h. The nitrification rate in the Pre-Den systems was higher than in the nitrifying Train B.

19. Pre-Den mode Trains that achieved biological nitrogen removal have produced lower sludge than the nitrifying Train B. The averaged sludge production for the best operational period was 3.5, 6.0, and 9.8 g of volatile suspended solids per day in Trains A, C, and B, respectively.

20. The observable yield, expressed in g of volatile suspended solids per g of biological oxygen demand, has been higher in the Pre-Den Train A than in Pre-Den Train C, proving a higher microbial activity in the former Train, which may account for the higher CO₂ consumption and higher pH in the nitrified mixed liquor.

CHAPTER 8: ENGINEERING SIGNIFICANCE AND FUTURE-WORK SUGGESTIONS

This study has answered as many questions as it has raised. Full nitrification was demonstrated and an effluent pH level higher than the expected level was produced. It was found that the use of pre-denitrification can raise the pH level well above the level expected from the alkalinity contributed by this process. The study suggested the possibility of the use of combined nitrification and carbon removal by a pure oxygen activated sludge system; and it has shown the expected dependence of nitrogen removal on the overall recycle ratio. In addition a new relationship between this recycle ratio, the influent TKN, and the desired effluent TKN has been proposed.

However, several unanswered questions that warrant further research have been formulated. The most important concerns the relationship between CO_2 and nitrification under slightly higher than the atmospheric CO_2 content in the head space of covered reactors. In particular, it is important to demonstrate whether there is a potential for acclimation to low pH of the nitrifying cultures because of the low pH level of ML in a covered reactor. This would also complement the full scale tests which showed the potential for low pH nitrification but could not (due to the nature of the full scale testing) elucidate factors affecting it.

Another question concerns the optimization of the Pre-Den mode with proper overall recycle ratio under variable C/N ratios in the range of temperatures encountered during Winter/Spring to fit the existing situation at the North End

Plant. It would also be important to find the relationships between the rates of nitrification and denitrification, the C/N ratio, and the head space CO₂-levels in the covered reactor.

It would also be useful to study the effects of the species and concentrations of carbon and nitrogen on denitrification rates, and to determine the relationships between oxidation-reduction potential, species of substrates, and denitrification rates.

It is recommended the use of a variable RNO₃ ratio based on TKN, as is suggested in the proposed Equation, which would allow higher nitrogen removal from a Pre-Den system, mainly in period when the raw wastewater is weak, and the start up of the process.

REFERENCES

- *Akunna J.C., Bizeau C., and Moletta R. (1993). Nitrate and nitrite reductions with anaerobic sludge using various carbon sources: glucose, glycerol, acetic acid, lactic acid, and methanol. *Jour. Wat. Res.*; 27,8; pp.1303-1312.
- *Anthonisen A., Loehr R.C., Prakasam T.B.S., and Srinath E.G. (1976). Inhibition of nitrification by ammonia and nitrous acid. *Jour. W.P.C.F.*; 48, 5 pp.835-852.
- *APHA, AWWA, WPCF (1989). Standard methods for the examination of water and wastewater, 17th Edition. APHA, Washington, DC, U.S.A.
- *APHA, AWWA, WPCF (1991). Standard methods for the examination of water and wastewater, supplement to the 17th Edition. Pages 16-22. APHA, Washington, DC, U.S.A.
- *Argaman Y. and Brenner A. (1986). Single-sludge nitrogen removal: modelling and experimental results. *Jour. W.P.C.F.*; 58, pp.853-860.
- *Bailey W., White W., Wilber C., Wilson T.E., and Bizzarri R. (1989). Sludge re-aeration in two-step nitrification. *Wat. Sci. Tech.*; 21, Brighton, pp.1347-1358.
- *Bailey D.A. and Thomas E.V. (1975). The removal of inorganic nitrogen from sewage effluents by biological denitrification. Paper presented for discussion at a meeting of the East Midlands Branch held in Nottingham, Feb.1975, pp.497-515.
- *Barnard J. (1975). Biological nutrient removal without the addition of chemicals. *Jour. Wat. Res.*, 9; pp.485-490.
- *Barth E.F. and Ryan B.W. (1978). nutrient control by plant modification at El Lago, Texas. *Jour. W.P.C.F.*; 55, 7, pp.1768-1785.
- *Batchelor B., and Lawrence A.W. (1978). Autotrophic denitrification using elemental sulphur. *Jour. W.P.C.F.*; 55, 8, pp.1986-2001.
- *Beccari M., Passino R., Ramadan R., and Tandoi V. (1983). Kinetics of dissimilatory nitrate, and nitrite reductions in suspended growth culture. *Jour. W.P.C.F.*, 55, 1, pp.58-64.

- *Benefield L.D., Judkins J.F., and Weand B.L. (1982). Process chemistry for water and wastewater treatment. Prentice-Hall, Inc, Englewood, Cliffs, N.J., U.S.A. pp.77-105
- *Benefield L.D. and Randall C.W. (1980). Biological process design for wastewater treatment. Prentice-Hall, Inc, Englewood, Cliffs, N.J., U.S.A.
- *Benefield L.D., Randall C.W., and King P.H. (1975). Process control by oxygen uptake and solids analysis. *Journ. W.P.C.F.*, 47, 10, pp.2498-2503.
- *Benninger R.W. and Sherrard J.H. (1978). Nitrification and alkalinity relationships in activated sludge. *Jour. W.P.C.F.*; 55, 9, pp.2132-2142.
- *Bishop D., Heidman J.A., and Stamberg J.B. (1976). Single-stage nitrification-denitrification. *Jour.W.P.C.F.*, 48, 3, pp.520-532.
- *Blachford A.J., Tramontini E.M., and Griffiths A. (1982). Oxygenated activated-sludge process: Evaluation at Palmersford. *Jour. Water Pollution Control*, pp.601-618.
- *Blankenship K. (1993). Reducing nutrient levels in the Chesapeake Bay. *Jour. Water Environment and Technology*, 5, 6; pp.19-22.
- *Bock E, Koops H.P., and Harms H. (1989). Nitrifying bacteria. pp 81-96 in Schlegel H.G., and Bowien (Editor). In Autotrophic Bacteria. Science Tech Publishers. Madison, Wisconsin, U.S.A.
- *Brannan K.P. and Randall W.C. (1987). The economics of nitrogen removal in a single-sludge activated sludge system. Proceedings conference on the Impact an Control of Nutrients in Surface Waters, Charleston, S.C. 30 pages, Environmental Systems Eng.Dept., Clemson University.
- *Braunscheidel D.E. and Gyger R.F. (1976). Nitrification in oxygen activated sludge systems. Paper prepared for presentation at the American Institute of Chemical Engineers Convention. Atlantic City, New Jersey, U.S.A.
- *Burchett M.E. and Tchobanogous G. (1974). Facilities for controlling the activated sludge Process by mean cell residence time. *Jour.W.P.C.F.*; 46, pp. 973.

- *Caponetto S.R., Oleszkiewicz J.A., and MacBride B.D. (1993). Nitrification-denitrification in pure oxygen activated sludge. Proceedings Joint CSCE-ASCE National Conference on Environmental Engineering, Vol. II, pp. 1867-1875, July 12-14, Montreal, Quebec, Canada.
- *Casey T.G., Wentzel M.C., Loewenthal R.E., Ekama G.A., and Maris G.V.R. (1992). A hypothesis for the cause of low F/M filament bulking in nutrient removal activated sludge systems. *Wat.Res.*; **26**, pp. 867-869.
- *Chapman T.D., Matsch L.C., and Zander E.H. (1976). Effect of high dissolved oxygen concentration in activated sludge systems. *Jour. W.P.C.F.*, **48**, pp. 2486-2510.
- *Charpentier J., Florentz M., and Lue-Hing C. (1981). Oxidation-reduction potential (ORP) regulation: A way to optimize pollution removal and energy savings in the low load activated sludge process. *Jour. Wat. Sci. Tech.*; **19**, Ri, pp. 645-655.
- *Christodoulatos C. and Vaccari D.A. (1993). Correlations of performance for activated sludge using multiple regression with autocorrelation. *Wat.Res.*; **27**, pp. 51.
- *Cliff R.C. and Andrews J.F. (1986). Gas-liquid interactions in oxygen activated sludge. *Journal of Environmental Engineering*, **112**, 1, ASCE ISS N 0733-9372/86; pp. 61-76.
- *Cook N.E., Silverstein J., Figueroa L.A., Cutter K., Hund R., and Veydovec W. (1993). pH control of denitrification of a high nitrate strength industrial wastewater. Paper presented at the 66th Annual Conference of Water Environmet Federation, Anaheim, California, Oct. 3-7, 1993.
- *Degyansky M.E. (1977). Effects of nitrification in the activated sludge process. *Jour. Water and Sewage Works*. June, pp. 94-96.
- *Daigger G.T., Waltrip G.D, Romm E.D., and Morales L. (1988). Enhanced secondary treatment incorporating biological nutrient removal. *Jour. W.P.C.F.*, **60**, 10; pp.1833-1842.
- *Daigger G.T., Waltrip G.D, Romm E.D., and Morales L. (1986). Report presented at the 59 th Annual Conference of Water Pollution Control Federation; Los Angeles,

Clifornia, U.S.A.

*De Renzo (1978). Nitrogen control and phosphorous removal in sewage treatment; Noyes Data Corporation.

*Drtil M., Neméth P., and Bodik I. (1993). Kinetic constants of nitrification. *Wat.Res.*, 27, 1; pp. 35-39.

*Ekama G.A. and Marais G.v.R. (1984). Biological Nitrogen Removal. In Theory, design and operation of nutrient removal activated sludge process. Water Research Commission, Pretoria.

*Elefsiniotis P., Manoharan R., and Mavinic D.S. (1989). The effects of sludge recycle ratio on nitrification performance in biological treatment of leachate. *Environmental Technology Letters*, 10, pp.1041-1050. Publications Divisions Selper Ltd, 1989.

*Figueroa L.A. and Silverstein J. (1992). The effect of particulate organic matter on biofilm nitrification. *Jour. Water Environment Research*, 64, 5; pp. 728-733.

*Fox C.J., Fitzgerald P.R., and Lue-Hing C. (1981). Sewage organisms: A color atlas. The Metropolitan Sanitary District of Greater, Chicago, Illinois, pp. 100-101.

*Garret M.T.,Jr. (1958). Hydraulic control of activated sludge growth rate. *Sew. E. Ind. Wastes*, 30, 253.

*Gaudy A.F. and Gaudy E.T. (1980). Microbiology for environmental scientists and engineers. McGraw-Hill, Inc.

*Gorenflo R. and Cross M. (1992). Creating anoxic zone solves settling problem. *Jour. Water Environmental & Technology*, 4, 11, pp. 16-18.

*Grabinska-Łoniewska A. (1991). Denitrification unit biocenosis. *Wat. Res.*, 25, 12; pp. 1565-1573.

*Haug R.T. and McCarty P.L. (1972). Nitrification with the submerged filter. *Jour. W.P.C.F.*, 44, pp. 2086.

- *Henze M., Dupont R., Grau P., and De La sota A. (1993). Rising sludge in secondary settler due to denitrification. *Wat. Res.*, 27, 2, pp. 231-236.
- *Henze M. (1987). Theories for estimation of the fraction of denitrifiers in combined nitrifying-denitrifying treatment plants. *Wat. Res.*, 21, 2, pp. 1521-1524.
- *Henze M. (1986). Nitrate versus oxygen utilization rates in wastewater and activated sludge systems. *Jour. Water Sci. Tech.*, 18,, Copenhagen, pp. 115-122.
- *Hutton W.C. and La Rocca S.A. (1975). Biological treatment of concentrated ammonia wastewaters. *Jour. W.P.C.F.*, 47, 5, pp. 989-997.
- *Jones P.H. and Sabra H.M. (1980). Effect of systems solids retention time. (SSRT or sludge age) on nitrogen removal from activated-sludge systems. Paper submitted for publication. *Wat. Pollut. Control*, pp. 106-116.
- *Judkins J.F. and Anderson G.A., Jr. (1992). Using denitrification for pH control. *Water Environment & Technology*, February 1992, pp. 62-65.
- *Kalinske A.A. (1976) Comparison of air and oxygen activated sludge systems. *Jour. W.P.F.C.*, 48, 11, pp. 2472-2485.
- *Kholdebarin, B. and Oertli J.J. (1977). Effect of pH and ammonia on the rate of nitrification of surface water. *Jour. W.P.C.F.*, 49, pp. 1688-1692.
- *King R.O. and Forster C.F (1990). Effects of sonication in activated sludge. *Enz. Microb. Technol.*, 12, pp.109-115.
- *Koopman B. and Codu K. (1993). Prediction of thickening capacity using diluted sludge volume index. *Wat. Res.*, 17, 10, pp. 1427-1431.
- *Kunihiro C.I., Reardon R.D., Wood K.C., Puhl W.N., and Clinger R.C., Jr. (1992). Retrofitting for biological nutrient removal. *Jour. Water, Environment and Technology*, July, 1992, pp. 67-72.
- *Lee Song-Eun, Koopman B., Bode H., and Jenkins D. (1983). Evaluation of alternative sludge settleability indices. *Wat. Res.*, 17, 10, pp. 1421-1426.

- *Manahan S.E. (1984). Environmental chemistry. IV th. Edition: PWS Publishers. Boston, U.S.A.
- *Marstaller T. (1992). Effect of chlorination on filamentous growth and nitrification in batch fed and continuous activated sludge systems. Master of Science Thesis, Division of Environmental Engineering, University of Manitoba, Winnipeg, MB, Canada.
- *McCartney D.M. and Oleszkiewicz J.A. (1990). Carbon and nutrient removal in sequencing batch reactor at low temperature. *Jour. Environment Technology*, **11**, pp. 99-112.
- *Metcalf and Eddy, Inc. (1991). Wastewater engineering treatment, disposal, and reuse. Third Edition. McGraw-Hill, New York, U.S.A.
- *Miskis J.J. and Jamesson G.M. (1992). Advanced treatment process succeeds in nutrient removal. *Jour. Water Environment & Technology*, **4**, 9, pp. 22-26.
- *Morales L.M., Daigger G.T., and Borberg J.R. (1991). Capability assessment of biological nutrient removal facilities. *Research Jour. W.P.C.F.*, **63**, 6, pp.900-910.
- *Morales L.M., Daigger G.T. and Borberg J.R. (1988). Assessment of the reliability of biological nutrient removal process. Paper presented at the 61 st. Annual Conference of Water Pollution Control Federation, Dallas, Texas, U.S.A. Oct. 2-6, 1988.
- *Nelson J.K. and Puntenney J.L. (1983). Performance comparison of the air and high-purity-oxygen activated sludge systems. *Jour. W.P.C.F.*, **55**, 4, pp. 336-348.
- *Okey R.W., Chen K.Y., and Sycip A.Z. (1978). Neutralization of acid wastes by enhanced buffer. *Jour. W.P.C.F.*, **50**, 7, pp. 1841-1851.
- *Oleszkiewicz J.A and Caponetto S.R. (1993). Feasibility of pre-denitrification in the pure oxygen activated sludge system. Unpublished Draft Final Report for The City of Winnipeg; Waterworks, Waste & Disposal Department, Man., Canada.
- *Oleszkiewicz J.A and Berquist S.A. (1988). Low temperature nitrogen removal in

sequencing batch reactors. *Wat. Res.*, **22**, 9, pp. 1163-1171.

*Painter H.A. and Loveless J.E. (1983). Effect of temperature and pH value on the growth-rate constants of nitrifying bacteria in the activated sludge process. *Wat. Res.*, **17**, 3, pp. 237-248.

*Parker D.S. and Merrill M.S. (1976). Oxygen and air activated sludge: another view. *Jour. W.P.C.F.*, **48**, 11, pp. 2511-2528.

*Payne W.J. (1973). Reduction of nitrogenous oxides by microorganisms. *Bacteriol. Rev.*, **37**, pp., 409-452.

*Poduzka R.A. and Andrews J.F. (1975). Dynamics of nitrification in activated sludge process. *Jour. W.P.C.F.*, **47**, 11, pp. 2599-2619.

*Qasim S.R., Parker C.E., and McMellon r.T. (1990). Biological nutrient removal a pilot plant study. Proceedings of the 45 th. Industrial Waste Conference, Purdue University, pp.303-310.

*Randall C.W., Barnard J.L., and Stensel H.D. (1992). Design and retrofit of wastewater treatment plants for biological nutrient removal. Technomic Publishing Company, Inc. U.S.A.

*Randall C.W. (1987). Economics of nitrogen removal at wastewater treatment plants. Paper prepared for the Third Annual Conference on the Economics of Chesapeake Bay Management. Annapolis, Maryland, U.S.A. May 27-29.

*Refling D.R., ReVair II G.J., and Johnson M. (1992). Removing nitrogen and phosphorous. *Jour. Water Environment and Technology*, **4**, 12, pp. 46-48.

*Reinhart D.R. (1979). Nitrification treatability study for Carrollton, Ga. *Jour. W.P.C.F.*, **51**, 5, pp. 1032-1039.

*Robertson L. A., vanNiel E.W.J., Torremans R.A.M., and Kuenen J.G. (1988). Simultaneous nitrification in aerobic chemostat cultures of *Thiosphaera pantotropha*. *Applied and Environment Microbiology*, **54**, 11, pp. 2812-2818.

- *Robertson L.A. and Kuenen J.G. (1984). Aerobic denitrification-old wine in new bottles?. *Antonie van Leeuwenhoek Journal of Microbiology and Serology*, **50**, pp. 525-544.
- *Searce S.N., Benninger R.W., Weber A.S., and Sherrard J.H. (1980). Prediction of alkalinity changes in the activated sludge process. *Jour. W.P.C.F.*, **52**, 2, pp. 399-405.
- *Sedlak R. (1991). Phosphorous and nitrogen removal from municipal wastewater Principles and Practice. Second Edition. The Soap and Detergent Association. Lewis Publishers, U.S.A.
- *Sikora L.J. and Kuney D.R. (1976). Denitrification of nitrified septic tank effluent. *Jour. W.P.C.F.*, **48**, 8, pp. 2018-2025.
- *Silverstein J. and Schroeder E.D. (1983). Performance of SBR activated sludge process with nitrification/denitrification. *Jour. W.P.C.F.*, **55**, 4, pp. 377-384.
- *Stankewich, Jr, M.J. (1972). Biological nitrification with the high purity oxygen process. Paper prepared for presentation at the Purdue Industrial Waste Conference 27 th. Annual Meeting.
- *Stensel H.D., Loher R.C., and Lawrence A.W. (1973). Biological kinetic of suspended-growth denitrification. *Jour. W.P.C.F.*, **45**, 2, 249-261.
- *Stenstrom M.K., and Song S.S. (1991). Effects of oxygen transport limitation on nitrification in the activated sludge process. *Research Journal W.P.C.F.*, **63**, 3, pp. 208-219.
- *Stenstrom M.K. and Poduzka R.A. (1980). The effect of dissolved oxygen concentration on nitrification. *Wat. Res.*, **14**, pp. 643-649.
- *Stumm W. and Morgan J.J. (1981). Aquatic chemistry an introduction emphasizing chemical equilibria in natural waters. John Wiley & Sons, Inc pp. 121, 185, 272.
- *Sutton P.M., Murphy K.L., Jank B.E., and Monaghan B.A. (1975). Efficacy of biological nitrification. *Jour. W.P.C.F.*, **47**, 11, pp. 2665-2673.

- *Tam N.F.Y., Wong Y.S., and Leung G. (1992). Effect of exogenous carbon sources on removal of inorganic nutrient by the nitrification-denitrification process. *Wat. Res.*, **26**, 9, pp. 1229-1236.
- *Toms R.G. and Booth M.G. (1982). The use of oxygen in sewage treatment. *Wat. Pollut. Control*, pp.151-165.
- *Urbain V., Block J.C., and Manen J. (1993). Bioflocculation in activated sludge: An analytic approach. *Wat. Res.*, **27**, 5, pp. 829-838.
- *U.S. Environmental Protection Agency (1987). The causes and control of activated sludge bulking and foaming. Summary Report. Office of Technology Transfer, Washington, D.C. EPA/625/8-87/012.
- *U.S. Environmental Protection Agency (1975). Process design manual for nitrogen control. Office of Technology Transfer, Washington, D.C.
- *Vaccari D.A. and Christodoulatos C. (1989). A comparison of several control algorithms for activated sludge waste rate. *Wat. Sci. Tech.* **21**, Brightons pp. 1249-1260.
- *Verstraete W., Vanstaen H., and Voets (1977). Adaptation to nitrification of activated sludge systems treating highly nitrogenous waters. *Jour. W.P.C.F.*, July, pp. 1604-1608.
- *Water Pollution Control Federation, MOP 11 (1990). Operation of municipal wastewater treatment plants. Manual Practice No 11, Vol. II. Second Edition, pp. 501-510, 543-553. Wat. Pollution Control Federation, Alexandria, VA, U.S.A.
- *Wentzel M.C., Ekama G.A., Dold P.L., and Marais Gv.R. (1990). Biological excess phosphorous removal-steady state process design. *Jour. Water South Africa*, **16**, 1, pp. 29-48.
- *Wild H.E., Sawyer C.N., and McMahon T.C. (1971). Factor affecting nitrification kinetics. *Jour. W.P.C.F.*, Sept. 1971, pp.1845-1854.
- *Wilson W.A. (1992). Full-scale biological nutrient removal trials at Bonnybrook-An

update. Paper presented at 43 rd Annual Conference of Western Canada Water & Wastewater Association; Calgary, Alberta, Canada. Oct. 13-16.

APPENDIX A

Table A.1: SRT & SVI in the first operational period

DAY #	Train A				Train B		Train C			
	Anoxic RI		Oxygen RII		Oxygen RIII		Anoxic RIV		Oxygen RV	
	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g
10	1.2	276	4.7	350	6.2	240	NA	NA	NA	NA
11	1.2	200	4.7	180	6.2	1110	NA	NA	NA	NA
12	1.2	180	4.7	270	6.2	240	NA	NA	NA	NA
13	0.8	160	3.1	220	5	270	NA	NA	NA	NA
14	1.4	110	5	160	3.6	250	NA	NA	NA	NA
17	1.8	160	7.1	150	6.1	270	NA	NA	NA	NA
18	1.4	130	5.3	170	5.3	280	NA	NA	NA	NA
19	1.3	120	5.5	150	7.5	280	NA	NA	NA	NA
21	2	110	7.6	120	7.5	280	NA	NA	NA	NA
24	1.6	130	6.4	130	6.3	350	NA	NA	NA	NA
25	2	110	7.9	130	6.2	330	NA	NA	NA	NA
26	1.7	125	6.8	90	6	280	NA	NA	NA	NA
31	1.4	110	5.5	110	5.7	100	NA	NA	NA	NA
33	2	80	8.2	80	6.3	90	NA	NA	NA	NA
35	2.6	100	10.8	140	5.7	120	NA	NA	NA	NA
38	1.6	120	6.1	90	7.4	140	NA	NA	NA	NA
39	2.4	110	9.5	110	6.9	220	NA	NA	NA	NA
42	1.08	90	7.1	90	8.8	170	1.6	90	6.2	80
47	2	100	8.1	80	9.3	70	0.9	90	4.0	80

Table A.2: SRT & SVI in the second period

Day #	Train A				Train B		Train C			
	Anoxic RI		Oxygen RII		Oxygen RIII		Anoxic RIV		Oxygen RV	
	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI RV mL/g
48	3	80	12	80	4.3	80	0.9	90	4.0	90
53	2.1	80	8.3	70	11.6	70	0.9	70	4.0	100
54	1.3	90	5	80	10	70	0.9	80	4.0	70
56	2.1	70	8.4	70	9.8	50	2.2	90	8.7	160
59	2	80	8	70	10.7	40	1.7	70	6.7	80
60	2.6	60	10.4	60	11.4	80	4.4	60	17.6	60
64	3.2	70	12.8	70	7.8	40	1.9	50	7.5	50
67	2	90	8	120	10	50	2.1	60	8.4	50
69	2	90	8	100	6.6	50	2	90	8	60
71	2.4	90	9.6	80	9.2	50	2.1	70	8.2	50
73	2.4	100	9.3	100	10.2	60	1.8	50	7.2	50
75	2.4	130	9.3	90	8.1	60	1.7	60	6.8	50
77	2.1	110	8.4	80	7.1	60	1.9	70	7.6	60
80	1.9	100	7.7	100	9.9	90	1.9	60	7.8	60
82	2.3	130	9.2	110	9.5	160	2	60	7.9	60
84	2.2	110	8.8	80	7.4	150	2.1	60	8.4	60
87	3.4	190	13.6	110	8.4	100	2	60	8	60

Table A.3: SRT & SVI in the third period

Day #	Train A				Train B		Train C			
	Anoxic RI		Oxygen RII		Oxygen RIII		Anoxic RIV		Oxygen RV	
	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g	SRT d	SVI mL/g
89	2.4	170	9.6	120	10.5	120	2.1	60	8.4	60
91	2.3	160	9.2	100	8.7	170	1.8	80	7	50
94	2	130	8.2	110	8.2	90	2	60	7.9	60
96	1.6	130	6.3	100	8.1	80	1.8	50	7	50
98	1.9	110	7.8	90	8	70	2.3	40	9.2	50
101	2.9	120	11.8	90	8.6	50	1.9	50	7.6	60
103	2.1	90	8.6	80	9.3	50	2.1	50	8.3	50
105	1.5	90	6.1	80	8	50	1.8	50	7.6	50
108	1.9	80	7.4	80	8.5	50	2	50	8.2	50
110	2.6	90	10.2	60	9	60	2.1	50	8.8	40
112	2	70	7.8	50	8.2	50	2.2	60	9	50
115	NA	90	NA	90	7	60	2	50	8.8	50
117	1.9	90	7.4	90	11	80	2.2	50	8.8	50
119	2.4	100	9.6	90	8.6	100	2	50	8.1	60
122		90		110		60	2	40	8.1	50

Table A.4: Suspended solid and volatile suspended solid concentrations.

Day #	Train A			Train B		Train C		
	RI, mg/L	RII, mg/L		RIII, mg/L		RIV, mg/L	RV, mg/L	
	ML	ML	RAS	ML	RAS	ML	ML	RAS
12	1250	1940	NA	2760	NA	NA	NA	NA
13	970	1450	NA	2740	NA	NA	NA	NA
14	970	1560	NA	2270	NA	NA	NA	NA
17	750	1370	NA	2220	NA	NA	NA	NA
18	920	1140	NA	2310	NA	NA	NA	NA
19	1020	1290	NA	2300	NA	NA	NA	NA
21	980	1180	NA	1930	NA	NA	NA	NA
24	820	970	NA	1700	NA	NA	NA	NA
25	960	1030	NA	2380	NA	NA	NA	NA
26	770	1320	NA	2390	NA	NA	NA	NA
27	700	1110	NA	2370	NA	NA	NA	NA
31	740	920	NA	1750	NA	NA	NA	NA
33	1010	1410	NA	2060	NA	NA	NA	NA
35	980	800	NA	1800	NA	NA	NA	NA
38	1220	1570	NA	2020	NA	NA	NA	NA
40	980	1260	NA	2030	NA	NA	NA	NA
42	910	1220	NA	2050	NA	730	1150	NA
47	430	690	NA	2110	NA	680	970	NA

Table A.5: Suspended solid and volatile suspended solid concentrations in the second period.

Day #	Train A			Train B		Train C		
	RI, mg/L	RII, mg/L		RIII, mg/L		RIV,mg/L	RV, mg/L	
	ML	ML	RAS	ML	RAS	ML	ML	RAS
48	1930	950	NA	1580	NA	510	710	NA
50	990	1300	1340	2150	2070	1430	1850	1790
53	1010	1620	1610	2590	2640	2590	1540	1970
54	720	1470	1040	2380	2460	1430	1540	2290
56	850	1540	900	2460	2500	1620	2410	2130
59	800	1140	1000	2560	3580	1780	2410	2140
60	1130	1600	1320	2640	2970	1490	1370	2370
63	1720	1480	1370	2670	2640	1760	2500	2320
66	1360	1010	3910	2420	2810	1660	1660	2220
68	1300	890	980	2270	2670	1590	2410	2070
70	1670	1290	1400	2780	2000	1900	2590	1890
73	1540	700	730	2510	2900	1710	2440	2220
75	1250	680	5360	2290	2080	1660	1880	2080
77	1250	1280	1330	2550	2760	1930	2460	2680
80	1290	1330	2240	2510	2720	2010	2250	2620
82	1200	1090	3360	2830	3220	1740	2490	4090
84	1630	1410	2860	2960	3430	2110	2940	3140
87	1900	1190	3720	2700	2890	2520	2440	2790

Table A.6: Suspended solid and volatile suspended solid concentrations in the third period.

Day #	Train A			Train B		Train C		
	RI, mg/L	RII, mg/L		RIII, mg/L		RIV,mg/L	RV, mg/L	
	ML	ML	RAS	ML	RAS	ML	ML	RAS
89	1220	1010	1980	2900	4440	1940	2810	2800
91	1890	1420	2990	2980	5280	1820	3100	2780
94	1110	720	3540	2440	3040	1530	2430	2360
96	1380	1080	3420	3150	3160	1930	2680	3100
98	1530	1220	4440	2820	2850	3630	2800	3360
101	1600	1270	4070	3140	2550	1600	2090	2950
103	2020	1500	3680	2180	3550	1880	2760	4020
105	1650	1560	2660	2850	3430	2070	2970	6720
108	1430	1410	1770	2520	3410	1900	2320	2920
110	4240	790	2470	2570	3520	1950	2800	4360
112	1400	1550	3680	2670	2930	2320	2740	3500
115	4250	1290	1820	2120	3070	1700	2560	4620
117	1160	970	5640	2000	2980	1780	2140	3720
119	1020	990	4350	2090	2540	1790	2330	2900
122	1280	870	3170	1990	2570	1790	2800	2390

Table A.7: NEWPCC'S PE characteristics in the first operational period

DAY #	NH3-N, mg/L	TN, mg/L	SOC, mg/L	C/N
1	22	38	91	2.39
2	22	37	72	1.95
3	20	41	91	2.22
4	28	48	80	1.67
5	29	41	112	2.73
7	24	37	80	2.16
8	20	33	75	2.27
9	21	30	63	2.10
10	27	38	67	1.76
11	28	41	77	1.88
12	28	41	81	1.98
13	9	16	50	3.13
14	13	20	47	2.35
15	12	24	60	2.50
16	15	20	42	2.10
17	14	21	44	2.10
18	26	34	65	1.91
19	15	24	71	2.96
21	31	42	61	1.45
22	20	35	60	1.71
24	24	32	55	1.72
25	38	46	78	1.70
26	32	42	68	1.62
27	26	36	57	1.58
28	28	54	71	1.31
31	24	47	68	1.45
33	34	60	68	1.13
35	27	47	60	1.28
38	29	40	59	1.48
39	36	46	75	1.63
42	8	11	38	3.45
44	7	18	36	2.00
47	14	19	47	2.47
Mean	23	35	66	2.00
Median	20	32	63	NA
Min	7	11	36	1.13
Max	38	60	112	3.45
STDS	8	12	16	0.54

Table A.8: NEWPCC'S PE characteristics in the second operational period.

DAY #	NH3-N, mg/L	TN, mg/L	SOC, mg/L	C/N
49	14	23	76	3.30
52	16	24	72	3.00
54	9	15	50	3.33
56	26	33	100	3.03
59	19	22	64	2.91
61	36	54	74	1.37
63	33	44	81	1.84
66	23	31	68	2.19
68	24	40	71	1.78
70	20	36	84	2.33
73	21	30	60	2.00
75	25	36	86	2.39
77	32	47	89	1.89
80	20	30	78	2.60
82	39	50	96	1.92
84	25	35	87	2.49
87	11	18	106	5.89
Mean	23	33	79	2.60
Median	22	32	76	NA
Min	9	15	50	1.37
Max	39	54	106	5.89
STDS	8	11	15	1.02

Table A.9: NEWPCC'S PE characteristics in the third operational period

DAY #	NH3-N, mg/L	TN, mg/L	SOC, mg/L	C/N
89	28	38	88	2.32
91	25	36	85	2.36
94	15	23	49	2.13
96	21	33	81	2.45
98	39	51	84	1.65
101	17	26	51	1.96
103	31	50	99	1.98
105	33	43	86	2.00
108	19	27	60	2.22
110	27	35	88	2.51
112	26	30	59	1.97
115	25	32	69	2.16
117	23	35	78	2.23
119	22	29	66	2.28
122	17	25	64	2.56
Mean	25	34	74	2.18
Median	23	32	78	NA
Min	15	23	49	1.65
Max	39	51	99	2.56
STDS	7	8	15	0.25

Table A.10: pH in all reactors and raw wastewater. First operational period.

Day #	pH RAW	pH-RI	pH-RII	pH Ef.RII	pH-RIII	EFRIII	pH-RIV	pH-RV	pH-Ef.RV
1	7.3	7.5	8	8.2	7.8	8	NA	NA	NA
2	7.3	7.5	8	8.2	7.6	8	NA	NA	NA
3	7.4	7.7	8.2	8.2	7.9	8	NA	NA	NA
4	7.7	7.7	8.2	8.2	7.9	8	NA	NA	NA
5	7.4	7.6	8	8	7.6	8	NA	NA	NA
7	7.6	7.8	8	8.1	7.8	8	NA	NA	NA
8	7.8	7.8	8	7.9	7.9	8	NA	NA	NA
9	7.3	7.6	7.8	7.9	8	8	NA	NA	NA
10	7.4	7.8	7.7	7.9	7.5	7.4	NA	NA	NA
11	7.3	7.8	7.7	7.8	7.6	7.8	NA	NA	NA
12	7.1	7.7	7.7	7.7	7.6	7.8	NA	NA	NA
13	7.3	7.5	7.5	7.7	7.3	7.3	NA	NA	NA
14	7.1	7.3	7.3	7.3	7.3	7.2	NA	NA	NA
15	7.2	7.3	7.3	7.3	7.2	7.2	NA	NA	NA
16	7.2	7.3	7.2	7.2	7	7.1	NA	NA	NA
17	7.2	7.3	7.2	7.3	7.2	7.1	NA	NA	NA
18	7.2	7.4	7.4	7.4	7.2	7.2	NA	NA	NA
21	7.2	7.5	7.4	7.2	7	7.2	NA	NA	NA
23	7.4	7.2	7.5	7.6	7.3	7.5	NA	NA	NA
24	7.5	7.8	7.6	7.5	7.5	7.2	NA	NA	NA
25	7.3	7.7	7.4	7.4	6.9	6.9	NA	NA	NA
26	7.5	7.5	7.4	NA	6.8	NA	NA	NA	NA
27	7.7	7.8	7.4	NA	6.9	NA	NA	NA	NA
28	7.6	7.6	7.4	NA	6.8	NA	NA	NA	NA
29	7.5	7.4	7.5	NA	7.1	NA	NA	NA	NA
30	7.5	7.5	7.5	7.7	7.1	7.4	NA	NA	NA
31	7.5	7.4	7.5	7.7	7.1	7.4	NA	NA	NA
32	7.5	7.5	7.5	7.7	7	7.3	NA	NA	NA
33	7.5	7.5	7.4	7.4	6.9	7.5	NA	NA	NA
34	7.7	7.5	7.4	7.8	7.1	7.4	NA	NA	NA
35	7.7	7.6	7.5	7.8	7.1	7.4	NA	NA	NA
36	7.5	7.5	7.6	7.6	7.2	7.7	NA	NA	NA
37	7.5	7.5	7.5	7.8	7.2	7.3	NA	NA	NA
38	7.6	7.5	7.5	7.6	7.2	7.4	NA	NA	NA
39	7.7	7.7	7.5	7.8	7	7.4	NA	NA	NA
40	7.5	7.7	7.5	7.7	7	7.2	NA	NA	NA
41	7.8	7.6	7.5	7.7	6.9	7.2	NA	NA	NA
42	7.6	7.5	7.7	7.8	7.3	7.6	7.5	7.6	7.4
43	7.5	7.5	7.7	7.7	7.2	7.5	7.5	7.6	7.6
44	7.9	7.8	8.1	8.1	7.8	7.9	7.6	7.9	7
45	7.6	7.6	7.9	7.9	7.6	7.7	7.6	7.6	7.7
47	7.4	7.4	7.7	7.6	7.5	7.4	7.5	7.5	7.8

Table A.11: pH in all reactors and raw wastewater (second operational period).

Day #	pH RAW	pH-RI	pH-RII	pH Ef.RII	pH-RIII	Ef.RIII	pH-RIV	pH-RV	pH-Ef.RV
48	7.5	7.6	7.8	7.9	7.6	7.8	7.7	7.8	7.8
49	7.5	7.6	7.9	7.8	7.8	7.6	7.7	7.9	7.8
50	7.6	7.7	7.9	7.9	7.6	7.7	7.6	7.6	7.8
51	7.5	7.6	7.9	7.9	7.5	7.6	7.6	7.7	7.7
52	7.6	7.5	7.9	7.8	7.5	7.6	7.6	7.6	7.7
53	7.5	7.7	7.9	7.8	7.3	7.5	7.7	7.6	7.6
54	7.6	7.5	7.8	7.8	7.3	7.4	7.5	7.4	7.6
55	7.4	7.6	7.7	7.8	7.4	7.5	7.5	7.4	7.6
56	7.3	7.4	7.5	7.9	7.1	7.3	7.3	7.2	7.5
57	7.5	7.6	7.6	7.6	7.3	7.3	7.5	7.3	7.4
58	7.5	7.5	7.7	7.7	7.4	7.4	7.4	7.5	7.5
59	7.5	7.5	7.7	7.7	7.3	7.4	7.4	7.5	7.6
60	7.5	7.6	7.5	7.6	7	7.2	7.5	7.2	7.3
61	7.3	7.4	7.3	7.5	6.8	7	7.3	7	7.2
62	7.3	7.6	7.5	7.7	7	7.3	7.4	7.1	7.3
63	7.3	7.6	7.6	7.7	7	7.1	7.4	7.2	7.3
64	7.2	7.4	7.7	7.6	7.1	7.2	7.3	7.3	7.3
65	7.3	7.6	7.5	7.8	7.3	7.4	7.4	7.3	7.4
66	7.4	7.5	7.7	7.8	7.2	7.6	7.4	7.4	7.6
67	7.2	7.4	7.5	7.7	6.9	7.1	7.5	7.3	7.4
68	7.3	7.5	7.5	7.5	7	7.1	7.4	7.2	7.2
69	7.3	7.5	7.4	7.5	6.8	6.9	7.4	7.2	7.2
70	7.4	7.6	7.6	7.5	7	7.1	7.5	7.3	7.3
71	7.3	7.6	7.7	7.6	7.1	7.1	7.5	7.4	7.4
72	7.3	7.4	7.7	7.6	7.1	7.2	7.3	7.3	7.4
73	7.4	7.6	7.6	7.6	7.1	7.2	7.4	7.3	7.4
74	7.4	7.6	7.7	7.6	7.1	7.2	7.4	7.3	7.4
75	7.5	7.7	7.7	7.8	7.1	7.3	7.6	7.4	7.4
76	7.4	7.7	7.5	7.8	6.7	6.8	NA	7.1	7.2
77	7.2	7.6	7.4	7.5	6.7	6.8	7.3	7.1	7.1
78	7.2	7.5	7.5	7.6	6.9	7	7.4	7.2	7.2
79	7	7.4	7.6	7.5	7.1	7	7.3	7.3	7.3
80	7.3	7.5	7.5	7.8	7.1	7.2	7.4	7.4	7.5
81	7.1	7.5	7.6	7.5	7	7	7.4	7.2	7.2
82	7.3	7.5	7.3	7.5	6.8	7	7.4	7	7.1
83	7.2	7.5	7.4	7.4	6.8	7	7.4	7.1	7.1
84	7.3	7.5	7.5	7.7	7	7.3	NA	7.3	7.4
85	7.3	7.5	7.6	7.7	7	7.1	7.4	7.3	7.4
86	7.3	7.5	7.7	7.7	7.1	7.2	7.4	7.4	7.4
87	7.1	7.3	7.6	7.7	7.1	7.2	7.1	7.3	7.4

Table A.12: pH in all reactors and raw wastewater (Third operational period).

Day #	pH RAW	pH-RI	pH-RII	pH Ef.RII	pH-RIII	Ef.RIII	pH-RIV	pH-RV	pH-Ef.RV
88	7.3	7.6	7.6	7.6	7	7.2	7.4	7.2	7.4
89	7.3	7.6	7.5	7.7	6.9	7	7.4	7.3	7.4
90	7.2	7.5	7.6	7.6	6.9	7	7.4	7.3	7.3
91	7.5	7.6	7.6	7.6	7	7.1	7.5	7.3	7.3
92	7.3	7.6	7.5	7.6	7	7.1	7.4	7.2	7.3
93	7.6	7.5	7.6	7.5	7.3	7.2	7.4	7.4	7.3
94	7.6	7.5	7.6	7.6	7.3	7.4	7.5	7.4	7.4
95	7.4	7.6	7.6	7.6	NA	7.3	7.5	7.3	7.5
96	7.4	7.5	7.7	7.6	7.3	7.3	7.6	7.5	7.4
97	7.4	7.5	7.6	7.5	NA	7.1	7.5	7.3	7.4
98	7.5	7.6	7.4	7.5	6.7	6.8	7.4	7.2	7.3
99	7.3	7.4	7.5	7.5	7	7.1	7.4	7.3	7.4
100	7.7	7.4	7.6	7.6	7.2	7.3	7.3	7.2	7.5
101	7.6	7.5	7.6	7.6	7.4	7.6	7.5	7.5	7.6
102	7.6	7.5	7.6	7.7	7.2	7.4	7.5	7.3	7.5
103	7.5	7.6	7.5	7.6	7.1	7.2	7.5	7.3	7.5
104	7.5	7.5	7.4	7.5	6.9	7.1	7.4	7.1	7.3
105	7.6	7.6	7.4	7.6	7	7.2	7.5	7.3	7.4
106	7.3	7.4	7.6	7.6	7.1	7.3	7.3	7.4	7.5
107	7.5	7.5	7.6	7.6	7.4	7.6	7.4	7.5	7.6
108	7.4	7.5	7.6	7.8	7.3	7.6	7.5	7.5	7.6
109	7.7	7.6	7.6	7.8	7.3	7.4	7.5	7.4	7.6
110	7.5	7.5	7.9	7.7	7.3	7.4	7.5	7.5	7.5
111	7.6	7.5	7.6	7.6	7.3	7.5	7.5	7.4	7.5
112	7.4	7.6	7.5	7.6	7.1	7.5	7.5	7.2	7.5
113	7.5	7.5	7.6	7.8	7.3	7.6	7.5	7.4	7.6
114	7.4	7.6	7.6	7.6	7.3	7.5	7.5	7.3	7.5
115	7.4	7.5	7.6	7.9	7.1	7.6	7.5	7.5	7.8
116	7.5	7.6	7.6	7.7	7.1	7.5	7.4	7.4	7.6
117	7.5	7.5	7.5	7.6	7.1	7.4	7.5	7.2	7.4
118	7.3	7.6	7.6	7.6	7.1	7.4	7.4	7.3	7.4
119	7.6	7.5	7.5	7.6	7.2	7.4	7.5	7.3	7.4
120	7.4	7.6	7.7	7.7	7.3	7.6	7.5	7.4	7.6
121	7.4	7.5	7.7	7.8	7.4	7.6	7.5	7.5	7.6
122	7.4	7.5	7.6	7.5	7.4	7.4	7.6	7.7	7.5

APPENDIX B

Table B.1: Characteristics of raw wastewater and effluent - Train B. First operational period.

DATE	DAY #	TKN, mg/L		NH3-N, mg/L		NO3-N, mg/L		TN-N, mg/L		SOC, mg/L		Alk.°	BOD5, mg/L	
		RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	Eff-RIII	RAW	EF.RIII
23-5-92	1	38	36	22	27	0	0	38	36	91	31	NA	NA	NA
24-5-92	2	37	38	22	27	0	0	37	38	72	37	NA	NA	NA
25-5-92	3	41	37	20	27	0	0	41	37	91	34	NA	NA	NA
26-5-92	4	48	44	28	32	0	0	48	44	80	46	NA	NA	NA
27-5-92	5	41	38	29	24	0	0	41	38	112	33	NA	NA	NA
29-5-92	7	37	37	24	30	0	0	37	37	80	25	NA	NA	NA
30-5-92	8	33	28	20	21	0	0	33	28	75	27	NA	NA	NA
31-5-92	9	30	28	21	20	0	0	30	28	63	36	NA	NA	NA
1-6-92	10	38	19	27	12	0	0	38	19	67	38	NA	NA	NA
2-6-92	11	41	17	28	12	0	0	41	17	77	28	NA	NA	NA
3-6-92	12	41	34	28	26	0	0	41	34	81	27	NA	NA	NA
4-6-92	13	16	5	9	0	0	0	16	5	50	21	NA	NA	NA
5-6-92	14	20	3	13	0	0	1	20	4	47	19	NA	NA	NA
6-6-92	15	24	3	12	0	0	16	24	19	60	23	NA	NA	NA
7-6-92	16	20	5	15	0	0	16	20	21	42	21	NA	NA	NA
8-6-92	17	21	3	14	0	0	14	21	17	44	24	NA	NA	NA
9-6-92	18	34	3	26	0	0	18	34	21	65	20	NA	NA	NA
10-6-92	19	24	3	15	0	0	18	24	21	71	21	110	90	7
12-6-92	21	42	8	31	0	0	25	42	33	61	21	NA	NA	NA
13-6-92	22	35	3	20	0	0	32	35	35	60	21	NA	NA	NA
15-6-92	24	32	3	24	0	0	26	32	29	55	21	NA	NA	NA
16-6-92	25	46	3	38	0	0	37	46	40	78	22	NA	NA	NA
17-6-92	26	42	3	32	0	0	36	42	39	68	22	50	90	3
18-6-92	27	36	11	26	0	0	22	36	33	57	18	NA	NA	NA
19-6-92	28	54	15	28	0	0	37	54	52	71	21	NA	NA	NA
22-6-92	31	47	13	24	0	0	28	47	41	68	20	NA	NA	NA
24-6-92	33	60	13	34	0	0	28	60	41	68	20	60	100	3
26-6-92	35	47	4	27	0	0	30	47	34	60	22	NA	NA	NA
29-6-92	38	40	4	29	0	0	26	40	30	59	21	NA	NA	NA
30-6-92	39	46	5	36	0	0	40	46	45	75	21	60	39	3
3-7-92	42	15	2	8	0	0	16	11	18	38	17	NA	NA	NA
5-7-92	44	18	2	7	0	0	13	18	15	36	19	NA	NA	NA
8-7-92	47	19	5	14	0	0	18	19	23	47	20	140	60	4

* as mgCaCO3/L.

Table B.2: Measured removal efficiencies in Train B. First operational period.

DAY #	SOC-R	BOD-R	NH3-R	TKN-R	TN, %	NO3-R
	%	%	%	%	Observed	%
1	66	NA	7	5	5	100
2	49	NA	-4	-3	-3	100
3	63	NA	13	10	10	100
4	43	NA	11	8	8	100
5	71	NA	11	7	7	100
7	69	NA	0	0	0	100
8	64	NA	19	15	15	100
9	43	NA	9	7	7	100
10	43	NA	61	50	50	100
11	64	NA	67	59	59	100
12	67	NA	21	17	17	100
13	58	NA	100	69	69	100
14	60	NA	100	85	80	94
15	62	NA	100	88	21	24
16	50	NA	100	75	-5	-7
17	45	NA	100	86	19	22
18	69	NA	100	91	38	42
19	70	92	100	88	13	14
21	66	NA	100	81	21	26
22	65	NA	100	91	0	0
24	62	NA	100	91	9	10
25	72	NA	100	93	13	14
26	68	97	100	93	7	8
27	68	NA	100	69	8	12
28	70	NA	100	72	4	5
31	71	NA	100	72	13	18
33	71	97	100	78	32	40
35	63	NA	100	91	28	30
38	64	NA	100	90	25	28
39	72	92	100	89	2	2
42	55	NA	100	87	-20	-23
44	47	NA	100	89	17	19
47	57	93	100	74	-21	-29

Table B.3: Characteristics of raw wastewater and effluent - Train B. Second operational period.

DATE	DAY #	TKN, mg/L		NH3-N, mg/L		NO3-N, mg/L		TN-N, mg/L		SOC,mg/L		Alk.*	BOD5,mg/L	
		RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	Eff-RIII	RAW	EF.RIII
10-7-92	49	23	4	14	2	1	7	23	11	76	26	NA	NA	NA
13-7-92	52	24	2	16	0	0	13	24	15	72	22	NA	NA	NA
15-7-92	54	15	2	9	0	0	16	15	18	50	23	90	50	3
17-7-92	56	33	2	26	0	0	20	33	22	100	25	NA	NA	NA
20-7-92	59	22	2	19	0	0	20	22	22	64	25	NA	NA	NA
22-7-92	61	54	4	36	0	0	39	54	43	74	22	60	100	5
24-7-92	63	44	5	33	0	0	39	44	44	81	23	NA	NA	NA
27-7-92	66	31	4	23	0	0	24	31	28	68	21	NA	NA	NA
29-7-92	68	40	4	24	0	0	28	40	32	71	22	70	85	3
31-7-92	70	36	4	20	0	0	29	36	33	84	21	NA	NA	NA
3-8-92	73	30	6	21	0	0	25	30	31	60	19	NA	NA	NA
5-8-92	75	36	2	25	0	0	23	36	25	86	21	70	120	4
7-8-92	77	47	2	32	0	0	31	47	33	89	23	NA	NA	NA
10-8-92	80	30	3	20	0	0	18	30	21	78	21	70	NA	NA
12-8-92	82	50	6	39	2	0	29	50	35	96	24	60	100	5
14-8-92	84	35	3	25	0	0	27	35	30	87	22	80	NA	NA
17-8-92	87	18	2	11	0	0	19	18	21	106	20	70	NA	NA

Table B.4: Characteristics of raw wastewater and effluent - Train B. Third operational period.

DATE	DAY #	TKN, mg/L		NH3-N, mg/L		NO3-N, mg/L		TN-N, mg/L		SOC, mg/L		Alk.*	BOD5, mg/L	
		RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	RAW	Eff-RIII	Eff-RIII	RAW	EF.RIII
19-8-92	89	38	4	28	0	0	26	38	30	88	20	80	120	3
21-8-92	91	36	4	25	0	0	22	36	26	85	22	70	NA	NA
24-8-92	94	23	3	15	0	0	15	23	18	49	15	60	NA	NA
26-8-92	96	33	4	21	0	0	25	33	29	81	24	60	130	4
28-8-92	98	51	4	39	0	0	39	51	43	84	18	90	NA	NA
31-8-92	101	26	4	17	0	0	19	26	23	51	23	90	NA	NA
2-9-92	103	50	3	31	0	0	26	50	29	99	22	40	120	6
4-9-92	105	43	4	33	0	0	37	43	41	86	23	110	NA	NA
7-9-92	108	27	3	19	0	0	21	27	24	60	18	110	NA	NA
9-9-92	110	35	2	27	0	0	28	35	30	88	27	80	120	10
11-9-92	112	30	3	26	0	1	28	30	31	59	21	120	NA	NA
14-9-92	115	32	4	25	0	0	24	32	28	69	20	100	NA	NA
16-9-92	117	35	3	23	0	0	31	35	34	78	24	140	125	6
18-9-92	119	29	3	22	0	0	26	29	29	66	20	160	NA	NA
21-9-92	122	25	5	17	0	0	24	25	29	64	28	120	NA	NA

Table B.5: Measured removal efficiencies in Train B. Second operational period.

DAY #	SOC-R	BOD-R	NH3-R	TKN-R	TN, %	NO3-R
	%	%	%	%	Observed	%
49	66	NA	90	83	52	67
52	69	NA	100	92	38	41
54	54	94	100	87	-20	-23
56	75	NA	100	94	33	35
59	61	NA	100	91	0	0
61	70	95	100	93	20	22
63	72	NA	100	89	0	0
66	69	NA	100	87	10	11
68	69	96	100	90	20	22
70	75	NA	100	89	8	9
73	68	NA	100	80	-3	-4
75	76	97	100	94	31	32
77	74	NA	100	96	30	31
80	73	NA	100	90	30	33
82	75	95	96	88	30	37
84	75	NA	100	91	14	16
87	81	NA	100	89	-17	-19

Table B.6: Measured removal efficiencies in Train B. Third operational period.

DAY #	SOC-R	BOD-R	NH3-R	TKN-R	TN, %	NO3-R
	%	%	%	%	Observed	%
89	77	98	100	89	21	24
91	74	NA	100	89	28	31
94	69	NA	100	87	22	25
96	70	97	100	88	12	14
98	79	NA	100	92	16	17
101	55	NA	100	85	12	14
103	78	95	100	94	42	45
105	73	NA	100	91	5	5
108	70	NA	100	89	11	13
110	69	92	100	94	14	15
112	64	NA	100	90	-3	-4
115	71	NA	100	88	13	14
117	69	95	100	91	3	3
119	70	NA	100	90	0	0
122	56	NA	100	80	-16	-20

Table B.7: Mesuared removal efficiencies in the Pre-Den Trains.
 First operational period

Day #	SOCR %	BODR %	NH3R %	TKNR %	TNR %	NO3R %
21	64	NA	100	95	57	60
22	65	NA	100	94	31	33
24	64	NA	100	91	16	17
25	74	NA	100	89	37	41
26	71	89	100	83	29	34
27	65	NA	100	67	17	25
28	70	NA	100	78	33	43
31	68	NA	100	74	32	43
33	72	98	100	80	40	50
35	67	NA	100	89	43	48
38	66	NA	100	88	25	29
39	73	98	100	91	39	43
42	47	NA	100	87	-20	-23
44	44	NA	100	89	17	19
47	55	87	100	79	11	13

Table B.8: Mesuared removal efficiencies in the Pre-Den Trains. Second operational period.

Day #	SOCR, %		BODR, %		NH3R, %		TKNR, %		TNR, %		NO3R, %	
	Train A	Train C	Train A	Train C	Train A	Train C	Train A	Train C	Train A	Train C	Train A	Train C
49	74	57	NA	NA	100	100	91	70	48	57	52	85
52	69	68	NA	NA	100	100	92	92	38	29	41	32
54	52	46	92	86	100	100	87	87	20	27	23	31
56	74	73	NA	NA	100	80	97	97	58	55	59	56
59	64	64	NA	NA	100	100	95	95	23	14	24	14
61	70	68	93	93	100	100	91	91	37	37	41	41
63	72	72	NA	NA	100	100	93	89	41	30	44	33
66	71	69	NA	NA	100	100	87	87	39	23	44	26
68	69	70	96	94	100	100	95	90	53	35	55	39
70	70	75	NA	NA	100	100	92	92	53	58	58	64
73	70	68	NA	NA	100	100	87	87	53	27	62	31
75	77	76	98	98	100	100	94	92	61	47	65	52
77	76	75	NA	NA	100	100	94	94	57	51	61	55
80	74	69	NA	NA	100	89	93	80	73	70	79	89
82	77	76	97	98	100	100	94	92	68	52	72	57
84	76	71	NA	NA	100	100	91	91	57	63	63	69
87	81	82	NA	NA	94	100	83	89	50	39	63	44

Table B.9: Mesuared removal efficiencies in the Pre-Den Trains. Third operational period.

Day #	SOCR, %		BODR, %		NH3R, %		TKNR, %		TNR, %		NO3R, %	
	Train A	Train C	Train A	Train C	Train A	Train C	Train A	Train C	Train A	Train C	Train A	Train C
89	74	74	97	97	100	100	87	89	68	66	79	74
91	69	73	NA	NA	100	100	86	89	72	64	84	72
94	65	67	NA	NA	100	100	87	87	43	30	50	35
96	77	72	96	98	97	100	88	88	48	55	57	62
98	77	79	NA	NA	100	100	92	94	69	59	74	63
101	59	69	NA	NA	100	100	88	85	38	31	43	36
103	79	79	97	94	100	100	96	92	64	68	67	74
105	74	73	NA	NA	100	100	93	93	37	37	40	40
108	70	72	NA	NA	100	100	89	89	22	33	25	38
110	75	75	95	95	91	100	83	91	29	37	41	41
112	71	61	NA	NA	100	60	90	50	30	13	33	56
115	67	61	NA	NA	100	100	88	88	47	50	54	57
117	76	77	96	95	100	100	91	91	46	43	50	47
119	67	59	NA	NA	100	100	90	90	34	21	38	23
122	72	73	NA	NA	100	100	80	84	32	40	40	48

Fig.B.1 TN-R Vs TKN-Ef/TKN-raw
Pre-Den Train A-First period

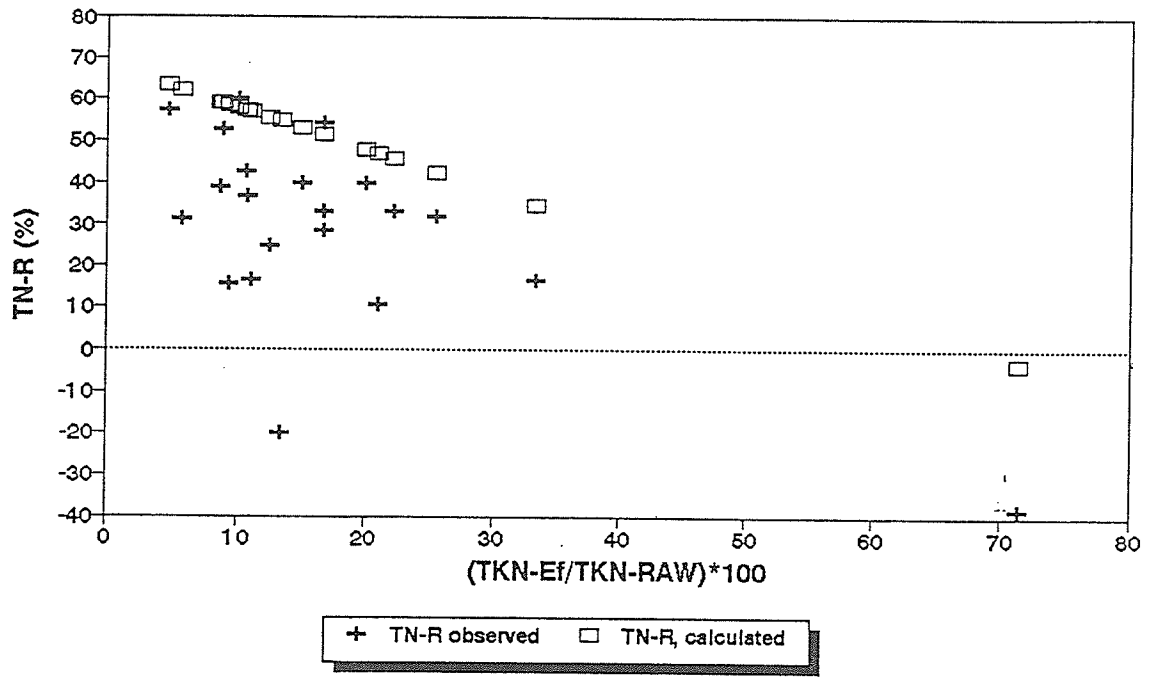


Fig.B.2 TN-R Vs TKN-Ef/TKN-RAW
Pre-Den Train A-Third period

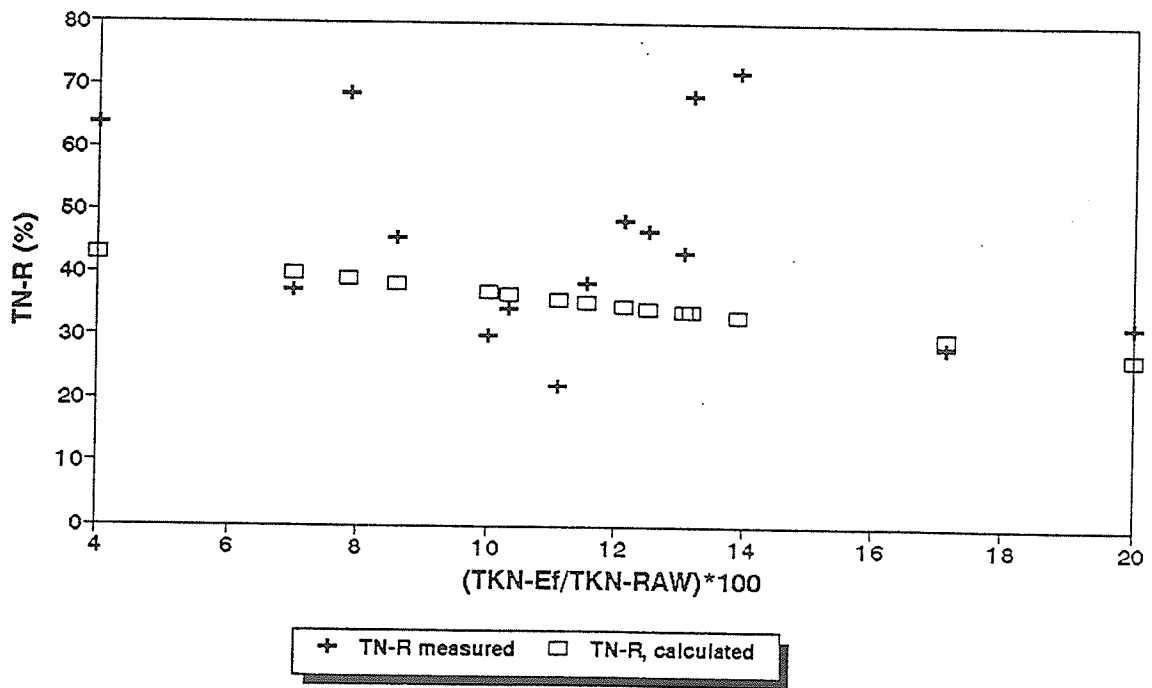


Fig.B.3 TN-R Vs TKN-Ef/TKN-raw
Pre-Den Train C-Second period

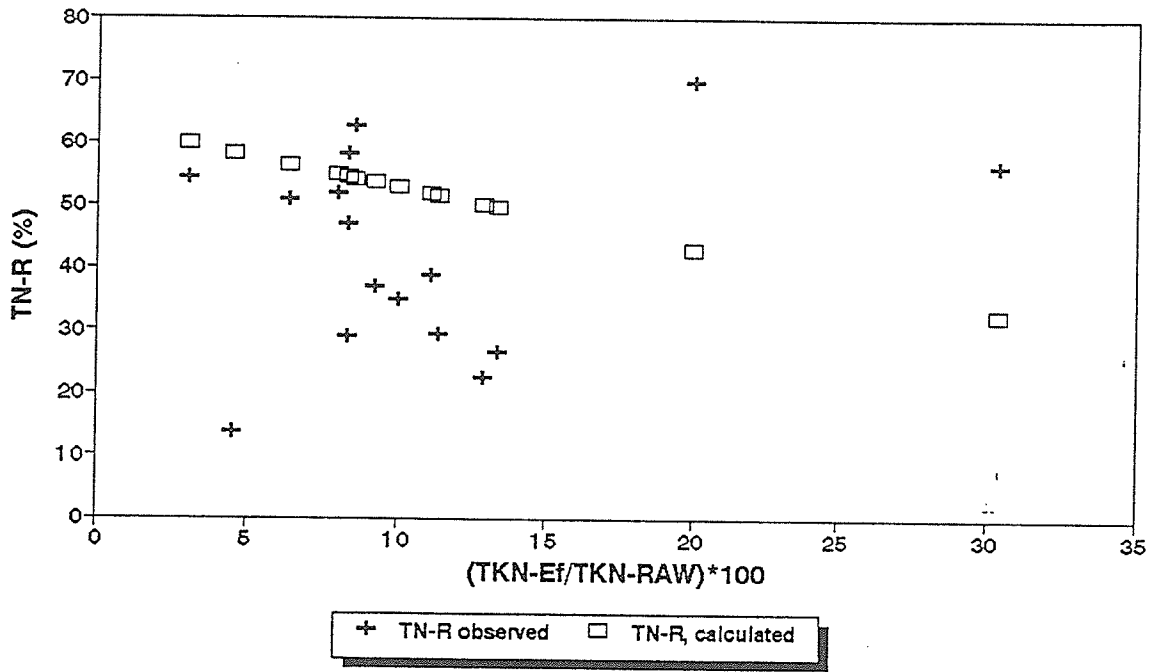
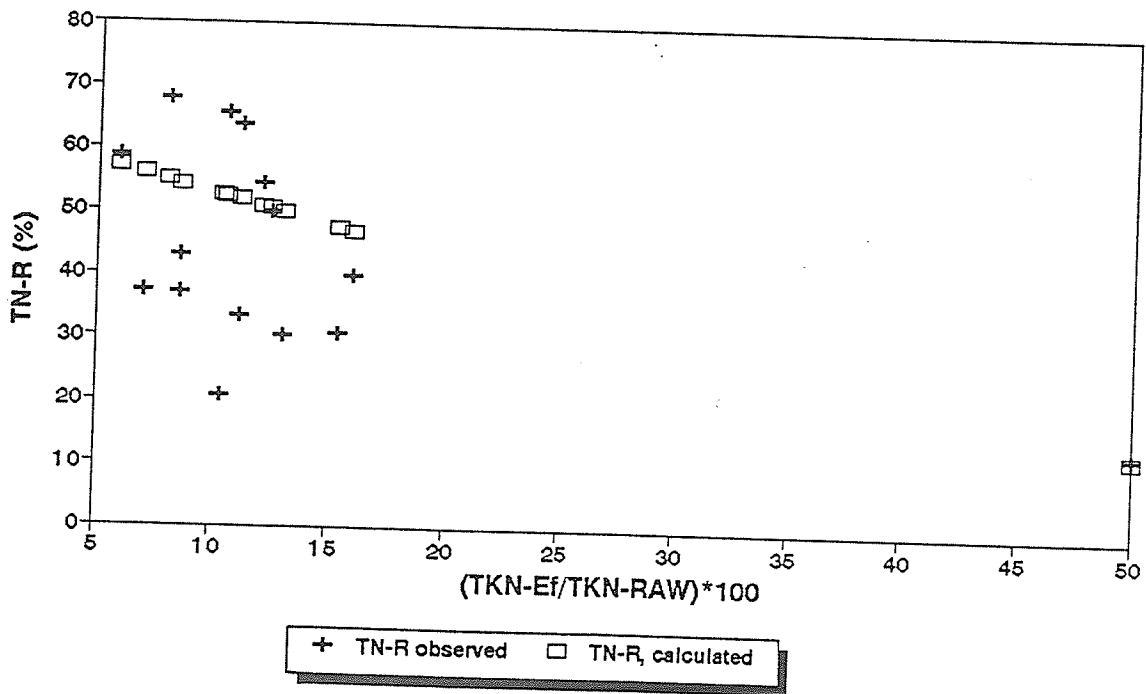


Fig.B.4 TN-R Vs TKN-Ef/TKN-RAW
In Pre-Den Train C-Third period



APPENDIX C

C.1 Oxygen up take rate on Aug.27, 1992

Time DO RIII First sample

0	5.3
0.25	4.85
0.5	4.55
0.75	4.15
1	3.9
1.25	3.7
1.5	3.4
1.75	3.3
2	3.15
2.25	3
2.5	2.8
2.75	2.6
3	2.45
3.25	2.3
3.5	2.2

Regression Output:

Constant	4.909583
Std Err of Y Est	0.177429
R Squared	0.967761
No. of Observations	15
Degrees of Freedom	13
X Coefficient(s)	-0.83786
Std Err of Coef.	0.042414

time DO RIII second sample

0	4
0.25	3.4
0.5	3.1
0.75	2.85
1	2.6
1.25	2.4
1.5	2.25
1.75	2.15
2	2
2.25	1.85
2.5	1.65
2.75	1.5

Regression Output:

Constant	3.589744
Std Err of Y Est	0.175146
R Squared	0.950017
No. of Observations	12
Degrees of Freedom	10
X Coefficient(s)	-0.80769
Std Err of Coef.	0.058586

C.2 Oxygen up-take on Sept. 3, 1992

Time DO RIII first sample

0	4.5
0.25	4.15
0.5	3.8
0.75	3.65
1	3.5
1.25	3.35
1.5	3.25
1.75	3.1
2	3
2.25	2.9
2.5	2.8
2.75	2.75
3	2.65
3.25	2.6
3.5	2.5
3.75	2.4
4	2.3
4.25	2.25
4.5	2.15
4.75	2.1
5	2
5.25	1.95
5.5	1.85
5.75	1.75

Regression Output:

Constant	3.984333
Std Err of Y Est	0.160022
R Squared	0.955702
No. of Observations	24
Degrees of Freedom	22
X Coefficient(s)	-0.41122
Std Err of Coef.	0.018875

Time DO RIII Second sample

0	4.5
0.25	4.15
0.5	3.85
0.75	3.7
1	3.5
1.25	3.4
1.5	3.3
1.75	3.15
2	3.05
2.25	3
2.5	2.9
2.75	2.8
3	2.7
3.25	2.65
3.5	2.55
3.75	2.5
4	2.4
4.25	2.3
4.5	2.2
4.75	2.15
5	2.1
5.25	2.05
5.5	2
5.75	1.9

Regression Output:

Constant	4.001167
Std Err of Y Est	0.15685
R Squared	0.953871
No. of Observations	24
Degrees of Freedom	22
X Coefficient(s)	-0.39461
Std Err of Coef.	0.018501

C.3 Oxygen up take on Sept. 10, 1992

Time DO RIII First sample

0	5.1
0.25	4.75
0.5	4.6
0.75	4.45
1	4.35
1.25	4.2
1.5	4.1
1.75	4
2	3.95
2.25	3.85
2.5	3.8
2.75	3.7
3	3.65
3.25	3.6
3.5	3.5
3.75	3.4
4	3.35
4.25	3.3
4.5	3.2
4.75	3.15
5	3.1
5.25	3.05
5.5	3
5.75	2.95
6	2.75
6.5	2.7
6.75	2.65
7	2.6
7.25	2.55
7.5	2.45
7.75	2.4
8	2.35
8.25	2.3
8.5	2.25
8.75	2.2
9	2.15
9.25	2.05
9.5	2
9.75	1.95
10	1.8

Regression Output:

Constant	4.586021
Std Err of Y Est	0.122055
R Squared	0.980555
No. of Observations	40
Degrees of Freedom	38
X Coefficient(s)	-0.28272
Std Err of Coef.	0.006459

//Cont.C.3

Time DO RIII Second sample
Sept.10

0	5
0.25	4.9
0.5	4.8
0.75	4.75
1	4.5
1.25	4.4
1.75	4.3
2	4.25
2.25	4.05
2.5	4
3	3.95
3.25	3.85
3.5	3.8
4	3.6
4.5	3.5
5	3.4
5.25	3.3
5.5	3.25
5.75	3.2
6	3.15
6.25	3.1
6.5	3
6.75	2.9
7	2.85
7.25	2.8
7.5	2.75
7.75	2.65
8	2.6
8.25	2.55
8.75	2.45
9.25	2.3
9.75	2.2
10	2.15
10.15	2.1

Regression Output:

Constant	4.808441
Std Err of Y Est	0.079646
R Squared	0.991635
No. of Observations	34
Degrees of Freedom	32
X Coefficient(s)	-0.27541
Std Err of Coef.	0.004472

//Cont.C.4

Time Rll DO Second sample

0	7.3
0.25	7
0.5	6.85
0.75	6.75
1	6.65
1.25	6.55
1.5	6.45
1.75	6.4
2	6.3
2.15	6.25
2.5	6.15
2.75	6.1
3	6.05
3.25	6
3.5	5.9
3.75	5.85
4	5.8
4.25	5.7
4.5	5.65
4.75	5.6
5	5.55
5.25	5.45
5.5	5.4
5.75	5.35
6	5.3
6.5	5.25
6.75	5.15
7	5.1
7.25	5.05
7.5	5
7.75	4.95
8	4.9
8.25	4.85
9	4.7
9.25	4.65
9.5	4.55
9.75	4.5
10	4.45
10.5	4.4
10.75	4.35
11	4.3
11.25	4.25
11.5	4.2
11.75	4.15

Regression Output:

Constant	6.8219
Std Err of Y Est	0.1124
R Squared	0.9836
No. of Observations	45
Degrees of Freedom	43
X Coefficient(s)	-0.238
Std Err of Coef.	0.0047

C.4 Oxygen up take on Aug.27, 1992

Time DO RII First sample

0	7.2
0.25	6.9
0.75	6.8
1	6.55
1.25	6.45
1.5	6.3
1.75	6.2
2	6.1
2.25	6.05
2.5	6
2.75	5.95
3	5.9
3.5	5.85
3.75	5.8
4	5.75
4.25	5.65
4.5	5.6
4.75	5.55
5	5.5
5.25	5.45
5.5	5.4
5.75	5.3
6	5.25
6.25	5.2
6.5	5.15
6.75	5.1
7	5
7.25	5
7.5	4.95
7.75	4.9
8.25	4.85
8.5	4.8
8.75	4.75
9	4.7
9.25	4.65
9.5	4.6
9.75	4.55
10	4.5
10.25	4.45
10.75	4.3
11.25	4.25
11.5	4.2

Regression Output:

Constant	6.6471
Std Err of Y Est	0.2583
R Squared	0.8928
No. of Observations	43
Degrees of Freedom	41
X Coefficient(s)	-0.225
Std Err of Coef.	0.0122

//Cont.

C.5 Oxygen up take Sept.3, 1992

Time DO RII First sample

0	6	Regression Output:	
0.25	5.8	Constant	5.5484
0.5	5.6	Std Err of Y Est	0.1115
0.75	5.5	R Squared	0.9861
1	5.4	No. of Observations	53
1.5	5.35	Degrees of Freedom	51
1.75	5.2		
2	5.1	X Coefficient(s)	-0.213
2.25	5	Std Err of Coef.	0.0035
2.75	4.9		
3	4.8		
3.5	4.75		
3.75	4.7		
4	4.65		
4.25	4.6		
4.5	4.55		
4.75	4.5		
5	4.4		
5.25	4.35		
5.5	4.3		
5.75	4.2		
6	4.15		
6.5	4.05		
6.75	4		
7	3.95		
7.25	3.9		
7.5	3.85		
7.75	3.8		
8	3.75		
8.25	3.7		
8.75	3.65		
9	3.6		
9.25	3.55		
9.5	3.5		
9.75	3.45		
10	3.4		
10.25	3.35		
10.5	3.3		
10.75	3.25		
11	3.2		
11.25	3.15		
11.5	3.1		
11.75	3.05		
12.25	3		
12.5	2.95		
12.75	2.9		
13	2.85		
13.25	2.8		
13.75	2.7		
14.25	2.65		
14.5	2.6		
14.75	2.55		
15	2.5		

//Cont.

//Cont.C.5

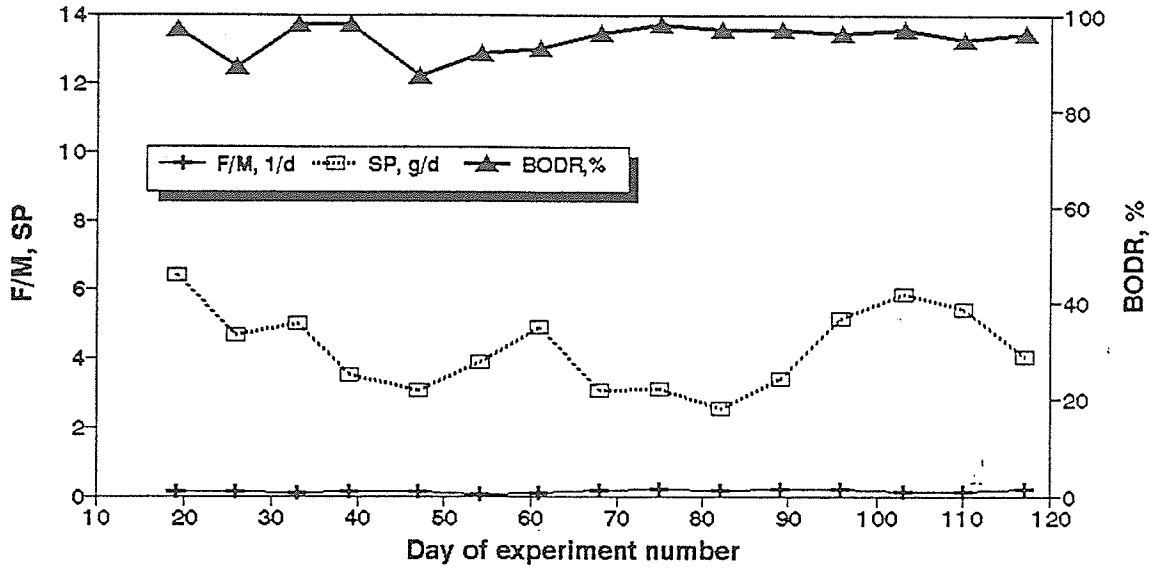
Time RII DO Second sample

Time	RII	DO
0	6	
0.25	5.9	
0.5	5.75	
0.75	5.65	
1	5.55	
1.25	5.45	
1.5	5.4	
1.75	5.35	
2	5.3	
2.25	5.2	
2.5	5.15	
2.75	5.05	
3	5	
3.25	4.95	
3.5	4.85	
3.75	4.8	
4	4.7	
4.25	4.65	
4.5	4.6	
4.75	4.55	
5	4.5	
5.25	4.45	
5.5	4.4	
5.75	4.35	
6	4.3	
6.25	4.25	
6.5	4.2	
6.75	4.1	
7	4.05	
7.25	4	
7.75	3.9	
8	3.85	
8.25	3.8	
8.75	3.7	
9	3.65	
9.25	3.6	
9.5	3.55	
9.75	3.5	
10.25	3.45	
10.5	3.4	
10.75	3.3	
11	3.25	
11.25	3.2	
11.75	3.15	
12	3.1	
12.25	3.05	
12.5	3	
12.75	2.95	
13	2.9	
13.5	2.8	
14	2.75	
14.25	2.7	
14.5	2.65	
14.75	2.6	
15	2.55	
15.25	2.5	

Regression Output:

Constant	5.6756
Std Err of Y Est	0.0997
R Squared	0.9901
No. of Observations	56
Degrees of Freedom	54
X Coefficient(s)	-0.217
Std Err of Coef.	0.0029

**Fig.C.1 F/M, SP, & BODR HISTOGRAPH
Pre-Den Train A -RI-RII**



**Fig.C.2 F/M, SP, & BODR HISTOGRAPH
Nitrifying Train B - RIII**

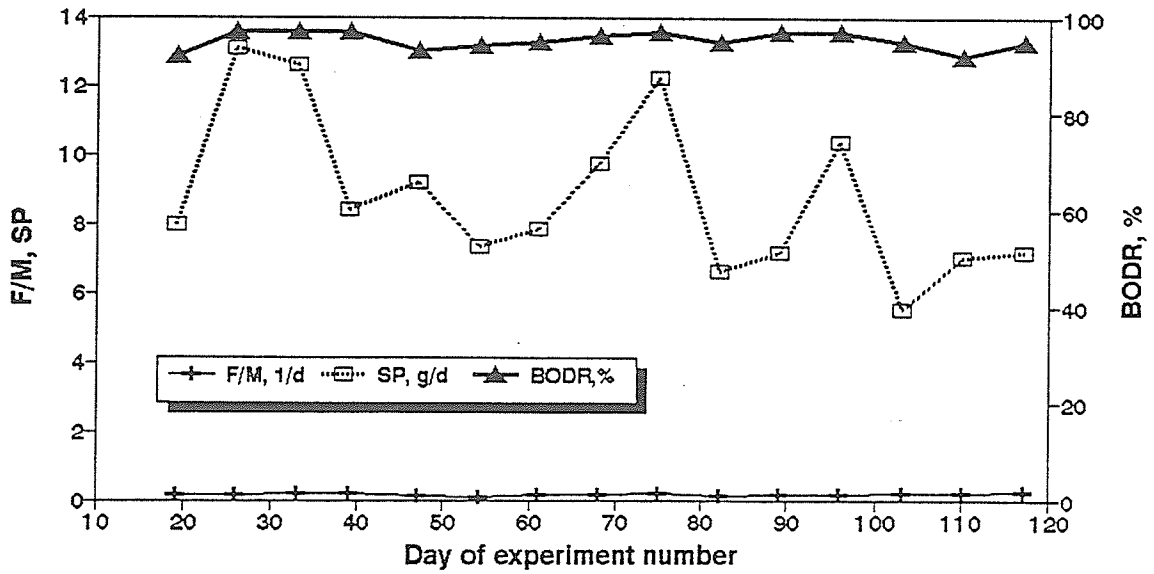


Fig.C.3 F/M, SP, & BODR HISTOGRAPH
Pre-Den Train C RIV-RV

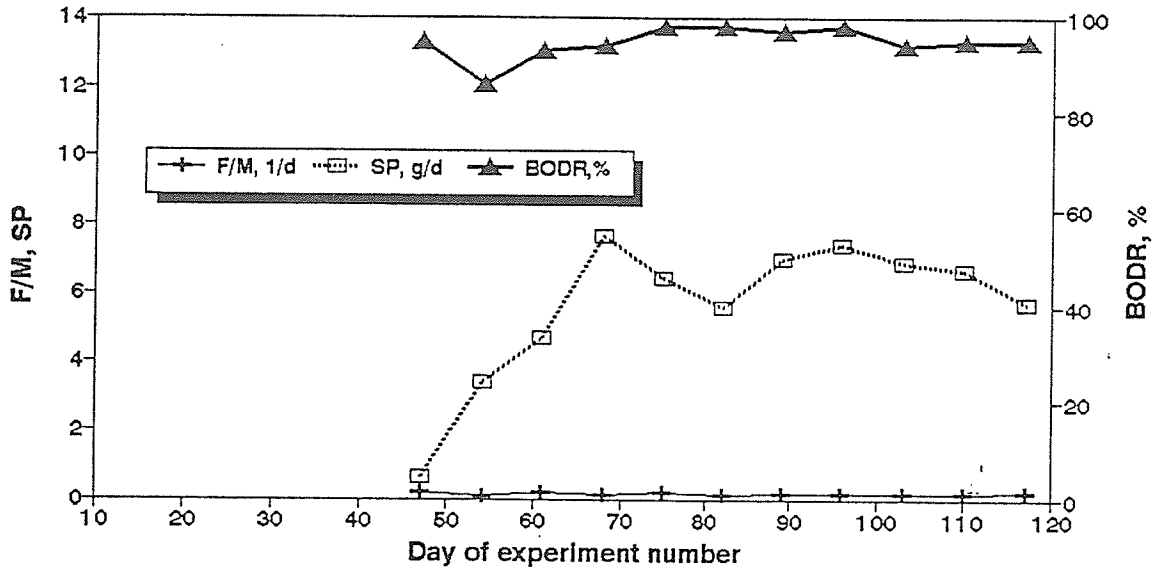


Fig.C.4 Comparison of SP in each Train Throughout the exeperiment

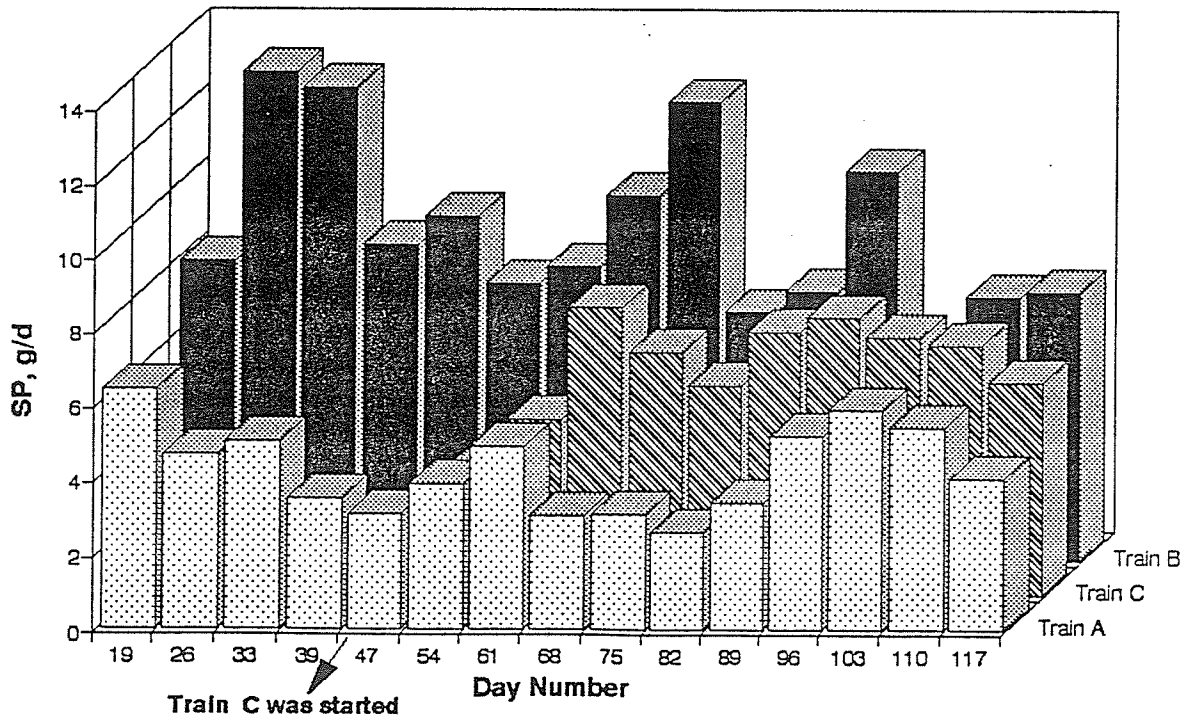


Fig.C.5 Oxygen up take rate (OUR) —
Nitrifying Train B First sample

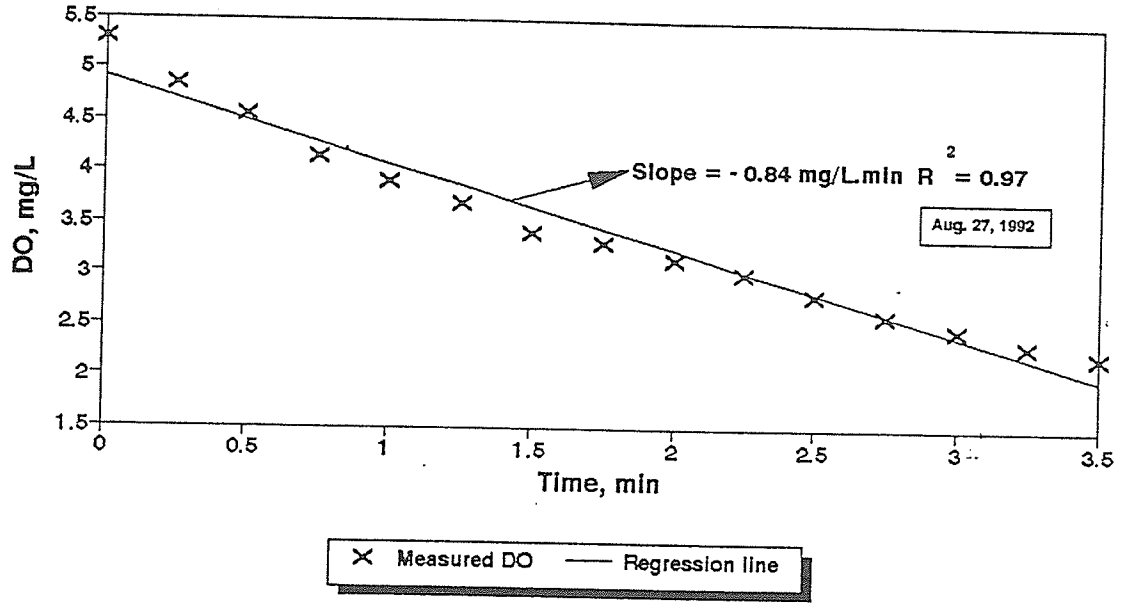
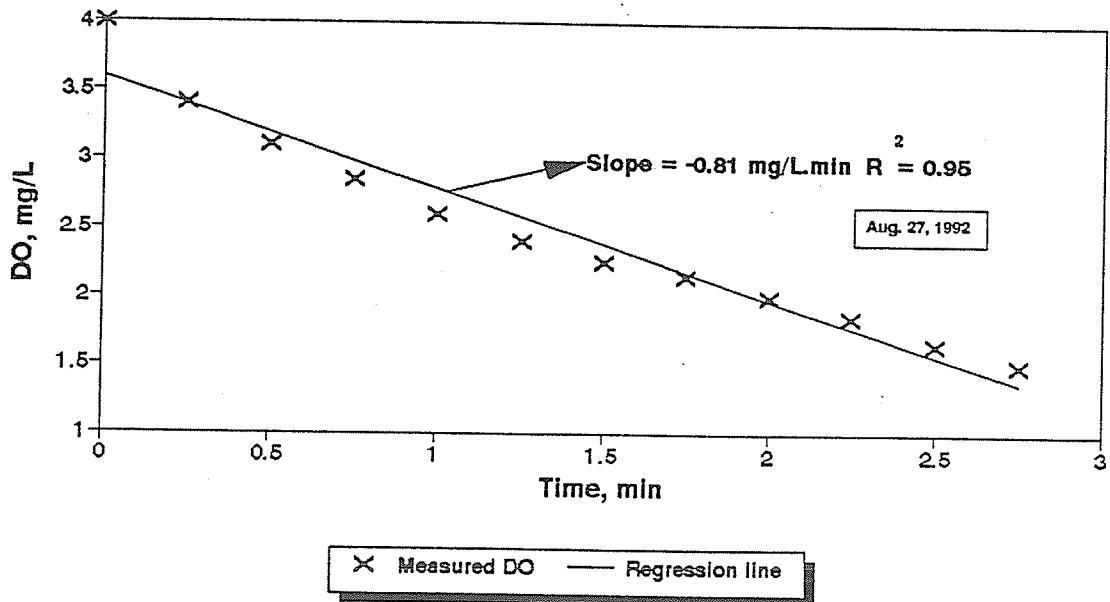
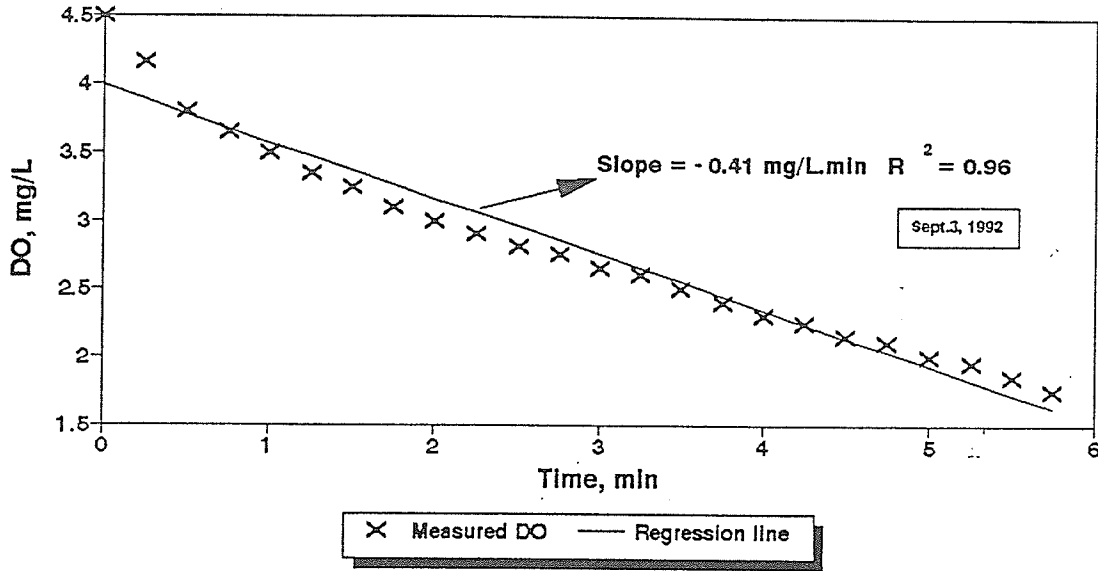


Fig.C.6 Oxygen up take rate (OUR) —
Nitrifying Train B Second sample



**Fig.C.7 Oxygen up take rate (OUR)
Nitrifying Train B First sample**



**Fig.C.8 Oxygen up take rate (OUR)
Nitrifying Train B Second sample**

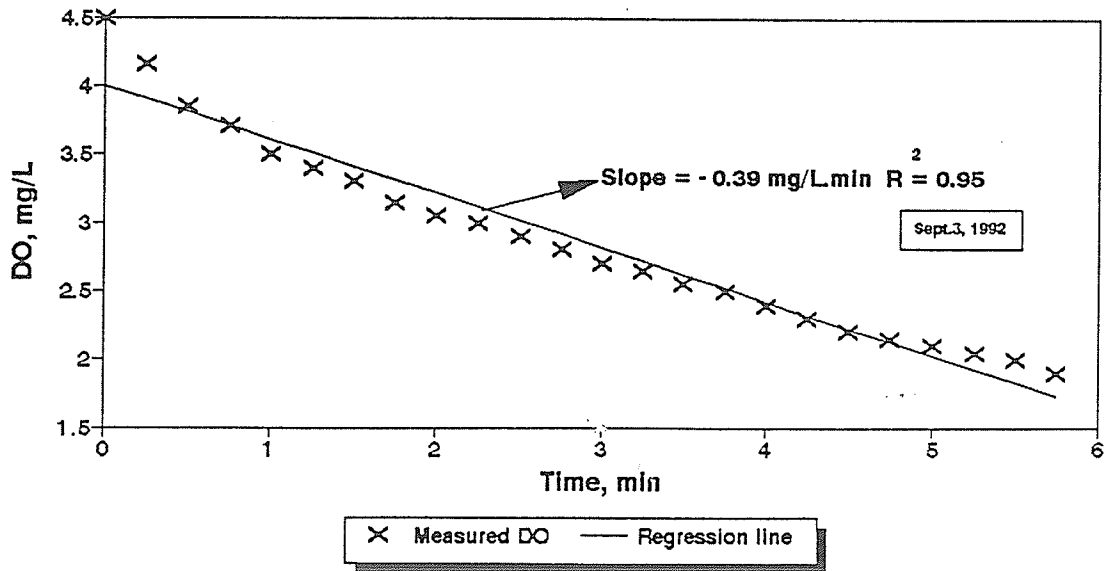


Fig.C.9 Oxygen up take rate (OUR)
Nitrifying Train B First sample

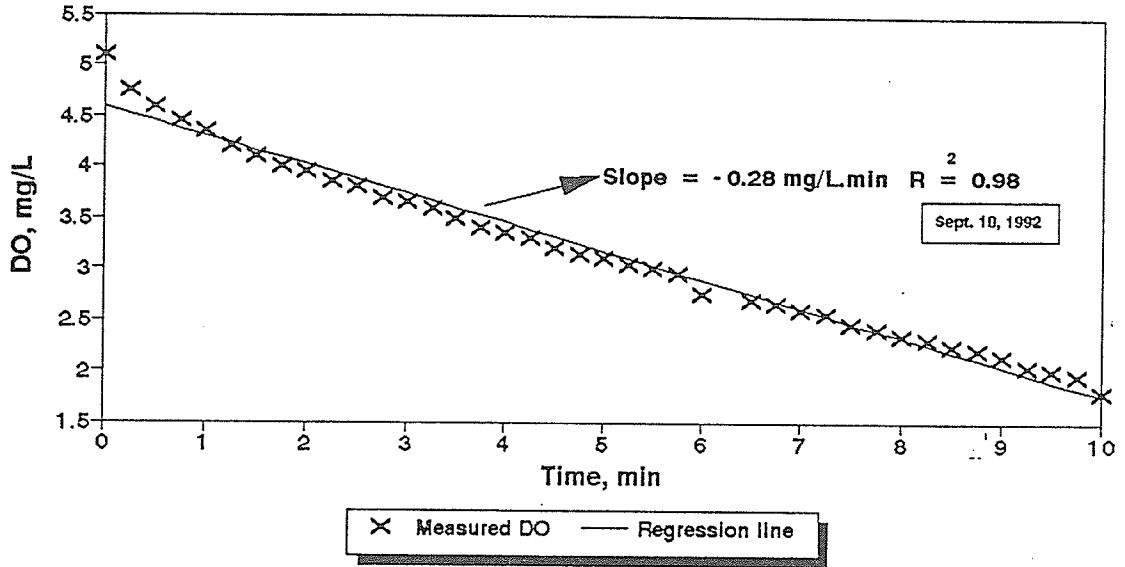


Fig.C.10 Oxygen up take rate (OUR)
Nitrifying Train B Second sample

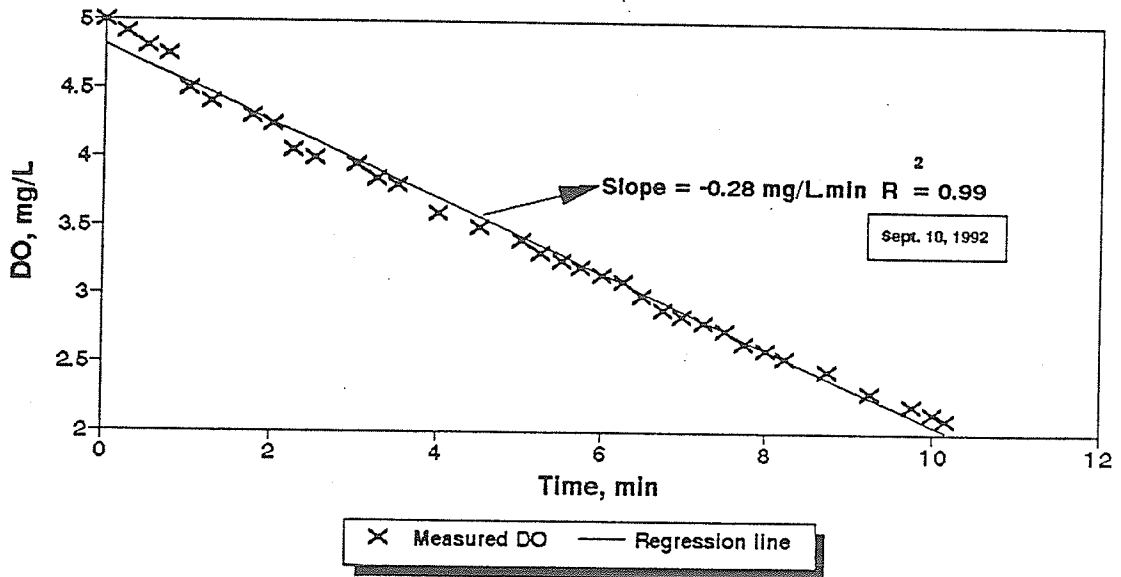


Fig.C.11 Oxygen up take rate (OUR)
Pre-Den Train A First sample

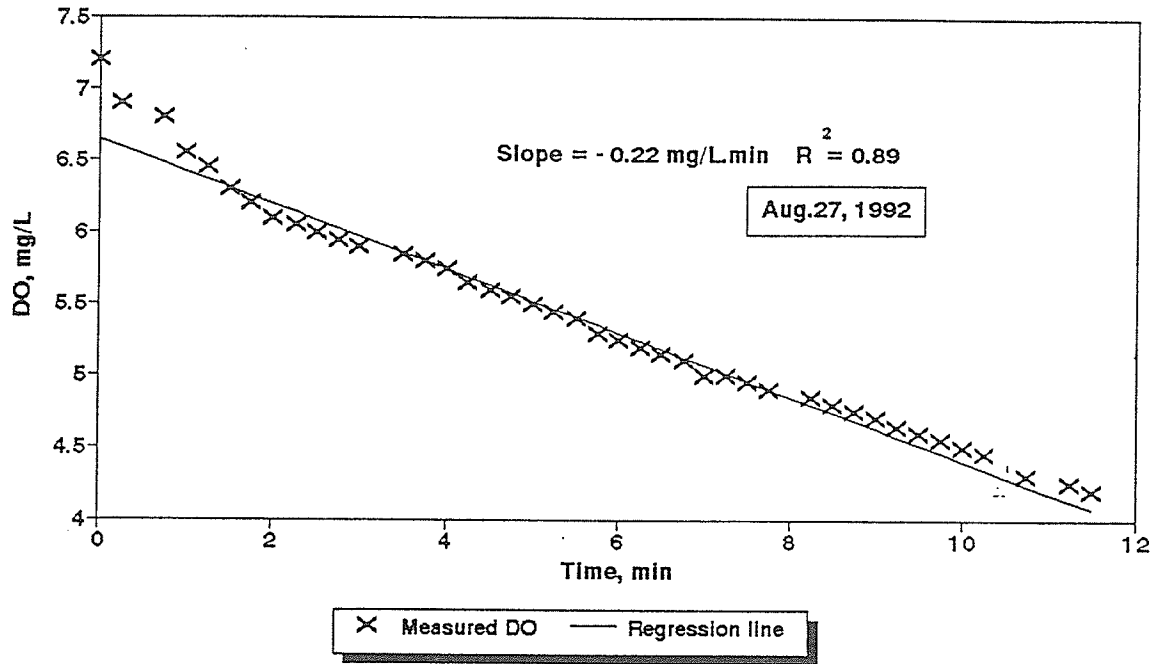


Fig.C.12 Oxygen up take rate (OUR)
Pre-Den Train A Second sample

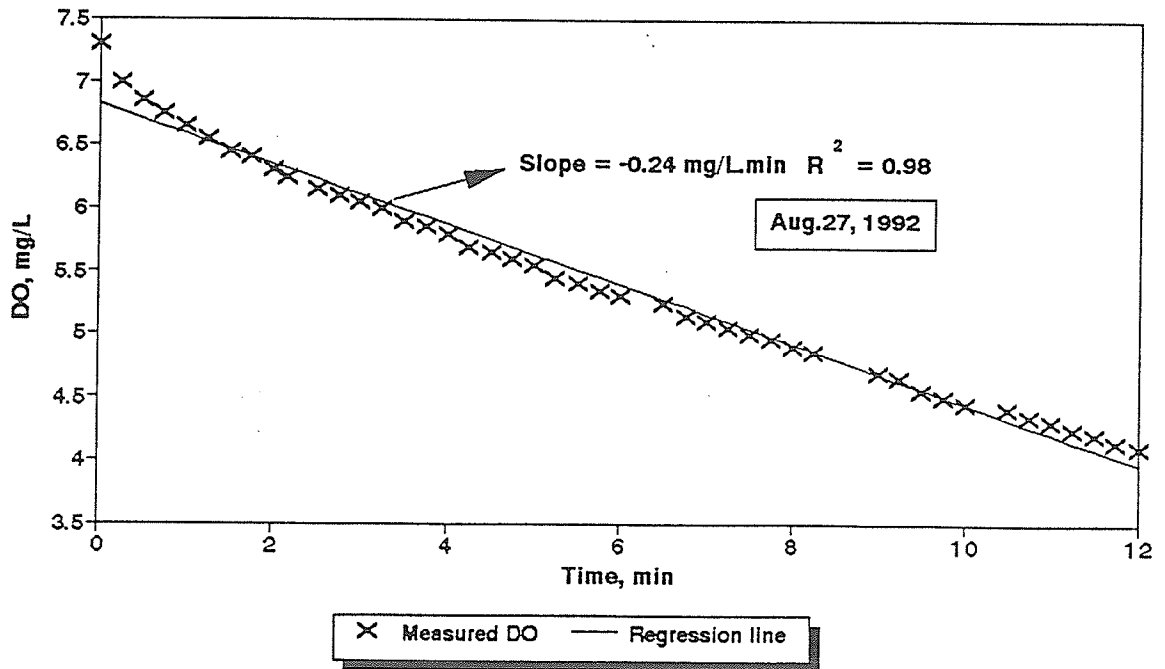


Fig.C.13 Oxygen up take rate (OUR)
Pre-Den Train A First sample

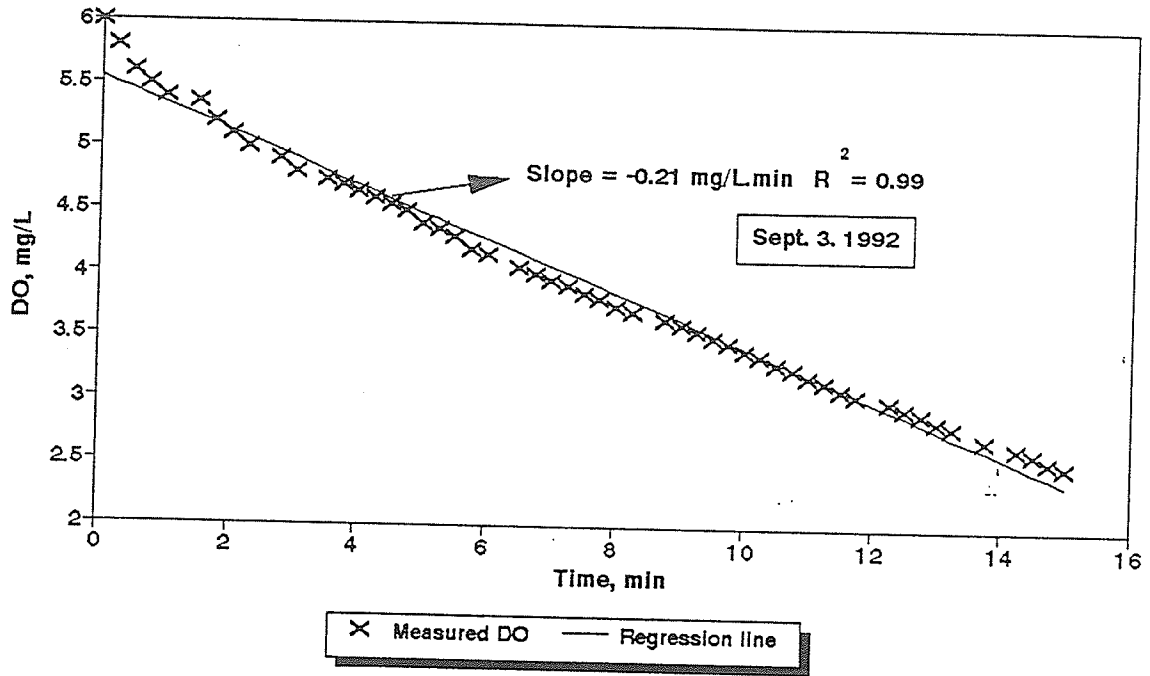
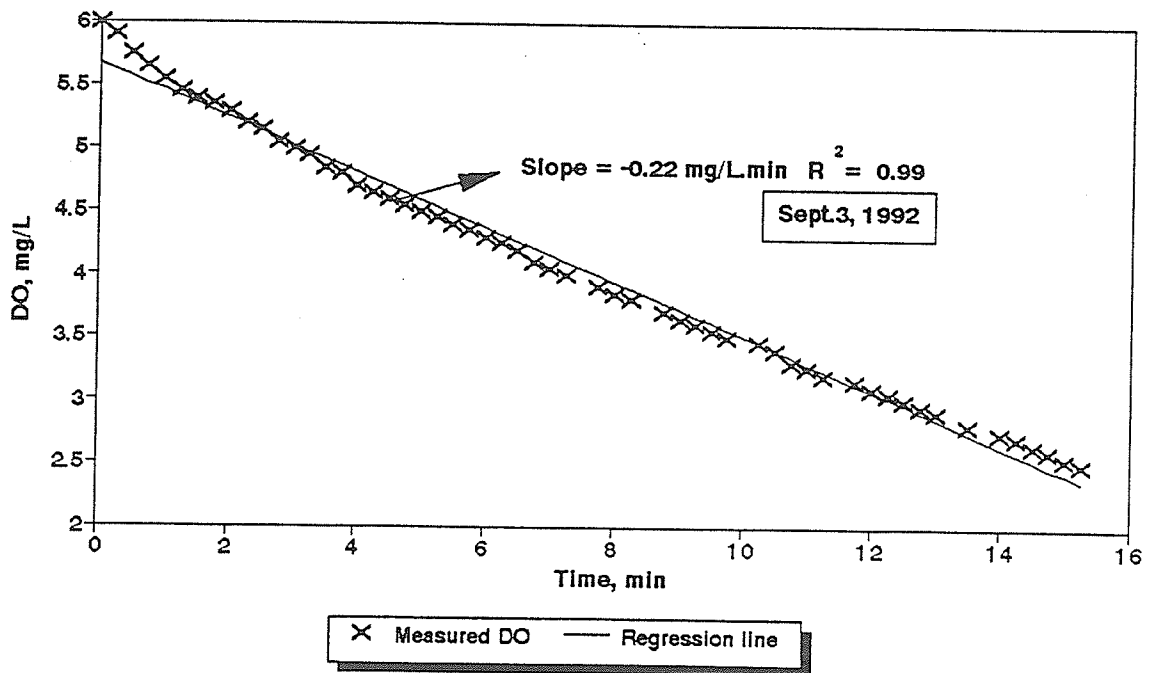


Fig.C.14 Oxygen up take rate (OUR)
Pre-Den Train A Second sample



C.6 Oxygen up take rate on Sept. 10, 1992

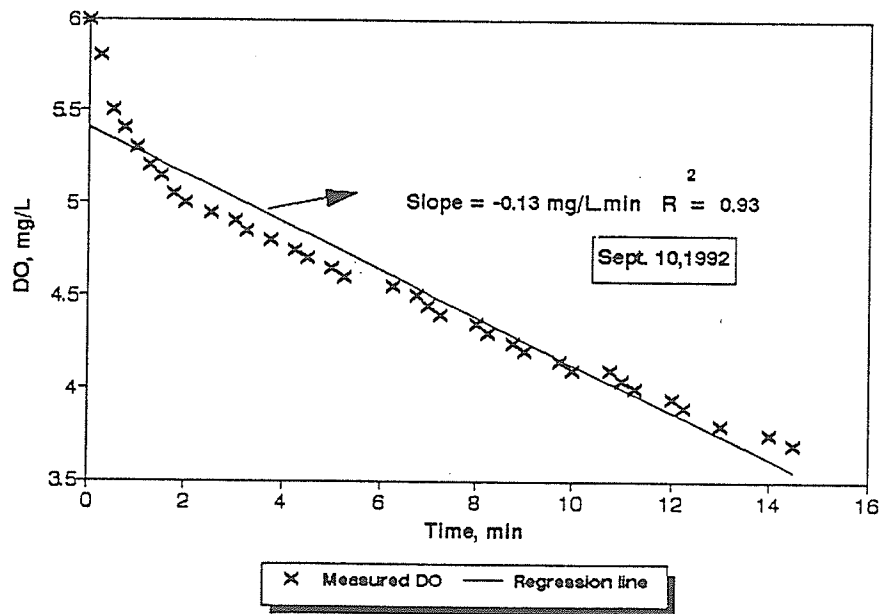
TIME RII DO

0	6
0.25	5.8
0.5	5.5
0.75	5.4
1	5.3
1.25	5.2
1.5	5.15
1.75	5.05
2	5
2.5	4.95
3	4.9
3.25	4.85
3.75	4.8
4.25	4.75
4.5	4.7
5	4.65
5.25	4.6
6.25	4.55
6.75	4.5
7	4.45
7.25	4.4
8	4.35
8.25	4.3
8.75	4.25
9	4.2
9.75	4.15
10	4.1
10.75	4.1
11	4.05
11.25	4
12	3.95
12.25	3.9
13	3.8
14	3.75
14.5	3.7

Regression Output:

Constant	5.409
Std Err of Y Est	0.1586
R Squared	0.9289
No. of Observations	35
Degrees of Freedom	33
X Coefficient(s)	-0.128
Std Err of Coef.	0.0062

Fig.C.15 Oxygen up take rate (OUR)
Pre-Den Train A First sample



C.7 Oxygen up take rate on Aug.27,1992

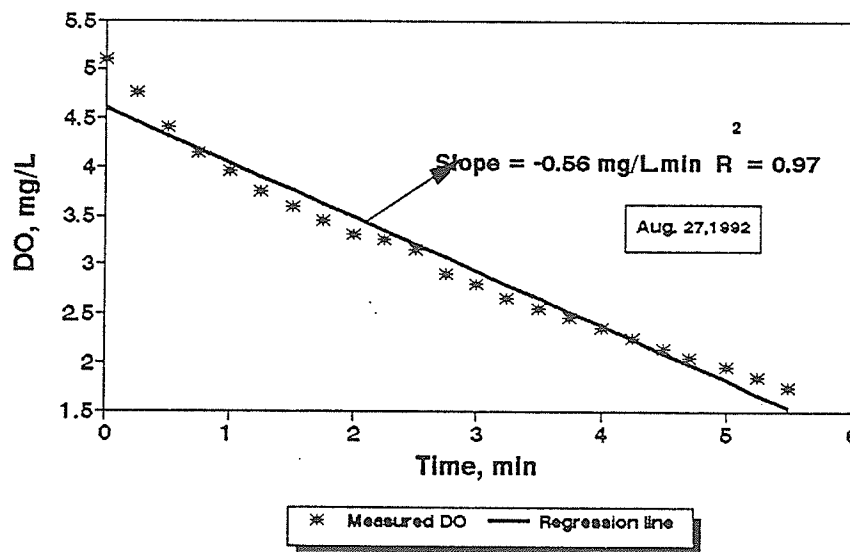
Time DO RV First Sample

0	5.1
0.25	4.75
0.5	4.4
0.75	4.15
1	3.95
1.25	3.75
1.5	3.6
1.75	3.45
2	3.3
2.25	3.25
2.5	3.15
2.75	2.9
3	2.8
3.25	2.65
3.5	2.55
3.75	2.45
4	2.35
4.25	2.25
4.5	2.15
4.7	2.05
5	1.95
5.25	1.85
5.5	1.75

Regression Output:

Constant	4.594289
Std Err of Y Est	0.177156
R Squared	0.967256
No. of Observations	23
Degrees of Freedom	21
X Coefficient(s)	-0.55567
Std Err of Coef.	0.02231

Fig.C.16 Oxygen up take rate (OUR)
Pre-Den Train C First Sample



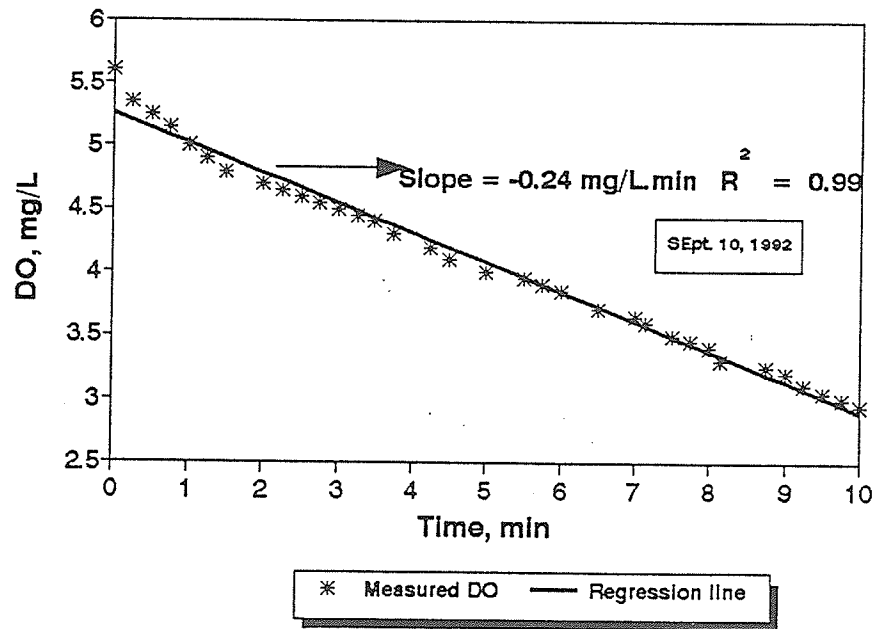
C.8 Oxygen up take rate on Sept. 10, 1992
 Time DO RV Second sample

0	5.6
0.25	5.35
0.5	5.25
0.75	5.15
1	5
1.25	4.9
1.5	4.8
2	4.7
2.25	4.65
2.5	4.6
2.75	4.55
3	4.5
3.25	4.45
3.5	4.4
3.75	4.3
4.25	4.2
4.5	4.1
5	4
5.5	3.95
5.75	3.9
6	3.85
6.5	3.7
7	3.65
7.15	3.6
7.5	3.5
7.75	3.45
8	3.4
8.15	3.3
8.75	3.25
9	3.2
9.25	3.1
9.5	3.05
9.75	3
10	2.95

Regression Output:

Constant	5.2609
Std Err of Y Est	0.086948
R Squared	0.986953
No. of Observations	34
Degrees of Freedom	32
X Coefficient(s)	-0.23587
Std Err of Coef.	0.004794

Fig.C.17 Oxygen up take rate (OUR)
 Pre-Den Train C Second Sample



C.9 Denitrification & SOC rate determinations on day 117

Time min	RI- Train A		RIV- Train C	
	NO3-N mgN/L	SOC mg/L	NO3-N mgN/L	SOC mg/L
0	7.8	30.8	9.3	29.5
30	6	28.1	6.75	27.1
60	4.95	26.8	5.4	25.3
90	4.77	25.9	4.2	24.9
120	3	24.7	2.5	24.5
150	2.25	24.2	2.2	24.1
180	1.35	23.6	1.5	24
210	1	23.1	0.75	23.2

Regression Output: NO3-N RI, 16-IX-92 (Day 117)

Constant 7.253333
 Std Err of Y Est 0.435806
 R Squared 0.971456
 No. of Observations 8
 Degrees of Freedom 6

X Coefficient(s) -0.03203
 Std Err of Coef. 0.002242

Regression Output: SOC RI, 16-IX-92 (Day 117)

Constant 29.45833
 Std Err of Y Est 0.786165
 R Squared 0.9213
 No. of Observations 8
 Degrees of Freedom 6

X Coefficient(s) -0.03389
 Std Err of Coef. 0.004044

Regression Output: NO3-N RIV,16-IX-92 (Day 1

Constant 8.13333
 Std Err of Y Est 0.75732
 R Squared 0.94256
 No. of Observations 8
 Degrees of Freedom 6

X Coefficient(s) -0.0387
 Std Err of Coef. 0.0039

Regression Output: SOC RIV, 16-IX-92 (Day 117

Constant 27.975
 Std Err of Y Est 0.92537
 R Squared 0.82414
 No. of Observations 8
 Degrees of Freedom 6

X Coefficient(s) -0.0252
 Std Err of Coef. 0.00476

C.10 Denitrification & SOC rate determinations on day 122

Time min	RI- Train A		RIV- Train C	
	NO3-N mgN/L	SOC mg/L	NO3-N mgN/L	SOC mg/L
0	6	31	5.25	29.4
30	4	28.7	4.15	27.5
60	3.7	27.7	3.25	27.5
90	3	25.8	2.5	25.6
120	1.7	24.5	1.25	25
150	1.25	23.8	0.5	22.4
180	1	23.4	0.25	20.5

Regression Output: NO3-N RI, 21-IX-92 (Day 122)

Constant 5.360714
 Std Err of Y Est 0.478465
 R Squared 0.940461
 No. of Observations 7
 Degrees of Freedom 5

X Coefficient(s) -0.02679
 Std Err of Coef. 0.003014

Regression Output: SOC RI, 21-IX-92 (day 122)

Constant	30.25
Std Err of Y Est	0.647412
R Squared	0.956219
No. of Observations	7
Degrees of Freedom	5

X Coefficient(s)	-0.04262
Std Err of Coef.	0.004078

Regression Output: NO3 RIV, 21-IX-92 (day 122)

Constant	5.053571
Std Err of Y Est	0.270581
R Squared	0.982938
No. of Observations	7
Degrees of Freedom	5

X Coefficient(s)	-0.02893
Std Err of Coef.	0.001705

Regression Output: SOC RIV, 21-IX-92 (day 122)

Constant	29.63571
Std Err of Y Est	0.719325
R Squared	0.955416
No. of Observations	7
Degrees of Freedom	5

X Coefficient(s)	-0.0469
Std Err of Coef.	0.004531

Fig.C.18 Pre-denitrification Rate- RI
on a day with high carbon content, 1-X

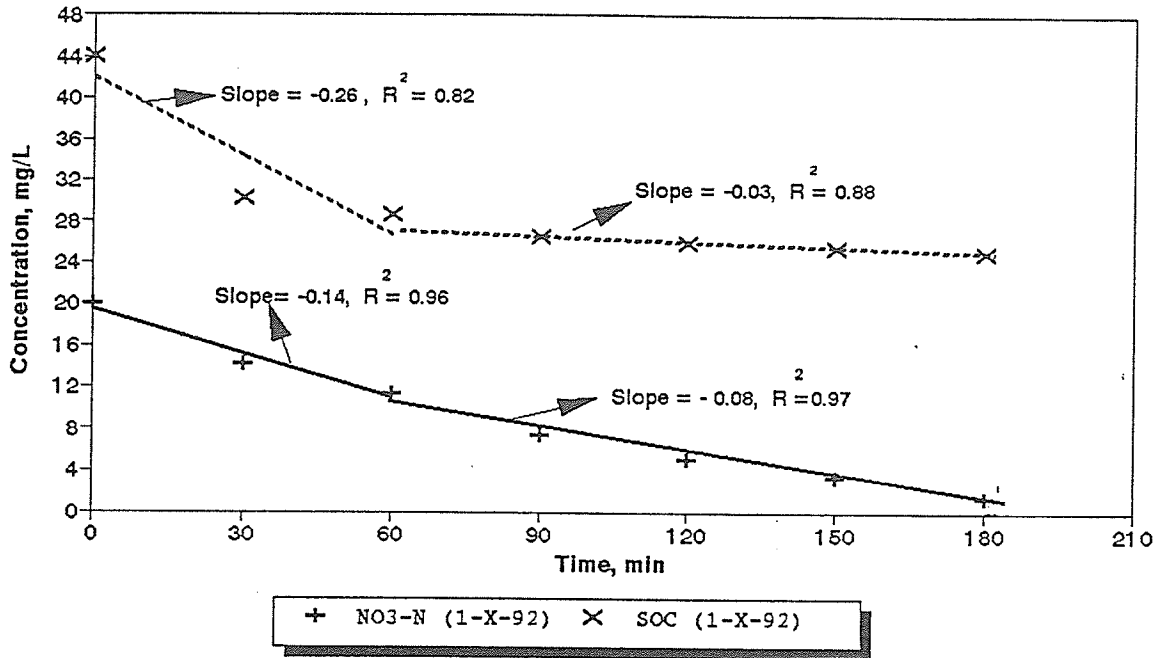


Fig.C19 Pre-denitrification Rate- RIV
on a day with high carbon content, 1-X

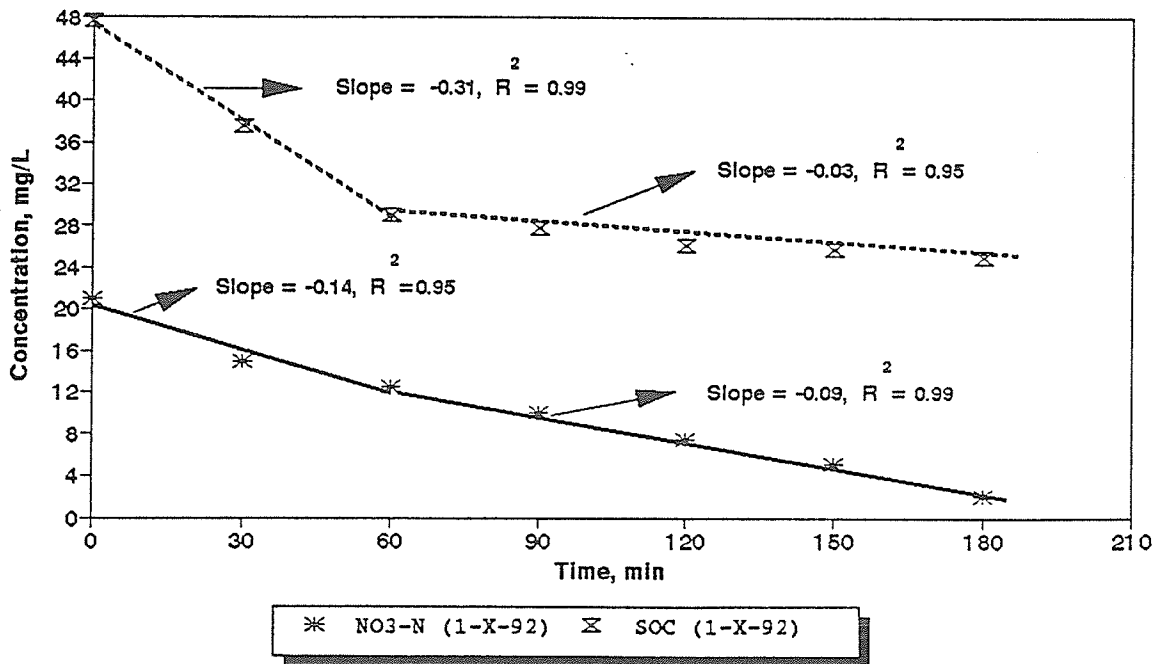


Fig.C.20 Specific Nitrification Rate Throughout the experiment

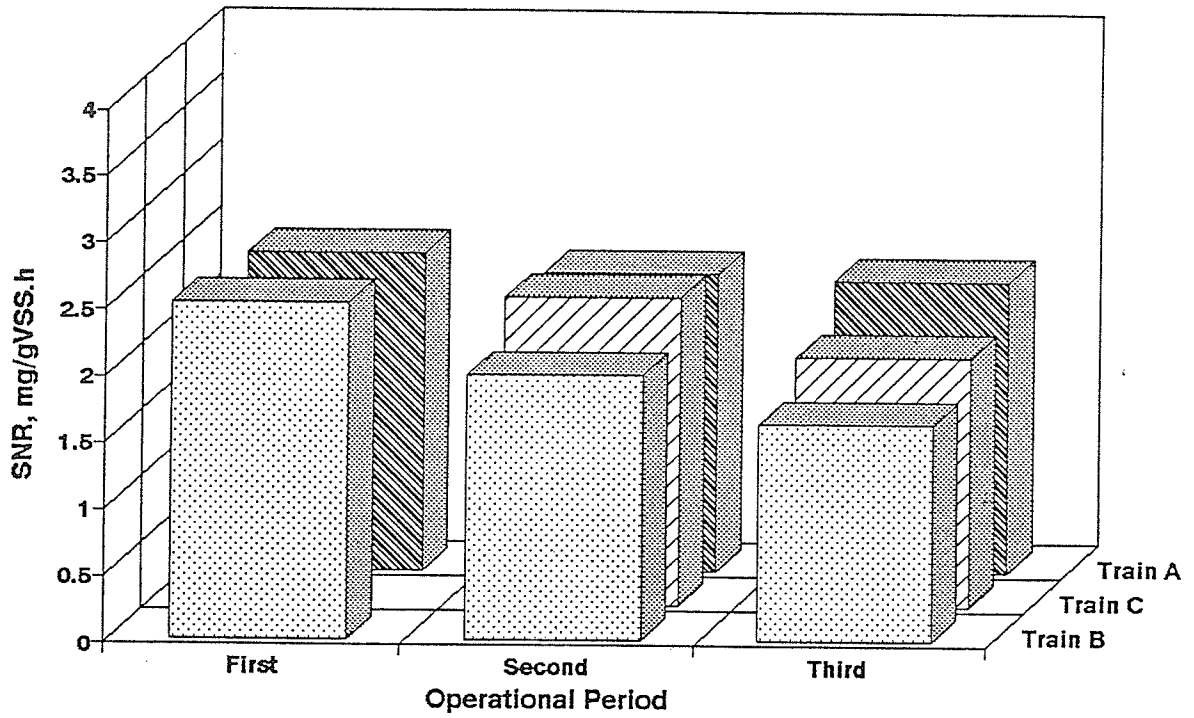


Fig.C.21 Comparison of SNR to Yobs, Throughout the experiment Train B

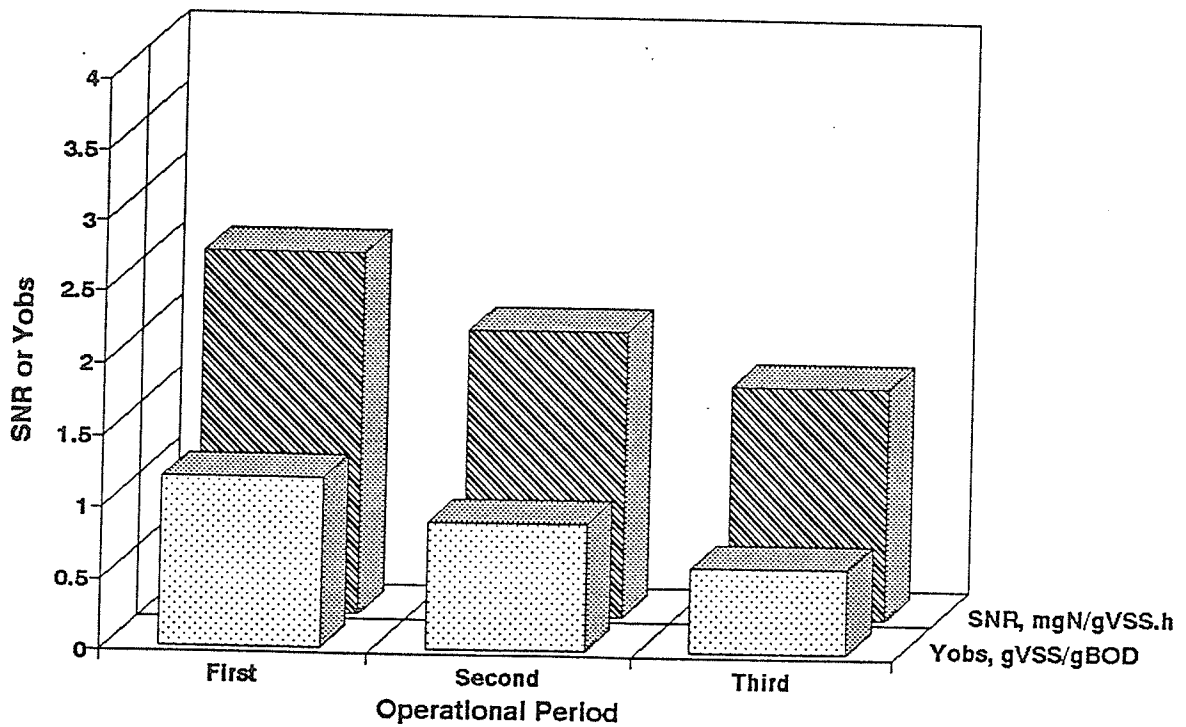


Fig.C.22 Alkalinity consumption
Throughout the experiment-Train A

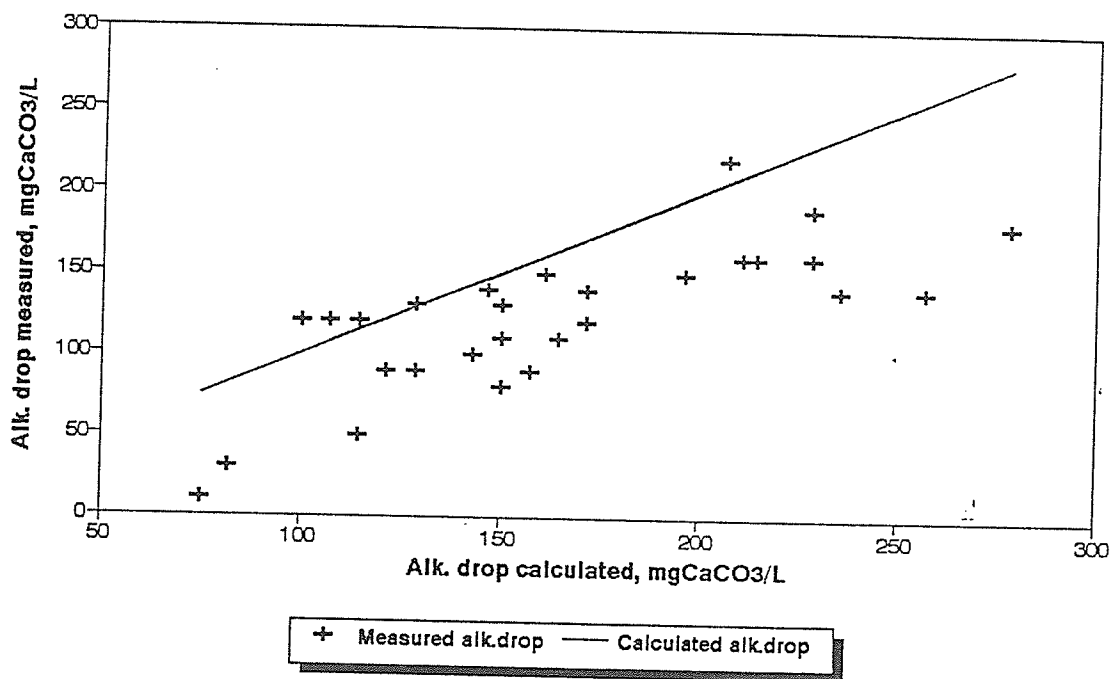


Fig.C.23 Alkalinity consumption
Throughout the experiment Train B

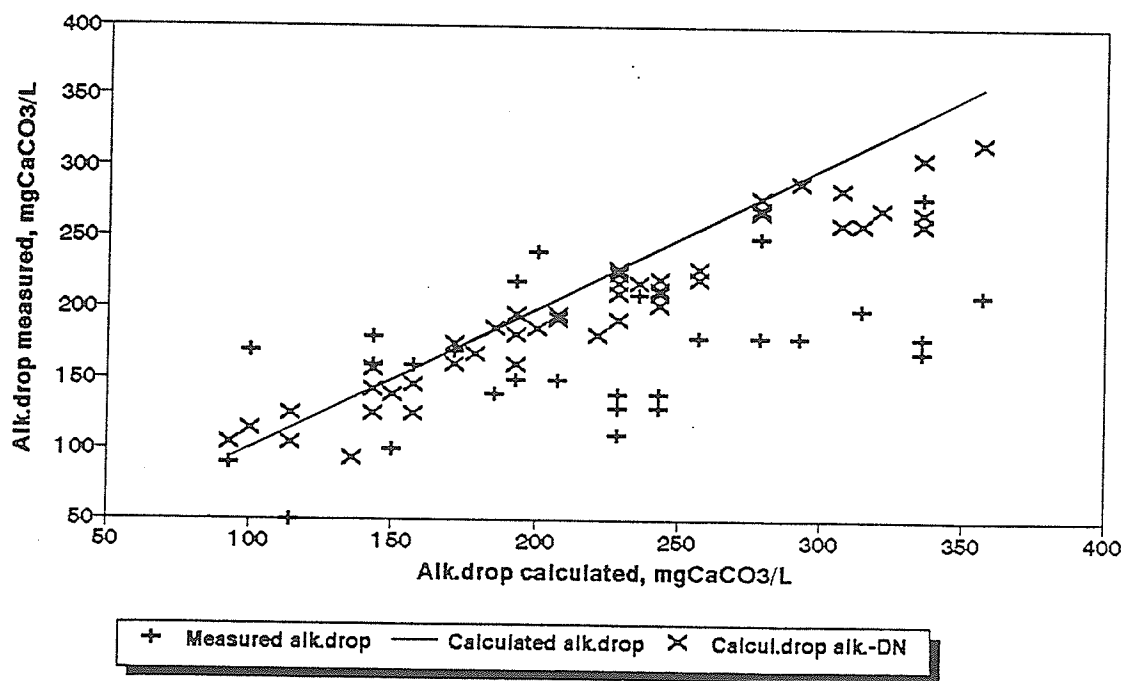


Fig.C.24 Alkalinity consumption
Throughout the experiment Train C

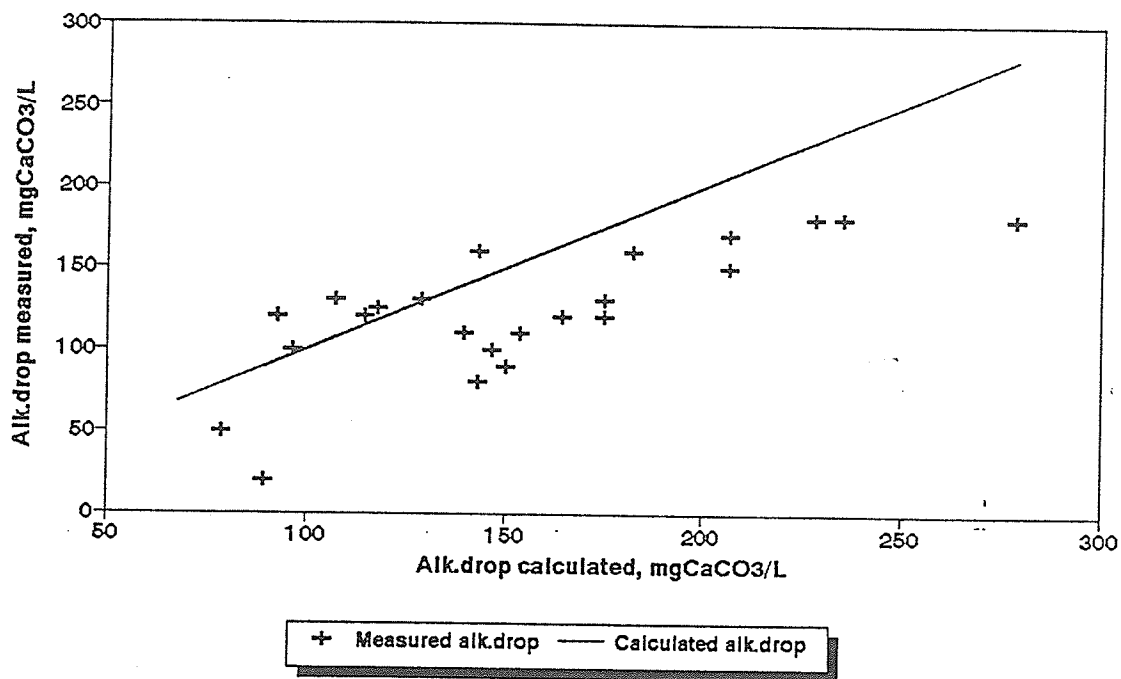


Fig.C.25 Histogram of Alkalinity

