COMPARISON OF RBC AND SBR SYSTEMS FOR AMMONIA REMOVAL FROM LANDFILL LEACHATE

By

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Abstract

Pilot scale RBC and SBR systems were compared in order to find out which system would be more cost effective for full scale treatment of Vancouver Landfill leachate. The leachate is an older leachate with NH_x-N concentrations between 83 and 336 mg/L, BOD_5 concentrations between 20 and 89 mg/L, and BOD_5:COD ratios between .06 and .19. Therefore, the primary objective of the study was to investigate NH_x-N removal through nitrification.

In general, the RBC recovered from nitrogen loading increases and process upsets more quickly and completely than the SBR did, and RBC process upsets were less frequent and less severe. This was attributed to the RBC's superior solids retention capabilities.

The RBC was operated successfully at an average nitrogen loading of 4.15 $g/m^2/d$ at an HRT of 0.35 days. However, loadings of 2 $g/m^2/d$ or less were required in order for effluent NO_2^--N levels to remain below 4 mg/L. The RBC was unable to acclimatize to several of the applied loadings due primarily to provision of insufficient HRT. HRTs greater than 0.3 days were required for NH_x-N removals between 2 and 8 $g/m^2/d$, and P limitation at the higher loadings inhibited complete nitrification. The SBR achieved complete nitrification at an average loading of 107 $g/m^3/d$ at an HRT of 1.93 days. Complete NH_x-N removals were achieved at an average loading of 331 $g/m^3/d$ at an HRT 0.71 days, but complete nitrification was not. It appeared that the lack of complete nitrification in the SBR system was also caused by P limitation.

Both systems were able to perform at low temperatures. The RBC achieved an NH_x-N removal of 1.51 $g/m^2/d$ at 2.5°C, and the SBR was able to remove 23.3 $g/m^3/d$ at 3°C. Nitrogen balance calculations were performed for both systems, but neither system exhibited significant N disappearances. The two systems performed similarily with respect to BOD_5 removal, but the RBC was superior in terms of COD and colour removal. While neither system produced large amounts of excess solids, the RBC solids had better settling characteristics. Evidence of precipitation of inorganic solids was found for both systems, but neither system had scale problems. No differences between the two systems were found in terms of Cd or Co removal, but the RBC tended to remove about 40% of Fe and Mn while the SBR removed 30%. Both systems tended to add rather than remove Zn, but the RBC was more likely to achieve positive removals. Overall, the performance of the RBC system was superior to the performance of the SBR

system.

Toxicity studies were carried out in order to determine whether a substitute could be found for the traditional 96 hour rainbow trout LC_{50} tests. Rainbow trout LC_{50} was found to vary with leachate NH_x-N according to the relationship $T = 2259/N$, where T = 96 hour LC_{50} (%) and N = NH_x-N concentration (mg/L), $R^2 = 0.90$. *Daphnia magna* 48 hour LC_{50} results correlated well with fish results based on the above relationship, but Microtox EC_{50} results did not, due to the high tolerance of the Microtox test for NH_x-N. The sucrose modified Microtox test is supposed to be more sensitive to NH_x-N, but it did not produce meaningful results in this experiment, as sucrose solutions tended to be toxic. The 2259/N relationship was found to be the best way to predict fish toxicity.

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Chapter 1

Introduction

Like many North American municipalities, the City of Vancouver disposes of its solid waste in a landfill. Precipitation which falls on a landfill percolates through the emplaced waste, picks up contaminants, and exits as a wastewater known as leachate. Landfill leachate can cause a variety of environmental problems, including eutrophication and deoxygenation of nearby surface or ground water, and toxicity to organisms living in or drinking the contaminated water. These problems have been recognized for approximately thirty years, and regulations requiring collection and treatment of leachate have been developed and imposed over the last twenty years [52].

Landfill leachate strength and composition are influenced by many factors, including local precipitation, site geology, and waste composition, and therefore vary widely from site to site. The composition of leachate at a given site also varies with time, depending upon the degree of stabilization of the waste. While the stabilization process can be divided into five stages [11, 55], leachates are commonly characterized as young/acidic or old/methanogenic [16, 22].

Leachate from the Vancouver Landfill has a high NH_x-N:BOD_5 ratio and a low BOD_5:COD ratio, and can therefore be considered an old/methanogenic leachate [4, 24]. In this study, NH_x-N concentrations ranged from 83 to 336 mg/L and averaged 200 mg/L, while BOD_5 concentrations ranged from 20 to 89 mg/L and averaged 44 mg/L. COD concentrations ranged from 198 to 483 mg/L and averaged 353 mg/L.

Leachate is collected and pumped from the Vancouver Landfill to the Annacis Island sewage treatment plant, which is currently being upgraded from primary to secondary treatment. The leachate makes up a significant portion of the inflow to the plant, and the high influx of leachate ammonia has the potential to upset the new process or to result in unacceptable effluent toxicity. As a result, the Greater Vancouver Sewerage and Drainage District required the City of Vancouver to investigate the removal of leachate ammonia as a condition of the City's 1993 permit for discharge to sewer.

The City decided to investigate ammonia removal through a pilot scale study. The UBC Environmental Engineering Group has carried out an ongoing program of leachate treatment research for over

twenty years, and was therefore asked to participate in the study. The Environmental Engineering Group agreed to contribute their expertise and equipment to the study if the City allowed a graduate student to take part in the project. This thesis is the result of UBC's participation.

Chapter 2

Research Rationale and Objectives

This chapter is divided into five sections. In the first section, the City of Vancouver's research rationale and objectives are stated. Each of the next three sections consists of a literature review and a set of potential research objectives identified as a result of that review. The final section states which of these potential objectives came to be emphasized as the study progressed.

2.1 City of Vancouver

2.1.1 Research Rationale

The City of Vancouver's 1993 permit for discharge of leachate to sewer required that removal of NH_x-N to levels of 20, 60, and 120 mg/L be investigated. The City's initial literature review indicated that aerobic biological treatment would be the most effective method of accomplishing this task [27]. Previous research at UBC [26, 4, 24, 52] and elsewhere [22] has indicated that both fixed film and suspended growth biological nitrification systems are effective in removing ammonia from leachates similar to Vancouver's. However, few studies are available which directly compare the effectiveness of fixed film and suspended growth systems. Therefore, it was decided that the pilot scale study would focus on comparison of fixed film and suspended growth aerobic biological systems.

Fixed film biological systems which have been used for nitrification of leachate ammonia include trickling filters and rotating biological contactors (RBCs) [22]. Previous experience with RBC treatment and the availability of a pilot scale RBC unit led to the selection of the RBC as the fixed film process to be studied [27].

Nitrification of ammonia in leachate has been achieved in suspended growth systems including conventional activated sludge, extended aeration, and aerated lagoons [22]. The sequencing batch reactor (SBR) is a simple activated sludge system in which aeration and settling are accomplished in the same basin. Because SBR systems are simpler to build, operate, and automatically control than continuous flow systems with recycle, and since parameters obtained for an SBR system would be valid in other

types of activated sludge systems, an SBR was chosen to be the suspended growth process to be tested in the study [27].

2.1.2 Research Objectives

The City's research objectives were to determine operating parameters (eg. loading rates, nutrient additions, etc.) for each system, and to monitor leachate composition and flow. Loading rates resulting in effluents of < 1, 20, 60, and 120 mg/L of NH_x-N were to be determined. These could be used to compare the costs of full scale systems which either treated the entire leachate stream to 20, 60 or 120 mg/L, or treated part of the stream more fully and mixed it with untreated leachate to achieve the effluent concentration desired. The results of the study will be used to design a full scale system which would give the best combination of performance and cost.

2.2 Nitrification of Landfill Leachate Ammonia

This section reviews literature pertaining to nitrification of landfill leachate ammonia, and emphasizes treatment of older leachates with RBCs and activated sludge. The purpose of this section is to provide background information and to emphasize the importance of the study as a whole.

2.2.1 Landfill Biochemistry

Waste placed in a landfill is initially degraded aerobically. Anaerobic conditions eventually predominate as waste is covered and compressed, precipitation percolates into the waste, and aerobes consume any remaining oxygen. The capacity of the waste to absorb water is eventually exceeded, leachate production begins, and anaerobic decomposition becomes fully established. At this point, the landfill is generally referred to as "young" or "acetogenic." Leachates of young landfills are characterized by low pH, high BOD_5 and COD, high BOD_5:COD ratio, and high ammonia. These leachate characteristics are caused by the predominance of acid forming anaerobic bacteria, which convert organic compounds in the solid waste to short chain fatty acids [11, 55]. Acidic conditions found in younger landfills also tend to mobilize metals.

Within 2 to 10 years [22], a large population of methanogenic bacteria typically develops, and the landfill is referred to as "old" or "methanogenic." Anaerobic methanogenic bacteria convert fatty acids to methane and carbon dioxide. As a result, leachates of old landfills are characterized by low BOD_5,

COD, and BOD_5:COD ratio, and by near neutral pH. Metal concentrations decrease, and recalcitrant humic and fulvic compounds are responsible for most COD. While anaerobic mineralization of organic compounds results in conversion of organic carbon to gaseous products, anaerobic mineralization of organic nitrogen (from proteins for example) stops at the production of ammonia. As a result, ammonia concentrations in older leachates remain high [11, 55].

Eventually, the landfill reaches a state of final stabilization. Gas production ceases as organic carbon resources are exhausted. Degradation of recalcitrant compounds may increase release of humic substances, some of which can remobilize metals [11, 55].

2.2.2 Nitrification Biochemistry

Biological treatment of younger landfill leachates involves removal of BOD_5 and ammonia. BOD_5 can be removed aerobically or anaerobically in fixed film or suspended growth biological reactor [22]. Because this research deals with an older leachate, BOD_5 removal is of secondary importance, and ammonia removal will be emphasized in the remainder of the literature review.

Ammonia can exist in water in two forms, ammonium ion (NH_4^+), and free ammonia (NH_3). Ammonia dissociates according to Equation 2.1 [46].

$$NH_4^+ \rightleftharpoons NH_3 + H^+ \quad K_a = 5.848 \times 10^{-10} \quad (20°C) \tag{2.1}$$

NH_3 is more abundant at higher pH and temperature, while NH_4^+ is more abundant at lower pH and temperature. At near neutral pH and normal leachate temperatures, most ammonia is in the NH_4^+ form. In this thesis, the terms "ammonia" or "NH_x" are used to refer to the sum of NH_4^+ and NH_3, and NH_3 is referred to as "free NH_3" to avoid confusion.

While ammonia can be removed through incorporation into biomass when sufficient BOD_5 is present [61, 59], ammonia is more commonly removed from older landfill leachates through nitrification. Nitrification is a two stage process carried out by autotrophic bacteria which use ammonia or nitrite as an energy source and oxygen as the final electron acceptor. In the first stage (Equation 2.2), ammonia is oxidized to nitrite, typically by *Nitrosomonas*. In the second stage (Equation 2.3), nitrite is oxidized to nitrate, typically by *Nitrobacter*.

$$55NH_4^+ + 76O_2 + 109HCO_3^- \longrightarrow C_5H_7NO_2 + 54NO_2^- + 57H_2O + 104H_2CO_3 \tag{2.2}$$

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \longrightarrow C_5H_7NO_2 + 3H_2O + 400NO_3^- \quad (2.3)$$

Source: [19]

Assuming that nitrifier biomass can be represented by the formula $C_5H_7NO_2$, theoretical cell yields of 0.15 mg cells/mg NH_4^+-N and 0.02 mg cells/mg NO_2^--N can be calculated for *Nitrosomonas* and *Nitrobacter*, respectively [19]. Omitting cell synthesis, 7.16 mg of alkalinity must be destroyed for every mg of NH_x-N nitrified [19].

Factors influencing nitrification include temperature, dissolved oxygen (DO), pH, free NH_3 NO_2^- and total BOD_5 concentration. The optimum pH range for *Nitrosomonas* is 7.9 to 8.2, while that for *Nitrobacter* is 7.2 to 7.6 [16].

It is generally recommended that DO concentration be kept above 2.0 mg/L if nitrification is to be achieved [43]. However, nitrification has been reported at DO levels as low as 0.3 mg/L, and values greater than 2.0 mg/L are sometimes reported to be necessary [63]. Nitrification can be accomplished at DO concentrations between 0.5 and 1.0 mg/L only if sufficient Mean Cell Residence Time (MCRT) is provided, and lower MCRTs will require higher DO concentrations [63]. Inhibition at low DO is often attributed to competition with faster growing heterotrophs, which can inhibit nitrifiers through competition if sufficient total BOD_5 (soluble or particulate) is available [20].

Nitrification is easily accomplished at ambient temperatures above 10 to 15°C, but may be difficult to maintain at lower temperatures [4, 24]. However, nitrification has been accomplished by acclimatized organisms at temperatures as low as 1 and 2°C in RBCs and SBRs, respectively [21, 47].

High concentrations of free NH_3 and NO_2^- can be inhibitory, particularly to *Nitrobacter*. Free NH_3 begins to inhibit *Nitrosomonas* at 10 to 150 mg/L, and 0.1 to 1.0 mg/L can inhibit *Nitrobacter*. Free nitric acid begins to inhibit nitrifiers at concentrations between 0.22 and 2.8 mg/L [1]. However, it is difficult to maintain NH_3 or NO_2^- inhibition, as the nitrifiers tend to become acclimatized to formerly inhibitory concentrations [65, 42].

2.2.3 Description of Fixed Film Processes

Fixed film processes which have been used for biological nitrification of wastewater ammonia include rotating biological contactors (RBCs) and trickling filters.

In a typical RBC, several sets of plastic disks are mounted on a common shaft. The shaft is situated

on the axis of a semi-cylindrical tank which is divided into stages, one for each set of disks. For aerobic processes such as nitrification, the disks are usually 40% submerged. While the disks are commonly rotated directly by driving the shaft with a motor, air driven versions also exist. In an air drive RBC, compressed air is introduced into the tank and caught in cup like projections on the disks, causing the disks to rotate. In either type of RBC, biofilms grow on the disks, and wastewater is introduced into the tank. Rotation of the disks creates turbulence and provides mixing and aeration of the wastewater. Oxygen also reaches the biofilm through the thin film of liquid which covers the biofilm when disk rotation exposes it to the atmosphere. Supplemental aeration is sometimes provided to motor driven RBCs, and the drive air contributes to aeration and mixing in air driven RBCs.

In a trickling filter, wastewater is sprayed over filter media which are usually arranged in a vertical cylindrical tank. The filter media are typically plastic or rock, and provide the surface on which the biofilm grows. The wastewater flow introduced is sufficient to keep the surface of the biofilm wet without filling the pore spaces in the media. Aeration is provided by oxygen diffusing into the thin film of wastewater trickling over the biofilm.

2.2.4 Review of Fixed Film Literature

The following literature review will emphasize nitrification of landfill leachate ammonia using RBCs.

2.2.4.1 Leachate Nitrification Studies

Henderson [26] used a lab scale RBC/anaerobic filter system to nitrify and denitrify an older leachate from a Taiwan landfill. The system was found to be effective in removing very high NH_x-N concentrations. Large, unexplained N disappearances occurred in the nitrification reactor, possibly due to simultaneous nitrification and denitrification or aerobic denitrification.

Knox [34] reported five years of full scale RBC leachate treatment at the Pitsea landfill, an older landfill in the U.K. The primary purpose of this plant was to nitrify leachate ammonia. The RBC process was chosen after pilot studies that also included trickling filter and suspended growth systems (see Section 2.2.7). While the system generally worked well, some problems with formation of calcium carbonate scale were encountered. The plant was designed to compensate for low temperature conditions by heating the leachate with landfill gas, supplemented by propane. Heating and pH adjustment were said to have contributed to the scale problem.

Spengel and Dzombak [62] treated an older landfill leachate with bench scale RBCs. First stage DO

was correlated with loading; lighter loading produced higher first stage DO. In the three least heavily loaded RBCs, almost all influent ammonia was removed in the first stage, and first stage DOs were 3.5, 1.9, and 1.8 mg/L. In the more heavily loaded RBC, first stage DO was 1.4 mg/L, and significant nitrification occurred in the first and third stages. Besides nitrifying ammonia, the RBCs removed most BOD_5, 30 to 38% of the COD, and some of the Fe and Mn.

Opatken and Bond [48] treated synthetic high ammonia leachate with a pilot scale RBC. Ammonia concentration was found to decrease at a constant rate with time at a given temperature (zero order reaction) at initial concentrations up to 700 mg NH_x- N/L. This lead these authors to conclude that changing the reactor configuration to a plug flow, completely mixed, series of stirred reactors, or batch operation would not affect the reaction time. Reactor pH values below 7.2 were found to inhibit nitrification, and the maximum treatable influent NH_x-N concentration was determined to be between 700 and 1000 mg/L for their system. Prediction of the effect of temperature on the reaction rate constant was judged to be possible using the Arrhenius equation, although temperatures investigated only ranged from 15.0 to 21.0°C.

Peddie [52] treated a younger landfill leachate with the same RBC pilot plant used in this study. Nitrification was achieved in conjunction with BOD_5 removal in most cases. However, heterotrophs were found to consume all the available ammonia through assimilation when the BOD_5:NH_x-N ratio exceeded 20:1. Low temperatures were found to be less inhibitory to nitrification than predicted by the Arrhenius equation with $\theta = 1.09$ (a value found by Peddie in his literature review). Extended HRTs used in cold temperature conditions were credited with reducing temperature effects. Nitrification efficiency was found to be reduced sharply at HRTs less than about four hours. This relationship was relatively independent of temperature. Peddie's thesis also included a very extensive literature review dealing with landfill leachate treatment.

2.2.4.2 Other Related Studies

Several studies in which high ammonia wastewaters, including landfill leachate, are treated by RBC systems focussed on simultaneous nitrification and denitrification [25, 66, 10, 41, 29, 67]. These studies are described further in Section 2.3.1.

Klees and Silverstein [32] used a pilot scale RBC system to treat secondary effluent from a full scale trickling filter plant used to treat municipal sewage. Recirculation of RBC effluent such that 50 or 75% of the influent flow was recirculation was found to improve nitrification compared to no recirculation. The

postulated reason for this was that recirculation diluted BOD_5 in the RBC influent, although extremely low concentrations of influent BOD_5 did not improve nitrification to the extent expected.

Boller et al. [7] investigated tertiary treatment of secondary effluent using pilot and full scale RBCs. They found periodic flow reversal to enhance nitrification performance, particularly under a fluctuating ammonia load. Flow reversal was said to allow more slow growing nitrifying biofilm to build up on the final disks, and therefore allow more effective use of the available surface during high loading situations. Without flow reversal, biofilm would not be able to build up on the final disks fast enough to contribute to treatment during peak loads. Tertiary nitrification was enhanced if secondary effluent was filtered before entering the RBC system, preventing build up of non- nitrifying biological matter on the disks.

Surampalli and Baumann [64] upgraded a full scale RBC plant treating municipal sewage. The plant had been designed for secondary treatment, but failed to meet secondary effluent criteria. Upgrading the plant by providing supplemental aeration not only allowed the plant to meet its secondary effluent standards, but also provided nitrification capabilities. Improved nitrification was reported to be the result of higher mixed liquor DO.

Figueroa and Silversteen [20] used synthetic wastewater to simulate tertiary treatment of municipal sewage in a pilot scale RBC. Particulate BOD_5 was found to inhibit nitrification in the same manner as dissolved BOD_5, i.e. through competitive exclusion of slow growing autotrophs by heterotrophs. Mixed liquor DO concentration was found to be independent of influent BOD_5 and ammonia removal, and mixed liquor suspended solids were extremely low in comparison to attached biomass. It was postulated that improved nitrification due to increased mixed liquor DO, such as that found by Surampalli and Baumann [64], is due to increased activity of suspended organisms rather than biofilm organisms. This theory is supported by the findings of Paolini [50] who found that the dominant aeration mechanism in RBC systems is "oxygen diffusion through the liquid film during the air exposure cycle."

Forgie [21] investigated low temperature effects on lab scale RBCs treating synthetic sewage intended to be "representative of individual households or workcamp installations" in northern Canada. Nitrification was achieved at temperatures as low as 1°C. Temperature effects at low temperatures were not found to follow the Arrhenius model traditionally used to model temperature effects. A replacement empirical approach which gave a better fit to the data was determined.

2.2.5 Description of Suspended Growth Processes

Suspended growth processes which have been used for biological nitrification of landfill leachate ammonia include continuous flow activated sludge (AS) plants, sequencing batch reactors (SBRs), and extended aeration systems. In suspended growth systems, active organisms grow in small clumps or "flocs" which are kept in suspension by mixing the contents of the reactor vessel, generally referred to as mixed liquor. Mixing is achieved through aeration or a combination of aeration and other forms of mechanical mixing. In continuous flow AS plants, influent and effluent enter and leave (respectively) the reactor vessel continuously. A clarifier vessel receives the effluent, and settled sludge is generally pumped back to the reactor vessel. SBRs combine mixing and settling in one vessel which operates on a timed cycle (eg. fill, aerate/react, settle, withdraw). Extended aeration systems can operate in a continuous or batch mode, and have lower F/M ratios and significantly longer HRTs than conventional activated sludge systems.

2.2.6 Review of Suspended Growth Literature

The following literature review will emphasize nitrification of landfill leachate ammonia using activated sludge systems.

2.2.6.1 Older Leachate Nitrification Studies

Azevedo [4] investigated nitrification and denitrification of high ammonia landfill leachate in a lab scale activated sludge system. The Vancouver (Burns Bog) Landfill leachate was used as the base wastewater, but ammonia was added to produce higher loadings. Influent ammonia concentrations as high as 1500 mg NH_x- N/L were successfully nitrified and denitrified at temperatures between 12 and 20°C; nitrification failed when the temperature was decreased from 12 to 10°C. Nitrification resumed at 10°C when aerobic wasting and methanol addition ceased, indicating that short solids retention times inhibit nitrification at temperatures below 12°C. Nitrification also failed when the influent NH_x-N concentration was raised from 1500 to 2000 mg/L, possibly due to insufficient DO, solids/scum/foaming problems, or inhibition by high NH_3 levels.

Guo [24] investigated the effects of low temperatures on nitrification and denitrification using the same treatment system and Vancouver Landfill leachate without adding extra ammonia. Ammonia removal was accomplished at 20, 12 and 4°C with aerobic solids retention times of 20 and 60 days. The 60 day aerobic SRT system achieved better ammonia removal than the 20 day aerobic SRT system at

4°C, although the 20 day system was capable of reducing an influent NH_x-N concentration averaging 210 mg/L to less than 14 mg/L. Nitrifiers were observed to require lengthy periods of acclimatization in order to recover from sudden drops in temperature. While membrane filtered PO_4^{3-}-P concentrations above 0.5 mg/L were adequate at 20°C, 0.8 mg/L were required at 12 and 4°C.

Manoharan et al. [40] used the same system and leachate to investigate the effects of high metal concentrations on leachate treatment. Zinc, chromium, and nickel were added to the leachate in order to determine their effects on the process. Apparent inhibition by high zinc concentrations was actually caused by zinc induced precipitation of PO_4^{3-}-P. PO_4^{3-}-P concentrations which appeared to be adequate when filtered through Whatman No. 4 filters were found to be inadequate when filtered through .45 μm membrane filters. It was recommended that membrane filtered PO_4^{3-}-P levels should be kept above 0.5 mg/L in order to avoid P limitation.

Robinson et al. [60] and Last et al. [36] have been involved with the design and operation of full scale leachate treatment plants in the U.K. since the early 1980s. Many successful plants have been built using a combination extended aeration/SBR approach to treat leachate in automated aerated lagoons. Advantages of this approach over conventional activated sludge systems include robustness due to long HRTs (days instead of hours), complete and simple automation, and more allowable settlement time. Because of the "notoriously problematic" settling characteristics of slow growing nitrifiers, the provision of long HRTs and long settling times were said to be particularly important. Removal of ammonia in these systems has been accomplished by assimilation (when the BOD_5:NH_3-N ratio is 100:3.6 or greater), and by nitrification when less BOD_5 is available.

Mena et al. [42] used a lab scale SBR reactor to treat leachate from an older landfill. DO was found to be a good indication of nitrification; during nitrification, DO remained between 1 and 2 mg/L, but when all NH_x-N had been nitrified, DO increased to saturation values. Free ammonia (NH_3) concentrations in the range of 30 to 40 mg/L inhibited *Nitrobacter*, producing nitrite buildups. However, acclimatization occurred within four months. Nitrification was found to occur as a zero order reaction, and high nitrification rates were attributed to the low BOD_5:NH_x-N in the leachate.

Hosomi et al. [30] also used a lab scale SBR reactor to treat older landfill leachate. Nitrification was successful, but denitrification required addition of methanol as a carbon source. Attempts to initiate endogenous denitrification were unsuccessful. Pretreatment with ozone was found to enhance COD removal.

Knox [33] used activated sludge and trickling filter pilot plants to treat an older landfill leachate.

Difficulty was encountered in using SRT as a process control parameter, as influent and effluent VSS were often high compared to expected solids production; also, it was impossible to determine what proportion of VSS was lost in the effluent. Settling problems were said to be common in nitrification systems with low BOD_5:NH_x-N ratios. Deliberate solids wasting was never found to be necessary.

2.2.6.2 Other Related Studies

Azimi and Horan [5] found that plug flow activated sludge reactors were superior to completely mixed activated sludge reactors for nitrification. Improved performance in plug flow situations was attributed to reduced free ammonia (NH_3) inhibition.

Liu et al. [38] treated a younger landfill leachate with lab scale SBRs. SBR treatment was found to be effective in removing ammonia and metals with and without pretreatment by ammonia stripping and metal precipitation.

Ying et al. [68] found that addition of powdered activated carbon to SBRs treating younger landfill leachate resulted in improved organic removal, better sludge settling and dewaterability, and improved nitrification.

Oleszkiewicz and Berquist [47] used lab scale SBRs to treat a mixture of domestic sewage and high nitrogen effluent from an estrogen factory. Four reactors were operated, two on a 12 hour cycle and two on an 8 hour cycle. Each had 2 hour "fill and mix" and "settle and decant" periods, and an HRT of 24 hours. The nitrification performance of the reactors was similar at 15°C, but the 12 hour cycle reactors were superior at 7, 5, and 2°C. Hourly measurements were found to be superior to daily measurements for determining if reactors were underloaded or operating at full capacity. The variation of reaction rate with temperature was found to be discontinuous.

2.2.7 Comparison Studies

Knox [34] described a decision to build a full scale RBC plant to treat leachate from an older landfill. Pilot studies were conducted with RBC, trickling filter, and activated sludge systems. Projected capital costs for a trickling filter system were much higher than for activated sludge and RBC systems, which were similar. Operating costs for an RBC system were expected to be much lower than those for an activated sludge system due to reduced power demands. Settling problems encountered in activated sludge pilot studies were another reason for the choice of an RBC system. While no problems with scale formation and metal precipitation were experienced at pilot scale, two serious incidents occurred at full

scale. A carbonate/bicarbonate equilibrium shift caused by leachate heating and pH adjustment was blamed for these incidents. The lack of scale problems at pilot scale was attributed to "pretreatment" in the open ditch leachate collection system at the landfill [33].

Lugowski et al. [39] compared pilot scale activated sludge and RBC plants for treatment of an older landfill leachate. No settling problems were found in either system, and both systems were severely inhibited by calcium and iron encrustation. After a pretreatment system for metal removal was installed, the systems were compared again, and both were found able to meet the required effluent criteria. Estimation of full scale costs indicated that the activated sludge system would have significantly lower capital and operating costs, and therefore a full scale activated sludge system was built.

Pisano et al. [53] compared the performance of lab scale RBCs and SBRs when subjected to shock loads of toxic organics, including toluene, benzene, and 2,4,6-trichlorophenol. A synthetic wastewater containing 85 mg/L of TKN and no NH_x or NO_x^- was used. Shock loads resulted in inhibition of nitrification in the RBC, although recovery occurred within 24 hours. Nitrification was unaffected by shock loading in the SBR. Shock loadings were said to represent "equivalent mass loading of organic shock within a 24 hour period." The concentrations of toxic organics added to the RBC system were six times those added to the SBR system, and it is unclear how the equivalence of mass loading was determined.

Galil and Rebhun [23] compared lab scale activated sludge and RBC systems treating oil refinery wastewater. The reactors studied had equivalent volumes, and therefore the RBC system developed about 10 to 50 times the mass of volatile solids as the activated sludge system. The RBC was also operated at one third of the HRT of the activated sludge system. Stressing the system by increasing phenol concentrations caused increased effluent solids levels in the activated sludge system, but not in the RBC system. As a result, the RBC system recovered more quickly from shocks. The RBC was found to produce less sludge with better settling and dewatering characteristics than the activated sludge system, even under normal operating conditions.

Ehrig [16] used a variety of systems including aerated lagoons, activated sludge, and RBCs to treat both older and younger landfill leachates at a variety of scales. While both suspended growth and fixed growth systems were investigated, no side by side comparisons were reported, and only general observations of a comparative nature can be gleaned from the study. Activated sludge systems were difficult to start up when older leachate was being treated unless nitrifying sludge was available. Such startup problems were not reported for aerated lagoons or RBCs. Both aerated lagoon and activated

sludge systems experienced nitrification and BOD removal problems at temperatures below 5°C. Low temperatures were also reported to cause settling problems in activated sludge systems, particularly at higher loading rates. No low temperature data were reported for RBC systems. RBC units were found to be capable of removing up to 95% of the NH_x-N at loadings of up to 10 $g/m^2/d$, and continue removing a"high" proportion of NH_x-N at loadings up to 17 $g/m^2/d$. However, loadings above 2 $g/m^2/d$ resulted in inhibition of NO_2^- oxidation, and therefore were not recommended.

Paolini and Variali [51] treated solid waste processing effluent (similar to younger leachate) with lab scale activated sludge and RBC systems. RBC sludge had better settling characteristics than activated sludge, and sludge recycle was not required in the RBC.

Clark et al. [12] treated domestic sewage with a pilot scale RBC. Full scale costs were estimated for an RBC system and several activated sludge configurations. Calculated capital costs were significantly higher for the RBC, while calculated operating costs were significantly lower.

Labella et al. [35] treated winery wastes (high BOD_5, low N) with pilot scale aerated lagoon, activated sludge, and RBC systems. While solids for all systems settled satisfactorily, RBC solids settled more quickly. Estimated full scale capital and operating costs were both found to be lower for an RBC system.

2.2.8 Research Objectives

Although both fixed growth and suspended growth systems have been studied extensively, very few side by side comparisons have been made. Even in a side by side study, it is difficult to compare the two types of systems, especially in terms of cost effectiveness. Only full scale costing based on pilot scale loading parameters could determine which system is more cost effective, and this is beyond the scope of this thesis. However, several useful comparisons can be made. Some of the topics which deserve coverage include comparisons of response to shocks (loading, temperature etc.), recovery from failures, waste solids production, incidental removal of metals, COD, BOD_5, colour, alkalinity etc. during nitrification, and general ease of maintenance and operation.

2.3 Nitrogen Disappearance from Nitrification Systems

Nitrification systems are designed to convert NH_x-N to NO_3^--N through the aerobic biological process of nitrification (see Section 2.2.2). Small amounts of dissolved N are expected to be lost due to NH_x-N volatilization and assimilation by bacteria, but the majority of the N is expected to remain in solution.

In contrast, the conversion of NO_3^--N to gaseous N compounds, or denitrification, is expected to result in the loss of dissolved N. However, biological denitrification is generally considered to be an anaerobic process, and is therefore not expected to occur in nitrification systems. In a recent UBC study, significant N disappearances were noticed in a nitrification reactor [26]. Two possible explanations for this N disappearance are simultaneous nitrification and denitrification (SND) and aerobic denitrification.

2.3.1 Simultaneous Nitrification and Denitrification

Masuda, Watanabe, et al. [41, 66, 67] published a series of studies in which simultaneous nitrification and denitrification (SND) was found to occur in systems intended primarily for nitrification of landfill leachate NH_x-N. Increased denitrification was found to occur with increased organic loading, increased temperature, and decreased atmospheric oxygen partial pressure. Acetate and methanol were found to be good carbon sources for SND. Biofilms were microscopically examined, and nitrifiers, denitrifiers, and other heterotrophs were found to coexist. The occurance of SND was attributed to the presence of micro-aerobic and micro-anaerobic environments, which temporarily exist within the biofilm due to the rotation of the disk.

Chen et al. [10] proved that the products of endogenous decay could be used as a carbon source for denitrification in both fixed growth and suspended growth systems. Synthetic wastewaters and lab scale systems were used.

Hosomi et al. [29] compared BOD_5 and ammonia removals from a high BOD, high ammonia landfill leachate in two lab scale systems. One system was a standard RBC, while the other was an RBC which had an anaerobic biofilter added to the tank beneath the disks. Addition of the biofilter was found to enhance COD and nitrogen removal (i.e. denitrification). SND occurred in both systems.

2.3.2 Aerobic Denitrification

Researchers at Delft University of Technology in the Netherlands published a series of articles dealing with *Thiosphaera pantotropha* [28, 58, 57]. This organism, which was isolated from a domestic sewage treatment plant, was found to be capable of aerobic denitrification, and was found to grow well in fixed and suspended growth situations.

Gupta et al. [25] evaluated the use of *T. pantotropha* in treating a high strength synthetic nitrogenous fertilizer wastewater. The organism was found to be capable of high N removals at loading rates up to 9.36 $g/m^2/d$ in an RBC system with an HRT of 2.0 days. HRT and loading rate were found to be

important process parameters.

2.3.3 Research Objectives

Disappearance of nitrogen from nitrification systems has been reported in a variety of studies and attributed to either aerobic denitrifying organisms or SND. Therefore, it was decided that if NH_x-N disappearance was noted, it should be investigated through rigorous N balances, including quantifying ammonia volatilization and possibly using 15-N tracer techniques.

2.4 Toxicity of Landfill Leachate

2.4.1 Previous Research at U.B.C.

Most local regulations and permits measure toxicity in terms of rainbow trout LC_{50}. Previous research at U.B.C. found that *Daphnia* LC_{50} and rainbow trout LC_{50} test results compared favourably for landfill leachate toxicity testing [3, 9]. *Daphnia* LC_{50} tests require smaller sample volumes, less laboratory space, and less time (48 hours versus 96 hours) than fish LC_{50} tests, and are therefore considerably less expensive. The Microtox(TM) EC_{50} test requires even less time ($<$ 1 hour), smaller sample volumes, and less laboratory space than the *Daphnia* LC_{50} test. If results for Microtox EC_{50} compared as favourably with rainbow trout as *Daphnia* LC_{50} test do, considerable savings of time and money could be achieved. The following section reviews studies in which fish, *Daphnia*, and Microtox bioassays are compared.

2.4.2 Comparison Studies

In the Microtox(TM) test, the decrease in light output of a marine luminescent bacteria (*Photobacterium phosphoreum*) upon exposure to toxicants is measured. This test was developed in the late 1970's by Microbics Corporation, and was first offered for sale in 1978 [18].

Bulich et al. [8] compared Microtox EC_{50} tests to published fish data for 20 pure compounds. Results were generally found to be similar. Also published were side by side comparisons of Microtox EC_{50} results to fish (mostly fathead minnow) and invertebrate (mostly *Daphnia*) LC_{50} results for 56 complex effluents. Microtox results were found to correlate better with fish than invertebrates.

Lebsack et al. [37] compared the Microtox assay to fish (rainbow trout and fathead minnow) LC_{50} tests for fossil-fuel process waters and phenolic constituents. They found good correlations between Microtox and rainbow trout, and poorer correlations with fathead minnows. Results for the two fish

species were found to be as different from each other as from Microtox results. Fish were more sensitive than Microtox in about half the cases, and were more sensitive to phenolic compounds in particular.

Curtis et al. [14] evaluated the potential of the Microtox test for predicting acute toxicity of organic chemicals to fathead minnows. Microtox EC_{50} results were compared to published fathead minnow LC_{50} results for 68 organic chemicals and pesticides. The reproducibility of the Microtox test was found to be similar to that expected of *Daphnia* and fish bioassays. Correlations were found to be better for organic chemicals (particularly alcohols) than for heavy metals. It was concluded that Microtox EC_{50} could only give an order of magnitude prediction of fish LC_{50}, and that the Microtox test was therefore only suitable for toxicity screening.

Qureshi et al. [56] compared the Microtox test to rainbow trout, *Daphnia*, and *Spirillum* bioassays. The Microtox test results compared favourably with the other bioassays in general. Better correlations were achieved with organic chemicals and complex effluents than with inorganic chemicals. The Microtox test was found to be a poor indicator of toxicity in wastewaters where the primary toxicants were ammonia or cyanide. As Microtox was not consistently the most sensitive test, it was advised that it could only be used in conjunction with other tests rather than as a replacement. It was mentioned that the addition of 2% NaCl to freshwater samples for osmotic protection of the marine bacterium could reduce sample integrity. The influence of using Microtox diluent, which may have a significantly different pH than the receiving water, was also questioned.

Plotkin and Ram [54] compared the toxicity of a low NH_x-N landfill leachate to fathead minnows, *Daphnia magna*, and *P. phosphoreum*. The leachate was highly toxic to *P. phosphoreum*, but not very toxic to fish or *Daphnia*. Toxicity to *Daphnia* and fish was attributed to NH_x, Ag, Hg, Pb, Cd, and Mn, but no source of Microtox toxicity was reported.

Kaiser and Esterby [31] used regression and cluster analysis to compare published acute toxicity results of 267 chemicals for several bioassays, including Microtox EC_{50}, *Daphnia* LC_{50} and fathead minnow LC_{50}. The 267 chemicals included a wide variety of organic chemicals, and high colinearity was found between Microtox and fathead minnow results.

Cronin et al. [13] compared published data for fathead minnows and *Daphnia* to their own Microtox data. Forty common organic pollutants were used. Correlations between fathead minnow results and *Daphnia* results were found to be better than correlations between fathead minnow results and Microtox results.

Day et al. [15] evaluated the toxicity of leachates from automobile tires based on several bioassays,

including Microtox EC_{50} and rainbow trout, fathead minnow, and *Daphnia* LC_{50}. Leachates were produced by immersing whole new or used tires in water; samples were removed after 5, 10, 20, and 40 days. Tire leachates were found to be non-toxic to *Daphnia* and fathead minnows, but toxic to rainbow trout and *P. phosphoreum*. The Microtox test was more sensitive than the rainbow trout test to leachates from new tires, and the two bioassays had similar sensitivity to leachates from older tires.

2.4.3 Research Objectives

The above comparison studies show that the Microtox test varies in its ability to predict toxicity to other organisms. Only one study was found which compared Microtox EC_{50} data to rainbow trout or *Daphnia* LC_{50} data for landfill leachate. Therefore, the initial toxicity research objective identified for this study was to determine how well Microtox EC_{50} results correlate with rainbow trout LC_{50} results for landfill leachate. As the study progressed, ammonia was identified as the primary toxicant affecting rainbow trout. Because of *P. phosphoreum*'s high ammonia tolerance, correlations between standard Microtox tests and rainbow trout LC_{50} were found to be poor. Substituting sucrose for NaCl for osmotic adjustment is said to increase the sensitivity of the Microtox test to ammonia [18], but little published information is available where this substitution has been used. Therefore, it was decided to investigate the use of sucrose as an osmotic adjustment, and to determine whether the modified Microtox test compares more favourably with the rainbow trout LC_{50} test.

2.5 Research Rationale and Objectives - Summary

The original plan for the study was that the City would keep both plants operating and contract a private laboratory (Cantest) to obtain the analytical data needed to achieve the City's objectives. The author would assist in monitoring and maintaining the plants while pursuing the objectives indicated in Sections 2.2.7, 2.3.3, and 2.4.3. By December 1993, it became apparent that keeping the pilot plants operating and collecting samples for analysis required more time than City personnel had allotted for the task. Also, significant nitrogen loss had not been detected up to this point. Therefore, it was decided that the author should spend more time operating and monitoring the pilot plants, share the objectives in section 2.1.2 (loading rates and leachate composition), and de-emphasize the objectives in Section 2.3.3 (nitrogen disappearance), while continuing with the objectives in Sections 2.2.7 (comparison of fixed and supended growth systems) and 2.4.3 (toxicity test comparisons).

Chapter 3

Study Design

3.1 Site Description

The Vancouver Landfill is located in the southwest corner of Burns Bog in the municipality of Delta. Burns Bog is a peat bog situated on the Fraser River delta. The soil layers beneath the landfill include a 2-5 m thick layer of peat overlying a 1-6 m layer of silt, overlying several hundred metres of silt and sand. The total area of the landfill is 635 ha, of which 172 ha have been filled since the landfill was opened in 1966.

Refuse is accepted from Vancouver, Delta, Richmond, UBC, and Whiterock; the landfill currently serves approximately 700,000 people. Refuse received averaged about 200,000 tonnes per year between 1966 and 1981, increased linearly to nearly 800,000 tonnes per year in 1987, then decreased again, averaging almost 500,000 tonnes per year since 1989.

Before refuse is emplaced in a given landfill cell, a 3 m thick demolition layer is deposited. The demolition layer consists of waste wood, concrete, asphalt, and soil, and has a higher hydraulic conductivity than the compressed peat and silt beneath it. The leachate is conveyed through the demolition layer to a ditch surrounding the site, and is pumped from a pump station at the south west corner of the site to the Annacis Island Sewage Treatment Plant. A drainage ditch surrounding the leachate ditch intercepts surface water approaching the landfill from off-site. Because leachate is pumped from the inner ditch, the water level in the inner ditch is approximately 30 cm below the water level in the outer ditch, and any flow between the ditches is from the outer ditch to the inner ditch. According to City of Vancouver data, 54% of the total precipitation that fell on the site during the study was collected as leachate. Previous hydrogeological studies estimated that approximately 50% of the total yearly precipitation which fell on the site evaporated.

Source: [27]

Figure 3.1: Photograph showing RBC, SBR, and Trailer

3.2 Treatment Systems

Two pilot plants, an RBC and an SBR, were operated in parallel during the study. The pilot plants were both placed at the south west corner of the landfill site, near the pump station.

Both pilot plants were automatically controlled using a programmable logic controller (PLC) and a series of solenoid valves. These items, and other expensive or sensitive equipment such as the air compressor and the field instruments, were housed in a trailer which was kept locked. The City of Vancouver supplied the trailer and all other equipment with the exception of the SBR reactor vessel, the RBC unit, and a few minor items, which were supplied by UBC. A photograph showing the trailer, SBR, and RBC is provided in Figure 3.1.

3.2.1 Leachate Supply

A common leachate supply was provided for both systems by running a 3/4" PVC line from the pressure side of the leachate pump to head tanks on the roof of the trailer. Leachate flow from the head tanks to each system was regulated by the PLC/solenoid valve control system. The original set up included a 50

L head tank supplied by the City. This was replaced by a set of two 70 L head tanks supplied by UBC on April 18, 1994, when problems with SBR filling indicated the need for greater storage capacity.

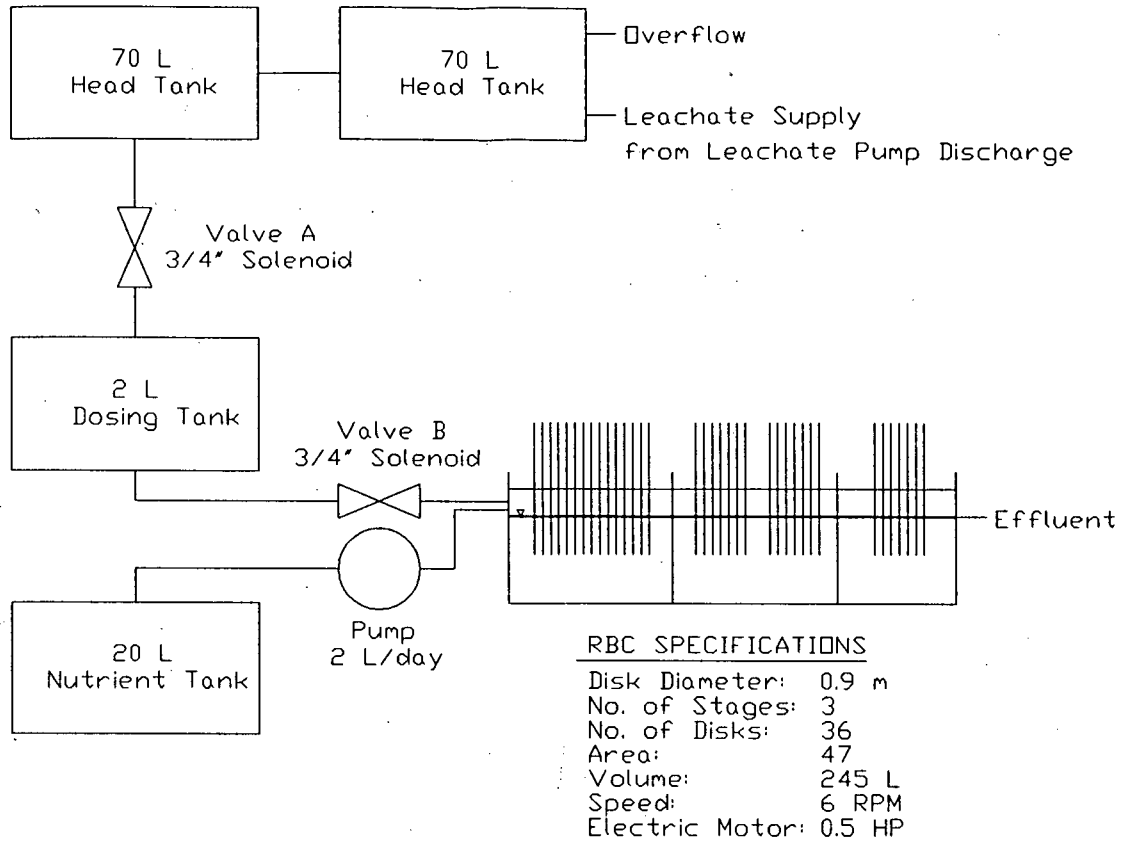
3.2.2 Phosphorus Addition

The leachate was deficient in phosphorus (P), and therefore a nutrient solution of Na_3PO_4 dissolved in tap water was fed to each system. Nutrient solution was mixed in 20 L plastic gasoline cans and poured into 20 L graduated plastic reservoirs from which it was pumped to the systems. The graduations on the reservoirs were used to determine the flow of nutrient solution to each system. At the beginning of the study, nutrient solution was pumped using two parallel Brooks Model EX225-419 bellows pumps supplied by UBC and 0.5" plastic tubing. Later, one bellows pump failed, and the other pump was used to operate two bellows at once. The bellows pumps were found to be somewhat unreliable, and therefore were replaced by the City with a double headed Masterflex pump on February 6, 1994. With the bellows pumps, P additions to the reactors could be varied by varying the flow rate of nutrient solution, but the Masterflex pump delivered at one flow only. Therefore, P additions from this point onward were achieved by varying the amount of Na_3PO_4 added when making nutrient solution. Nutrient solution reservoirs and pumps were housed in the trailer.

3.2.3 RBC System

A schematic of the RBC system, including a flow chart detailing the process control, is given in Figure 3.2. The RBC unit was a Model S5 package plant manufactured by CMS Equipment Limited of Mississauga Ontario, and was the same unit used by Peddie in a previous UBC leachate treatment study [52]. Specifications of the unit are also given in Figure 3.2.

The RBC unit includes a primary settling tank, a disk zone, and a secondary settling tank. However, only the disk zone was used for this study. Leachate was added directly to the first stage, and effluent samples were taken from the final stage. The disk zone was divided into four stages during Peddie's study [52], but the divider between the second and third stages had been removed prior to this study, so that the disk zone consisted of three stages. The first stage contained one set of fifteen disks, the second stage two sets of seven disks, and the third stage one set of seven disks. Each set of disks consisted of two solid fibreglass disks and thirteen or five plastic mesh disks (see Figure 3.3). The mesh disks were 4 mm thick and had 10 mm square openings.



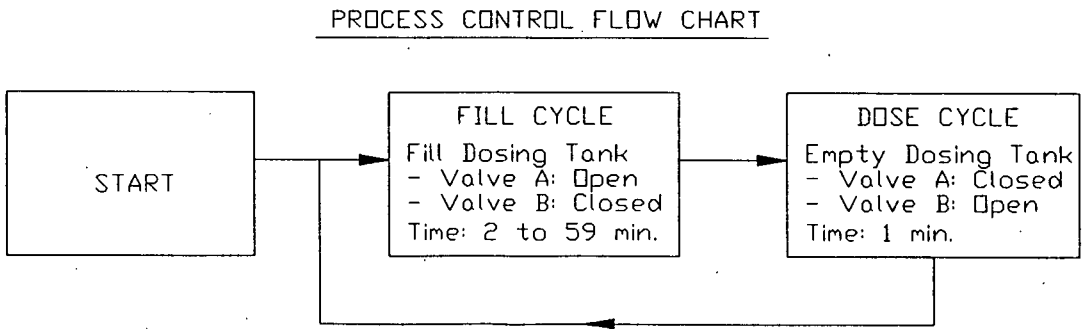


Figure 3.2: RBC System Schematic

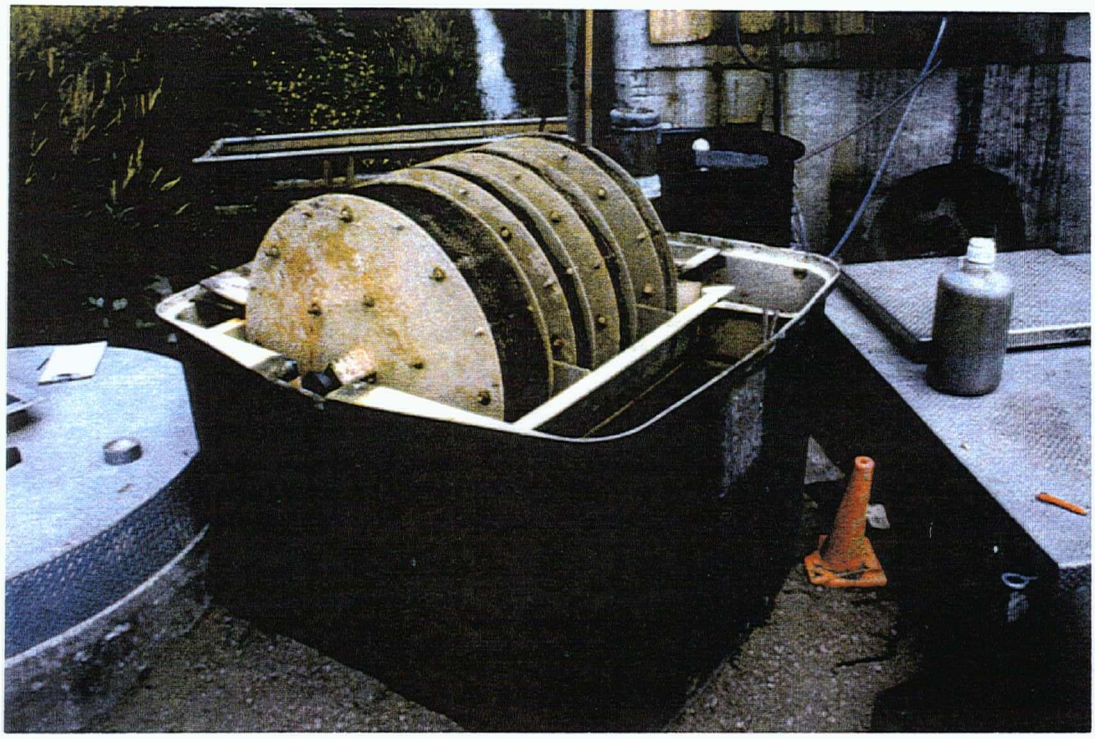


Figure 3.3: Photograph of RBC Unit

The disks were rotated by a 0.5 horsepower electric motor, and were 30% submerged. Aeration was accomplished by disk rotation alone.

When setting up the system, it was discovered that cross leaks occurred between all three sections of the RBC unit. Several attempts were made to seal the leaks, but leakage continued. As a result, it was decided that all three sections would be filled to the same level, and that effluent would be withdrawn from the final clarifier at a level just high enough to allow disk zone effluent to exit the disk zone by the normal pathway. It was assumed that the lack of hydraulic gradients between sections would prevent any inappropriate mixing.

3.2.3.1 Gas Collection Modifications

In order to allow collection of gases from the disk zone without mixing disk zone and primary or secondary clarification zone air space, the RBC unit was modified as follows. Plexiglass sheets were cut to size, placed over the clarification zones, and screwed down. Silicone sealant was used to seal the edges, screwholes, and any other cracks or holes. An inverted weir was constructed at the channel where disk zone effluent enters the secondary clarification zone, so that the effluent could flow from one zone to the

other without contacting the atmosphere. The vents at the top of the RBC cover were sealed using the vent covers, plexiglass, and silicone sealant. Any other holes in the cover were also sealed with silicone sealant. The male end of a plastic coupling was then attached to the rear of the cover. The female end of this coupling was attached to the gas collection apparatus, which included an air pump. When the RBC cover was closed tightly, and the pump was turned on, it was assumed that air would exit only through the pump and enter everywhere else.

3.2.3.2 Crane

A crane was constructed so that the RBC lid could be lifted easily by a single operator. The crane is shown in Figure 3.4. A T shaped beam made by nailing wooden two by sixes together was suspended between the top of the trailer and a post made of another two by six. Clothesline pulleys were attached to the beam directly above the ends of the disc/axle assembly, and cables were attached to the lid at corresponding points. Lifting cables were clipped to the lid, and strung through the pulleys to a boat winch fastened to the beam. The lifting cables could be removed from the lid in order that the crane could also be used to lift and weigh the disk/axle assembly. However, the crane was never used to weigh the disk/axle assembly.

3.2.4 SBR System

A schematic of the SBR system, including a flow chart detailing the process control, is given in Figure 3.5 (from [27]). The reactor vessel used was a high density polyethylene container supplied by UBC. When filled to the overflow point, the total liquid depth was 100 cm, and the volume was 365 L.

Ten ports at depths of 7,17,27,...,97 cm were used to vary the loading by moving the effluent discharge line and adjusting the fill time. A photo of the SBR vessel showing these ports and the perforated pipe used to distribute raw leachate during loading is provided in Figure 3.6. Originally, aeration began immediately after filling stopped, and solids were wasted by draining a small percentage of the mixed liquor at the end of each aeration cycle.

3.2.4.1 Process Control Modifications

When the SBR was set up in early July 1993, a solids wasting cycle was inserted between the aerate and settle cycles in order to provide a theoretical SRT of approximately 20 days. However, problems retaining solids led to the discontinuation of intentional solids wasting on November 21, 1993. Solids

Figure 3.4: Crane

wasting was never reinstated, so the SBR operated with an infinite theoretical SRT for the balance of the study.

In order to get the SBR going (after all the solids washed out during the 1993/94 Christmas break), leachate loading and effluent withdrawal were discontinued for a short time. The reactor was reinoculated with sludge from the UBC Pilot Plant at B.C. Research, heated with two 300 W aquarium heaters, and fed ammonium sulfate and sodium bicarbonate beginning on January 17th. On January 26th, leachate loading and effluent withdrawal were reinstated. On January 28th, settling time was increased from 1 hour per cycle to two hours per cycle. In order to retain an 8 hour cycle, the aeration time was reduced by 1 hour. One heater was removed on February 16th, and the second was removed on February 18th.

After intentional wasting was discontinued, it was noticed that unintentional wasting continued to occur due to mixed liquor overflow. Mixed liquor overflow occurred for two reasons, each requiring its own remedy. First, aeration began immediately after filling stopped, so that mixing occurred before extra leachate had finished overflowing; maximum level in the tank was regulated by an uncontrolled open overflow port. It was difficult to ensure that the reactor would fill exactly to the overflow point each time by regulating fill time alone. Therefore, an overflow cycle (in which no aeration or filling occurred)

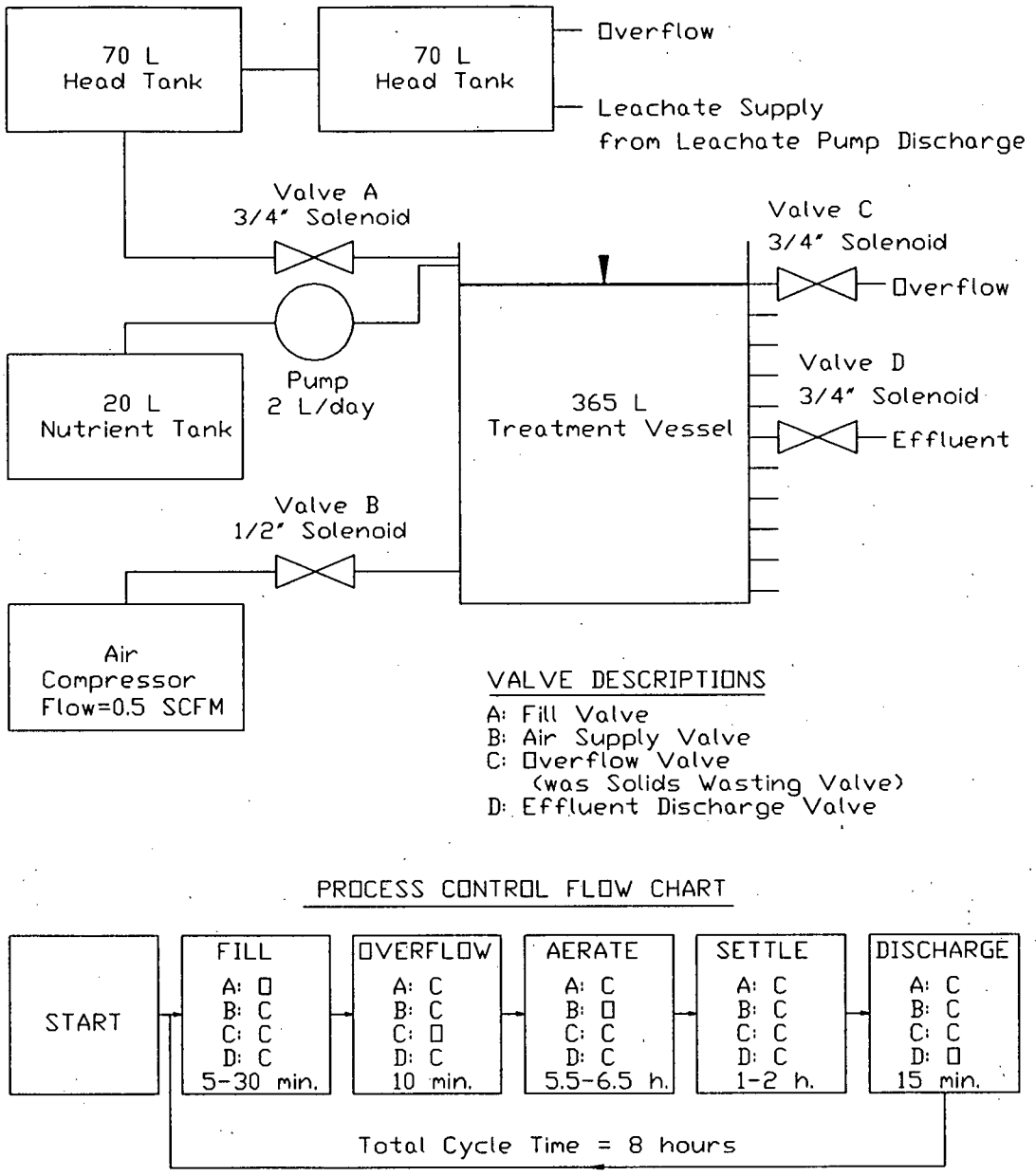


Figure 3.5: SBR System Schematic

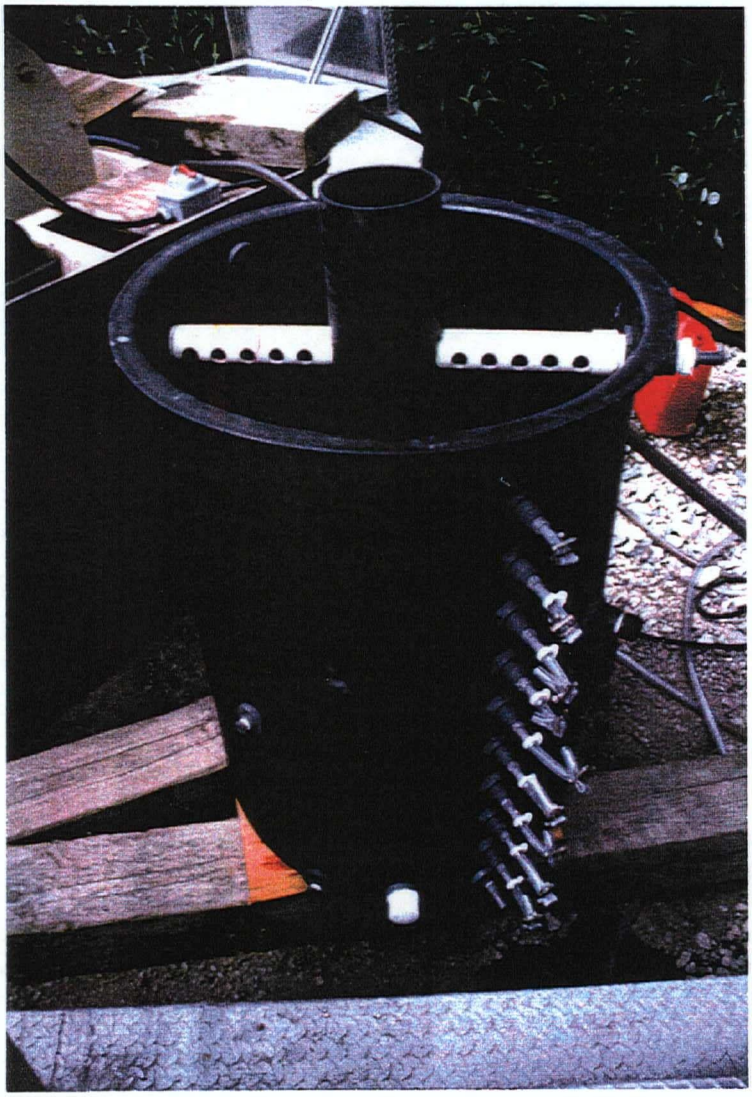


Figure 3.6: Photograph of SBR

was inserted between the fill and aerate cycles on March 30th. Extra leachate could then freely overflow before significant mixing occurred.

The second source of unintentional mixed liquor loss was noticed at this time. When aeration began, the free surface of the mixed liquor raised slightly, presumably due to the volume displaced by the air bubbles. This extra volume flowed out the uncontrolled overflow port. In order to stop this, the unused solids wasting valve was placed on the overflow port and the PLC was programmed to open it only during the overflow cycle, leaving it closed at all other times. From this point on the only solids lost were unsettlable solids in the effluent. The process control flow chart in Figure 3.5 shows the process control scheme as of April 11th, when this final modification was implemented.

3.2.4.2 Gas Collection Modifications

The SBR vessel was supplied as shown in Figure 3.6, and therefore a cover was required if gas collection was to be accomplished. While a simple cover could have been fashioned by sealing a flat plate over the lip of the reactor, this would have allowed a headspace of only a few centimetres above the surface of the mixed liquor. Such a headspace would not have been comparable to the RBC headspace. This could have been remedied by lowering the fill point and changing the reactor volume, but the experiment was already underway before the cover was added, and therefore changing the volume was considered undesirable.

A cover for the SBR vessel was fashioned from an inverted plastic container (a child's sandbox) which allowed a headspace of 23 cm. To facilitate access to the inside of the SBR during normal operation, a portal was fashioned into the top of the cover. A rectangular hole was cut into the sandbox, and a plexiglass sheet with a 30 cm diameter hole in the center was fastened to the sandbox with screws. A piece of aluminum extrusion was fastened to the sandbox along each edge of the plexiglass sheet to provide rigidity. All edges and screw holes were sealed with silicone, and a silicone bead was placed around the circular hole to act as a gasket. A 35 cm diameter plexiglass disk was used to cover the hole during gas collection, when it was fastened down with six screws. The threads of the screws were sealed with teflon tape.

The cover was attached to the top of the SBR vessel with screws, and the seam and screw holes were sealed with silicone sealant. The male end of a plastic coupling was attached to the wall of the cover, and the matching female end of this coupling was attached to the gas collection apparatus, as for the RBC. While it is somewhat difficult to make out, the SBR can be seen with the gas collection apparatus

installed in Figure 3.4.

Originally, it was intended that the entire gas stream produced by aeration would pass through the gas collection apparatus without operating the air pump. However, the gas collection apparatus created too much back pressure, causing some silicone seals on the cover to burst. If the pump was turned on during gas collection, most seam bursting was prevented, but air still escaped between the plexiglass disk and the silicone gasket. As a result, it was assumed that the air in the headspace was completely mixed, and the airflows from the compressor to the SBR, and through the gas collection apparatus, were both measured.

3.2.5 Effluent Discharge

Effluents from both plants and overflows from the head tanks, RBC dosing tank, and the SBR were allowed to flow back to the leachate ditch. Since the combined daily flow through the pilot plants was less than 0.2% of the total leachate flow, it was assumed that concentrations of leachate constituents and leachate flow measurements would not be significantly affected.

3.3 Sample Collection

Both City personnel and the author collected samples for laboratory analyses. Unless otherwise noted, information in this section refers to equipment and techniques used by the author.

Samples were collected once weekly by City personnel and one to three times weekly by the author. City personnel placed samples in plastic bottles supplied by Cantest, and transported them to Cantest in coolers with ice packs. The author's samples were not placed in coolers, as they were delivered to the UBC laboratory within two hours of collection. Once at the laboratory, samples were either prepared for analysis immediately or refrigerated at 1°C. Refrigerated samples were usually prepared for analysis the following morning, although samples were sometimes refrigerated for two days, particularly when sampling was done on two consecutive days.

Leachate samples were generally taken from the head tank overflow line, although City personnel used a Watera pump to take samples from the leachate well for the first few months of the study. Leachate samples on which *Daphnia* and Fish LC_{50} were to be done were taken from the leachate well in a 15 litre galvanized steel bucket. RBC effluent samples were taken from the final stage of the RBC with a Watera pump. SBR effluent and mixed liquor samples were either dipped out of the top of the reactor or poured

from a valve on the side. Samples were usually placed in 500 mL to 1 L bottles. When analyses required greater volumes per sample, several 500 mL or 1 L containers were filled. In order to ensure uniformity among different bottles of the same sample, a 15 litre galvanized steel bucket was rinsed several times with the sample in question, filled, and stirred, and bottles were filled from the bucket.

3.4 Analytical Methods

Laboratory analyses of samples collected by City personnel were carried out by Cantest. Analyses of samples collected by the author were carried out at the UBC Environmental Engineering Laboratory by the author or with the assistance of laboratory staff. Table 3.1 lists the parameters determined during the experiment, detection limits, and the frequency with which they were determined by Cantest and UBC. When detection limits differed between Cantest and the UBC laboratory, two numbers are given. The number in brackets is the UBC detection limit.

Cantest's analyses were conducted according to procedures found in *Laboratory Manual for the Chemical Analysis of Water, Wastewater, Sediments and Biological Materials*, 2nd Edition, published by the Government of B.C. , Ministry of the Environment, Water Resource Services, 1976, and *Standard Methods for the Examination of Water and Wastewater*, 17th Edition, 1989, and 16th Edition, 1985, published by the American Public Health Association.

According to City instructions, Cantest analyzed samples of leachate and SBR effluent directly for all listed parameters. SBR mixed liquor samples were analyzed for TSS only, and RBC samples were analyzed directly for TSS, then settled for 30 minutes and analyzed for all listed parameters (including TSS).

Unless otherwise noted, information in the remainder of this section refers to equipment and procedures used by the author.

3.4.1 Preparation of Glassware

Glassware for most occasions was prepared by rinsing once with hot tap water and twice with distilled water. Visible stains, if present, were scrubbed off with detergent and a brush before rinsing. When analyses were to include metals or when diluent solutions and reference toxicant solutions were made for Microtox testing, all glassware and other apparatus (eg. filtering apparatus, sample containers, measuring apparatus) were acid washed with 10 or 20% nitric acid before thoroughly rinsing with

Table 3.1: Analytical Parameters

Parameter	Detection Limit	Cantest Frequency	UBC Frequency
pH		weekly	1 to 3 times per week
True Colour	5 units	weekly	never
TSS	1 mg/L	weekly	1 to 3 times per week
VSS	1 mg/L	rarely	1 to 3 times per week
Total Alkalinity	0.5 mg/L as $CaCO_3$	weekly	during SBR recovery
NO_3^--N	0.02 mg/L	weekly	never
NO_2^--N	0.002 mg/L	weekly	never
NO_x^--N	0.02 mg/L	weekly	1 to 3 times per week
COD	25 mg/L	weekly	never
NH_x-N	0.02 mg/L	weekly	1 to 3 times per week
PO_4^{3-}-P	0.02 mg/L	weekly	1 to 3 times per week
TKN	0.5 mg/L	monthly	1 to 2 times per month
BOD_5	10 mg/L	monthly	never
Total Cd	0.004 mg/L	never	4 times total
Total Cr	0.03 mg/L (.01 mg/L)	monthly	4 times total
Total Co	0.02 mg/L	never	4 times total
Total Cu	0.01 mg/L	never	4 times total
Total Fe	0.03 mg/L (1.0 mg/L)	monthly	4 times total
Total Pb	0.08 mg/L	monthly	never
Total Mn	0.003 mg/L	monthly	never
Total Ni	0.025 mg/L (0.02 mg/L)	monthly	4 times total
Total Zn	0.015 mg/L (0.02 mg/L)	monthly	4 times total
Dissolved Cd	0.004 mg/L	never	4 times total
Dissolved Cr	0.01 mg/L	never	4 times total
Dissolved Co	0.02 mg/L	never	4 times total
Dissolved Cu	0.01 mg/L	never	4 times total
Dissolved Fe	1.0 mg/L	never	4 times total
Dissolved Ni	0.02 mg/L	never	4 times total
Dissolved Zn	0.02 mg/L	never	4 times total

distilled water.

3.4.2 Temperature, pH, Dissolved Oxygen, and Conductivity

Instruments used to determine temperature, pH, dissolved oxygen, and conductivity in the field and in the laboratory are listed in Table 3.2. Towards the end of the study, the field DO meter could no longer be used, and therefore the laboratory DO meter was brought to the site occasionally .

Table 3.2: Analytical Instruments

Parameter	Field	Laboratory
pH	Hanna HI 8314	Beckman
Dissolved Oxygen	Hanna HI 8543	YSI 54ARC
Temperature	Glass bulb mercury thermometer	same
Conductivity	Hanna HI 8033	same

The DO meter was calibrated using Hanna zero dissolved oxygen solution to set the zero and the air calibration method to set the slope. Membranes were changed as problems were noticed. The field pH probe was calibrated using pH 7.01 buffer solution in the field, and pH 4.00, 7.01, and 10.0 solution in the lab. The conductivity meter was calibrated using Hanna 12880 microsiemen solution.

3.4.3 Suspended Solids

Whatman 934AH glass fibre filters were placed in aluminum foil dishes and dried at 104°C for 30 to 60 minutes before cooling in a dessicator and using an electronic balance to record their tare weight. Samples were shaken and small amounts were poured into a graduated cylinder, then into a filter apparatus containing one of the tared filters. The graduated cylinder was rinsed once with approximately 10 mL of distilled water, which was also poured over the filter. The filter was then replaced in its aluminum dish and dried at 104°C for at least one hour, cooled in a dessicator, and weighed. If volatile suspended solids (VSS) were to be determined, the filter and dish were then fired at 550°C for at least 15 minutes, cooled in a dessicator, and weighed. Samples were dried and weighed once, then fired and weighed once. Calculations of total suspended solids (TSS) and VSS were performed as indicated in Standard Methods [2].

Samples on which *Daphnia* LC_{50} was to be done were also tested for settleable suspended solids. Samples were allowed to stand in their bottles for one hour after shaking. A small volume of sample was then removed from near the middle of the container with a 25 mL wide mouthed graduated pipette

and poured through a filter apparatus fitted with a filter paper as described above. The remainder of the procedure was identical to that indicated above, and calculations were again performed according to Standard Methods [2].

3.4.4 Dissolved Ammonia Nitrogen

Samples were prepared for dissolved NH_x-N analysis by filtering through a Whatman 934AH filter and adjusting to pH 3 with 10% sulphuric acid. If the sample was expected to be above the highest standard, it was diluted accordingly before pH adjustment.

pH adjusted samples were poured into plastic test tubes, capped, and refrigerated at 4°C until analysis. Prepared NH_x-N samples were generally analyzed within a few hours to a day, but were occasionally refrigerated for up to a week before analysis.

Adjustment to pH 3 served the dual purpose of preserving the sample and bringing it to the same pH used in making standards, as the analysis method used is sensitive to pH. For the major part of the research, verification of pH adjustment was accomplished using pH paper to achieve a reading between 2.5 and 3. During the final weeks of the research, a pH probe was used to measure the pH more accurately. Samples were adjusted to various pH values between 2 and 3 in order to quantify the error which may have been caused by relying on pH paper.

Analysis of NH_x-N was carried out with a Lachat Quickchem Automated Ion Analyzer according to *Methods Manual for the QuikChem Automated Ion Analyzer (1987).*

3.4.5 Volatilized Ammonia Nitrogen

The procedure and apparatus used to collect and measure volatilized NH_x-N was essentially the same as that used by Miller in a previous UBC study [45]. While it is somewhat difficult to make out, the gas collection apparatus can be seen in Figure 3.4.

The female end of a plastic coupling was connected to the inlet of a residential gas flow meter with 3/4" PVC tubing. A right angled bend was placed in the tubing with a copper elbow in order that the coupling could be horizontal while the flow meter could stand upright on the ground. A 1/2" plastic barbed fitting was placed on the outlet of the meter, and 1/2" tygon tubing was used to connect this barb to the inlet of the air pump. 1/2" tubing connected the outlet of the air pump to the inlet of the first gas bubbler. The other two bubblers were connected to the first in series, also with 1/2" tygon tubing. The 12 V DC air pump was powered by an automotive battery charger.

Seventy mL of 20,000 mg/L boric acid was placed in each bubbler with a 100 mL graduated cylinder. The cylinder and the bubblers were rinsed with distilled water between runs, and samples were stored in plastic bottles filled to exclude air space. The samples were stored in a refrigerator at 4°C for several months before analyzing them for NH_x-N. Miller [45] stated that standards were found to be stable for well over a month, and it was therefore assumed that this storage period was acceptable. NH_x-N analysis was carried out exactly as in Section 3.4.4 above, except that boric acid standards were made and a special run was done. The term NH_x has been used for "volatilized" ammonia, as the method of collection and analysis can not separate NH_3 gas from NH_4^+ aerosols. A more detailed explanation for this phenomenon is given by Miller [45]. Both can be considered lost N, and therefore measuring them together serves this author's objective of obtaining an N balance.

3.4.6 Nitrate and Nitrite Nitrogen

Samples were prepared for Nitrate + Nitrite (NO_x^-) analysis by filtering through a Whatman 934AH filter, diluting with distilled water if necessary, pouring into plastic test tubes, then preserving with one drop of phenyl mercuric acetate solution. Samples were capped and refrigerated at 4°C before analysis. While samples were occasionally prepared immediately before analysis, they were usually refrigerated for up to a week after preparation.

Analysis of NO_x^--N was carried out with a Lachat Quickchem Automated Ion Analyzer according to *Methods Manual for the QuikChem Automated Ion Analyzer (1987).*

3.4.7 Total Kjeldahl Nitrogen

Samples were preserved for TKN analysis by freezing. Dissolved TKN samples were filtered through a Whatman 934AH filter before freezing in all cases except for the November 1993 samples, which were filtered after thawing. Total TKN samples were not filtered, and were shaken before pipetting into a TKN tube with a wide mouthed pipette. TKN samples were frozen for up to two months before analysis.

After thawing, samples were pipetted into TKN tubes in appropriate volumes according to TKN estimates based on NH_x measurements. They were then digested in a Technicon Block Digester BD40 according to the *Technicon Block Industrial Method No. 376-75W (1975)*, and analyzed according to the *Technicon Methodology No. 329-74W (1975).*

3.4.8 Orthophosphate

Routine PO_4^{3-}-P measurements were done simultaneously with NO_x^--N measurements, using the same samples. More accurate measurements were made using membrane filtered, undiluted samples when metal samples were being prepared. These samples were always analyzed on the same day, while routine samples were usually refrigerated for up to a week. Undiluted samples filtered with Whatman 934AH filters were also done near the end of the research, typically on the same day as preparation and sampling.

Analysis of PO_4^{3-}-P was carried out with a Lachat Quickchem Automated Ion Analyzer according to *Methods Manual for the QuikChem Automated Ion Analyzer (1987).*

3.4.9 Alkalinity

Alkalinity measurements were done during January and February when the SBR was being heated and fed ammonium sulfate, in order to determine the amount of sodium bicarbonate to add to stabilize the pH. Alkalinity measurements were carried out according to Standard Methods [2]. Unfiltered samples were used.

3.4.10 Metals

Metal samples were prepared for analysis as follows: 1 L samples of leachate or effluent were shaken, then poured through a clean filter apparatus equipped with a Whatman 934AH filter until the sample container was roughly half empty. The filtrate was collected in a flask, then poured back through the filtering apparatus, now fitted with a .45 μm cellulose acetate membrane filter and a clean flask. This filtrate was measured in a clean graduated cylinder, then poured into a clean plastic bottle for storage. The remainder of the original sample was shaken, poured into the above graduated cylinder, measured, and poured back into the original sample container. Any sample beyond 500 mL was discarded. Subsequently, both filtered and unfiltered samples were preserved with 5 mL of concentrated nitric acid. Samples were stored in the cold room at 1°C until analysis.

All glassware and other apparatus allowed to touch samples during preparation for metal analysis were previously acid washed with 10 or 20% nitric acid, except for Whatman 934AH and membrane filters.

To correct for metals which may have been added by filtration or other error sources, controls for both total and filtered metals were prepared by conducting the above procedure with distilled water

before allowing samples to touch the apparatus. Three sets of apparatus were prepared (leachate, RBC, and SBR), and the control was prepared using the leachate apparatus, as it would likely have the most metals and therefore be least affected by metals which could have been washed away or added by the distilled water. Metal samples were filtered and/or preserved within 5 hours of sample collection.

3.4.11 Fish LC_{50}

Rainbow trout 96 hour LC_{50} tests were carried out for the City by Beak Consultants on a monthly basis until April 1994. Tests were done according to *Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to Rainbow Trout* EPS 1/RM/13 (July 1990), and the B.C. Ministry of Environment, 1982. LC_{50} was calculated according to the method found in *Aquatic Toxicology and Hazard Evaluation*, American Society for Testing and Materials, 1977. Fish LC_{50} was determined on raw leachate only.

3.4.12 *Daphnia* LC_{50}

A starter culture of *Daphnia magna* was obtained from EVS consultants in early September, 1993. Although Environment Canada culturing instructions (found in [17]) were followed as closely as possible, difficulty was encountered in meeting the health criteria required for accurate testing. Specifically, the fecundity requirement of 15 offspring per female per brood was never reached. This culture died out due to inattention over the Christmas 1993/1994 break.

Subsequently, an alternate source for neonates (i.e. *Daphnia* less than 24 hours old, as required for testing) was found. A researcher at Paprican agreed to supply neonates and dilution water, and did so for the February and March tests, after which sufficient surplus neonates were no longer available. Another starter culture was obtained, this time from the Environment Canada Aquatic Toxicity Laboratory in North Vancouver. This culture was used to produce neonates for the April tests. As the organisms were in the process of being acclimatized to their new environment when neonates were removed for testing, fecundity was approximately 10 offspring per female per brood. Since fish testing frequency was reduced after the April test, *Daphnia* testing was discontinued.

Daphnia 48 hour LC_{50} tests were conducted according to procedures recommended by Environment Canada [17]. Raw leachate, RBC effluent, and SBR effluent were tested. Unused culture water was used for diluent (i.e. clean culture water with no food). Samples to be tested were stored in clean 1 L containers and refrigerated at 1°C for 24 to 48 hours before use. 200 mL volumes of sample or diluted

sample were placed in identical, clean (acid washed), 500 mL plastic beakers, and allowed to reach room temperature. Temperature, pH, and DO were measured in selected beakers before adding *Daphnia*. Ten neonates were added to each beaker, with the exception of nine control beakers, each of which contained 200 mL of undiluted sample (three each for raw, RBC, and SBR) to be used for subsequent chemical analysis. All beakers were then randomly placed on a shelf in a temperature controlled room (February) or incubator (March and April) set at 20°C. Paper covers were placed over the beakers, and the photoperiod was maintained at 16 hours light/8 hours darkness using a fluorescent light and a timer. Since the turbidity and colour of the leachate and effluents made it impossible to count the neonates by sight, counting was only done at the end of the test (i.e. after 48 hours). All samples were counted by pouring the contents of the beaker into a fine net, then resuspending the contents of the net in clean culture water. Neonates were considered dead if gentle prodding with a probe produced no movement. LC_{50} was calculated according to the method found in *Aquatic Toxicology and Hazard Evaluation*, American Society for Testing and Materials, 1977.

When pouring out the beakers, the net was placed over another beaker (either a clean one or an empty beaker formerly containing more dilute sample), and the pH, and sometimes temperature were measured after the organisms had been removed. DO measurements obtained after pouring out the beakers would not be accurate due to agitation of the sample. Putting the DO probe in the beaker with the *Daphnia* could cause counting errors, as organisms could adhere to the probe. As a result, end-of-experiment DO measurements were only made on the controls containing no *Daphnia*. The controls always had sufficient DO to support *Daphnia*, and it was therefore assumed that the less concentrated samples would also have sufficient DO.

After *Daphnia* were counted and end-of-experiment measurements were finished, the control samples were combined by pouring them into a clean 1000 mL plastic beaker. Care was taken to avoid resuspending particulate matter which had settled to the bottom or adhered to the sides of the beaker. To avoid including this material in the combined sample, a small amount of liquid was left in the bottom of each 500 mL beaker. The combined sample was then mixed, and prepared and analyzed for NH_x-N, NO_x^--N, PO_4^{3-}-P, total metals, and dissolved metals as described above in Sections 3.4.4, 3.4.6, 3.4.8 and 3.4.10. These measurements were done in order to indicate an "after" number to correspond to the "before" number produced by analysis of samples which had not been left in a plastic beaker for two days at 20°C. Total and settleable suspended solids (see Section 3.4.3) were only determined as "before" quantities.

3.4.13 Microtox EC_{50}

Microtox EC_{50} testing was done on a Microbics Toxicity Analyzer Model 500 belonging to the UBC COFI Chair and set up in the laboratory of the Pulp and Paper Centre. Procedures recommended by Environment Canada [18] were followed. Microtox EC_{50} values were determined at 5 and 15 minute exposure times.

Both Basic and 100% test protocols were followed, and Microtox Osmotic Adjustment Solution (MOAS), solid NaCl, and solid sucrose were used for osmotic adjustment at various times. Three samples were usually tested at once when performing the Basic test, and four to six samples were tested at once when performing the 100% test. Samples were collected on Wednesday and/or Thursday mornings, and refrigerated at 1°C until Thursday afternoon. On Thursday afternoon, 10 mL aliquots of sample were placed in clean vials with teflon lined caps (COD vials) using a wide mouthed graduated pipette. If solid NaCl or solid sucrose were to be used for osmotic adjustment, 0.2 +0.025 -0.000 g of NaCl or 2.0 +0.025 - 0.000 g of sucrose were added to the vial before the sample was added. Sucrose and NaCl were weighed in clean disposable plastic dishes, one for each chemical. A clean, dry funnel was used to add the chemical to the vial. The vials were then capped and shaken until all NaCl or sucrose had dissolved. As a final preparatory step , the vials were centrifuged to remove interference which may have been caused by turbidity. Although the centrifuged samples of leachate and effluent were still quite coloured, the Colour Correction Protocol was not used. Since colour correction is intended to account for light absorption due to sample colour [18], neglecting colour correction should give an EC_{50} value which is lower than or equal to the value achieved using colour correction. It is therefore conservative to neglect colour correction, because a lower EC_{50} value indicates a more toxic solution.

Although Microtox cuvettes are intended to be disposable, they are very expensive. Testing indicated no significant decrease in light emission between diluent held in new cuvettes and diluent held in previously used cuvettes that had been thoroughly rinsed with distilled water. As a result, disposal of used cuvettes was stopped, and cuvettes were rinsed with distilled water between uses. COD vials used to contain samples during centrifugation were also washed by rinsing with distilled water, except when metals were being determined or when high purity reference toxicants were being prepared, in which case the vials were also acid washed and rinsed with deionized distilled water.

Preliminary results indicated that the Microtox test was not very sensitive to leachate ammonia concentration. Microbics [44] indicates that using 20% sucrose instead of 2% NaCl for osmotic adjustment

can increase the sensitivity of the test to ammonia and certain metals. Environment Canada [18] recommends that sucrose tests be done in addition to NaCl tests if ammonia is suspected to be a significant source of toxicity in a sample. Therefore, sucrose tests were also done.

In order to test a sample which has been osmotically adjusted with sucrose, sucrose diluent must be prepared. Sucrose diluent was prepared using distilled water, deionized distilled water, pH adjusted (with sodium bicarbonate and sulphuric acid) deionized distilled water, and Microtox Reconstitution Solution (recon) with 20% solid reagent grade sucrose added. 2% NaCl diluent was also prepared in exactly the same manner using solid reagent grade NaCl and MOAS. The procedure followed in preparation of diluent using deionized distilled water is described below. When distilled water was used, it was used for rinsing and filling volumetric flasks. When pH adjusted deionized distilled water and recon were used, deionized distilled water was used for rinsing.

First, glassware and utensils which would contact the solutions or dry chemicals were acid washed with 20% nitric acid and rinsed thoroughly with deionized distilled water. Scoops and funnels, which would be used with dry chemicals, were dried by placing them on a clean paper towel in the 104°C oven. A separate funnel was used for each solution prepared, and separate scoops were used for NaCl and sucrose. Dry chemicals were weighed out into new disposable plastic dishes, poured into funnels, and washed into volumetric flasks with deionized distilled water. After shaking to dissolve solids, finished solutions were poured into clean Microtox Diluent vials and taken directly to the Pulp and Paper laboratory for analysis.

Environment Canada [18] recommends monthly testing of reference toxicants to ensure precision and reliability of results. Reference toxicants should also be tested if the reconstituted reagent is used for more than two hours. Although Microtox testing was done over a period of six months, the same batch of reagent was used for all but the first three tests, and a given vial of reagent was rarely used for longer than two hours after reconstitution. As a result, testing of reference toxicants was left to the end of the experimental program. Because both zinc and ammonia were expected to be present in the leachate, and since Microtox is reportedly more sensitive to both when sucrose is used for osmotic adjustment, zinc and ammonia were chosen as reference toxicants.

Reference toxicant solutions were prepared as described for diluent above, with a few exceptions. Zinc sulphate ($ZnSO_4 \cdot 7H_2O$) and ammonium sulphate ($(NH_4)_2SO_4$) were used as sources of zinc and ammonia. The same scoop was used to measure out NaCl, $ZnSO_4 \cdot 7H_2O$, and $(NH_4)_2SO_4$. Diluents were prepared before reference toxicants, and the scoop was wiped between uses with a clean Kimwipe.

A separate scoop was used for sucrose. After all solutions were prepared, samples to be tested with sucrose had dry sucrose added as described above for leachate and effluent samples. As no turbidity was present, reference toxicant solutions were not centrifuged before use. However, all solutions were placed in capped vials and shaken (i.e. whether they had solid sucrose added or not). Solutions tested included 14 mg/L and 1.4 mg/L $ZnSO_4 \cdot 7H_2O$ (i.e. 3.18 and .318 mg Zn^{++}/L), and 25000 and 1000 mg/L $(NH_4)_2SO_4$ (i.e. 5301 and 212 mg N/L).

Chapter 4

Results and Discussion

4.1 Ammonia Nitrogen

4.1.1 Responses to Increased Loading

Figure 4.1 summarizes the operational history of the systems with respect to the most important parameter in this study, NH_x-N. Both systems were set up and innoculated with nitrifying sludge from the UBC pilot plant in early July 1993. The first effluent samples were taken on August 12th, which corresponds to day 0 on Figure 4.1. The last date recorded on the graph, day 391, corresponds to September 7, 1994.

In Tables 4.1 and 4.2, "Acclimatization Time" is the time taken to reach greater than 90% NH_x-N removal consistently, i.e. for more than one week. "N/A" is entered in this column when this criterion was never achieved, and "< x" is entered when the criterion has been reached by the next measurement, taken x days after the loading increase. Where less than 90% removals were measured, but a measurement was not taken the day before the recovery date, an envelope is given. "Operating Time" is the time between acclimatization (if reached) or loading increase (if not reached) until the next loading increase or the next prolonged degradation in performance.

Table 4.1: RBC Loading History

Start Day	Start Date	Average HRT (days)	Average Loading ($g/m^2/d$)	Acclimatization Time (days)	Operating Time (days)	Average Temperature (°C)
0	Aug 12	5.24	0.29	?	55	17.0
55	Oct 6	2.25	0.38	< 6	95	8.4
150	Jan 9	0.80	0.83	< 2	21	8.2
171	Jan 30	0.65	1.29	12<t<14	21	5.8
206	Mar 6	0.41	2.18	< 1	35	9.9
241	Apr 10	0.27	4.88	N/A	68	15.9
309	Jun 17	0.17	6.02	N/A	44	19.9
353	Jul 31	0.35	4.15	< 5	38	20.5

Figure 4.1: Leachate and Effluent NH_x-N versus Time

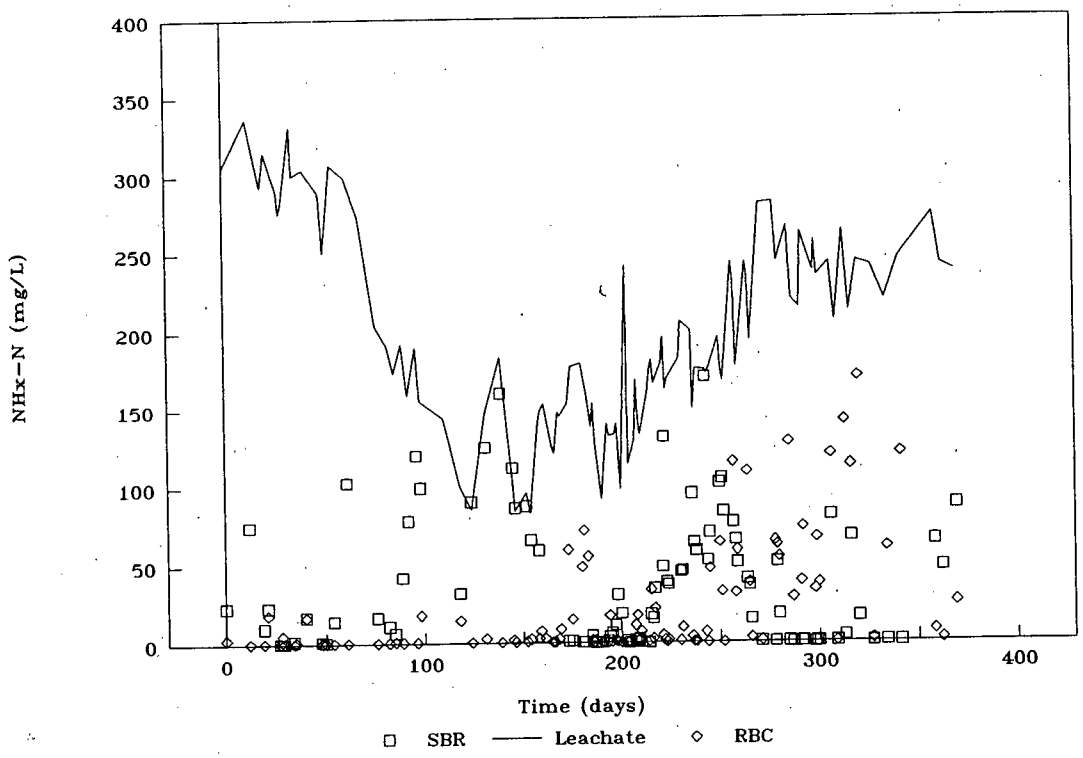


Table 4.2: SBR Loading History

Start Day	Start Date	HRT (days)	NH_x-N Loading ($g/m^3/d$)	Acclimatization Time (days)	Operating Time (days)	Average Temperature (°C)
0	Aug 12	4.64	63.5	?	34	17.1
55	Oct 06	2.15	87.8	6<t<13	17	8.2
131	Dec 21	4.66	23.3	N/A	27	6.6
158	Jan 17	4.63	33.0	9	23	12.5
190	Feb 18	4.59	30.2	< 3	24	5.8
214	Mar 14	1.93	107	52	36	13.4
302	Jun 10	0.71	331	14<t<18	31	19.6
351	Jul 29	0.43	580	N/A	25	22.2

Tables 4.1 and 4.2 show that when it did recover from loading increases, the RBC generally recovered more quickly than the SBR. The only case in which the RBC had not recovered from a loading increase by the next effluent measurement was during the loading increase starting on January 30th. In this case, the RBC was also struggling aginast temperature shock (for example, ice formed on the disks on February 8th) and occasional phosphate deprivation (see section 4.3). It should perhaps be noted that, while removals of greater than 90% were consistently reached after the March 6th loading increase, it was 3 days before removal returned to 99%. Also, unexplained process upsets occurred on March 15th and 17th during which less than 90% removals were achieved (see Table 4.3). While it never reached the defined acclimatization condition at the high NH_x-N loadings applied during the periods starting on April 10th and June 17th, the RBC did consistently remove 3 to 5 $g/m^2/d$ during these periods. Paolini [50] indicated that oxygen transfer through the liquid film on the exposed disks is more important in RBC systems than oxygen transfer through the mixed liquor, so mixed liquor dissolved oxygen concentration in not necessarily indicative of oxygen limitation. However, RBC mixed liquor DO measurements were always greater than 2 mg/L during these loading periods, so it is unlikely that DO limitation was responsible for the lack of acclimatization.

The SBR never recovered from an increase in loading by the next effluent measurement (there was no loading increase on February 18th). The minimum SBR recovery times were in the range of the maximum RBC recovery times. One could conclude from this that the RBC recovers more quickly from increased loading. However, it could be argued that the SBR increases were somewhat more severe than the RBC increases, as the HRT was generally halved when the RBC loading was increased and the HRT was generally decreased by more than half for an SBR loading increase. It should be noted that the 9 day recovery time listed for the loading applied starting January 17 was the amount of time the SBR was heated and fed dry ammonium sulfate before leachate feed was renewed on January 26th. No adjustment period was required when the leachate feed began, but feeding leachate rather than dry ammonium sulfate resulted in a decrease in loading.

While Table 4.2 shows that the SBR recovered from the June 10th loading increase, this is not strictly true. NH_x-N removals of greater than 90% were obtained consistently from June 28th to July 19th, but only 3 to 13% of the influent NH_x-N was being fully nitrified; the rest remained in the form of NO_2^--N. The author was making weekly visits to the site at this time, but was no longer taking measurements. The nitrite buildup was not noticed until sometime in September, by which time the SBR loading had been increased once more and the process had failed.

A possible cause for the lack of full nitrification was low dissolved oxygen. Regular measurement of DO had been suspended earlier in the study when the site's DO meter had failed. DO was measured in the SBR twice during July, on the 8th and the 15th. On the 8th, the DO was greater than 2 mg/L for the greater part of the reactor a few minutes after aeration began. However, the DO was lower at the reactor bottom, and DO continued to drop as aeration continued. The DO ranged from 1 to 1.8 mg/L in the reactor after about one hour of aeration, and the air was turned up from 0.5 cfm to 0.55 cfm. After 20 more minutes of aeration, the DO had not changed much, but the airflow was not increased further, for fear the compressor would fail. (The dual compressor had been operating on one side only for several weeks already, and had previously failed when operating on only one side. The single sided operation was caused by failure of the other motor, and since it was near the end of the study, the City did not plan to repair the compressor again if another failure occurred). On the 15th, measurement ceased after 20 minutes of aeration, when the DO was 2.5-3 mg/L throughout the reactor, but the DO could have continued to drop as it did on the 8th. Because nitrification is possible at DO less than 2.0 mg/L if MCRT is long enough [63], and because there was very little BOD_5 in the leachate (and therefore little concern about competition with heterotrophs), the slightly low DO levels did not seem important at the time. However, they could have been a factor in the final failure of the process.

Another possible cause for the occurrence of incomplete nitrification at this time could have been inhibition of *Nitrobacter* by high free NH_3 levels. The reactor was heavily loaded, and therefore there was less treated effluent in the reactor to dilute influent raw leachate in the initial stages of the aeration cycle. *Nitrobacter* is known to be more sensitive to high free NH_3 levels than *Nitrosomonas* [16, 1]. *Nitrobacter* is also sensitive to NO_2^-, so as NH_3 was converted to NO_2^-, the NH_3 inhibition could be replaced by NO_2^- inhibition. More discussion of this possibility is found in Section 4.2.3. Phosphate deprivation may also have been a factor (see Section 4.1.7).

4.1.2 Process Upsets

Examination of Figure 4.1 reveals several process upsets which were caused by factors other than increased loading. Tables 4.3 and 4.4 describe these upsets. Events were entered in the process upset table when unusual (generally low) NH_x-N removals were achieved. In the Table 4.3, two instances of no flow were entered to explain the unusually low effluent NH_x-N seen on days 271 and 309 in Figure 4.1. Otherwise, upsets were generally defined as events in which less than 90% NH_x-N removal was achieved. "Recovery Time" was entered as N/A when recovery had not occurred by the time of the next upsetting

Table 4.3: RBC Process Upsets

Start Day	Start Date	Duration (days)	Recovery Time (days)	Cause
98	Nov 18	2	N/A	cold?
101	Nov 21	< 3	N/A	power failure, cold
103	Nov 23	7	N/A	system frozen
113	Dec 3	7	< 6	disk no. 1 failed, cold
215	Mar 15	1	< 1	unknown
217	Mar 17	1	< 4	unknown
271	May 10	< 5	< 2	wet well pump failed, no flow
309	Jun 17	1	< 1	clogged valve, no flow

Table 4.4: SBR Process Upsets

Start Day	Start Date	Duration (days)	Recovery Time .(days)	Cause
12	Aug 24	< 12	< 7	unknown
61	Oct 12	N/A	N/A	improper sample collection
89	Nov 9	N/A	N/A	improper samplecollection
89	Nov 9	> 3	N/A	no nutrient flow, cold
101	Nov 21	< 3	N/A	power failure, cold
104	Nov 23	7	N/A	system frozen
111	Dec 1	22	N/A	nutrient pump failure
135	Dec 25	1	N/A	compressor failure
139	Dec 29	1	N/A	influent valve leak
198	Feb 26	2	2<t<5	no nutrient flow, cold
271	May 18	< 1	< 1	unknown

event, or when the system never recovered on its own. In Table 4.4, "improper sample collection" entries refer to cases where it is known that a mixed liquor sample was collected instead of an effluent sample.

During the time period from about day 89 (November 9th) to day 158 (January 17th) the SBR completely failed. While the high NH_x-N value reported on November 9th was clearly caused by collecting a mixed liquor sample instead of an effluent sample, no phosphate was reaching the SBR on the 9th or the 12th. Lack of phosphate combined with cold temperatures could have caused the low NH_x-N removal observed on the 12th. It is interesting to note that a similar phosphate pump failure on October 19th, when it was warmer, had no effect on effluent NH_x-N levels.

The low NH_x-N removals on November 16th and 18th, when phosphate was apparently reaching the reactor, could have been the result of a failure to recover from the cold aggravated phosphate deficiency. Low solids levels may also have been a factor. While the mixed liquor TSS remained at about 200 mg/L

from October 12th (when the SBR was apparently still working) to November 16th, it was felt that 200 mg/L was rather low, and solids wasting was discontinued on November 21st in an attempt to build up solids levels. Unfortunately, after the system froze on the 23rd, the SBR was never able to fully recover. Poor solids settleability continued throughout the failure period, probably due to low temperatures and phosphate deprivation. Phosphate deprivation occurred almost continuously until December 23rd, and was caused first by freezing, then by running out of phosphate solution, and finally by the failure of the bellows pump. Mixed liquor and effluent suspended solids remained almost equal, and the solids were gradually washed out. The first mixed liquor TSS measurement after the freeze up (December 8th) was only 93 mg/L, and subsequent measurements on the 14th and 21st were only 49 and 52 mg/L. The SBR HRT was increased to 4.66 days on December 21st in order to give the reactor a chance to recover.

On December 29th, an influent valve leak was discovered, which probably caused any remaining solids to be lost. The system was reinoculated with UBC pilot plant sludge on January 7th. After about 10 days, it became obvious that mere innoculation would have little effect at low January temperatures. On January 17th, the SBR was reinoculated, fed dry ammonium sulfate and heated. After 9 days, the system seemed to be doing well, so leachate feeding and effluent withdrawal were resumed. The heaters were removed by February 18th, and the system's performance remained satisfactory.

No phosphate was delivered by the nutrient pump between February 26th and 28th, causing a noticeable decrease in performance. 2 L of phosphate solution were added manually on the 25th, but this addition occurred only during the first cycle on the 25th, and wouldn't necessarily produce the same effect as continuous addition throughout 3 cycles. It is interesting to note that a phosphate failure on February 13th, when the reactor temperature was 12°C, had a less significant effect. The data in Table 4.5 illustrate more fully the combined effect of phosphate deprivation and low temperature. Both low temperature and phosphate deprivation appeared to cause minor upsets when acting alone, but seemed to cause more significant process upsets when acting together. A similar relationship between phosphate addition and temperature was reported by Guo [24], who found that higher effluent PO_4^{3-}-P concentrations were required at low temperatures in order to maintain nitrification.

This phenomenon did not appear to occur in the RBC system. While no phosphate was delivered to the RBC on several occasions, these occasions never appeared to correspond to process upsets. When the RBC was attempting to recover from a loading increase in early February, there were two occasions when low temperatures (5.5 and 2.5°C) were accompanied by lack of phosphate delivery. This may have been part of the reason that the RBC took an uncharacteristic 12 to 14 days to recover from the loading

increase. However, there were two occasions when RBC reactor temperatures were low (Dec. 21 and 29, T = 4 and 4.5°C), no phosphate was delivered, and performance remained satisfactory. On both of these occasions, the RBC was receiving leachate in significant quantities (134 and 110 L/day, respectively). For the SBR system, every time phosphate deprivation occurred in conjunction with low temperatures, a process upset occurred.

It should perhaps be noted here that there were 13 instances between the end of May and the beginning of the experiment when no nutrient flow reached the RBC and an effluent PO_4^{3-} measurement was taken. While these PO_4^{3-} measurements were often lower than neighbouring measurements taken during normal nutrient pump operation, they were frequently similar or even greater.

For the SBR, there were only four occasions on which nutrient flow was zero and an effluent PO_4^{3-} measurement was taken. Again, there was no clear trend relating the effluent PO_4^{3-} concentration to the lack of nutrient flow. A possible explanation for this is that if excess PO_4^{3-} was not typically supplied, then the organisms would use up the available phosphate to a limiting concentration, regardless of whether or not the nutrient pump was operating properly. This limiting concentration would be between 0.1 and 1.0 mg/L PO_4^{3-}-P. Interestingly, this range of PO_4^{3-}-P concentrations is roughly similar to the level of PO_4^{3-}-P supplied in the leachate. Another possible explanation could be that PO_4^{3-}-P samples were not always membrane filtered, and therefore PO_4^{3-}-P apparently left in the effluent was not necessarily available to the nitrifying organisms. Lack of nutrient flow was used as the criterion defining nutrient deprivation rather than effluent PO_4^{3-}-P concentration because of the lack of correlation between the two, and because nutrient pump failure and process upset appeared to be linked, at least for the SBR.

Throughout this study, the SBR experienced process upsets more frequently, more severely, and for longer time periods than the RBC. Process upsetting events such as power outages, cold temperature episodes, nutrient pump failures, and valve leaks tended to either directly (through hydraulic washout) or indirectly (through reducing solids settleablility) result in solids loss from the SBR. Similar events did not cause solids sloughing in the RBC, and this could have been why the RBC was able to recover more quickly, as recovery did not require replacing lost solids. When the influent RBC valve was stuck open resulting in continuous flow, the flow rate seen was not typically that much higher than the normal flow rate. Other investigators have also noticed solids settling and washout problems in response to shocks in suspended growth nitrification systems [16, 34, 60]. While low temperature episodes, nutrient pump failures, and valve leaks could cause solids washout in any activated sludge system, losses due to power

Table 4.5: Low T/Low P SBR Data

Date	Reactor Temperature (°C)	Effluent NH_x-N (mg/L)	NH_x-N Removal (%)	Phosphate Flow (L/day)
Feb 8	11.0	0.13	99.9	1.6
Feb 9	11.5	0.21	99.9	0.0
Feb 11	13.5			2.5
Feb 13	12.0	4.3	96.9	0.0
Feb 14	13.0	0.05	100	2.5
Feb 15	11.5	0.17	99.9	2.4
Feb 18	12.5	0.03	100	1.0
Feb 21	5.5	0.82	99.4	1.3
Feb 22	3.5	3.5	97.3	2.3
Feb 23	4.0	5.8	95.6	1.0
Feb 25	0.5	11.0	91.7	2.3
Feb 26	3.0	30.5	78.2	0.0
Feb 28	8.5	18.3	81.4	0.0
Mar 3	9.5	1.1	99.5	2.3

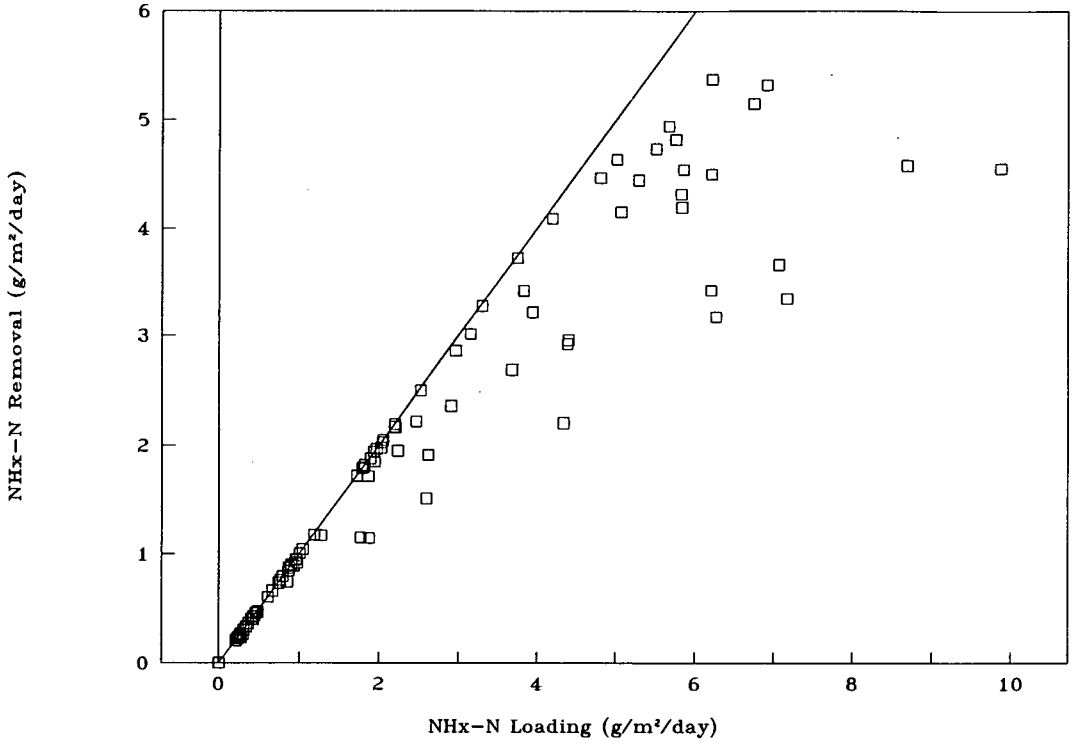
outages may have been a problem specific to this experimental set up. When the power came back on after an outage, the system would be aerated continuously until it was reset. When reset, the fill cycle would begin immediately, which would result in mixed liquor overflow unless appropriate precautions were taken. This could be particularly severe in cases where the SBR was heavily loaded, and may have been a major factor in the failure of the SBR from July 29th to the end of the study. (A power failure and restart was reported on August 4th, but solids levels were still high on August 5th. Major solids losses occurred later, but no other power failures were reported).

4.1.3 Loadings and Removals

4.1.3.1 RBC

Figure 4.2 includes all the results prior to the HRT experiment (see Section 4.1.5.1), and shows that while much higher loadings were applied, the maximum RBC NH_x-N removal was 5.38 $g/m^2/d$ at a loading of 6.22 $g/m^2/d$. The NO_2^--N concentration was not measured that day, but surrounding measurements on which the loading was equal or higher and the removal was lower had NO_2^--N concentrations of 4.8 and 10.2 mg/L. The maximum loading at which the RBC was able to achieve 99% NH_x-N removal was 3.75 $g/m^2/d$ (September 7, 1994), but full removals occurred much more commonly at loadings below 2.5 $g/m^2/d$, and always occurred at loadings below 1 $g/m^2/d$. The NO_2^--N concentration on Sept. 7th

Figure 4.2: RBC NH_x-N Removal versus NH_x-N Loading



was 34.8 mg/L, which was 16% of NO_x^--N. Effluent NO_2^--N concentrations were 2 mg/L or less (with one exception of 3.2 mg/L) at loadings below 2 $g/m^2/d$, but at loadings above 2 $g/m^2/d$ the NO_2^--N level always exceeded 4 mg/L. These results agree with the findings of Ehrig [16], who concluded that NH_x-N loadings should be kept below 2 $g/m^2/d$ in order to avoid NO_2^- buildups. Ehrig also found that NH_x-N removals of greater than 95% were possible at a loading of 10 $g/m^2/d$. The RBC system used in our study did not seem to be capable of such high removals. Further discussion of factors limiting the RBC system are found in Sections 4.5 and 4.1.5.1.

4.1.3.2 SBR

Figures 4.3 and 4.4 show that most of the data for the SBR system were gathered under rather lightly loaded conditions. Activated sludge loadings are generally expressed in terms of g NH_x-N/g MLVSS/d. However, the City did not monitor MLVSS, and solids levels in the SBR were extremely variable. Therefore, results are expressed the conventional way as well as in $g/m^3/d$ (where m^3 refers to reactor volume). MLVSS was calculated in cases where no measurement was taken by multiplying MLSS by the average MLVSS:MLSS ratio, which was found to be 0.62.

Figure 4.3: SBR NH_x-N Removal versus NH_x-N Loading ($g/m^3/d$)

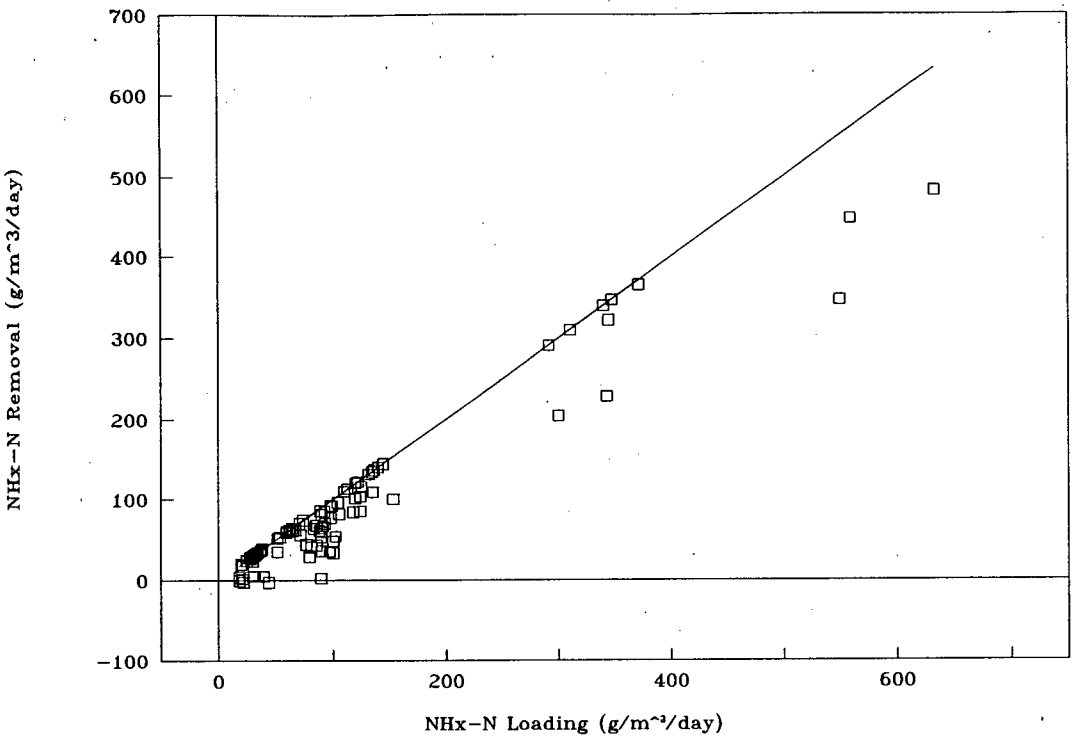
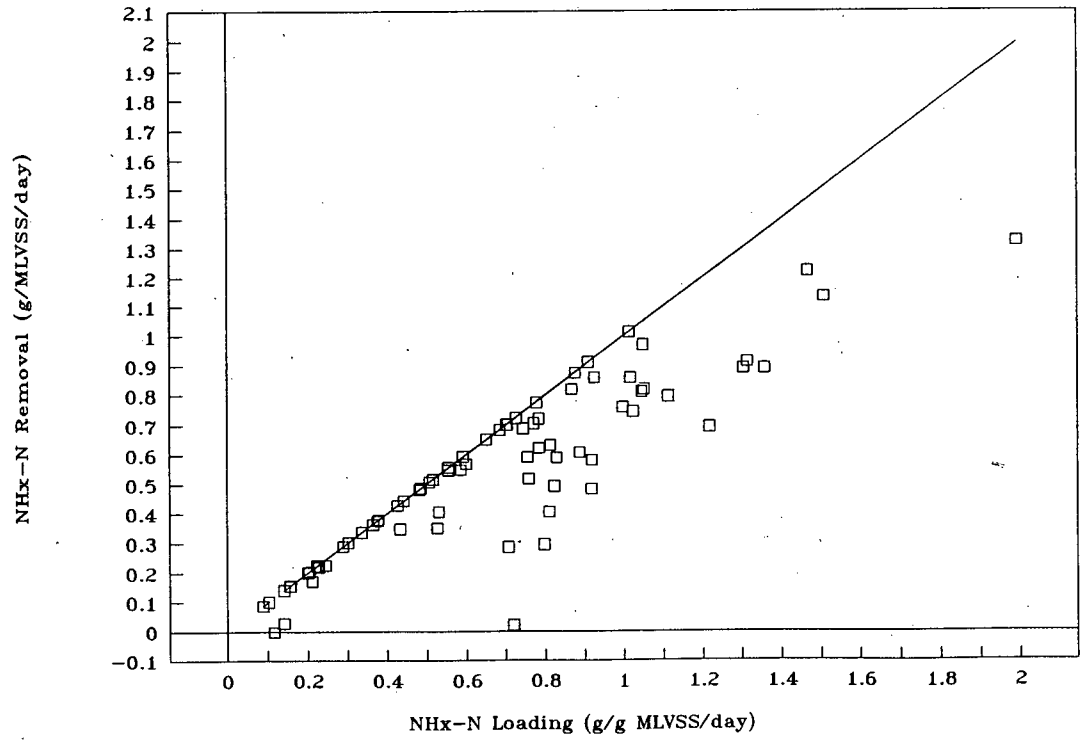


Figure 4.4: SBR NH_x-N Removal versus NH_x-N Loading (g/g MLVSS/d)



In terms of MLVSS, the maximum SBR NH_x-N loading at which >90% removal was achieved was 1.01 g/g MLVSS/d (99.9%). This removal occurred on May 17th, 1994, during the time the SBR was operating successfully at a 1.9 day HRT. Most of the higher loadings occurred shortly before May 17th, during the period of acclimation to the 1.9 day HRT. It should be noted that the effluent NO_2^--N was rather high (15 mg/L or 7 % of NO_x^--N) at that time. The next highest loading at which full nitrification (99.5%) was achieved was 0.87 g/g MLVSS/d and occurred a week later. There were a few other times during the study when the loading was between .87 and 1.01 g/g MLVSS/d and full NH_x-N removal was achieved, but these occasions also corresponded to NO_2^- buildups.

The maximum volumetric SBR NH_x-N loading at which full removal was achieved was 371 $g/m^3/d$, but the effluent NO_x^- was 18% NO_2^- at that time. This removal occurred on June 21, 1994, shortly after the SBR's HRT had been lowered from 1.9 days to 0.7 days. Full nitrification was never achieved during this loading phase. The next highest loading at which full nitrification (99.9%) was achieved was 143.7 $g/m^3/d$ on May 10, 1994, when the HRT was 1.9 days.

Table 4.6 compares data from this study to data from three other studies in which activated sludge systems were used to nitrify NH_x-N in older landfill leachates. The loading values reported represent the range of values for which full NH_x-N removal was achieved. The parameter which most distinguishes this study from the others is MLVSS, which is significantly lower for this study. The fact that the g/g MLVSS/d loadings are lower is probably a direct result of the low MLVSS concentration, given the fact that the $g/m^3/d$ loadings are similar in the other study reported. While the $g/m^3/d$ loadings are not directly comparable due to the fact that Knox's system was continuously aerated, adjusting the data to account for aeration period would not cause the loadings observed in our study differ significantly from those tested by Knox [33].

While low influent BOD_5 and NH_x-N concentrations would result in lower MLVSS concentrations in the short term, over the long term solids should build up. A possible reason for the lack of solids buildup in this study was the rather poor settling characteristics of the effluent (see Section 4.3.4). However, settling problems were also observed in two of the other studies [33, 16], and solids concentrations reached quite high levels. While similar effluent solids concentrations would have a greater impact on a system with lower influent BOD_5 and NH_x-N concentrations, this factor alone may not be sufficient to explain the lack of solids build up observed.

Another factor which differentiates the studies is period of continuous aeration. Knox [33] and presumably Ehrig [16] used conventional activated sludge systems, which are continuously aerated. Mena

Table 4.6: Activated Sludge Loading Data

Parameter	This Study	Knox [33]	Ehrig [16]	Mena et al [42]
NH_x-N loading (g/g MLVSS/d)	0.09 - 1.01	0.008 - 0.131	0.02 - 0.3	0.23 - 0.44
NH_x-N loading ($g/m^3/d$)	18 - 371	17 - 508	not given	not given
HRT (days)	0.4 - 4.7	0.5 - 8	6	1.16 - 2
Temperature (°C)	0.5 - 23	0 - 23.7	not given	25 - 30
MLVSS (mg/L)	45 - 1290	1000 - 4000	2000 (MLSS)	not given
Leachate NH_x-N (mg/L)	83 - 336	241 - 487	1200	300 - 750
Leachate BOD_5(mg/L)	27 - 89	56 - 290	<300	100 (ave)
System Type	SBR	CMAS	CMAS?	SBR

et al [42] used an SBR system for which the aeration time ranged from 14 to 23 hours per 18.5 to 24 hour cycle. This SBR was operated on an 8 hour cycle with an aeration time of 5.5 to 6.5 hours. Mena et al [42] noted that an increase in leachate feed concentration caused a greater upset when the aeration period was shorter, and suggested that systems with longer aeration periods are more stable. Oleskiewicz and Berquist [47] found that SBRs with a 4 hour aeration period were less tolerant of temperature decreases and loading changes than SBRs with an 8 hour aeration period. They also found that more efficient nitrification could be achieved at lower temperatures with the longer aeration period. The short aeration period herein may have contributed to the rather poor performance of the SBR.

Other investigators at UBC, who also used Vancouver Landfill leachate, were able to build up and maintain high solids concentrations in their laboratory scale conventional activated sludge systems [4, 24]. However, both of these systems were single sludge nitrification-denitrification systems. Therefore, an external carbon source was added, and a heterotrophic population made up a significant portion of the biomass. However, the fact that the nitrification reactor was continuously aerated may also have been a factor.

4.1.4 Temperature Effects

4.1.4.1 RBC

Figure 4.5 shows that the RBC system was found to be capable of nitrification at temperatures below 5°C. However, few data were available in this temperature range.

One point appears to show quite good NH_x-N removal at a mixed liquor temperature of only 0°C. It should be noted that at this time the RBC effluent port was frozen, causing the RBC to fill to about twice its normal volume. In addition, the sample on which measurements were taken was collected from

Figure 4.5: RBC NH_x-N Loading and Removal versus Temperature

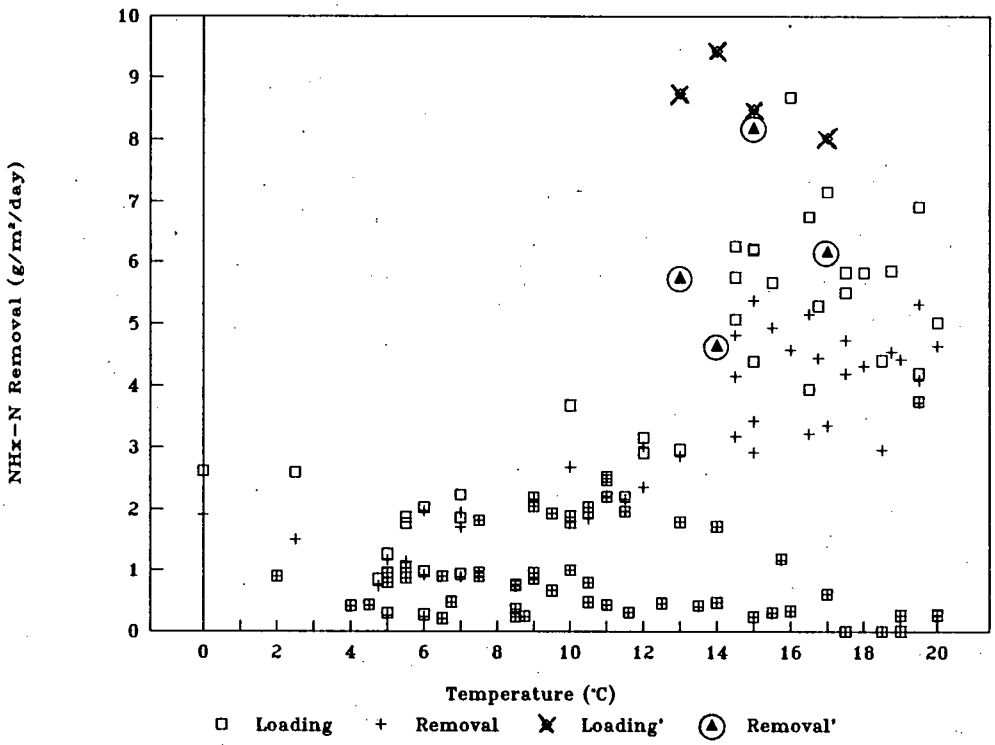
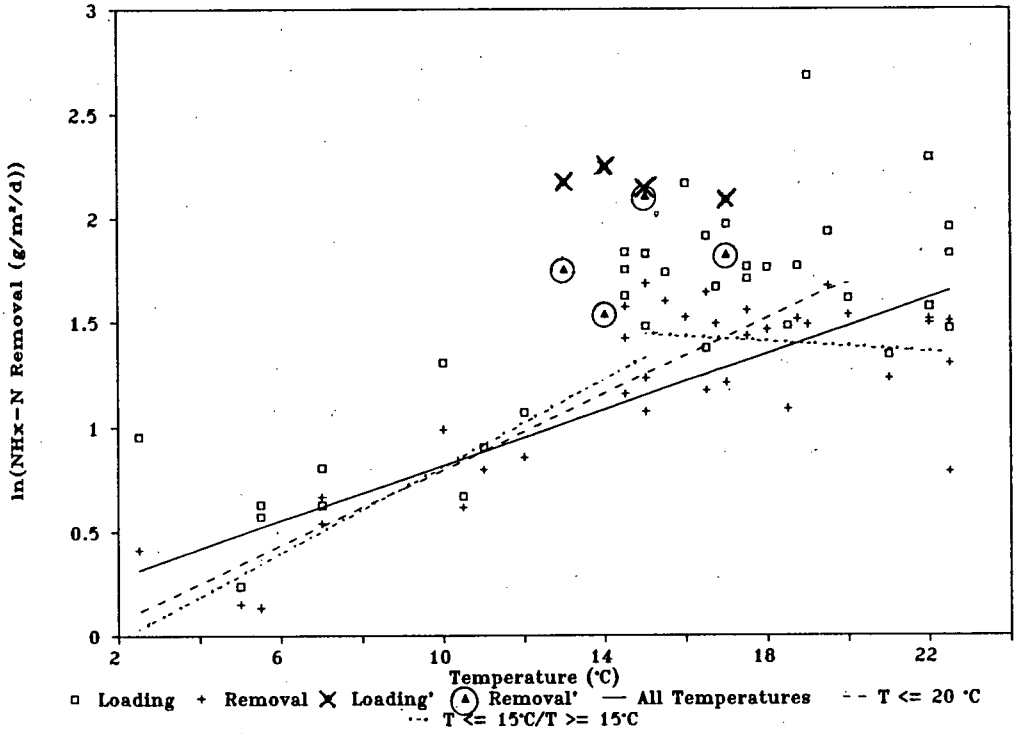


Figure 4.6: RBC Ln(NH_x-N Loading and Removal) versus Temperature



the effluent port (after it was freed) instead of from the last stage mixed liquor. As a result, significant dilution could have taken place, and the results can not be considered accurate. It is impossible to determine whether the observed NH_x-N removal included any removal which took place at 0°C or if it was only the result of dilution by effluent which had been treated before the temperature dropped to 0°C. The next day (February 9th), the effluent sample was collected normally, overfilling was no longer occurring, and the HRT was 0.34 days, so the diluted mixed liquor of the previous day had been replaced several times. Although the effluent NH_x-N concentration was 72 mg/L, a removal of 1.51 g/m^2/d was achieved at a temperature of only 2.5°C. While NO_2^--N was not measured on February 9th, the fact that NO_2^--N concentrations on February 8th and 11th were 14.6 and 19.0 mg/L indicates that there was probably a NO_2^--N concentration greater than 10 mg/L on the 9th as well.

The removal reported at 2°C, which occurred on February 25th, also requires some explanation. While the effluent port also froze on this occasion, resulting in overfilling, the sample was collected normally. Therefore, less dilution uncertainty is present than on February 8th, especially since the effluent NH_x-N concentration was only 1 mg/L. The NH_x-N removal was 0.9 g/m^2/d. The NO_2^--N concentration was not measured on the 25th, but on the 26th it was 1.72 mg/L.

The effect of temperature on biological processes is often modelled with the Arrhenius equation (Equation 4.4). Manipulation of this equation yields Equation 4.5. According to Equation 4.5, a plot of ln(NH_x-N removal) versus temperature should yield a straight provided that loadings greater than or equal to the maximum for a given temperature are provided.

$$k_T = k_{20}\theta^{T-20} \tag{4.4}$$

Where:

T = Temperature (°C)

k_T = NH_x-N removal rate at T°C (g/m^2/d)

k_{20} = NH_x-N removal rate at 20°C (g/m^2/d)

θ = 1.10

Source: [49]

$$lnK_T = mT + b \tag{4.5}$$

Where:

m $= \ln\theta$ = slope

b $= \ln K_{20}$ - $20\ln\theta$ = y-intercept

Figure 4.6 includes all RBC data for which less than 95% NH_x-N removal was achieved. (Data with greater than 95% removal were excluded in order to avoid skewing θ calculations with removals for which the applied loading was much less than the theoretical maximum). A linear regression on these data yields a θ value of 1.07 (R^2 = 0.62). If only the the data for temperatures less than or equal to 20 and 15°C are included in the regression, the θ values calculated are 1.09 and 1.11, respectively. The R^2 value in both cases is 0.80, indicating a significantly better line fit than if the entire temperature range is included. If only the data for temperatures greater than or equal to 15°C are included, the θ value is 0.99. While the correlation is poor (R^2 = 0.02), the θ value is less than one, and therefore the reaction rate no longer appears to increase with increasing temperature after a point somewhere between 15 and 20°C. It is important to note that the maximum removal achieved prior to the HRT experiment (defined below) was 5.38 $g/m^2/d$ on day 258 (April 27, 1994) when the temperature was only 15°C.

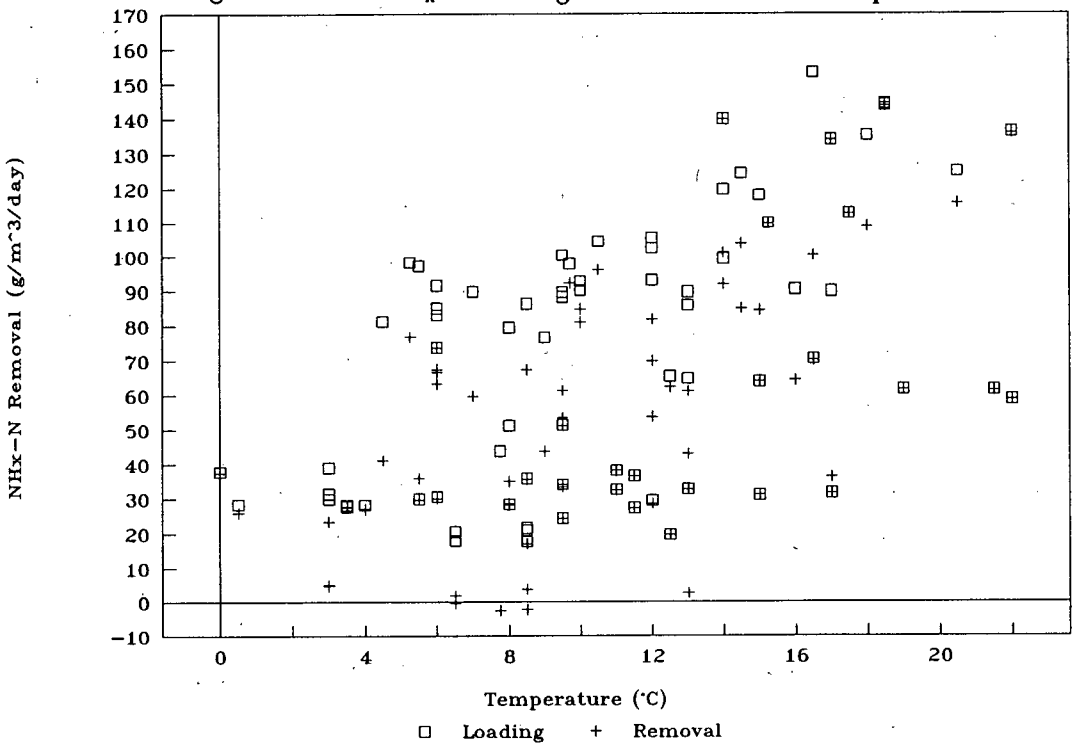
Values of θ for RBC nitrification found in the literature include 1.09 and 1.10 [49, 52]. These values agree well with the θ values calculated at temperatures below 20°C.

It is unclear why the rate of nitrification did not appear to continue to increase with temperature after a point somewhere between 15 and 20°C, but several possibilities exist. Forgie [21] suggests that the use of the Arrhenius equation with constant θ values may only be valid for small temperature ranges, as θ is a function of temperature. Knox [34] did not report θ values, but did report similar overall removals at 15 and 20°C. It is possible that the relationship in Equaton 4.5 is no longer valid after a certain maximum point, which in this case was somewhere between 15 and 20°C.

The rate of oxygen transfer from air into wastewater is generally considered to be proportional to the difference between the existing and equilibrium concentrations of dissolved oxygen [43]. As temperature increases, the equilibrium concentration decreases, and therefore the rate of oxygen transfer decreases. It is possible that the rate of oxygen transfer could slow down enough to limit the nitrification rate at high temperatures. Other investigators have suggested this possibility [34].

It is also possible that some other factor unrelated to temperature was limiting the RBC at higher temperatures. One limiting factor investigated was HRT. The points labelled *Loading'* and *Removal'* on

Figure 4.7: SBR NH_x-N Loading and Removal versus Temperature



Figures 4.5 and 4.6 are the results of this investigation. These points and the HRT investigation are discussed further in Section 4.1.5.1.

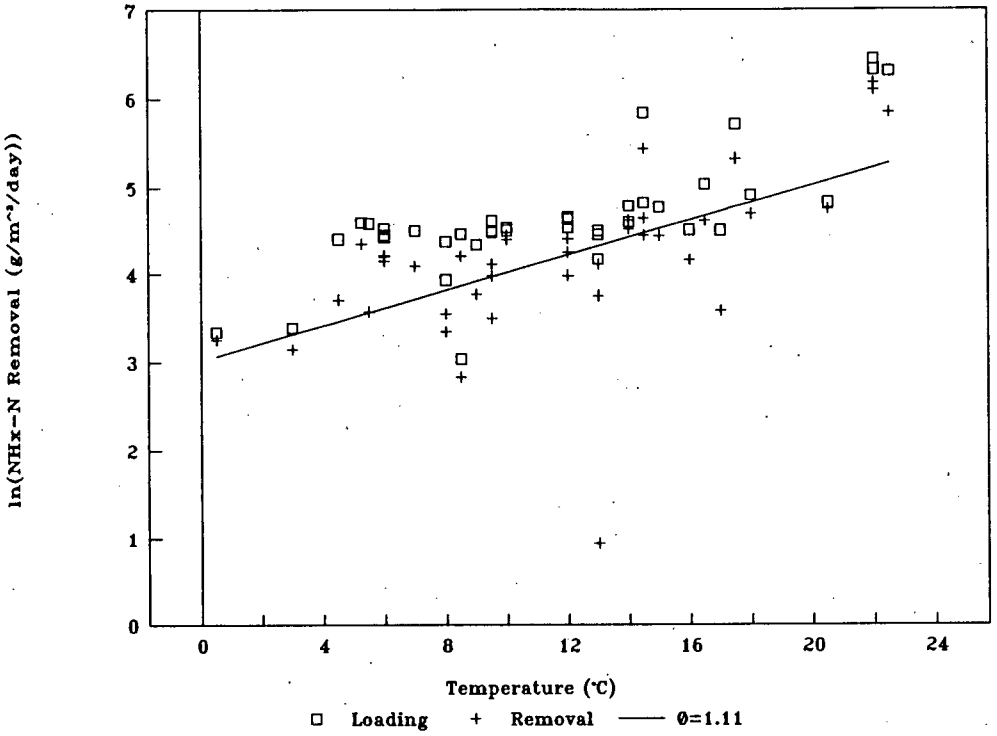
4.1.4.2 SBR

Figure 4.7 shows that several good NH_x-N removals were achieved at temperatures below 6°C. Fewer low temperature data are available for the SBR than are available for the RBC, since the SBR failed during the winter and had to be heated in order to restart the process.

The point at 0.5°C occurred on February 25th, and was included because some questionable points were included for the RBC during this time period. However, the actual loading which was applied at this time is uncertain because the influent and effluent lines to the SBR were frozen solid when the temperature measurement was taken, and it would therefore be wise to ignore this point.

There were no problems with any of the other measurements which occurred at temperatures below 4°C; the experiment log shows that the system was operating normally at those times. Although the SBR effluent NO_2^--N was not measured for every low temperature event, NO_2^--N measurements at temperatures below 6°C were always 1 mg/L or less.

Figure 4.8: SBR Ln(NH_x-N Loading and Removal) versus Temperature



Equations 4.4 and 4.5 can be used to describe the relationship of nitrification rate to temperature in both suspended growth and fixed growth systems. The nitrification rate for activated sludge systems is typically expressed in terms of g NH_x-N/g MLVSS/d. However, unreliable solids measurements (see Section 4.3.4) caused high variability in reaction rates in terms of g/g MLVSS/d compared to variability in reaction rates in terms of g/m^3/d. For example, over the period from April 5th to 7th, 1994, nitrification rate varied from 0.48 to 1.32 g/g MLVSS/d, but only ranged from 43.7 to 59.7 g/m^3/d, while NH_x-N removal ranged from 86 to 116 mg/L. Therefore, it was decided to express nitrication rate in terms of g/m^3/d in this case.

In Figure 4.8, all data for which less than 95% NH_x-N removal was achieved are plotted. A linear regression on these data yields a θ value of 1.11 (R^2 = 0.35). A textbook value for suspended growth nitrification processes is $\theta = e^{0.098} = 1.10$ [43]. While there is considerable data scatter and the correlation is poor, these data exhibit the general relationship expected. However, it should be mentioned that not all researchers agree with the textbook model. For example, Oleskiewicz and Berquist [47] found that the response of SBR nitrification to temperature was discontinuous, with data below 7°C having a steeper slope on the ln(K) versus T graph (θ = 1.40) than data above 7°C (θ = 1.02).

Table 4.7: Comparison of RBC and SBR θ Values

Temperature Range °C	RBC		SBR	
	θ	R^2	θ	R^2
0 to 25	1.07	0.62	1.11	0.35
0 to 20	1.09	0.80	1.07	0.14
0 to 15	1.11	0.80	1.06	0.09
15 to 25	0.99	0.02	1.29	0.67

Unlike the RBC, the SBR temperature data show no evidence of leveling off as temperature continues to increase. Table 4.7 shows that the opposite tendency is exhibited; θ values increase as higher temperatures are used in the regression calculation. The θ values determined for the SBR are very similar to the values determined for the RBC, except in the temperature interval from 15 to 25°C, where the SBR shows its highest θ value, and the RBC its lowest.

Two of the possible reasons that RBC removals leveled off while temperature continued to increase were: a) the nitrification rate may not continue to increase with temperature beyond a certain point; and b) oxygen transfer rate may have become the rate limiting factor as temperature increased. If reason a) were true, one would reasonably expect to observe the same phenomenon in the SBR, since the same microorganisms are probably involved in the nitrification reaction. If reason b) were true, the argument that the same phenomenon should be observed in the SBR is weaker, since aeration mechanisms are so different. However, it still seems reasonable to expect that oxygen transfer rate would limit both systems in a similar fashion; the limitation expected is based on the temperature dependent solubility of oxygen, and the RBC and SBR systems tended to have similar temperatures. The SBR results therefore seem to add force to the argument that something other than temperature was limiting the RBC above temperatures between 15 and 20°C.

4.1.5 HRT Effects

4.1.5.1 RBC

During the late spring/early summer months of 1994, it was noticed that while loading continued to be increased, removals leveled off. This trend is clearly visible in Figure 4.9. The first three lines of Table 4.8 illustrate that while N loading was increased, removal decreased as HRT decreased. The cause of the decrease in removal may have been HRT limitation. The fourth line of the table, and the points labelled *Loading'* and *Removal'* in Figures 4.9, 4.6, and 4.5 are the results of an investigation conducted

Table 4.8: RBC Loading and HRT Data

Average HRT (days)	Average Loading ($g/m^2/d$)	Average Removal ($g/m^2/d$)	Maximum Removal ($g/m^2/d$)	Average Temperature (°C)
0.17	6.02	2.72	4.54	19.9
0.27	4.88	3.60	5.38	15.9
0.35	4.15	3.93	4.63	20.5
0.29	8.68	6.20	8.21	14.8

by the City after the author discontinued laboratory work to begin writing this thesis.

In order to determine whether or not the RBC system was unable to achieve higher removals due to HRT limitation, the HRT was increased and the RBC was fed a nutrient mixture containing NH_x-N, Na_3PO_4, and $NaHCO_3$ in addition to leachate. However, the City only collected four data points during this portion of the investigation.

Comparing lines 2 and 4 of Table 4.8, one sees that with similar HRTs, increased average loading results in increased average removal, but percent removals remain similar. Increasing and decreasing the average HRT appeared to have caused percent removals to increase and decrease, respectively. However, Figure 4.9 illustrates that the four data points obtained are considerably scattered. The effect of HRT appears to be quite different when the individual data obtained in the City's HRT investigation are examined (see Table 4.9). If the data are sorted in order of HRT, one can easily observe that the highest removal occurred at the highest HRT, while the lowest removal occurred at the lowest HRT. The highest removal did not occur at the highest loading, nor at the highest temperature. While the highest removal occurred at the lowest NH_3-N loading, the lowest removal occurred at the second lowest NH_3-N loading, indicating that the limiting factor was probably not free NH_3 inhibition. Since removal increased with HRT, and no other factor appears to have been the cause of inhibition, it seems probable that HRT was the limiting factor at higher loadings. (Note: free NH_3-N loading was calculated as a function of temperature and pH using an empirical formal for K_a found in reference [46]).

Peddie [52], using the same RBC plant, stated that nitrification was limited at HRTs below 4 hours (0.17 days), while these data seem to indicate that an HRT of at least 0.30 days is required for full NH_x-N removal. Peddie used a younger landfill leachate, with lower NH_x-N concentrations and higher BOD_5 concentrations, and his NH_x-N removal rates ranged up to about 1.2 $g/m^2/d$ with loadings of up to 4 $g/m^2/d$. The differences in loading may account in part for the difference in required HRT. Examination of his data also reveals that, while nitrification efficiency is very poor at HRTs below 0.17

Figure 4.9: RBC NH_x-N Loading and Removal versus 1/HRT

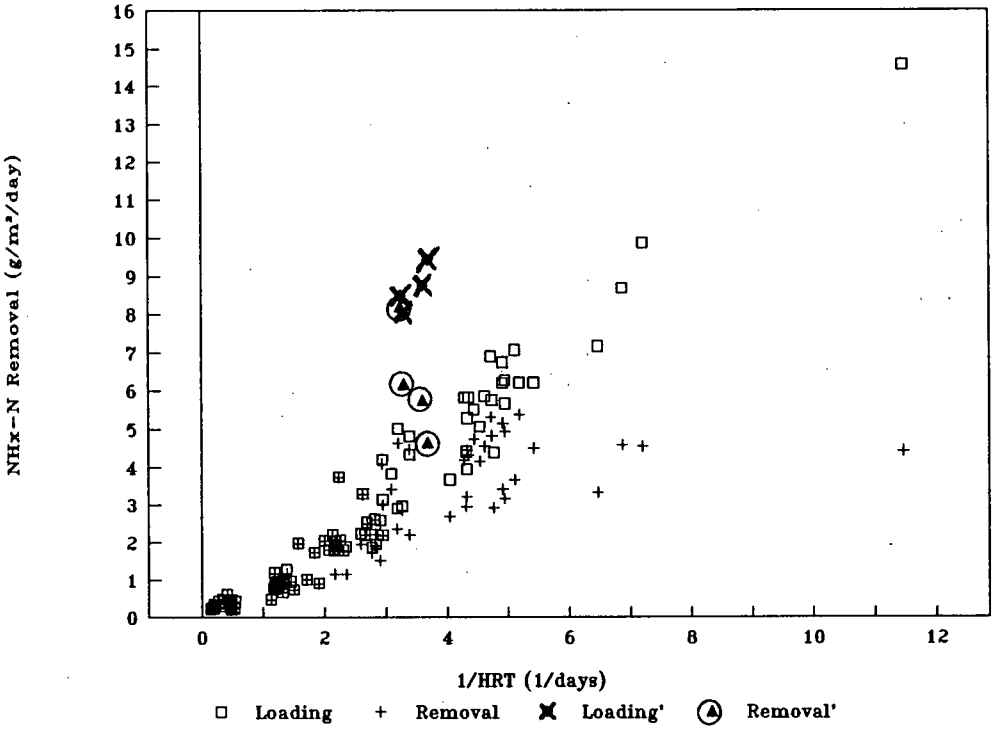


Table 4.9: RBC N Loading and HRT Data from HRT Investigation

Date	HRT (days)	NH_x-N Loading ($g/m^2/d$)	NH_x-N Removal ($g/m^2/d$)	Temperature (°C)	pH	NH_3-N Loading $g/m^2/d$
10/20/94	0.27	9.43	4.65	14	7.92	0.194
10/26/94	0.28	8.75	5.76	13	8.78	1.082
09/29/94	0.30	8.03	6.18	17	8.22	0.402
10/05/94	0.31	8.49	8.19	15	7.5	0.073

Table 4.10: RBC θ and R^2 Values with HRT Experiment Data

Temperature Range °C	No HRT Expt. Data		All Data	
	θ	R^2	θ	R^2
0 to 25	1.069	0.62	1.068	0.50
0 to 20	1.093	0.80	1.096	0.69
0 to 15	1.109	0.80	1.129	0.75
15 to 25	0.989	0.02	0.972	0.08

days, nitrification performance is more clearly independent of HRT at HRTs above 0.3 days. In between 0.17 days and 0.3 days, performance increases with increasing HRT, ranging from about 70 to 100%. These data likewise include many points at which greater than 70% NH_x-N removal is achieved at HRTs between 0.17 and 0.30 days. Therefore, the two data sets agree reasonably well; while an HRT of 0.17 days is sufficient for full NH_x-N removal if the NH_x-N loading is below about 1.2 $g/m^2/d$, an HRT greater than 0.30 days is required for full removal of NH_x-N loadings between 2 and 8 $g/m^2/d$.

It is important to note that while full NH_x-N removal was achieved at the highest HRT, full nitrification was not, and large NO_2^- buildups occurred. Further discussion of this phenomenon is found in Section 4.2.3.

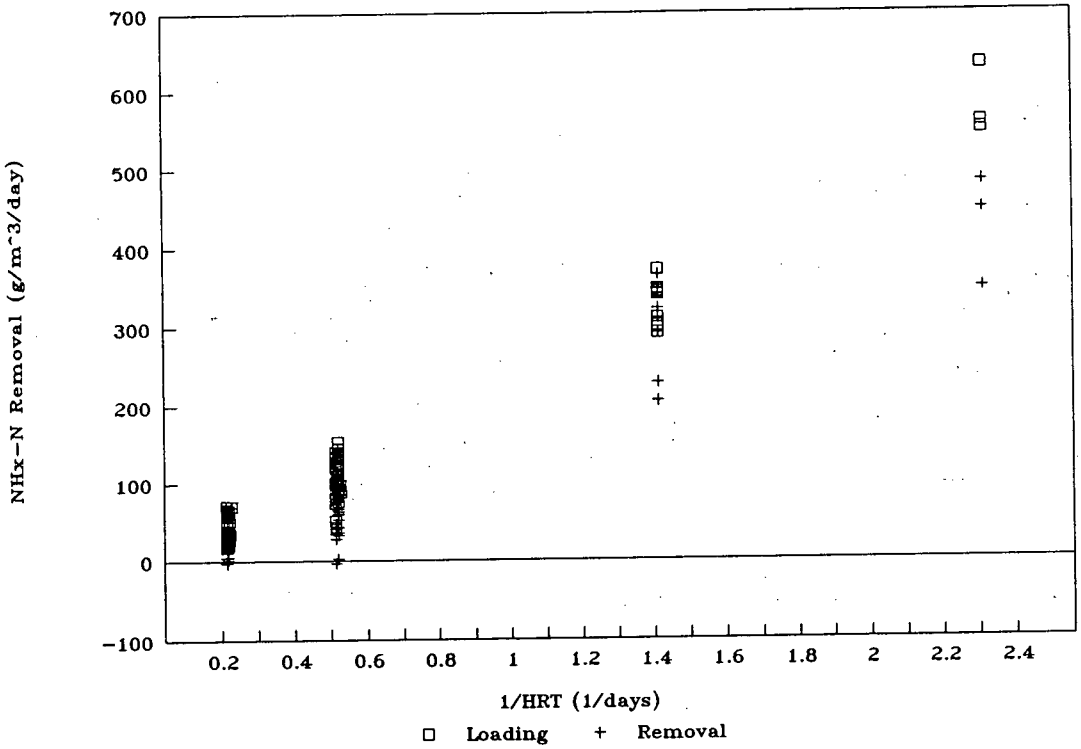
Referring to Figure 4.6, the four points from the HRT experiment appear to fit reasonably well with the rest of the data, although they tend to be higher than corresponding points at a given temperature. If they are included in the linear regression calculations, as shown in Table 4.10, they do not typically change the θ values significantly, although they tend to decrease the R^2 value. Unfortunately, the HRT experiment data were collected at temperatures of 13, 14, 15, and 17°C; they lie in the range of temperatures where removals begin to level off as temperature continues to increase. A much stronger argument for or against HRT limitation could have been made had there been HRT experiment data at temperatures between 17 and 25°C.

Peddie [52] indicated that the HRT limitation he found was independent of temperature. This HRT investigation did not take place over a wide enough range of temperatures to verify or deny this result.

4.1.5.2 SBR

Figures 4.10 and 4.11 show the relationship of SBR loading and removal to HRT in terms of g/g MLVSS/d and $g/m^3/d$. Figure 4.10 shows a clear linear relationship between increasing 1/HRT and increasing volumetric loading, which is to be expected given that the leachate concentration was fairly constant over the period of decreasing HRT. It also shows that removals follow loading up to the lowest HRT.

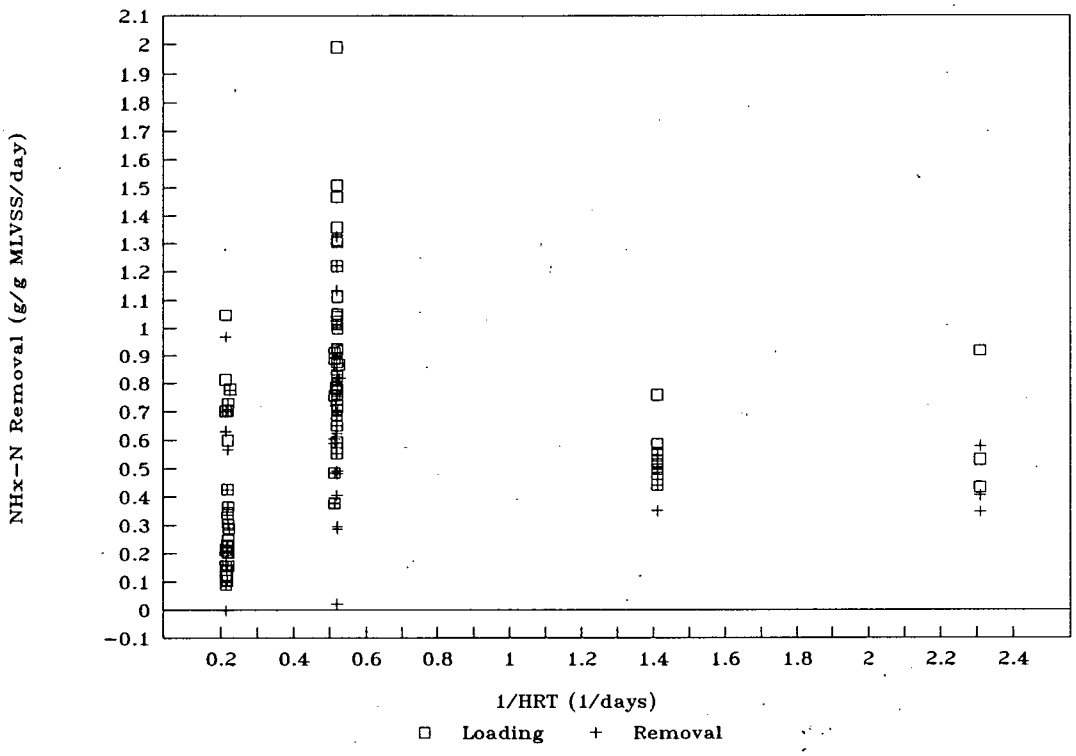
Figure 4.10: SBR NH_x-N Loading and Removal ($g/m^3/d$) versus 1/HRT



The SBR never achieved full nitrification at the two lowest HRTs (0.43 and 0.71 days), and at some point nitrification would probably have been limited by HRT. Knox [33] achieved nitrification in a similar leachate with an HRT of 0.5 days in continously aerated activate sludge system. Oleskiewicz and Berquist [47] achieved nitrification of a high N wastewater with an HRT of 1 day in an SBR, but since aeration occurred for only 4 hours out of an 8 hour cycle, the "aerated HRT" would have been only 0.5 days. Since this SBR was aerated for 5.5 out of 8 hours, the equivalent aerated HRTs at the lowest HRTs were about 0.3 and 0.5 days. The low "aerated HRT" value may have contributed to the difficulty encountered in achieving full nitrification at the 0.71/0.5 day HRT, but it is probable that full nitrification would have been achieved had the system been given longer to acclimatize. Since the 0.43/0.3 day HRT is lower than any found in the literature, it is more likely that the SBR was limited by HRT in that case, and that full nitrification may never have been achieved.

Figure 4.11 shows that removals in terms of g/g MLVSS/d show no apparent relationship to 1/HRT. While removals between 0.3 and 0.6 g/g MLVSS/d are possible at all HRTs investigated, higher removals were achieved at the longer HRTs. If full nitrification had been achieved at the two lowest HRTs, the solids concentration probably would have been higher (due to a higher population of *Nitrobacter*), and

Figure 4.11: SBR NH_x-N Loading and Removal (g/g MLVSS/d) versus 1/HRT



therefore removals in terms of g/g MLVSS/d would have been lower. It therefore seems probable that the highest nitrification rates in terms of g N/g MLVSS/d would still have occurred at the 1.9 day HRT.

Intentional solids wasting was not performed for the greater part of the experiment; the theoretical SRT was infinite except during the first few months (when it was approximately 17 days). However, considerable amounts of solids were lost in the effluent throughout the experiment. Therefore, actual SRTs were longer when HRTs were longer. The longer SRTs, which resulted from the longer HRTs, could have been responsible for the higher g/g MLVSS/d removals seen during the longer HRTs.

4.1.6 Alkalinity Consumption

Theoretically, 7.16 mg of alkalinity (as $CaCO_3$) should be consumed for every mg of NH_x-N nitrified [19]. Table 4.11 gives the results for this study. While values far above and far below 7.16 were found, the values were generally above 7.16, as shown by the averages given. (Note: for the SBR, the values obtained during the winter failure period from December 14th to January 16th were not included in the results given in Table 4.11, as no real nitrification was taking place and therefore results appeared questionable). The ratio was not calculated during periods of dry ammonium sulfate feeding. All other

Table 4.11: Alkalinity Consumption

	RBC	SBR
AVERAGE	9.24	8.99
MAXIMUM	19.06	19.73
MINIMUM	4.92	4.21

values were used, since the wide scatter of the data made it difficult to identify outliers. Many values of the ratio, such as the minimum and maximum values given in the table, are very different from theoretical values. Alkalinity consumption in excess of the theoretical requirement for nitrification could be caused by $CaCO_3$ precipitation, and consumption ratios lower than the theoretical value could be caused by dissolution of previously precipitated $CaCO_3$. It is not known if this mechanism would be sufficient to account for the observed variation.

There was always sufficient natural alkalinity in the leachate for nitrification; no alkalinity additions were necessary when the systems were operating normally. Alkalinity addition to the SBR was required in late January when it was being heated and fed dry ammonium sulfate in order to build up solids. Alkalinity addition was required for the RBC during the HRT experiment, when NH_x-N was added to the RBC to test higher loadings at a longer HRT. The alkalinity consumption ratio was not calculated during either of these periods.

4.1.7 Phosphate Addition and Consumption

Tables 4.12 and 4.13 show PO_4^{3-}-P addition and consumption data for the loading periods given in Tables 4.1 and 4.2. "Average Influent PO_4^{3-}-P" includes PO_4^{3-}-P pumped into the reactor by the nutrient pump as well as the background PO_4^{3-}-P concentration in the leachate. "Average N:P Ratio" refers to the average of individually calculated NH_x-N removed to PO_4^{3-}-P consumed ratios.

Referring to Tables 4.12 and 4.1, the loading period at which the longest RBC acclimatization period was required began on day 171. During this period, the RBC suffered several severe temperature shocks and experienced its lowest average temperature. It was previously stated that low temperatures and temperature shocks during acclimatization were responsible for the long acclimatization time. Table 4.12 shows that the RBC also experienced its lowest average influent and effluent PO_4^{3-}-P levels during this time; a low P supply may have contributed to the lengthy acclimatization period. However, the system was able to acclimatize eventually, and the N:P ratio was similar to those of surrounding loading periods.

The RBC was never able to acclimatize during the loading periods beginning on days 241 and 309.

Table 4.12: RBC Phosphate Addition and Consumption

Start Day	Average Loading ($g/m^2/d$)	Average HRT (days)	Acclimatization Time (days)	Average Influent PO_4^{3-}-P (mg/L)	Average Effluent PO_4^{3-}-P (mg/L)	Average Leachate NH_x-N (mg/L)	Average N:P Ratio
0	0.29	5.24	?	8.91	1.29	298	41
55	0.38	2.25	< 6	1.77	0.89	168	62
150	0.83	0.80	< 2	1.92	0.31	129	121
171	1.29	0.65	12<t<14	1.08	0.14	146	130
206	2.18	0.41	< 1	1.45	0.22	169	138
241	4.88	0.27	N/A	1.56	0.20	224	171
309	6.02	0.17	N/A	4.98	0.65	238	50
353	4.15	0.35	< 5	3.32	2.85	275	67

The average HRTs during these periods were 0.27 and 0.17 days, respectively. In Section 4.1.5.1, fairly conclusive evidence indicates that the RBC requires an HRT greater than 0.3 days in order to achieve full NH_x-N removal at loadings above 2 $g/m^2/d$. Since sufficient P appears to have been provided during the day 309 period, and since the 0.17 day HRT is clearly less than 0.3 days, the failure of the RBC to acclimatize was probably solely due to insufficient HRT. The day 241 period's HRT is much closer to 0.30 days, and the effluent PO_4^{3-}-P concentration was not significantly lower than the effluent PO_4^{3-}-P maintained during the previous successful loading periods (P addition was determined based on the effluent P concentration achieved during the previous successful loading periods). However, the N:P ratio for the day 241 period is much higher than it was for any other loading period. While the RBC was probably unable to acclimatize to the loading applied during the day 241 period due to insufficient HRT, P limitation could have been a contributing limiting factor.

Referring to Tables 4.13 and 4.2, the SBR appears to have had a sufficient PO_4^{3-}-P supply during the second loading period, and therefore chronic P limitation was probably not a factor in the failure which occurred during this time. A low P supply may have contributed to the failure of the SBR to recover when the loading was decreased on day 131, but low temperatures and solids loss were more likely the cause. The effluent PO_4^{3-}-P level during the day 158 period refers to measurements taken after the dry ammonium sulfate feeding period, i.e. during the period when the SBR was fed leachate but heated. This effluent P level can therefore be considered a healthy effluent P level. Given that 0.92 mg/L is an acceptable PO_4^{3-}-P level, the SBR should not have been P limited during the day 190 and day 214 periods. The ratio of average leachate NH_x-N to influent PO_4^{3-}-P was lower during the day 214 period than during the day zero period, which would also seem to indicate that PO_4^{3-}-P was

Table 4.13: SBR Phosphate Addition and Consumption

Start Day	Average Loading ($g/m^3/d$)	Average HRT (days)	Acclimatization Time (days)	Average Influent PO_4^{3-}-P (mg/L)	Average Effluent PO_4^{3-}-P (mg/L)	Average Leachate NH_x-N (mg/L)	Average N:P Ratio
0	63.5	4.64	?	2.85	2.78	298	128
55	87.8	2.15	6<t<13	2.00	1.82	178	81
131	23.3	4.66	N/A	2.61	0.28	110	6.4
158	33.0	4.63	9	2.97	0.92	150	61
190	30.2	4.59	< 3	3.99	2.49	142	55
214	107	1.93	52	2.56	1.02	208	165
302	331	0.71	14<t<18	3.44	0.42	234	71
351	580	0.43	N/A	5.09	0.07	275	37

not limiting. However, the N:P ratio is much higher for the day 214 period than for any other loading period, so P limitation could have contributed to the long acclimatization time after day 214.

The SBR loading period beginning on day 302 had the lowest average effluent PO_4^{3-}-P concentration, but had a mid range N:P ratio and had a high influent P concentration in relation to the leachate N concentration. While the effluent P concentration was higher than was typically required for proper RBC operation, the two processes may not be comparable in that respect. The SBR achieved complete NH_x-N removal but did not achieve complete nitrification during this period. Effluent NO_2^--N concentrations below 50 mg/L corresponded to effluent PO_4^{3-}-P concentrations above 0.68 mg/L, and effluent PO_4^{3-}-P concentrations below 0.142 mg/L corresponded to effluent NO_2^--N concentrations above 186 mg/L. While additions of PO_4^{3-}-P were generally intended to correspond to loading increases, examination of the experiment log indicates that the PO_4^{3-}-P addition was only doubled after the loading was tripled on day 302. It is very likely that PO_4^{3-}-P limitation was a major factor in the failure of the SBR to achieve full nitrification during this time.

While the loading and PO_4^{3-}-P addition were both doubled on day 351, the PO_4^{3-}-P addition was insufficient on day 302, and was therefore still insufficient. It is unclear why the SBR experienced total solids washout between days 369 and 376, rather than achieving incomplete nitrification as it had after day 302. It would have been interesting to see if the incomplete nitrification with full NH_x-N removal experienced between days 302 and 351 could have been maintained indefinitely, had the loading not been increased, or if the failure was inevitable.

4.1.7.1 Membrane Filtered PO_4^{3-}-P Results

Manoharan [40] recommended that soluble PO_4^{3-}-P concentrations greater than 0.5 mg/L be maintained in order to avoid P limitation, where "soluble" indicates that the sample has been filtered through a 0.45 μm membrane filter. Membrane filtered P samples were collected by the author when membrane filtration was being performed for metals samples on March 9th, April 13th, and May 18th, 1994 (days 209, 244, and 279). Membrane filtration was not done more regularly as it was very tedious. Effluent PO_4^{3-}-P measurements on the majority of effluent samples were performed in combination with NO_x^--N analyses on samples which had been diluted 1:10 or 1:20, preserved with phenyl mercuric acetate, and refrigerated for up to a week. Measurements of undiluted samples for PO_4^{3-}-P only on April 4th and May 18th indicated that preserved/diluted sample measurements tended to be significantly lower than direct sample measurements. However, the author's measurements were not typically lower or higher than the City's measurements.

PO_4^{3-}-P measurements on membrane filtered SBR effluent samples were all above 0.50 mg/L on the days tested, but the day 244 and 279 samples were lower than the day 209 sample. Membrane filtered measurements were 52 to 80% of unpreserved sample measurements, and 56 to 450% of preserved/diluted sample measurements. Overall, these observations support the previously made arguments that the SBR was not P limited between days 190 and 214, and may have been P limited between days 214 and 302.

The RBC is a different system, and the 0.50 mg/L criterion may not be valid for it (as evidenced by the fact that effluent PO_4^{3-}-P measurements without membrane filtration were frequently below 0.5 mg/L during successful operation). However, the RBC measurements on days 209, 244, and 279 were 1.2, 0.12, and 0.05 mg/L, respectively. These measurements add force to the argument that the RBC may have been PO_4^{3-}-P limited between days 241 and 309; they also support the argument that the RBC was not PO_4^{3-}-P limited between days 206 and 241.

The City's laboratory (Cantest) did not begin reporting membrane filtered P measurements until August 5th (day 358), when the City began requesting membrane filtration. Cantest had not been required to membrane filter P samples prior to this date. While the City received a letter in August indicating that PO_4^{3-}-P samples prior to August 5th were membrane filtered, they had never been reported as such, and they were not found to be significantly different from the author's Whatman 934 AH filtered samples. Because of this confusion, City measurements prior to August 5th were not considered to be membrane filtered. The following paragraph refers to results reported by the City after

Table 4.14: TKN Data

	Leachate TKN:NH_x-N	Organic N Removed (mg/L)		TKN Removed: NH_x-N Removed	
		RBC	SBR	RBC	SBR
AVERAGE	1.069	4.33	5.14	1.00	0.98
MAXIMUM	1.184	47.9	40.1	1.37	1.24
MINIMUM	0.929	-33.0	-25.5	0.84	0.87

August 5th.

The ratio of membrane filtered to normal samples ranged from 0 to 0.6 and averaged 0.4 for the RBC, and ranged from 0 to 0.5 with an average of 0.23 for the SBR. The RBC was not P limited in the loading period which began on day 353, judging by its performance, and effluent membrane filtered P only dipped below 0.5 mg/L twice during this time. The SBR's effluent membrane filtered P measurements were 0.02, 0, and 0 on days 358, 362, and 369, respectively, which reinforces the assertion that the SBR was P limited after day 351. Because the ratio of P supplied to loading was the same after day 302 and after day 351, these measurements are also evidence that the SBR was P limited after day 302.

Membrane filtered P analysis was also performed by the City during the HRT experiment. Ratios ranged from 0.19 to 0.62 and again averaged 0.4. While the RBC achieved full ammonia removal at the highest HRT during the HRT experiment, it did not achieve full nitrification. More discussion of this phenomenon is found in Section 4.2.3.

4.2 Other Nitrogen Forms

4.2.1 TKN

During the course of the research, the ratio of leachate TKN to NH_x-N was determined 20 times. There were two clear outliers, one at 0.792, and another at 1.401. The remainder of the data are summarized in Table 4.14. TKN values below the NH_x-N values were found a total of 3 times, (0.792, 0.929, 0.985). Each of these results was produced by the author at the U.B.C. laboratory rather than by Cantest. Two of these results were obtained from samples collected on the same day (0.792 and 0.985), and the lower of the two was probably caused by a low NH_x-N measurement, as the TKN measurements and NO_x^- measurements were similar. Another U.B.C. graduate student who used the same leachate also had trouble with TKN results being below NH_x-N results and found NH_x-N measurements to be more reproducible [4].

Table 4.14 also gives the organic N (i.e. TKN - NH_x-N) removed and the ratio of TKN removed to NH_x-N removed in each system. For both systems, the average value of the ratio was very nearly 1, and little organic N was generally removed. Both systems also occasionally appeared to create organic N. This could be due to cell lysis, but could be exaggerated by experimental errors and lack of correlation between NH_x-N and TKN measurements. In general, the results indicate that NH_x-N removal accounted for most TKN removal, and there were no significant differences in TKN removal between the two systems. (Note: the only outlier removed in calculating the TKN data for the SBR and RBC was the point mentioned above when the TKN:NH_x-N ratio was 0.792. There were no RBC or SBR TKN measurements on the day when the ratio was 1.401 for the leachate).

4.2.2 Nitrogen Balances

Leachate nitrogen was primarily in the form of NH_x-N, but included small amounts of organic N (see Section 4.2.1) and NO_x^--N. The average NO_x^--N concentration in the leachate was 0.76 mg/L, and the average NO_2^--N concentration was 0.03 mg/L; influent NO_x^--N was primarily NO_3^--N. Effluent NO_x^--N from both systems was also primarily NO_3^--N, except under stressed conditions when NO_2^--N buildups occurred in both systems (see Section 4.2.3).

Tables 4.15 and 4.16 give nitrogen balance data for the RBC and SBR respectively. "Lost N" is the difference between total influent and effluent N, where total N = TKN + NO_x^--N. "Lost NH_x+NO_x^-N" is the same figure calculated with NH_x-N in place of TKN on occasions when TKN was measured. The only value excluded from the calculations for these first two columns was the point for which theTKN:NH_x-N ratio of the leachate was found to be 0.792 (see Section 4.2.1). "Overall Lost NH_x+NO_x^-N" includes data from the entire experiment (i.e. data is included whether or not TKN was measured). SBR data obtained during the period of dry $(NH_4)_2SO_4$ feeding and for 5 days (1 HRT) afterward were excluded, as were RBC data obtained during the HRT experiment (when the leachate feed was augmented with dry $(NH_4)_2SO_4$). Extreme minimum values (-106% for the RBC and -163% for the SBR) were excluded from the table in order to avoid skewing the average value. If these extreme values are included, the average is -3.6% for the RBC and 1.8% for the SBR.

On average, neither system was observed to lose much nitrogen, and the percentage differences between influent and effluent nitrogen were usually small enough to be attributed to sums of acceptable measurement error limits.

For example, repeated NH_x-N analyses of the same sample were found to vary by up to 10%. If

Table 4.15: RBC Nitrogen Balance Data

	Lost N (%)	Lost $NH_x+NO_x^-$ N (%)	Overall Lost $NH_x+NO_x^-$ N (%)
AVERAGE	1.5	-0.7	-1.9
MAXIMUM	26.0	16.3	64.3
MINIMUM	-18.6	-18.6	-37.5

Table 4.16: SBR Nitrogen Balance Data

	Lost N (%)	Lost $NH_x+NO_x^-$ N (%)	Overall Lost $NH_x+NO_x^-$ N (%)
AVERAGE	7.7	8.1	4.7
MAXIMUM	20.9	24.9	78.0
MINIMUM	-21	-6.2	-48.9

the pH difference between the two samples was adjusted to approximately 0.5 units, the possible total variation was found to be just over 20%. However, the variation between repeated measurements was usually under 5% both with and without small pH differences.

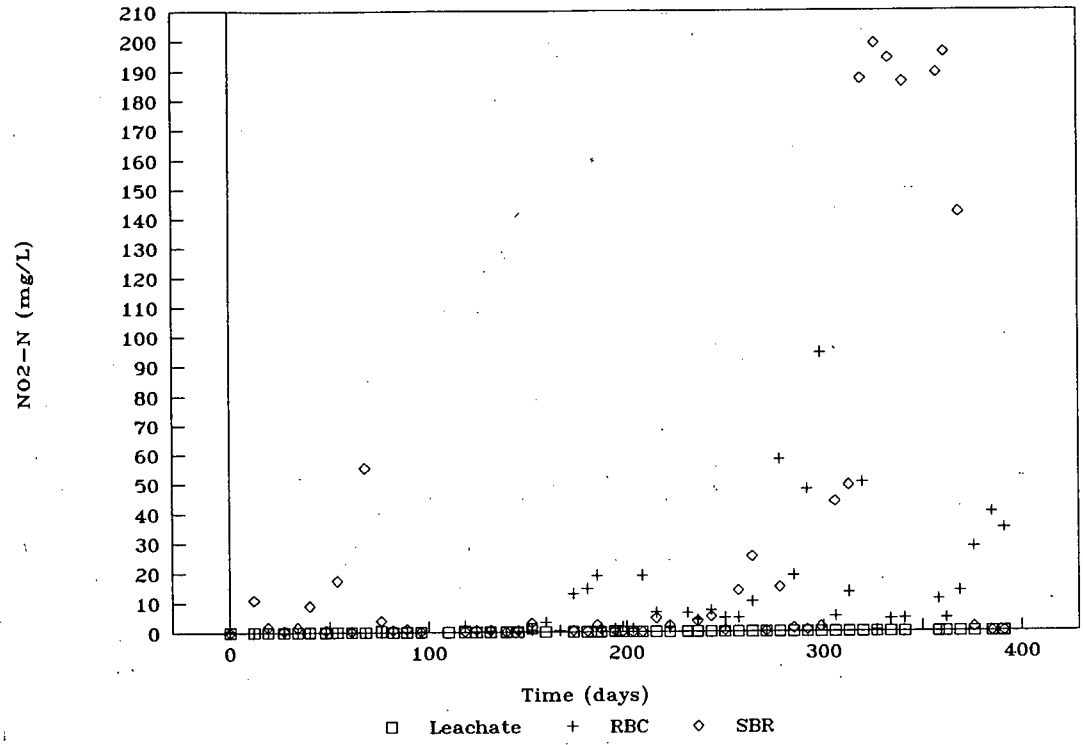
Lost TKN values are very close to lost NH_x-N values obtained at the same time, but overall lost NH_x-N values are somewhat different. However, the differences are probably not large enough to be significant.

Ammonia volatilization was measured twice for each system during November 1993. The RBC headspace was found to contain approximately 0.2 to 0.4 mg of NH_x-N during each trial, and approximately 400 mg of NH_x-N were added to the reactor every 30 minutes. During these measurements, the air pump was removing about 28 % of the RBC headspace volume every 30 minutes. Assuming that neglible headspace air left the RBC from points other than the air pump inlet, 0.01 to 0.03 % of the NH_x-N added was lost to volatilization.

For the SBR, approximately 1 to 5 mg of NH_x-N volatilized during the 5.5 hour aeration cycle, while 10 to 10.8 g of NH_x-N were added in the leachate; 0.01 to 0.05 % of the NH_x-N added was lost through volatilization.

While some volatilized NH_x-N was detected for each system, the amount of N lost to volatilization was neglible. This result was expected due to the mixed liquor temperatures and pH values observed at

Figure 4.12: Leachate and Effluent NO_2^--N versus Time



that time (Temperature 4 to 10°C, pH 7.8 to 8.4). No subsequent ammonia volatilization measurements were undertaken in the warmer months due to time constraints and the lack of N loss observed as the study progressed.

4.2.3 Nitrite

Figure 4.12 shows that NO_2^--N buildups were fairly common in both systems. Dates of loading increases and process upsets are given in Tables 4.1, 4.2, 4.3, and 4.4.

4.2.3.1 RBC

For the RBC, the first significant NO_2^--N buildups occurred between days 171 and 185, and were probably caused by the loading increase on day 171. Effluent PO_4^{3-}-P concentrations taken when the NO_2^--N buildups occurred were somewhat lower than average measurements before day 171. PO_4^{3-}-P addition was not increased in conjunction with the loading increase, so PO_4^{3-}-P limitation resulting from the loading increase may have been a factor. (It should be noted that these were not membrane filtered samples, but that any PO_4^{3-}-P measurement taken at the same time as an NO_2^--N measurement was

performed by the City laboratory, and was therefore less prone to preservation/dilution error than the author's PO_4^{3-}-P measurements).

The next NO_2^--N spike occurred on day 208, and followed the loading increase on day 206. PO_4^{3-}-P was not detected in the effluent on day 208, but PO_4^{3-}-P addition had been doubled on day 206. NO_2^--N concentrations generally remained above 4 mg/L until day 309, and the loading increase on day 241 did not have a significant effect, even though PO_4^{3-}-P addition was not increased until day 287. On day 271, the wet well pump failed, which resulted in lack of leachate feed to both systems for several days. The shock of resumed leachate feed could be partly responsible for the NO_2^--N spike on day 278. However, effluent PO_4^{3-}-P was not detected, and PO_4^{3-}-P levels continued to be low while the NO_2^--N buildups worsened from day 278 to day 299. The experiment logbook shows that PO_4^{3-}-P addition was tripled on day 287 due to suspected P limitation, but effluent P remained below 0.03 mg/L until day 306 when it was 1.0 mg/L. The NO_2^--N level on day 306 was only 5 mg/L, while it had been 94 mg/L on day 299. Existing PO_4^{3-} solution may have been used up rather than making up a new batch immediately. The HRT averaged 0.27 days from day 241 to day 308.

The loading increase on day 309 did not occur in conjunction with a PO_4^{3-}-P addition increase, and was not followed by an immediate NO_2^--N buildup. A spike occurred on day 320 when the NH_x-N loading abruptly more than doubled due to influent valve malfunctions. The increased loading also resulted in a very low effluent PO_4^{3-}-P concentration. PO_4^{3-}-P addition was doubled again on day 334, and effluent NO_2^--N was 4 mg/L on day 334 and day 341 while effluent NH_x-N increased from 61 to 121 mg/L even though loading decreased from 6.2 to 4.3 g/m^2/d. The HRT averaged 0.17 days from day 309 to day 352.

The loading decrease on day 353 was followed by NO_2^--N levels at 2 to 7.6% of NO_x^--N from day 358 to day 369 when membrane filtered PO_4^{3-}-P levels were 1 to 2.9 mg/L. The NO_2^--N levels from day 376 to 391 were 15.6 to 19.8% of NO_x^--N while membrane filtered PO_4^{3-}-P levels were 0 to 0.8 mg/L. The lack of complete nitrification from day 358 to day 369 may have been due to free NH_3-N inhibition, since effluent PO_4^{3-}-P levels were satisfactory. However, P limitation may have occurred between days 376 and 391.

Free NH_3-N inhibition of *Nitrosomonas* begins at 10 to 150 mg/L NH_x-N, while inhibition of *Nitrobacter* begins at 0.1 to 1.0 mg/L [1]. *Nitrobacter* is more sensitive to free NH_3 than *Nitrosomonas*, and almost every NO_2^--N buildup in the RBC system occurred in conjunction with an increase in NH_x-N loading. It is therefore possible that NO_2^--N buildups were caused by free NH_3 inhibition.

However, NO_2^--N buildups also tended to occur in conjunction with low effluent PO_4^{3-}-P concentrations. Because low effluent PO_4^{3-}-P concentrations could be caused by increasing loading without increasing P addition, it is difficult to determine whether the increased loading itself, or the P limitation caused by the increased loading resulted in NO_2^--N buildups. The situation is further complicated by the fact that the RBC was likely HRT limited at higher loading rates. No evidence linking P limitation and incomplete nitrification was found in the literature.

The last few points on Figure 4.12 were collected during the HRT experiment conducted by the City. Huge NO_2^--N buildups occurred at first, but the system gradually returned to a more normal (but still high) NO_2^--N level.

Table 4.17 includes data from the HRT experiment, and shows that effluent NO_2^--N levels of 23, 72, 224, and 245 mg/L corresponded to free NH_3-N loadings of 0.073, 0.402, 0.194, and 1.082 $g/m^2/d$, respectively. The two highest NO_2^--N loadings were the first two measurements, and therefore the fact that 0.194 $g/m^2/d$ was associated with a higher NO_2^--N concentration than 0.402 $g/m^2/d$ could be explained by acclimatization. It could also be explained by the fact that these numbers are loadings rather than concentrations. (Meaningful concentration values are difficult to calculate for the RBC system since it is not completely mixed). In any case, the highest and lowest NH_3-N loadings correspond to the highest and lowest effluent NO_2^--N levels.

While it appears that the NO_2^--N levels decreased with time, Table 4.17 shows that arranging the results with respect to time also arranges the results with respect to increasing effluent membrane filtered PO_4^{3-}-P concentration and decreasing NO_2^--N fraction. While NH_3-N loading shows an apparent relationship to effluent NO_2^--N concentration, the relationship between NH_3-N loading (or NH_3-N loading fraction) and NO_2^--N fraction is less clear. NO_2^--N fraction is a better indication of differential *Nitrobacter* inhibition than NO_2^--N concentration because NO_x^--N levels were variable. Examination of the NO_2^--N and PO_4^{3-}-P results does not change the fact that NH_x-N removal increased with increasing HRT, but it does indicate that complete nitrification may have been prevented in the HRT experiment through PO_4^{3-}-P limitation, rather than through NH_3 inhibition.

If NO_2^--N buildups during the HRT experiment were caused by P limitation, it is likely that P limitation was also primarily responsible for NO_2^--N buildups observed in the RBC system during the rest of the study.

Table 4.17: RBC NO_2^--N and PO_4^{3-}-P Data from HRT Investigation

Date	HRT (days)	NH_x-N Removal (%)	Effluent NO_2^--N (mg/L)	NO_2^--N/NO_x^--N Fraction (%)	Effluent Soluble PO_4^{3-}-P (mg/L)	NH_3-N Loading ($g/m^2/d$)
09/29/94	0.30	76.9	224	65.7	0.08	0.402
10/05/94	0.31	96.5	245	50.0	0.17	0.073
10/20/94	0.27	49.3	72	41.5	0.27	0.194
10/26/94	0.28	65.8	23	11.2	1.20	1.082

4.2.3.2 SBR

Referring to Figure 4.12, the SBR experienced three small NO_2^--N buildups prior to its first loading increase on day 55. One of these corresponded with an unexplained process upset which occurred on day 12, and effluent quality was somewhat poor on the other two occasions, but neither higher than normal NH_x-N loading nor lower than normal effluent PO_4^{3-}-P occurred on any of these occasions. The NO_2^--N spike on day 68 (55 mg/L) came almost two weeks after the loading increase on day 55. The effluent PO_4^{3-}-P level on day 68 was 0.93 mg/L, but on day 82, when the effluent PO_4^{3-}-P level was 0.29 the NO_2^--N level was only 0.62. However, both of these P levels were significantly lower than surrounding values, and the NH_x-N loading on day 82 was only 70% of day 68's.

After this, NO_2^--N levels stayed near zero until day 215 when the NO_2^--N concentration was 4.7 mg/L. The loading had been increased on day 214, but the effluent PO_4^{3-}-P (0.88 mg/L) was similar to P levels observed during acceptable operation in the previous loading period. Three high NO_2^--N concentrations occurred on days 257, 261, and 278 when the NH_x-N loading exceeded 120 $g/m^3/d$ and effluent P levels were 0.43 to 0.6. On days 271 and 299, similar loadings did not produce NO_2^--N buildups when effluent PO_4^{3-}-P concentrations were higher (1.3 and 0.69), but similar loadings on days 285 and 292 did not produce NO_2^--N buildups even though effluent PO_4^{3-}-P concentrations were low (0.43 to 0.62).

Initial free NH_3-N levels in the reactor were calculated using site pH and temperature measurements and an empirical formula from reference [46]. The first three high NO_2^--N events corresponded to higher than average initial NH_3-N levels for that time period. However, not all high initial NH_3-N events produced a high NO_2^--N event. Between day 167 when leachate feed was resumed and the next loading increase on day 214, calculated initial free NH_3-N levels exceeded 1 mg/L only once. After day 214 initial free NH_3-N levels almost always exceeded 1 mg/L. However, initial free NH_3-N levels on days when NO_2^--N buidups occurred after day 214 (i.e. days 257, 261, and 278) were not significantly different from levels

on surrounding days without NO_2^--N buildups. Neither free NH_3 inhibition nor P limitation appears to be an adequate explanation for NO_2^--N buildups observed prior to day 302.

Effluent NO_2^--N levels following the loading increase on day 302 increased dramatically, and complete nitrification was never achieved in this loading period or in the following period which began on day 351. Initial free NH_3-N levels between days 302 and 351 were similar to those in the previous loading range when full nitrification was achieved. In contrast, effluent NO_2^--N concentrations below 50 mg/L corresponded to effluent PO_4^{3-}-P concentrations above 0.68 mg/L, and effluent PO_4^{3-}-P concentrations below 0.142 mg/L corresponded to effluent NO_2^--N concentrations above 186 mg/L. These results seem to indicate that the nitrite buildups after day 302 were caused by P limitation, rather than by free NH_3 inhibition.

The low NO_2^--N levels shown after day 375 are the result of the SBR system's failure.

In an SBR system, the free NH_3-N concentration would be relatively high during the "fill" stage, and would taper off as NH_x-N was nitrified during the "react" stage Therefore, nitrifiers would be exposed to a much more variable NH_3-N concentration than they would be in a continuous flow activated sludge system. The high variability might make acclimatization more difficult in an SBR system than in a completely mixed system. While free NH_3 inhibition was not shown to be the prime cause of NO_2^--N buildups during this experiment, it could be partly responsible for the overall poor performance of the SBR.

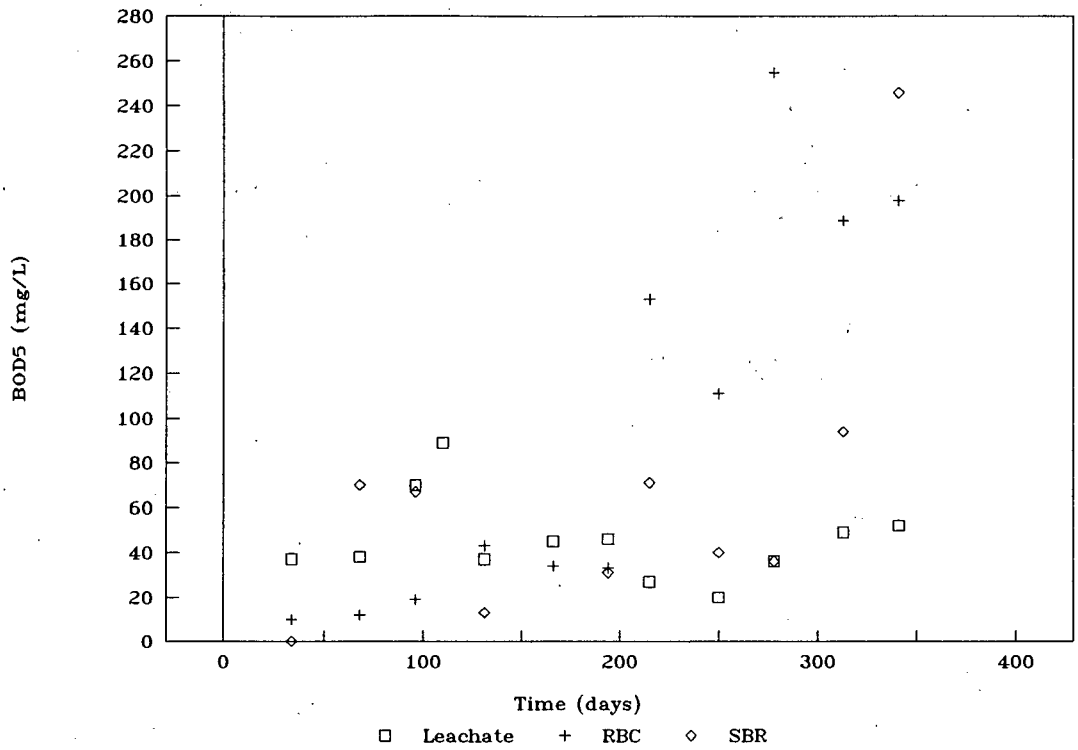
4.3 Organics and Suspended Solids

4.3.1 BOD_5

Figure 4.13 shows that while leachate BOD_5 concentration varied from 20 to 89 mg/L, it was generally nearer the average value of 45.5 mg/L. While both systems were capable of removing BOD_5 during periods of relatively light NH_x-N loading, each tended to be more likely to add BOD_5 under heavier NH_x-N loading conditions. RBC BOD_5 was measured on samples which had been settled in the laboratory for 30 minutes, while SBR BOD_5 was measured directly on effluent samples which had been settled in the reactor for 1 to 2 hours. However, total (i.e. unfiltered) BOD_5 was measured for both systems. Therefore, it is possible that more BOD_5 was added under heavier loading conditions because effluent solids exhibited poorer settlability.

Figures 4.14 and 4.15 show BOD_5 and COD plotted against total suspended solids for the RBC and

Figure 4.13: Leachate and Effluent BOD_5 versus Time



SBR, respectively. Both BOD_5 and COD seem to increase with TSS for the RBC, but the relationship is not definite. The relationship between BOD_5 COD, and TSS is even less clear for the SBR. Since the City did not measure VSS regularly, and since the author did not measure oxygen demand, a plot of BOD_5 or COD versus VSS, which may have provided more insight, could not be produced. While it is possible that increased BOD_5 measurements at higher loadings were caused by poor solids settlability, the data do not prove this assertion conclusively, particularly for the SBR.

While there is very little BOD_5 data on which to base a comparison, it appears that the two systems performed similarly with respect to BOD_5 removal.

4.3.2 COD

Figure 4.16 shows the performance of each system with respect to COD removal. The RBC system generally performed better than, or similar to, the SBR system. The SBR performed better for a short period from about day 250 to day 300 (mid April to mid June), but this was a period during which the RBC received its second highest loading while the SBR received its third highest loading. During the SBR's two most heavily loaded phases, beginning on days 306 and 358, SBR effluent COD was typically

Figure 4.14: RBC BOD_5 and COD versus TSS

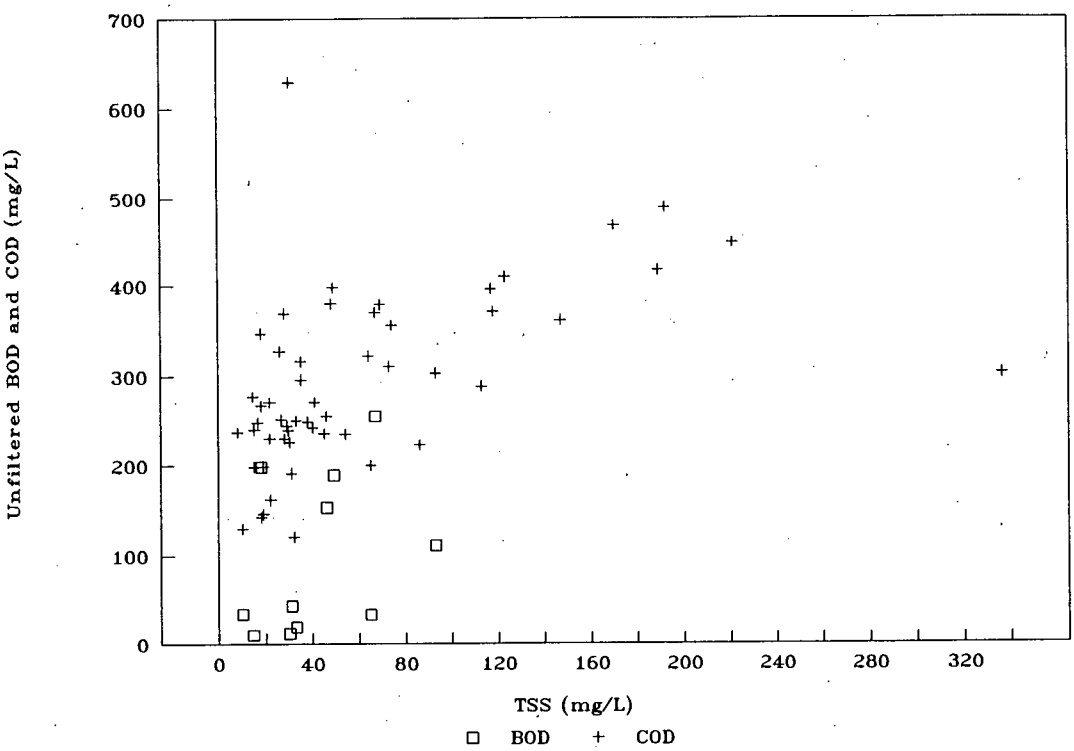


Figure 4.15: SBR BOD_5 and COD versus TSS

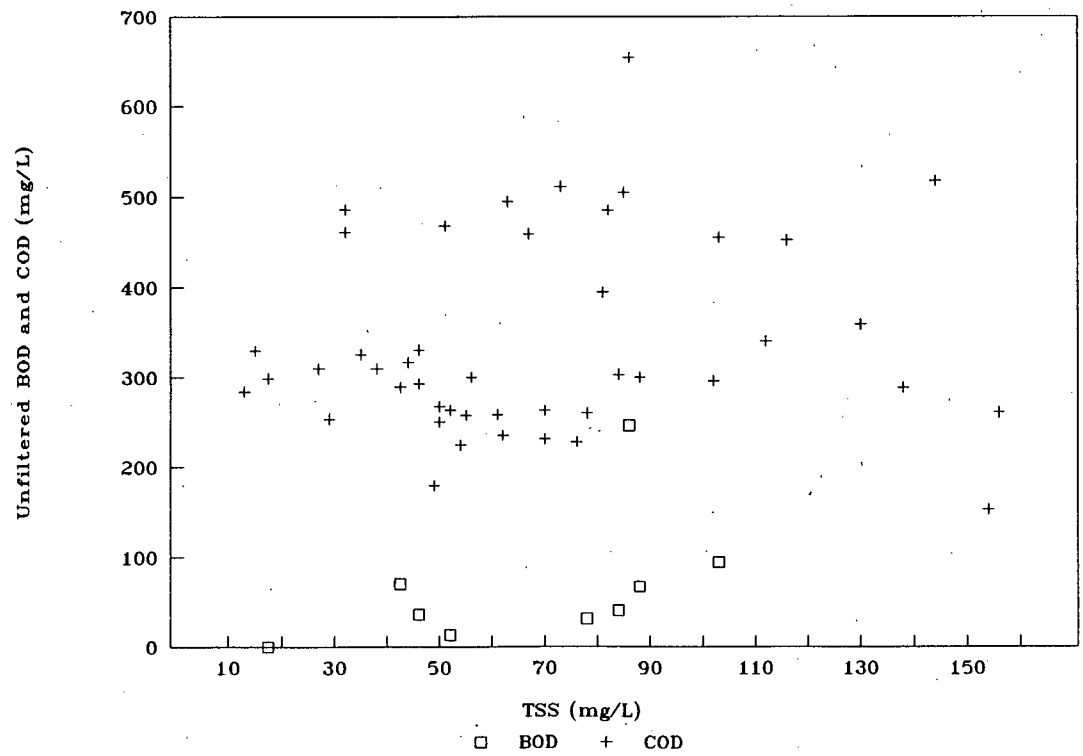
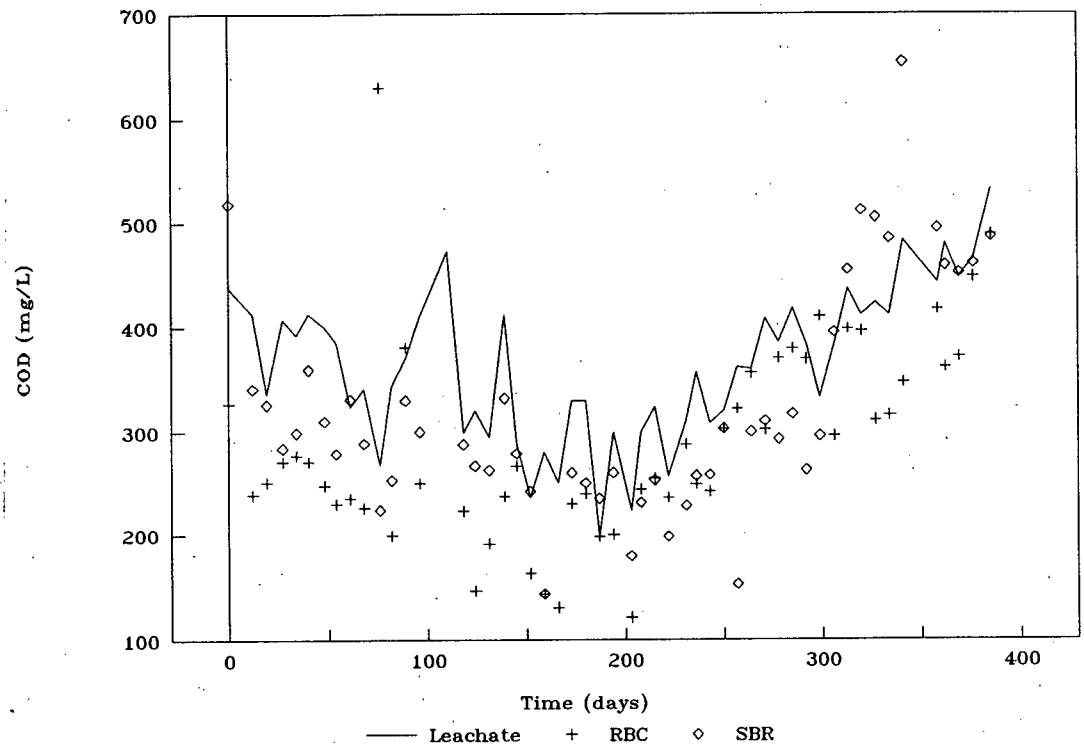


Figure 4.16: Leachate and Effluent COD versus Time



greater than or equal to influent COD. Most of the points which lie on the influent COD line fall after day 376, when the SBR solids were almost completely washed out. In contrast, while the RBC's performance suffered during its most heavily loaded phase, it usually still achieved some COD removal.

The overall average COD removal for the RBC was 21.2%, while that for the SBR was 11.0%. If the average is taken over the period from August 24/93 to June 7/94 (day 12 to 299), in order to exclude most negative removals by the SBR, then the numbers are closer (24.0 and 19.2 for the RBC and SBR, respectively). If the average removal for the RBC is calculated with points during the period of heaviest loading removed, the result is 26.6%. In summary, the RBC system performed better than the SBR system with respect to COD removal, particularly under heavily loaded conditions.

4.3.3 Comparison of BOD_5 and COD

Influent and effluent BOD_5:COD ratios are given in Table 4.18, and Figures 4.17 and 4.18 show the relationship of COD removal to BOD_5 removal for the RBC and SBR, respectively.

Figures 4.17 and 4.18 clearly show that both systems generally removed more COD than BOD_5 when there was a net removal of BOD_5, indicating that some recalcitrant compounds (i.e. COD) were

Table 4.18: BOD_5:COD Ratios

	Leachate	RBC	SBR
AVERAGE	0.124	0.320	0.175
MAXIMUM	0.188	0.689	0.376
MINIMUM	0.063	0.036	0.000

converted to more readily biologically oxidizable compounds (BOD_5) and removed. When there was a net addition of BOD_5 and a net removal of COD, the addition of BOD_5 was usually smaller than the removal of COD for the SBR, and much larger than the removal of COD for the RBC; however, it is difficult to make a meaningful conclusion based on this observation. Since COD includes BOD_5, a zero or net positive removal of COD in combination with a net increase in BOD_5 could mean that some recalcitrant compounds were converted to more readily oxidizable compounds and/or biomass, but only part of the BOD_5 created was removed.

BOD_5 addition tended to occur under more heavily loaded conditions. It is possible that this was because the systems were unable to finish the process of oxidizing recalcitrant compounds when the systems were heavily loaded.

An addition of both COD and BOD_5 to the effluent could also indicate addition of effluent BOD_5 due to losses of unsettlable biological solids. On days 313 and 341 (see Figure 4.18), when the SBR was heavily loaded and experiencing nitrite buildups, the BOD_5 measurements were 94 and 246 mg/L, while the TSS measurements were 103 and 86 mg/L, respectively. Unfortunately, no VSS measurements are available for days 313 or 341. These data do not prove that the increases in BOD_5 were related to unsettlable solids in the effluent. The fact that TSS and BOD_5 are not clearly related could indicate that another factor, such as cell lysis, contributed to the increase in BOD_5.

Addition of BOD_5 due to cell lysis is difficult to identify if a net removal of COD has occurred, because the addition of BOD_5 due to cell lysis would be masked by the addition of BOD_5 due to COD conversion. It is therefore difficult to know if any addition of BOD_5 by the RBC was due to cell lysis. In any case, Figure 4.16 indicates that the effluent COD concentration was greater than the influent COD concentration more often for the SBR than the RBC, so it appears that the SBR was more likely to add BOD_5 due to cell lysis than the RBC.

Figure 4.17: Comparison of RBC COD and BOD_5 Removal

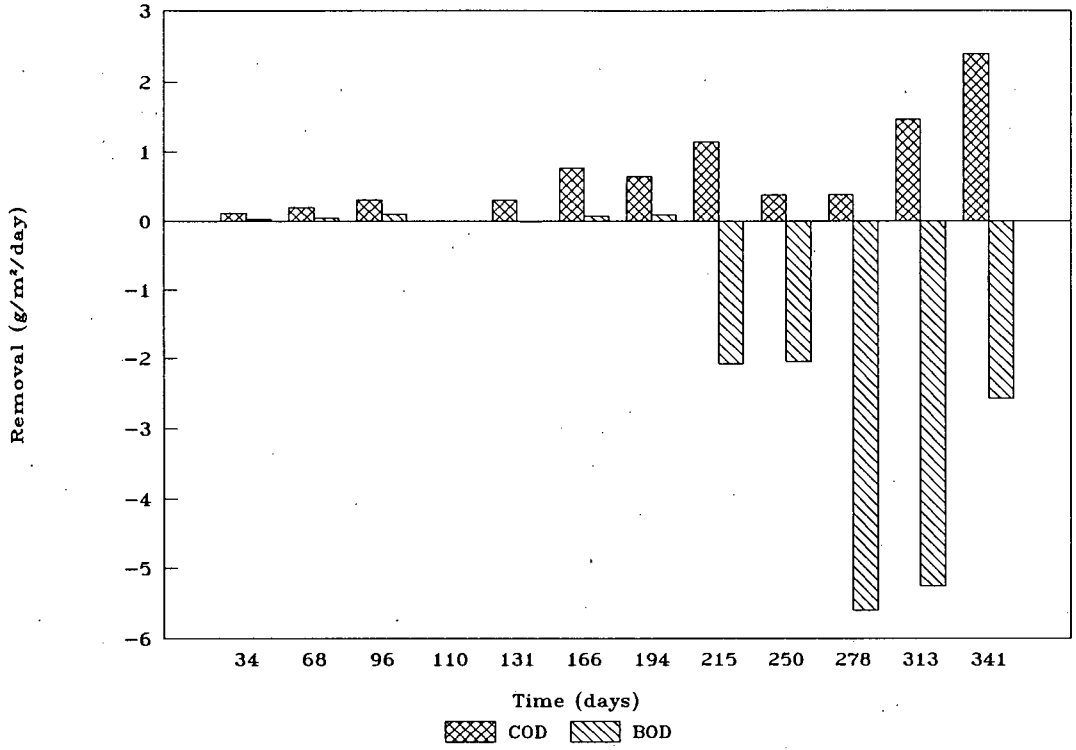


Figure 4.18: Comparison of SBR COD and BOD_5 Removal

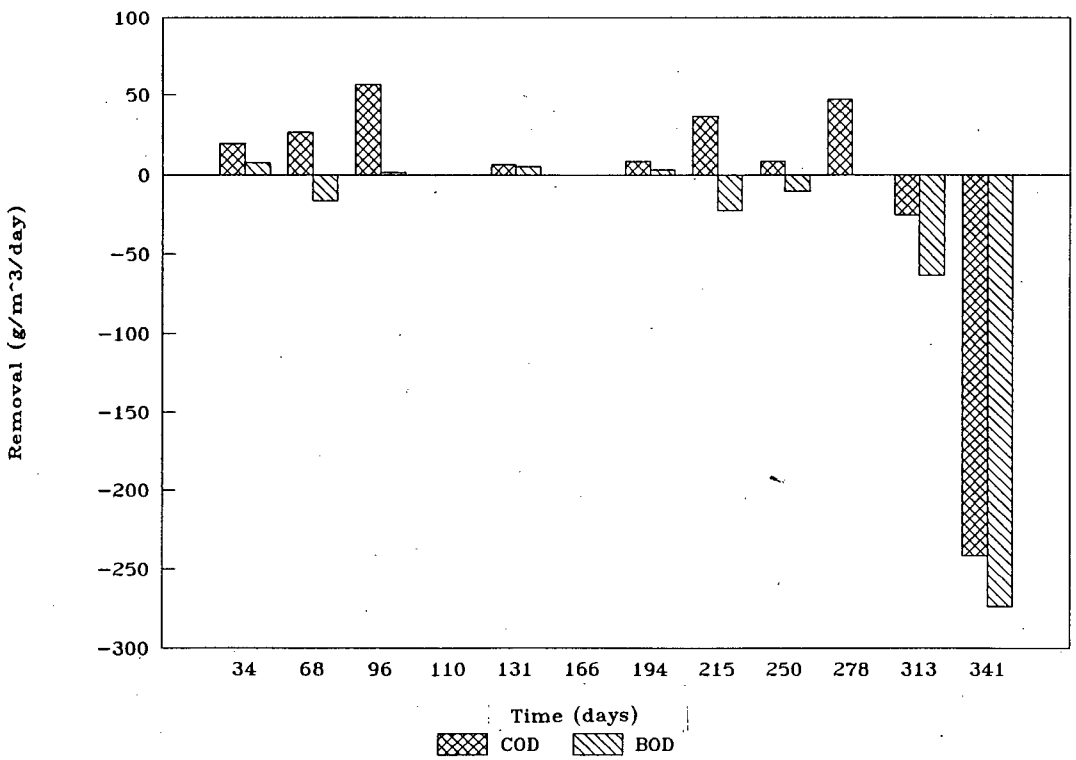
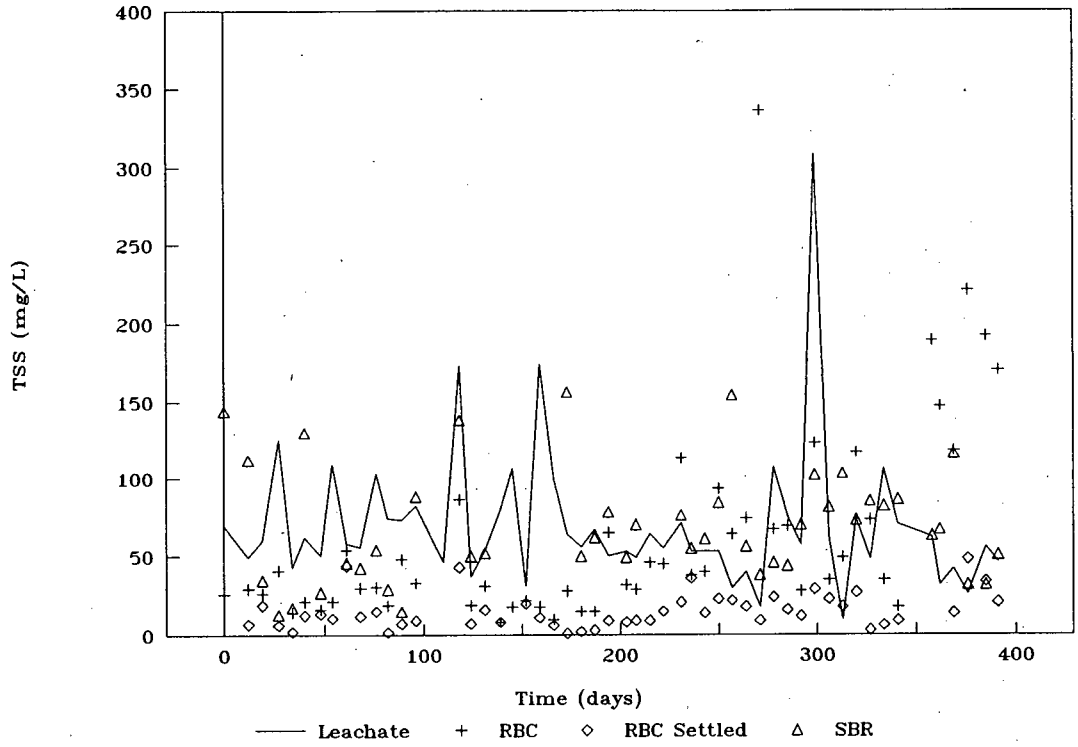


Figure 4.19: Leachate and Effluent Total Suspended Solids



4.3.4 Suspended Solids

Figure 4.19 shows the leachate and effluent total suspended solids data obtained during the study. "RBC" refers to RBC mixed liquor removed from the final stage, while "RBC Settled" refers to this sample after half an hour of quiescent settling in the lab. "SBR" refers to SBR effluent, which was settled in the reactor for 1 hour prior to January 28th (Day 169), and 2 hours subsequently.

The SBR removed solids reasonably well until approximately day 90 (Nov. 10/93), after which SBR effluent solids were typically similar to leachate solids. The RBC effluent solids began to climb after about day 200 (Feb. 28/94), possibly due accumulated solids on the reactor bottom (there was no provision for solids wasting). However, laboratory settling continued to remove solids to low levels, ranging from 1 to 44 mg/L and averaging 15 mg/L.

In contrast, SBR effluent TSS (reactor settled) ranged from 13 to 156 mg/L and averaged 64 mg/L. Leachate TSS ranged from 10 to 308 mg/L and averaged 67 mg/L. While the average TSS levels were similar, the average VSS:TSS ratio was 0.60 for the SBR effluent and 0.50 for the leachate. There was not much overlap between the leachate and SBR effluent VSS:TSS data; the maximum recorded for

Table 4.19: RBC Disk Scrapings

Date	VSS (%)	TSS (%)	VSS:TSS
April 20	3.6	8.1	0.45
May 17	4.36	10.5	0.415
June 21	0.57	10.1	0.056
July 19	4.00	16.8	0.238
August 5	3.50	13.4	0.261
September 7	4.45	11.1	0.401

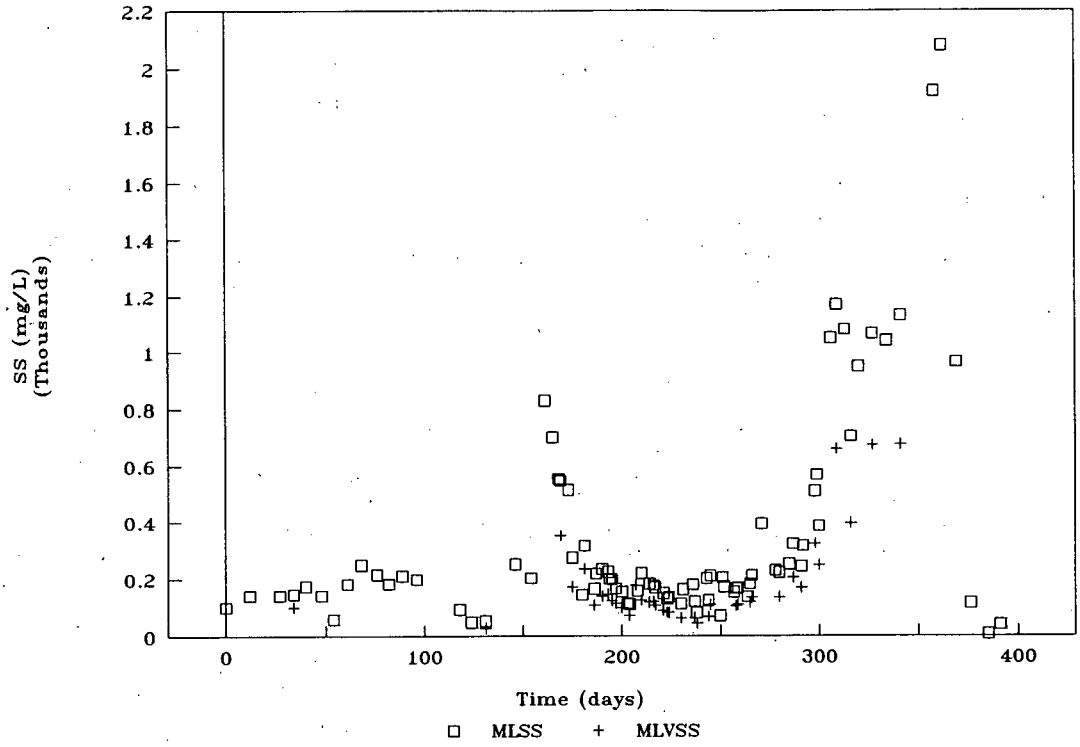
the leachate was 0.63 (similar to the average for the SBR), while the minimum for the SBR was 0.51 (greater than the average for the leachate). These data indicate that the solids leaving the SBR were not typically the same as the ones that entered in the leachate; some removal of fixed solids appears to have occurred within the SBR. One possible mechanism for fixed solids removal is accumulation of fixed solids, or "scale" on the walls of the supply tank, the plumbing, and the reactor itself. The fixed solids, which can make up scale, include calcium and iron compounds such as $CaCO_3$ and $Fe(OH)_3$ [33, 39].

While supply and effluent lines for both reactors were periodically changed when scale built up, no major problems with scale occurred, and neither reactor was observed to have a large scale buildup on its walls. Consequently, there was no proof that fixed solids removal in the SBR was caused by accumulation within the reactor. Precipitation of inorganic compounds can cause trouble in activated sludge systems by encrusting the biological flocs [39], but no evidence of this was seen.

The RBC VSS:TSS ratio averaged 0.58 and ranged from 0.48 to 0.68, but since the effluent solids levels were not similar to leachate levels, this fact can not be used to indicate whether or not inorganic solids were building up. However, no tendency for the effluent VSS:TSS ratio to increase or decrease was observed over the course of the experiment. In order to determine whether inorganics were building up on the discs, several samples of disc scrapings were analyzed for VSS and TSS over the last few months of the experiment. The results are given in Table 4.19. The net amount of VSS in a given sample does not change significantly (with the exception of the June 21 result, which may have been a poor sample). While the VSS:TSS ratio varies quite significantly, there does not appear to be a trend for it to decrease with time; it reached low levels but was able to recover.

Other investigators have had severe scale problems with RBC systems [39, 34]. However, open ditch leachate collection systems, such as the system at the Vancouver Landfill, can prevent scale formation in the reactor by acting as a "pretreatment stage" [33]. No problems due to scale were observed during

Figure 4.20: SBR Mixed Liquor Suspended Solids



this study, and it is unlikely that encrustation would become a problem in the long term.

Figure 4.20 shows the variation in mixed liquor total and volatile solids for the SBR with time. MLVSS data shown are direct measurements. The average VSS:TSS ratio was 0.62, and this value was used to calculate MLVSS from MLSS for loading calculations when necessary.

Tables 4.2 and 4.4 give the times at which loading increases and process upsets occurred. Loading increases occurred on days 55, 167, 214, 302, and 351. The SBR was reinoculated with bio-P sludge and fed dry $(NH_4)_2SO_4$ from day 158 to 167. Following a loading increase, the SBR suspended solids concentration typically increased significantly, then fell off until the next loading increase occurred. In one case (day 214 to day 302), solids concentrations began to increase before the next loading increase was applied.

The decreases in MLSS between days 100 and 158 were associated with process upsets caused by cold and/or various equipment failures (power, compressor, nutrient pump, leaking influent valve). The heaters were removed from the reactor on day 190, which corresponds to the beginning of a solids loss trend that lasted until the loading was increased again on day 214. The large solids losses which occurred shortly after day 167 were probably caused by a decrease in N loading due to the transition from dry

$(NH_4)_2SO_4$ feeding to leachate feeding. The cold/no nutrient flow event on day 198 took place during a period of decreasing solids concentration, but may have contributed to the overall solids loss.

Significant day to day variations in both MLSS and MLVSS occurred between day 200 and day 300. Solids balances performed to check these variations indicate that more variation is sometimes seen than one would expect, given the influent and effluent solids concentrations and the growth rates of nitrifying organisms. Solids measurements were based on the average of duplicate samples, and all calculations were checked carefully. Solids samples were usually taken 5 minutes after the start of aeration, which may not have been long enough for complete mixing to have occurred. However, City solids measurements were generally taken an hour or more into the aeration cycle, and they show the same type of variability as the author's. There is no tendency for City measurements (MLSS) to be higher or lower than the author's. One possible cause for the unexpected variations in suspended solids measuements is poor reactor mixing.

4.3.5 Colour

The colour of the leachate ranged from 150 to 1000 units, and averaged 615 units. RBC colour removals ranged from -100 to 62.5% and averaged 20.1%. SBR colour removal ranged from -60 to 50% and averaged 12.8%.

The leachate was typically brown or red-brown in colour, and these colours are typically associated with humic materials. Humic materials are typically biologically recalcitrant, and are therefore represented by COD rather than BOD_5. Another possible source of red-brown colour is iron oxides. Since the RBC removed more COD and more iron than the SBR, it is not surprising that the RBC also removed more colour.

4.4 Metals

The City measured total chromium, iron, lead, manganese, nickel and zinc once per month.

The author selected total and dissolved cadmium, chromium, cobalt, copper, iron, nickel, and zinc as metals to monitor in conjunction with toxicity studies. These metals were selected because historical data indicated that their concentrations in the leachate occasionally reached or exceeded toxicity thresholds for *Daphnia*. Metals were measured in samples which had been preserved shortly after collection and in samples which had been kept at 20°C in control beakers during *Daphnia* LC_{50} tests prior to preservation.

4.4.1 Cadmium

Cadmium measurements ranged from 0.004 mg/L to 0.010 mg/L, and averaged .007 mg/L. The detection limit was 0.004 mg/L. There were no significant differences between leachate and effluent concentrations, or between dissolved and total values. Samples left standing in control beakers showed no significant differences from samples preserved immediately.

4.4.2 Chromium

The City's laboratory never detected chromium in the leachate or the effluents. Their detection limit was 0.03 mg/L.

Total chromium measurements from the UBC lab, using a graphite furnace indicated that all leachate samples were between 0.005 and 0.010 mg/L. Measurements were complicated by double peak responses and a low signal:noise ratio, and thus it was recommended that the chromium concentrations be listed as "<0.01 mg/L" for all samples. As a result, no other samples were analyzed for chromium by the author.

4.4.3 Cobalt

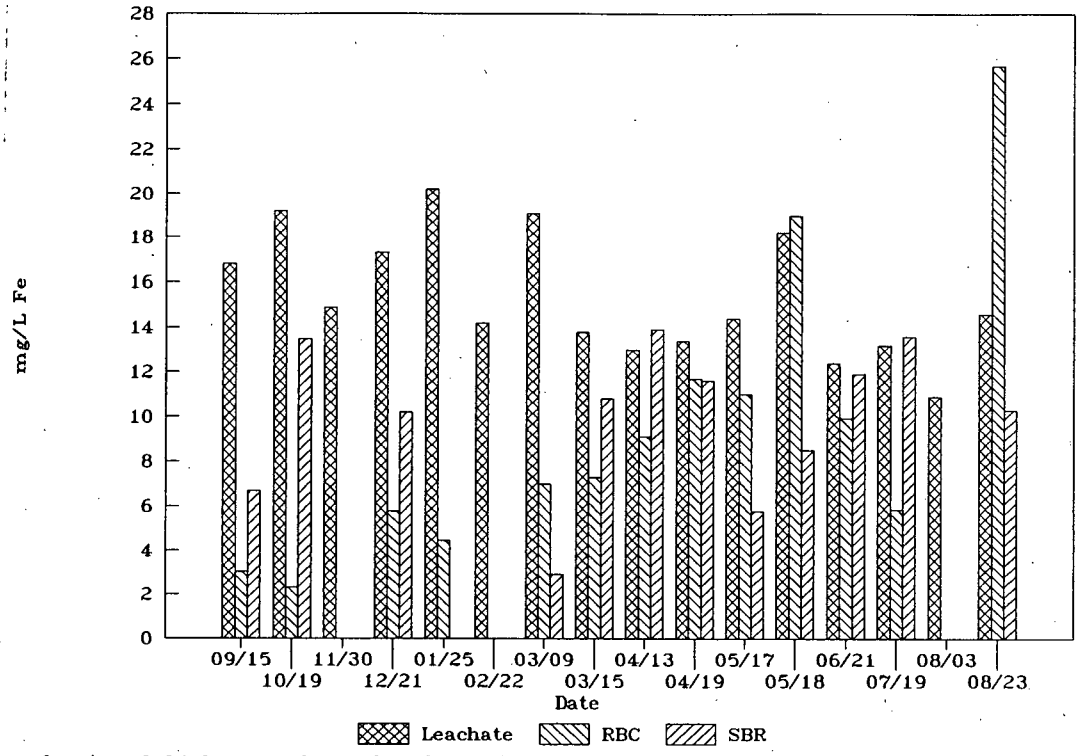
The detection limit for cobalt was 0.02 mg/L. Measurements ranged from 0.02 to 0.05 mg/L and averaged 0.034 mg/L. No significant differences were observed between leachate, effluent, dissolved, or total samples. Samples left in beakers were not significantly different than those preserved immediately.

4.4.4 Copper

The detection limit for copper was 0.01 mg/L. Measurements ranged from 0.01 mg/L to over 1 mg/L. Effluent results were always higher than leachate results, and dissolved results were always higher than total results. The nutrient solution added to the reactors was made using tap water and low grade (i.e. not reagent grade) Na_3PO_4. It is possible that the effluent results were higher than the total results due to contamination by the nutrient solution. While the chemical composition of the nutrient solution was not analyzed, it is not uncommon for water supplies in the area to have high copper concentrations.

Deionized distilled water with pure nitric acid added had a copper concentration of 0.02 mg/L, and distilled water plus acid measured 0.04 mg/L. The sample concentrations measured were typically between .02 and .04 mg/L for total samples. Dissolved samples were sometimes within this range, but

Figure 4.21: Leachate and Effluent Total Iron



were often much higher. Both total and dissolved samples were probably contaminated by the dilution water supply during the digestion process. Additional contamination in the dissolved samples may have occurred during filtration.

4.4.5 Iron

Figure 4.21 summarizes the total iron concentration data obtained in the study. Out of twelve occasions on which iron was measured in both systems, 7 showed superior RBC performance, 4 showed superior SBR performance, and 1 showed similar performance. RBC removal ranged from -76.0 to 88.0% and averaged 37.4%. If the minimum removal (-76%; a fairly clear outlier) is not included in the calculation, the average is 46.9%. SBR removal ranged from -6.9 to 84.8%, and averaged 32.3%. Excluding the highest and/or lowest removals from the calculations makes very little difference to the average SBR removal value. In general, the RBC was somewhat more successful in removing total iron than the SBR.

Measurement of leachate and effluent dissolved iron was only undertaken on three occasions. Effluent dissolved iron measurements for both systems exceeded leachate dissolved iron twice. On one occasion, the SBR dissolved iron level was far above the total leachate level, indicating possible contamination.

On the other two occasions, the SBR had lower dissolved iron than did the RBC, but the measurements were fairly close together. It is probable that the RBC removed more total iron than the SBR due to better effluent settling characteristics.

In general, the dissolved iron concentration was a small fraction of the total, particularly for the leachate.

Samples left in beakers during *Daphnia* LC_{50} tests generally showed significant removals of both total and dissolved iron. This was probably due to precipitation of $Fe(OH)_3$.

4.4.6 Lead

Lead was only measured by the City's laboratory (Cantest). No lead was detected in any leachate or effluent samples. The detection limit was 0.08 mg/L.

4.4.7 Manganese

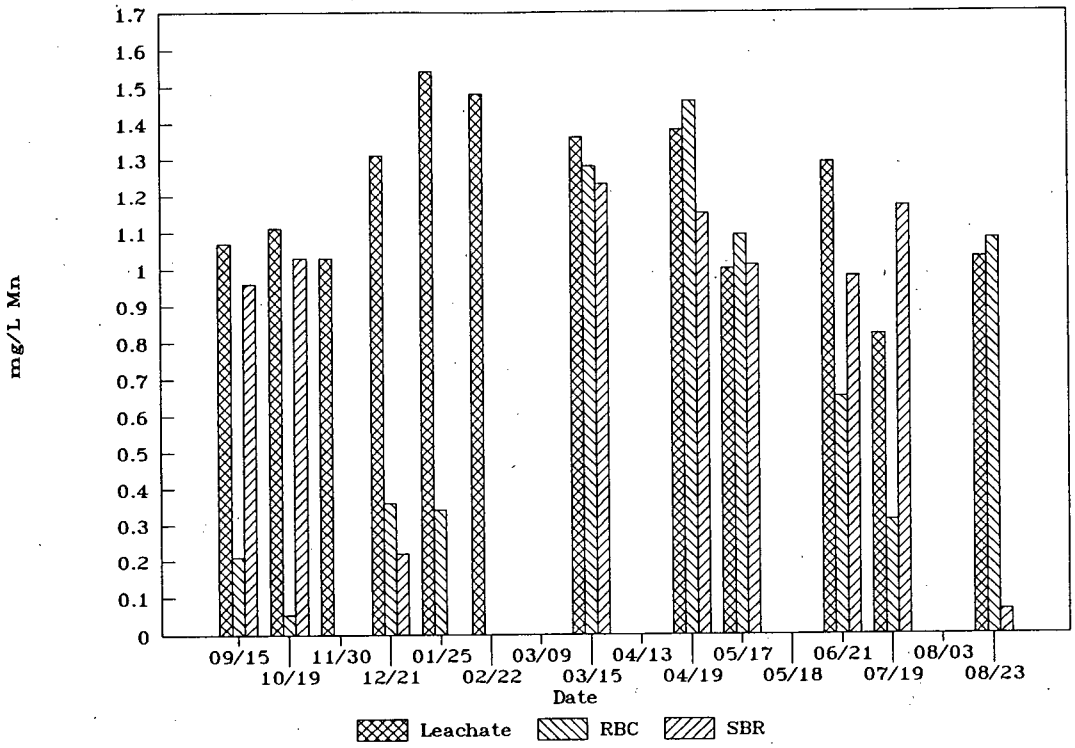
Figure 4.22 summarizes total manganese measurements taken during the study. Out of 9 occasions on which total manganese measurements were obtained, the RBC effluent concentration was lower 4 times, and the SBR concentration was lower 5 times. RBC removals ranged from -9.0 to 95.2% and averaged 42.4%. SBR removals ranged from -47.0 to 93.8% and averaged 22.3%. The average works out to 30.5% if the -47.0 point is removed from the calculation, but no significant changes to either system's average are obtained if the top and bottom points are removed from the calculations.

While the SBR's effluent total manganese concentration was often lower than the RBC's, the SBR's two best manganese removals occurred on Dec. 21/93 and on Aug. 23/94. The SBR was not removing significant NH_x-N on either of these occasions due to near total losses of MLSS, so these removals can not be attributed to uptake by nitrifying organisms.

4.4.8 Nickel

Figure 4.23 summarizes total nickel data obtained during the study. While the SBR tended to have a lower total nickel concentration than the RBC, both effluents tended to have higher concentrations than the leachate. RBC removals ranged from -42.9 to 16% and averaged -7.2%. Positive nickel removals were only measured 3 times. SBR removals ranged from -21.4 to 14.3% and averaged -3.3%, also with three positive removals. There could have been a source of nickel in each system, such as the stainless steel

Figure 4.22: Leachate and Effluent Total Manganese



bar used as a weight on the SBR aeration tube, and perhaps some fasteners in the RBC. The nutrient solution may also have been a source of nickel contamination.

While three sets of dissolved nickel measurements were attempted, the dissolved nickel concentration was typically higher than the total nickel concentration. Stainless steel filter apparatus used in filtration was probably the source of sample contamination. Since all metal analysis was performed on preserved samples at the conclusion of the study, there was no opportunity to correct this error.

There was no significant change in total nickel concentration when samples were left standing in beakers during *Daphnia* LC_{50} tests.

4.4.9 Zinc

Figure 4.24 summarizes total zinc measurements obtained during the study. The RBC achieved a positive total zinc removal on 6 out of 13 occasions on which leachate and RBC effluent zinc were determined. Removals ranged from -122.9 to 47.8% and averaged -4.8%. Average removals of 5.0 and 15.4% are obtained by excluding the lowest one and two removals from the calculations, respectively.

The SBR achieved positive removals on only 3 out of 12 occasions on which SBR effluent total zinc

Figure 4.23: Leachate and Effluent Total Nickel

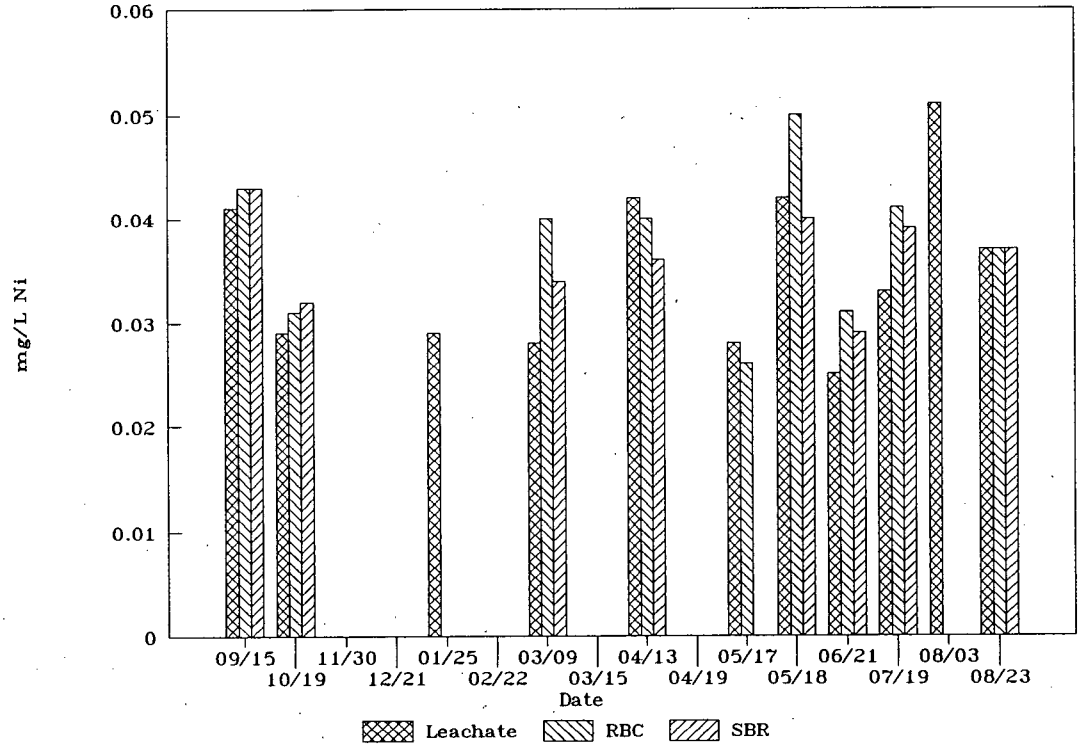
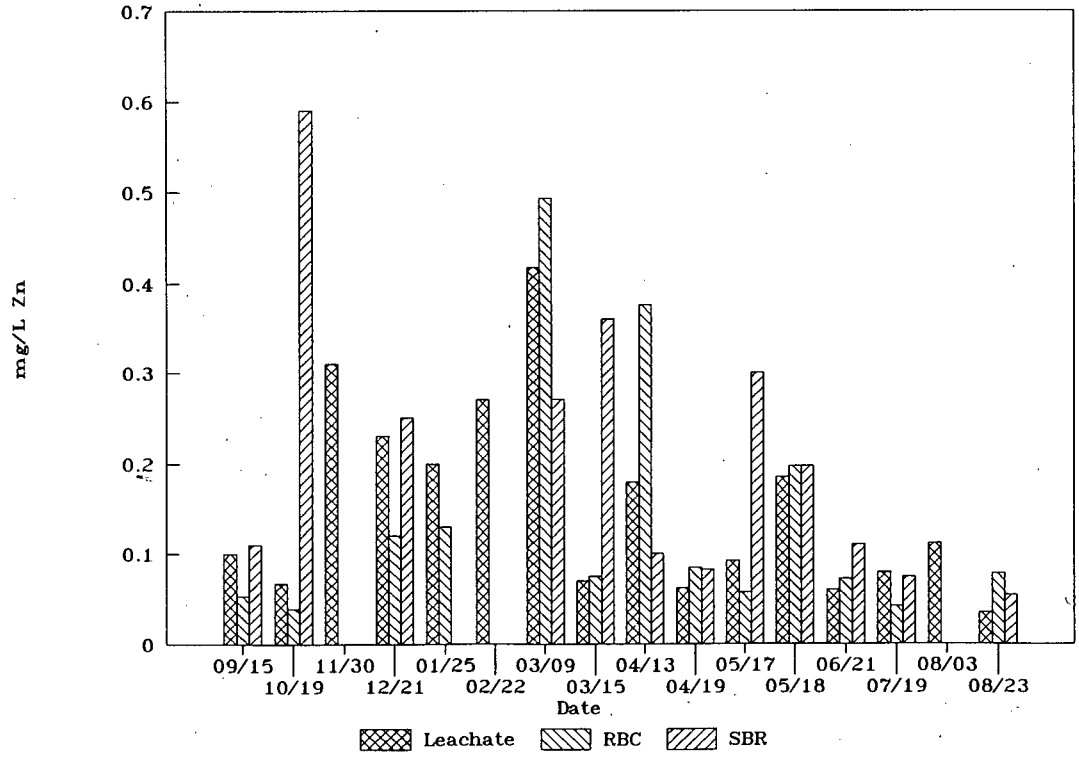


Figure 4.24: Leachate and Effluent Total Zinc



was determined. While removals ranged from -780.6 to 44.4% and averaged -127.5, the three lowest removals were significantly different from all the other data. However, exclusion of these points from the calculation still yields an average removal of -12.1%.

The frequent occurrence of negative removals in both systems indicates that there may have been an intermittent source of zinc contamination in both reactors. The author's samples were mixed on site in a galvanized bucket in order to achieve combined samples for toxicity, metals, and other analyses. However, leachate and effluent samples were treated equally, zinc concentrations were high relative to the detection limit, and City results were similar to the author's, so it is doubtful that the bucket caused a problem. The nutrient solution is another possible source of zinc contamination.

The dissolved zinc concentration was typically a small fraction of the total for effluent and leachate samples. The RBC and SBR effluents had similar dissolved zinc concentrations. Samples left standing during *Daphnia* LC_{50} tests typically had significantly lower total zinc concentrations and similar dissolved zinc concentrations, compared to samples preserved immediately after collection.

4.4.10 Summary of Metal Removal Results

No indication of performance based on chromium, copper, lead or nickel could be obtained due either to poor results or to extremely low concentrations. No significant removals of cadmium or cobalt were achieved by either system.

The RBC performed better in terms of iron and manganese removal, with removals averaging approximately 40% compared to the SBR's 30%. While frequent negative total zinc removals were obtained by both systems, the RBC system achieved more positive removals. However, the zinc results are suspect due to the high number of negative removals.

4.5 Toxicity

4.5.1 Rainbow Trout LC_{50}

One of the initial aims of the experiment was to directly compare the city's monthly rainbow trout LC_{50} data to Microtox EC_{50} and *Daphnia* LC_{50} tests based on a shared sample. A relationship between leachate ammonia concentration and fish LC_{50} was discovered by the City in February 1994, and as a result the conditions of the discharge permit changed so that after April 1994 the City was required to perform fish LC_{50} tests quarterly rather than monthly. As a result, toxicity tests were only performed

Table 4.20: Fish LC_{50} Correlation Calculations

Leachate Constituent	$\ln(LC_{50})$ vs. $\ln(X)$		LC_{50} vs. 1/X	
	R^2	X-Coefficient	R^2	X-Coefficient
NH_x-N	0.64	-0.95	0.78	2092
Cu	0.03	-0.89	0.01	0.55
Zn	0.26	0.41	0.24	-0.83
Ni	0.10	0.58	0.13	-0.24
Mn	0.52	2.32	0.51	-35.7
Fe	0.05	0.33	0.06	-107

on three shared leachate samples.

The three shared samples each had a 96 hour rainbow trout LC_{50} value of 13%. Fish toxicity values reported by the City during 1993 and 1994 ranged from 7 to 24%.

Since a reliable comparison between fish, *Daphnia* and Microtox can not be made with only three points, toxicity comparisons will be primarily based on correlations between toxicity measurements and chemical analyses of leachate. The first step in this process is determining the leachate constituents associated with fish toxicity.

Table 4.20 gives the results of calculations based on City data obtained in the first 9 months of 1993 (prior to the study). Chemical analyses were performed on 24 hour composite samples, and LC_{50} tests were performed on a grab sample taken at the end of the 24 hour period. All metals are totals. While measurements of chromium, lead, cadmium, molybdenum, and cobalt were also taken during this time, these metals were seldom detected, and therefore there was insufficient data to show correlations with toxicity. Calculated R^2 values are based on linear regressions. Regressions were done on a ln-ln basis first, but when the x-coefficient of NH_x-N was found to be near -1, the LC_{50} versus 1/X relationship was evaluated.

Table 4.20 clearly shows that fish LC_{50} is correlated with NH_x-N concentration to a much greater degree than the metals, and that the LC_{50} versus $1/NH_x$-N relationship is better than the ln-ln relationship. The positive x-coefficient of the LC_{50} vs. $1/NH_x$-N relationship indicates that LC_{50} decreases with increasing NH_x-N concentration. Since a low LC_{50} indicates a high toxicity, this means that toxicity increases with increasing NH_x-N concentration. The negative x-coefficient of the ln-ln relationship indicates the same general trend. Out of the five metals shown, only copper has x-coefficients with the same sign as NH_x-N, and its R^2 values are very low. All of the other metals have higher R^2 values than

copper. However, their x-coefficients have the opposite sign to NH_x-N's x-coefficient, indicating decreasing toxicity with increasing concentration. Since toxicity of a solution does not typically decrease as the concentration of a toxic substance increases, it is clear that the other metals have even less influence on toxicity than copper. Therefore, it seems obvious that NH_x-N has the greatest influence on leachate toxicity.

The City calculated the relationship in Equation 4.6 using the 1993 data and 3 points from a 1977 investigation [6]. While the 1977 data may not seem relevant due to its age, it is the only other rainbow trout LC_{50} data available based on Vancouver Landfill leachate. The 1994 data fit into the relationship in Equation 4.6 well; adding them into the calculations does not significantly change the constants or the R^2 value. However, a better correlation ($R^2 = 0.906$) is achieved by the relationship given in Equation 4.7. If the 1977 points are not used in the calculations, the R^2 value is 0.78 and the x-coefficient is 2098; these values are very similar to values obtained using data from the first 9 months of 1993 (see Table 4.20). The constant in Equation 4.8 is calculated by using the same data (all data) as Equation 4.7 and setting the y-intercept to zero. Equation 4.8 fits the data similarly ($R^2 = 0.902$) to Equation 4.7, and is simpler; therefore, it will be used when comparing fish LC_{50} data to *Daphnia* and Microtox data in the following sections. While the constants change depending on which data is included in the regression, the lines drawn using the constants are fairly close together (see Figure 4.25). Figure 4.25 also illustrates the importance of the 1977 data; the two right most points belong to the 1977 data set, and no other fish data in the high LC_{50} (i.e. low toxicity) range is available for this leachate.

$$T = 40.3e^{-0.00606N} \tag{4.6}$$

Where:

T = Rainbow trout LC_{50} (%)

N = NH_x-N concentration (mg/L)

R^2 = 0.67

$$T = 2407/N - 1.28 \tag{4.7}$$

$$T = 2259/N \tag{4.8}$$

While fairly good correlations are achieved by comparing NH_x-N concentration to fish LC_{50} the toxic component of NH_x-N is usually considered to be free NH_3-N. NH_3-N concentrations were calculated using NH_x-N and pH data with $K_a = 6.053 \times 10^{-10}$. The K_a value was taken from reference [46] assuming a temperature of 15°C, since LC_{50} tests were done with temperature kept between 14 and 16°C. However, the best R^2 value which could be calculated from these data was only 0.50. Figure 4.26 illustrates the relative lack of correlation between NH_3-N and fish LC_{50} in comparison to NH_x-N.

4.5.2 *Daphnia* LC_{50}

Previous work at UBC has indicated that *Daphnia* LC_{50} correlates well with rainbow trout LC_{50} for landfill leachate [9]. In this study, *Daphnia* testing was performed in conjunction with fish testing 3 times, and 9 data points were obtained (3 leachate and 3 of each effluent). Figure 4.27 shows the *Daphnia* data together with fish data taken simultaneously and the fish LC_{50}/NH_x-N relationship given in Section 4.5.1. The *Daphnia* data correlate well with the LC_{50}/NH_x-N relationship. Four of the effluents tested showed no *Daphnia* toxicity (i.e. $LC_{50} > 100\%$). On each occasion, the NH_x-N concentration was 2 mg/L or less; i.e. removal of NH_x-N corresponds to removal of toxicity.

Unlike the fish data, the *Daphnia* correlates well with the free NH_3-N data. The R^2 value for LC_{50} versus $1/NH_3$-N is 0.83, provided that NH_x-N and pH data from the end of the *Daphnia* experiment are used to calculate free NH_3. If the data from the beginning of the *Daphnia* experiment are used, R^2 is only 0.02. The R^2 values for NH_x-N are 0.88 and 0.90 for before and after data, respectively. Perhaps the fish data would also correlate better with free NH_3 data if end-of-experiment pH and NH_x-N data were available. If free NH_3 were the toxic component of NH_x, one would expect NH_3 to correlate better with the toxicity data. One possible reason for the slightly poorer correlation (0.83 vs. 0.90) is that different dilutions of sample used in the LC_{50} tests would have somewhat different pH values, so that the NH_3-N fraction would not be constant from one dilution to the next.

No differences in toxicity removal which could not be accounted for by differences in NH_x-N concentration were observed between the RBC and SBR effluents.

4.5.3 Microtox EC_{50}

Figure 4.28 shows that Microtox EC_{50} does not correlate well with either fish LC_{50} or NH_x-N. This is not surprising, since EC_{50} values for NH_x-N reported in the literature range from 3600 to 4500 mg/L as NH_3 [44, 56].

Figure 4.25: Fish LC_{50} versus $1/NH_x$-N

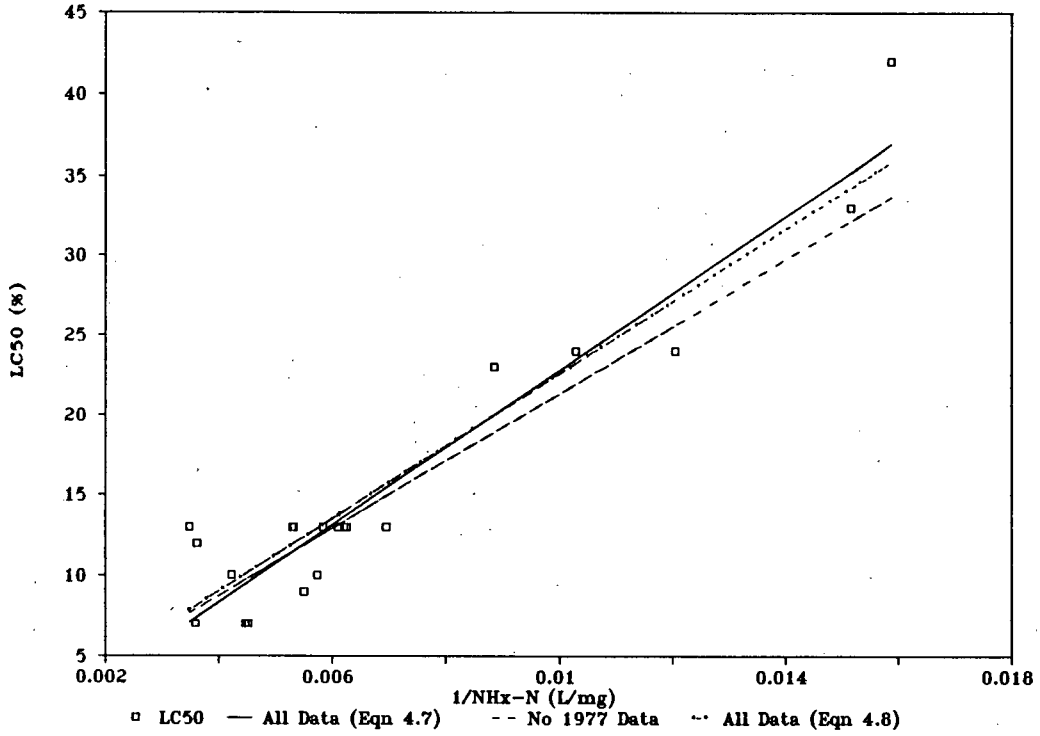


Figure 4.26: Relationship of NH_x-N and NH_3-N to Fish LC_{50}

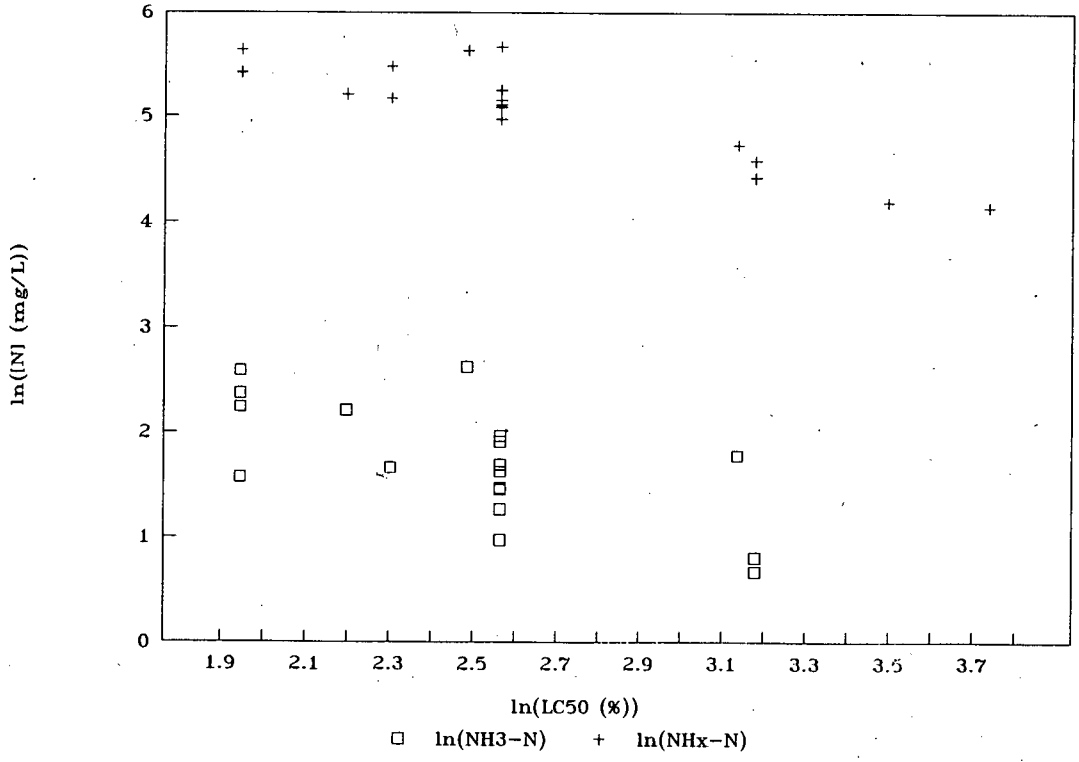


Figure 4.27: Relationship of *Daphnia* LC_{50} to Fish LC_{50} and NH_x-N

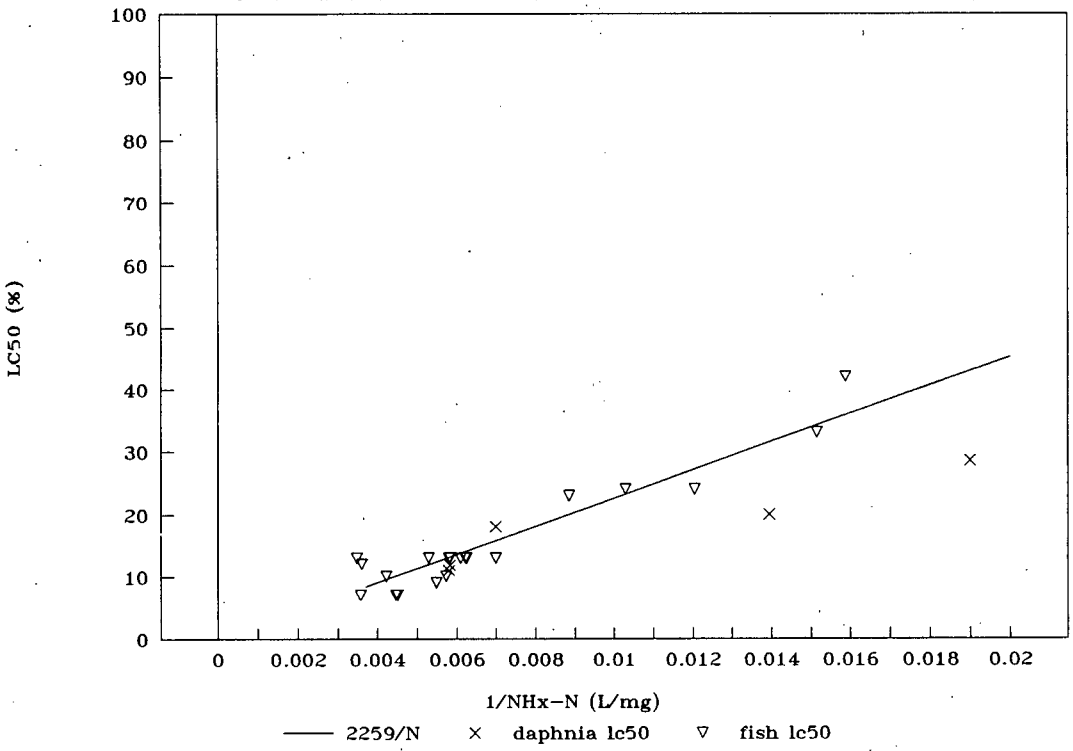
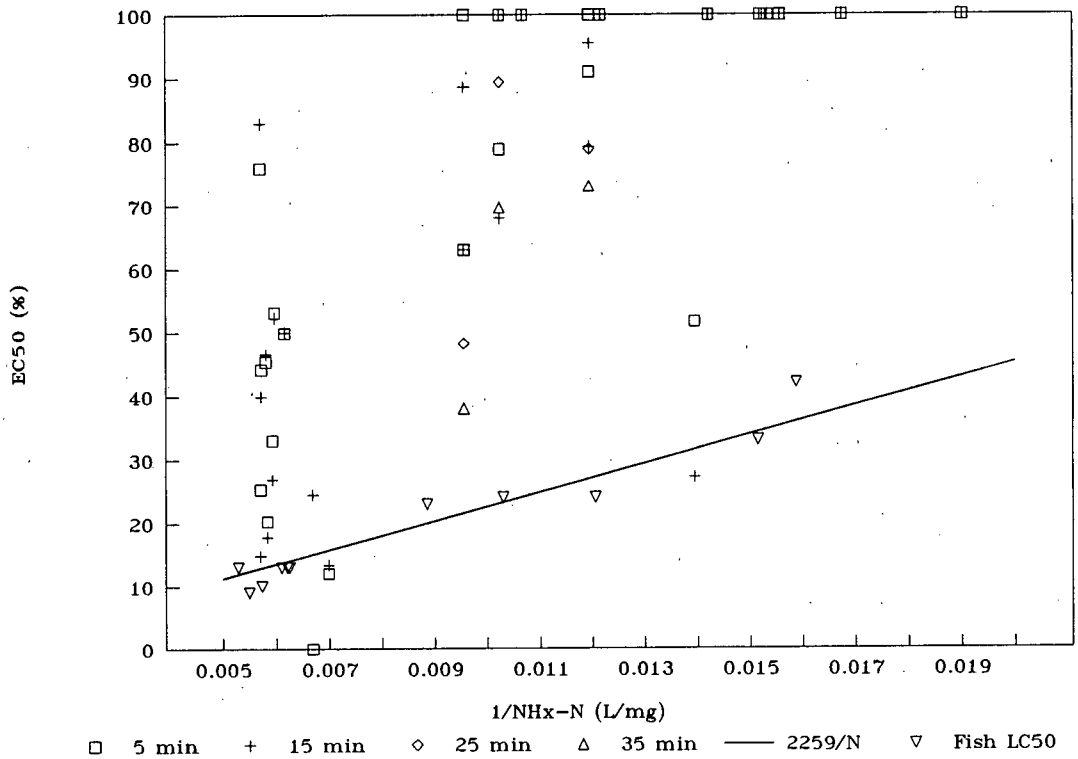


Figure 4.28: Relationship of Microtox EC_{50} to Fish LC_{50} and NH_x-N



One suggested cause of the decreased sensitivity of Microtox to NH_x is that the toxic component of NH_x is free NH_3, and Microtox diluent solutions tend to have low pH (eg between 6.0 and 6.5 compared to 7.3 to 7.8 for rainbow trout) [56]. Microbics indicates that pH between 6.3 and 7.8 causes no problems with light production, and Environment Canada widens this range to 6.0 to 8.5, based on an allowable pH range of 5.5 to 9.0 found in another study [18]. The pH values measured by the author in reference toxicants prepared with Microtox diluent or reconstitution solution ranged from 5.5 to 5.9, which seemed low at the time, but are fairly close to the values given by Qureshi et al [56]. However, even when these pH values are used to calculate free NH_3, the graph of EC_{50} versus $1/NH_3$-N looks very similar to Figure 4.28; the correlation between EC_{50} and $1/NH_3$-N is still very poor.

Microbics suggests that the sensitivity of the Microtox EC_{50} test to ammonia can be improved by using sucrose as the osmotic adjusting agent rather than NaCl [44]. Sucrose based Microtox EC_{50} tests were attempted several times in order to determine if the modified test would improve the correlation of the EC_{50} test to Rainbow trout LC_{50}. Sucrose diluent was made with reagent grade sucrose and progressively purer sources of dilution water, including distilled water, deionized distilled water, and finally Microtox reconstitution solution. As a control, normal diluent was made at the same time using reagent grade NaCl. While the home made NaCl diluent tended to be slightly toxic compared to the Microtox diluent (light losses from 0 to 33% after 5 minutes), home made sucrose diluent never came close to being non- toxic (light losses ranged from 50 to 68% after 5 minutes).

When samples were tested with sucrose diluent (100% test, dry sucrose added to 100% sample), the control typically had lower light readings than leachate or effluent samples (dilutions no. 2, 3, and 4). Although the control readings were higher than the 100% dilution's (no. 1), no result could be calculated. When samples were tested with reference toxicant solutions prepared in sucrose diluent, the responses had normal ratios (i.e. control > no. 4 > no. 3, etc.), but light levels in sucrose solutions were still approximately 50% lower than light levels in corresponding NaCl solutions.

While it is possible that light was absorbed by sucrose in the sucrose diluent, this seems unlikely since equal amounts of sucrose were added to all four dilutions of leachate and effluent, and all but the no. 1 dilution gave off more light than controls. Therefore, it appears that sucrose is toxic to *P. phosphoreum*. In the *Daphnia* LC_{50} test, one has to be very careful to provide healthy controls or the test is considered invalid (i.e. greater than 10% dead in control invalidates the test) [17]. Therefore, it seems rather strange to place a marine bacterium in a 20% sucrose solution rather than a 2% NaCl solution and to expect valid toxicity results. Because sucrose results were so poor, and because sucrose

appeared to be toxic to *P. phosphoreum*, the sucrose modification of the Microtox EC_{50} does not appear to be a valid test.

The EC_{50} value for ammonia determined in the sucrose test by Microbics is 124 mg/L as NH_3. This value is considerably higher than reported values for rainbow trout (62 mg/L of NH_x as NH_3, or 1.4 mg/L free ammonia) [56]. Therefore, whether or not the sucrose test is valid, it is clear that the Microtox EC_{50} test is not as sensitive to ammonia as the rainbow trout LC_{50} test. A substitute bioassay should either correlate well with the substituted bioassay, or be more sensitive. Therefore, Microtox EC_{50} is not a good substitute for rainbow trout LC_{50} for Vancouver Landfill leachate, and probably would not be a good substitute for any other waste water in which ammonia was the main toxic component.

On three of the occasions when Microtox EC_{50} tests were performed, metal analyses (total and dissolved Cd, Co, Cr, Cu, Fe, Ni, and Zn) were also performed. This would have given a total of 9 data points for each metal, but in two cases the effluent EC_{50} values were both $> 100\%$, so there were only 5 useful points for each metal. No correlations or trends worth mentioning were found. The source of Microtox EC_{50} toxicity in the leachate is therefore unknown.

Both RBC and SBR effluents were almost always non-toxic, and no differences in toxicity removal between the two systems were observed.

Chapter 5

Summary and Recommendations

5.1 Summary

Pilot scale RBC and SBR systems were compared in order to determine which system would be more cost effective for full scale treatment of Vancouver Landfill leachate. The leachate is an older leachate with NH_x-N concentrations between 83 and 336 mg/L, BOD_5 concentrations between 27 and 89 mg/L, and BOD_5:COD ratios between 0.06 and 0.19. The systems were primarily compared based on nitrification performance. Other topics compared included nitrogen balances, removal of $BOD_5$and COD, solids settlability, and metal removal. The possibility of using Microtox bioassays to predict the traditional fish toxicity determination for this leachate was also investigated. The main part of the study lasted from August 12, 1993 to September 7, 1994, for a total of 391 days.

In general, the RBC recovered from NH_x-N loading increases more quickly than the SBR did. However, loading increases to the SBR tended to be more severe.

The RBC unit used in this investigation was also used by Peddie [52]. Combined results indicated that this unit was capable of complete nitrification of NH_x-N loadings less than 1.2 $g/m^2/d$ at HRTs greater than 0.17 days; however, an HRT greater than 0.3 days was required for full NH_x-N removal at loadings between 2 and 8 $g/m^2/d$.

The RBC was operated successfully at an average loading/HRT of 4.15 $g/m^2/d$/0.35 days. However, loadings of 2 $g/m^2/d$ or less were required in order for effluent NO_2^--N levels to remain below 4 mg/L.

The RBC was unable to acclimatize to average loadings of 4.88 and 6.02 $g/m^2/d$ at HRTs of 0.27 and 0.17 days, respectively. In the latter case, insufficient HRT was likely responsible for the lack of acclimatization. In the former case, insufficient HRT was probably responsible, but phosphate limitation may also have played a role.

While the RBC was able to provide high NH_x-N removals at high NH_x-N loadings if the HRT was sufficient, incomplete nitrification was frequently observed, particularly during the HRT experiment. Free NH_3 inhibition and P limitation were investigated as possible causes of incomplete nitrification

during the HRT experiment; P limitation appeared to be the most likely explanation. While it was difficult to tell if NO_2^--N buildups observed during the rest of the experiment were caused by NH_3-N inhibition or P limitation, the results of the HRT experiment indicate that P limitation was most likely responsible.

The SBR achieved complete nitrification at an average loading of 107 $g/m^3/d$ when the HRT averaged 1.93 days. Complete NH_x-N removals were achieved at an average loading of 331 $g/m^3/d$ when the HRT averaged 0.71 days, but complete nitrification was not. Free NH_3 inhibition, HRT limitation, low dissolved oxygen concentration, and PO_4^{3-}-P limitation were investigated as possible causes of incomplete nitrification; again P limitation appeared to be the most likely explanation. During the final loading phase (580 $g/m^3/d$, 0.43 days), the SBR experienced total solids washout. The reason for this is unclear, but the SBR may have been HRT limited in addition to being P limited. NO_2^--N buildups experienced during the rest of the experiment were unexplained.

Process upsets occurred less frequently in the RBC than in the SBR, and the RBC was more likely to recover from upsets than the SBR. The SBR completely failed twice during the experiment, and it was unable to recover without heating and reinoculation in the first instance. Causes of process upsets in both systems included cold temperatures, mechanical failures, and power failures. The SBR was probably more susceptible to process upsets than the RBC because these events tended to cause solids washout in the SBR.

While both nutrient pump failure and cold temperatures are capable of causing process upsets on their own, the SBR was particularly affected when these two events coincided. This phenomenon was not apparent for the RBC system.

Both systems were able to perform at low temperatures. The RBC achieved a NH_x-N removal of 1.51 $g/m^2/d$ at only 2.5°C, and the SBR was able to remove 23.3 $g/m^3/d$ at only 3°C.

Average alkalinity consumption ratios for each system were higher than theoretically required for nitrification. This was probably due to precipitation of $CaCO_3$.

Nitrogen balance calculations were performed for both systems including and excluding organic nitrogen. In both cases, N losses in the SBR were greater than N losses in the RBC, but the differences were not significant. Lost N results determined in nitrogen balance calculations could easily be accounted for by sums of acceptable measurement errors.

The two systems performed similarily with respect to BOD_5 removal, but the RBC was superior in terms of COD and colour removal. While neither system produced large amounts of excess solids, the

RBC solids had better settling characteristics. Evidence of precipitation of inorganic solids was found for both systems, but neither system had scale problems.

No differences between the two systems were found in terms of cadmium or cobalt removal, and results based on chromium, copper, lead, and nickel were inconclusive. However, the RBC tended to remove about 40% of iron and manganese while the SBR removed 30%. Both systems tended to add rather than remove zinc, but the RBC was more likely to achieve positive removals.

Rainbow trout $LC_{50}$was found to vary with leachate NH_x-N according to the relationship $T = 2259/N$, where T = 96 hour LC_{50}(%) and N = NH_x-N concentration (mg/L), $R^2 = 0.90$. *Daphnia* LC_{50} results correlated well with fish results based on the above relationship, but Microtox EC_{50} results did not.

Both *Daphnia* and rainbow trout results correlated better with NH_x-N than with free NH_3-N. Free NH_3-N correlations could probably be improved if pH variations between sample dilutions could be accounted for or eliminated.

Microtox EC_{50} results did not correlate well with fish LC_{50}results because of the insensitivity of the Microtox test to ammonia. Using sucrose rather than NaCl as the osmotic adjustment agent is purported to increase the sensitivity of the Microtox test to ammonia. However, sucrose dilution water tended to be more toxic than all but the 100% leachate dilution. The usefulness of the sucrose modified Microtox test is therefore questionable. Even if the sucrose test is valid, published results indicate that the modified Microtox test is still much less sensitive to ammonia than the rainbow trout or *Daphnia* bioassays.

No differences in toxicity removal were observed between the RBC and SBR, other than differences in *Daphnia* toxicity which could be completely accounted for by NH_x-N concentration.

The RBC used in this experiment was a very simple system, and only loading could be varied. Other parameters such as rotational speed and % submergence of the disks were basically set by the manufacturer and were therefore probably near optimum values. Many more parameters could have been varied in the SBR system. Besides increasing the settling time in the reactor, no attempt was made to optimize the SBR cycle times. It therefore may not have been performing to its full potential. For example, information found in the literature indicates that the aeration cycle may have been too short. As such, this experiment may not have been a fair comparison of the two systems.

It is also possible that a completely mixed or plug flow continous flow system would have performed better than even a fully optimized SBR system, indicating that this experiment may not have been a fair comparison of suspended growth to fixed growth systems in general.

5.2 Recommendations

While this experiment may not have been a completely fair comparison of fixed and suspended growth systems, the RBC outperformed the SBR in every respect in which a difference was observed between the two systems. The major deficiency of the SBR was its inability to recover quickly from process upsets and loading increases, and the reasons for this are documented in other studies: the slow growth rate of nitrifying organisms, poor solids settlability in general, and even poorer solids settlability when stressed. Therefore, it is recommended that an RBC system should be used to treat the Vancouver landfill leachate at full scale.

Few studies have been done which directly compare the effectiveness of fixed and suspended growth systems. The original intent of this study was that a comparison based on cost effectiveness be made between two systems, both of which had been shown to be successful in treating the leachate in question. Unfortunately, the SBR seldom performed adequately, so a comparison based on cost effectiveness derived solely from this study would undoubtedly favour the RBC. If another study such as this is undertaken, each system should be optimized before attempting to make a comparison based on cost effectiveness.

Phosphate limitation was suggested as a possible cause for incomplete nitrification or slow acclimatization to a given NH_x-N loading several times for each system. It is obvious that more care should have been taken to prevent P limitation. Higher effluent PO_4^{3-}-P values should have been maintained and more membrane filtered PO_4^{3-}-P measurements should have been done. In future studies, it is recommended that more attention be paid to PO_4^{3-}-P.

Additions of leachate to the SBR were conducted by using a timed fill cycle and allowing excess leachate to overflow from the reactor. Any overflow has the potential to result in solids loss if mixing has occurred during filling. It is recommended that a level switch be used to determine when filling should stop in future SBRs in order to prevent overflow and solids loss.

Phosphate limitation may have been responsible for prolonged nitrite buildups in both systems. It is unclear whether these nitrite buildups could have been maintained for any length of time. More study is needed to determine if P limitation could be used to produce extended NO_2^--N buildups, particularly for the RBC, for which less data were available from this study. The ability to maintain a nitrite buildup could be useful in shortening the nitrification-denitrification pathway (as proposed by Turk and Mavinic [65]).

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Appendix A

Calculation Definitions

Note: Quantities defined for a previous section are not redefined.

Leachate N Data

NO_x^--N = NO_3^--N + NO_2^--N

NH_x-N = NH_3-N + NH_4^+-N

Alk. = Alkalinity in mg/L as $CaCO_3$

AVERAGE = overall average of all data

MAXIMUM = maximum value recorded

MINIMUM = minimum value recorded

Quantities following Loading Periods are averages calculated for that loading period.

RBC Nitrogen Data

Flow (L/d) = (Flow L/cyc)×(24 hr/d)×(60 min/hr)/(Fill Time min + 1 min)

HRT = (245 L)/(Flow L/d + Nut. Flow L/d)

NH_x-N Ldg. ($g/m^2/d$) = (Flow L/d)×(Leachate NH_x-N mg/L)×(1g/1000 mg)/(47 m^2)

NH_x-N Removal ($g/m^2/d$) = NH_x-N Ldg. - (Flow L/d)×(RBC NH_x-N mg/L)×(1g/1000 mg)/(47 m^2)

NH_x-N Rem. (%) = NH_x-N Removal/NH_x-N Ldg.×100%

NH_x-N+NO_x^--N Removal (%) = ((Leachate NH_x-N+NO_x^--N)-(RBC NH_x- N+NO_x^--N))/(Leachate NH_x-N)×100%

Alk:NH_x-N Removal = (Leachate Alk. - RBC Alk.)/(Leachate NH_x-N - RBC NH_x-N)

SBR Nitrogen Data

HRT = (365 L)/(Flow L/d + Nut. Flow L/d)

NH_x-N Loading ($g/m^3/d$) = (Leachate NH_x-N mg/L)×(Flow L/d)×(1g/1000 mg)×(1000 L/m^3)/(365 L)

NH_x-N Removal ($g/m^3/d$) = NH_x-N Loading - (SBR NH_x-N mg/L)×(Flow L/d)×(1g/1000 mg)×(1000 L/m^3)/(365 L)

NH_x-N Removal (%) = NH_x-N Loading/NH_x-N Removal×100

NH_x-N Loading (g/g/d) = (Leachate NH_x-N mg/L)×(Flow L/d)/(MLVSS mg/L)/(365 L)

NH_x-N Removal (g/g/d) = NH_x-N Loading (g/g/d) - (SBR NH_x-N mg/L)×(Flow L/d)/(MLVSS mg/L)/(365 L)

MLVSS = 0.62×MLSS if MLVSS not measured

RBC P and Misc. Data

Nutrient Addition (g/20 L) = g $Na_3PO_4 \cdot 12H_2O$ added to 20 L of Nutrient Solution

Nutrient Addition (mg/L) = ((Nutrient Addition g/20 L)×(1000 mg/g)/(20 L)) ×((mw P)/(mw $Na_3PO_4 \cdot 12H_2O$))× ((Nutrient Flow L/day)/(Flow L/day + Nutrient Flow L/day))

mw P = 30.9738 g

mw $Na_3PO_4 \cdot 12H_2O$= 30.9738+3×22.9898+16×15.9994+24×1.0079

Influent PO_4^{3-}-P (mg/L) = (Leachate PO_4^{3-}-P mg/L) + (Nutrient Addition mg/L)

Cond. mS = Conductivity μSiemens

Leachate TKN

TKN = Total TKN

TKN Diss. = Dissolved TKN

TKN:NH_x= TKN/NH_x-N

RBC TKN

Organic N Removed (mg/L) = (Leachate TKN - NH_x-N) - (RBC TKN - NH_x-N)

TKN Rem ($g/m^2/d$) = ((Leachate TKN mg/L) - (RBC TKN mg/L))×(Flow L/d)×(1g/1000 mg)/(47 m^2)

NH_x-N Rem:TKN Rem = (NH_x-N Rem $g/m^2/d$)/(TKN Rem $g/m^2/d$)

Lost N (%) = ((Leachate TKN + NO_x^--N) - (RBC TKN + NO_x^-- N))/(Leachate TKN + NO_x^--N)×100%

Total N Rem (%) = ((Leachate NH_x-N + NO_x^--N) - (RBC NH_x-N + NO_x^--N))/(Leachate NH_x-N + NO_x^--N)×100%

(misnomer, should be NH_x-N+NO_x^--N removal)

SBR TKN

TKN Rem ($g/m^3/d$) = (Leachate TKN - SBR TKN mg/L)×(Flow L/d)×(1g/1000 mg)(1000 L/m^3)/(365 L)

NH_x-N Rem:TKN Rem = (NH_x-N Rem $g/m^3/d$)/(TKN Rem $g/m^3/d$)

Miscellaneous Leachate Data

BOD:COD = BOD_5/COD

RBC Organics

COD Loading ($g/m^2/d$) = (Flow L/d)×(Leachate COD mg/L)×(1g/1000 mg)/(47 m^2)

COD Removal ($g/m^2/d$) = COD Loading ($g/m^2/d$) - (Flow L/d)×(RBC COD mg/L)×(1g/1000 mg)/(47 m^2)

BOD Loading ($g/m^2/d$) = (Flow L/d)×(Leachate BOD_5 mg/L)×1g/1000 mg)/(47 m^2)

BOD Removal ($g/m^2/d$) = BOD Loading ($g/m^2/d$) - (Flow L/d)×(RBC BOD_5 mg/L)×(1g/1000 mg)/(47 m^2)

COD Removal (%) = (COD Removal)/(COD Loading)×100%

BOD Removal (%) = (BOD Removal)/(BOD Loading)×100%

COD:BOD Removal = (COD Removal $g/m^2/d$)/(BOD Removal $g/m^2/d$)

Colour Removal = (Leachate Colour - RBC Colour)×100%

TSS = RBC last stage MLSS

TSS Stld. = RBC last stage MLSS settled for 30 minutes

SBR Organics

COD Loading ($g/m^3/d$) = (Leachate COD mg/L)×(Flow L/d)×(1g/1000 mg)×(1000 L/m^3)/(365 L)

COD Removal = COD Loading ($g/m^3/d$) - (SBR COD mg/L)×(Flow L/d)×(1g/1000 mg)×(1000 L/m^3)/(365 L)

COD Removal (%) = (COD Removal $g/m^3/d$)/(COD Loading $g/m^3/d$)×100%

BOD Loading ($g/m^3/d$) = (Leachate BOD_5 mg/L)×(Flow L/d)×(1g/1000 mg)×(1000 L/m^3)/(365 L)

BOD Removal = BOD Loading ($g/m^3/d$) - (SBR BOD_5 mg/L)×(Flow L/d)×(1g/1000 mg) ×(1000 L/m^3)/(365 L)

BOD Removal (%) = (BOD Removal $g/m^3/d$)/(BOD Loading $g/m^3/d$)×100%

COD:BOD Removal = (COD Removal $g/m^3/d$)/(BOD Removal $g/m^3/d$)

Metals

Metal Removal (%) = (Leachate Metal - Effluent Metal)/(Leachate Metal)×100%

Toxicity Data

Quantities are defined on data sheets

Appendix B

Raw and Calculated Data

Leachate N Data

Date	Day	Flow	Airpt. Precip.	Airpt. Temp	Air Temp	Temp	Cond.	Site pH	pH	TSS	Alk.	NO3-N	NO2-N	NOx-N	NHx-N	PO4-P
		m³/day	mm	°C	°C	°C	mS			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
08/12/93	0	0	0	17.6					7.4	70	2870	0.32	0.00	0.32	305	0.31
08/24/93	12	0	0	15.7		20			7.8	50	2720	0.00	0.02	0.02	336	0.33
08/31/93	19	946	0	15.4		20			7.2	60	3140	0.20	0.06	0.26	293	0.52
09/02/93	21	893	0	18.3										14.90	315	0.86
09/08/93	27	893	0	16.6		20			7.2	125	3210	0.04	0.00	0.04	290	0.68
09/09/93	28	899	0	19.2	22	21	6.74	7.4						7.76	276	0.38
09/10/93	29	858	0	18.9										0.87	280	0.32
09/15/93	34	854	0	13.9		17.25			7.4	43	2950	0.33	0.00	0.33	331	0.66
09/16/93	35	800	0	14.3	16.5	16.5	6.3	7.6							300	
09/21/93	40	962	0	10.9	14.5	16	5.9	7.6	7.43	62	3650	0.64	0	0.64	304	0.84
09/29/93	48	978	0	14.3		16.5			7.4	50	2910	0.08	0.00	0.08	289	
10/01/93	50	879	0	13.6										16.03	250	0.18
10/05/93	54	938	1.4	11.4	18.4	14.75	6.1	7.5	7.3	109	3420	0.04	0.00	0.04	307	0.88
10/12/93	61	956	1.5	14.6	17.5	17.5	6.34	7.6	7.9	58	2590	0.83	0.00	0.83	299	0.73
10/19/93	68	957	0	11	16	17.5	6.04	7.5	7.5	56	2470	0.36	0.00	0.36	273	0.58
10/27/93	76	1470	0	7.5		14			7.7	103	3360	1.10	0.23	1.33	204	0.65
11/02/93	82	2095	11.9	9.9	11	12	4.6	7.5	7.2	74	3810	0.68	0.00	0.68	191	0.39
11/05/93	85	2025	0	7.3										1.00	173	0.36
11/09/93	89	1724	0	3.6	8	9.5	4.75	7.4	7.1	73	1850	0.03	0.00	0.03	192	0.31
11/12/93	92	1580	0	4.5	6	8.5	4.18	7.3						1.49	159	0.36
11/16/93	96	1997	0	4.3	12	11	4.72	7.3	7.2	82	1760	0.60	0.03	0.63	190	0.80
11/18/93	98	1704	0	3.4	3	7	4.34	7.5						2.535	155.2	0.221
11/30/93	110	2655	6.8	4.5	6	8.5	3.69	7.3	7.3	46	1650	0.02	0.01	0.03	144	0.99
12/08/93	118	5192	14.7	6.4	7.5	10	3.73	7.4	7.2	173	1700	0.02	0.01	0.03	100	0.69
12/14/93	124	6543	4.4	7.3	9	11			7.1	37	1250	0.68	0.00	0.68	85.5	0.10
12/21/93	131	3486	0	1.6	0.5	7	4.11	7.23	7.5	54	1700	0.03	0.00	0.03	147	0.13
12/29/93	139	3316	4.6	4.9	3	9	4.98		7.3	79		0.03	0.00	0.03	183	0.00
01/04/94	145	8359	13.4	8.5	8.75	9.5	2.41		7.3	106		3.40	0.01	3.41	101	0.00
01/05/94	146	6128	0.4	5.8	7	8.5	3.21								85	
01/11/94	152	5772	3	7.4	8	10	3.27	7.1	7.1	31	1005	0.57	1.10	1.67	96	0.05
01/13/94	154	7045	6.8	9.6	10	11	3.05							0.78	83	0.12
01/17/94	158	4160	0	6.5										0.78	141	0.28
01/18/94	159	4009	0.8	5.1	6	10	4.18	7.3	7.1	174	1940	0.03	0.00	0.03	148	0.04
01/20/94	161	3733	0	4.6	1.5	8	4.75	7.3			1576			1.06	153	0.32
01/24/94	165	4297	0.2	6.9	8	12		7.1			1185			2.65	126	0.28
01/25/94	166	3724	0	7	7.5	10.5	4.11	7.2	8.0	99	1950	0.05		0.05	121	0.21
01/27/94	168	3304	0	6.2	7	11	3.9							0.72	148	0.28
01/28/94	169	3216	0	3.8	3	9	4.5	7.0						0.80	145	0.34
02/01/94	173	2977	0	-0.7	5	8.5	5.1	7.0	8.0	64	2220	0.66	0.00	0.66	153	0.06
02/03/94	175	2665	0	1.9										1.16	177	0.31
02/08/94	180	2600	1.2	-2.5	-1	5.5	5.51	7.4	7.8	56	2310	0.03	0.00	0.03	179	0.12
02/09/94	181	2381	7.2	2.3	1	5	4.73	7.6						1.07	172	0.30
02/11/94	183	2609	3.8	3	5.5	9								0.42	158	0.32
02/13/94	185	3249	9.6	4.7	7	9	3.8	7.4				1.90	0.00		138	
02/14/94	186	3604	4.8	5.5	6	7.5								3.33	153	0.35
02/15/94	187	4382	5.2	8.2	8	9	3.7		7.6	67	1480	1.40	0.01	1.41	128	0.03
02/18/94	190	5581	0.2	5.4	6	8.5	3.1							0.96	92	0.25
02/21/94	193	4222	4.8	4	6	9.5	3.8							0.65	140	0.32
02/22/94	194	4353	3.2	3.9	4.5	7.5	4.4		7.4	50	1720	0.15	0.15	0.30	132	0.05
02/23/94	195	3928	0	3.5	2.5	6								1.20	132	0.26
02/25/94	197	4059	6.2	-0.7	0.5	6	4.53							2.06	133	0.27
02/26/94	198	4811	8	4.9	5	9	3.03	7.3				0.72	0.00	0.72	140	
02/28/94	200	8445	12.2	9.7	9.5	10.5								1.07	98	0.26
03/03/94	203	10278	6.2	7.6	9.5	12	3.64	7.2	8.0	53	1540	0.04	0.00	0.04	241	0.07
03/04/94	204	7692	5.2	8.8	9.5	11	3	7.4						0.63	114	0.21
03/07/94	207	5073	0	4.6	3.5	8.5								0.42	130	0.29
03/08/94	208	4779	0	5.2	9.5	13		7.2	7.2	49	1830	0.33	0.00	0.33	168	0.05

Leachate N Data

Date	Day	Flow	Airpt. Precip.	Airpt. Temp	Air Temp	Temp	Cond.	Site pH	pH	TSS	Alk.	NO3-N	NO2-N	NOx-N	NHx-N	PO4-P
		m³/day	mm	°C	°C	°C	mS			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
03/10/94	210	4157	3.2	7.5	8	12								1.05	133	0.09
03/14/94	214	3666	0	8.7		12.5								0.45	160	0.29
03/15/94	215	3568	0.6	8.7		14		7.5	7.6	64	2200	0.03	0.00	0.03	176	0.04
03/16/94	216	3535	9.6	6.5		13								1.38	181	0.15
03/17/94	217	3928	9.8	5.7		9		7.7						0.13	166	0.12
03/21/94	221	2946	6.2	4.1		9		7.3						0.03	179	0.17
03/22/94	222	3011	10.6	3.8		16		7.3	7.5	55	1990	0.54	0.00	0.54	196	
03/23/94	223	2684	0.8	4.8		10									162	0.28
03/24/94	224	2821	0	4.4		11		7.4							169	0.26
03/30/94	230	2301	0	10.5		13								0.16	182	0.24
03/31/94	231	2411	0	9.8		19.5		7.5	7.8	71	2330	0.04	0.00	0.04	206	0.07
04/05/94	236	2932	1.2	8.9		14		7.5	7.6	53	2510	0.05	0.00	0.05	200	0.04
04/06/94	237	2905	19.2	7.5		10.5								1.72	150	0.16
04/07/94	238	3153	3.2	9.1		11		7.5						1.09	175	0.28
04/12/94	243	2415	9.4	9.6		17		7.5	7.8	53	2060	0.05	0	0.05	175	0.05
04/13/94	244	2491	0.8	9.2										1.07	172	0.33
04/14/94	245	2436	0.4	7.9		13.5								1.61	175	0.28
04/19/94	250	2000	1.8	14.4		21			7.4	53	2400	0.06	0	0.06	196	0.06
04/20/94	251	2134	0	11.1		18.5								0.57	175	0.20
04/21/94	252	2087	6.8	13.3		14.5								0.77	168	0.21
04/26/94	257	1755	1.2	12.7		17			7.9	30	2440	0.02	0	0.02	243	0.07
04/27/94	258	1741	0	12.9		17								0.57	231	0.19
04/28/94	259	1763	0	13.1		18.5								0.55	177	0.21
05/03/94	264	1710	0	9.8		16.5			7.7	40	2500	2.70	0	2.70	243	0.06
05/04/94	265	1756	3.4	13.2		15								0.42	234	0.58
05/05/94	266	1595	0	12		16.5								0.41	194	0.33
05/10/94	271	5391	0.2	16.5		22			7.6	18	2610	0.95	0	0.95	281	0.08
05/17/94	278	1432	0	14.2		22			7.9	107	2130	0.27	0	0.27	282	0.04
05/18/94	279	2355	0	14.8		18								1.54	264	0.18
05/19/94	280	1335	0	16		21								1.12	244	0.05
05/24/94	285	1133	0	17.4		25.5			8.0	75	2750	0.02	0	0.02	266	0.11
05/26/94	287	1246	0	13.4		21								3.27	220	0.00
05/30/94	291	1456	0	12.9		16.5								1.04	215	0.38
05/31/94	292	1179	4.6	14.2		19			7.8	57	2770	0.79	0	0.79	262	0.12
06/06/94	298	1390	5.3	13.5		17.5								0.96	238	0.15
06/07/94	299	1136	0	12.6		17.52			7.8	308	2590	0.00	0	0.00	257	0.14
06/08/94	300	773	0	15		18.5								1.58	234	0.10
06/14/94	306	1388	5.4	13.1		17			7.5	61	1880	0.04	0	0.04	243	0.04
06/17/94	309	1837	0	14.4		21								0.32	206	0.30
06/21/94	313	1394	0	16.9		24.5			7.5	10	2580	0.03	0	0.03	263	0.19
06/24/94	316	1502	0	15.1		17.5								0.70	213	0.34
06/28/94	320	1204	0	18.9		19.5			7.7	74	2590	0.00	0	0.00	244	0.23
07/05/94	327	1496				18			7.7	48	2510	0.00	0.00	0.00	241	0.47
07/12/94	334	1132				20			7.7	106	2550	0.00	0.00	0.00	220	0.05
07/19/94	341	0				21			7.6	70	2800	0.02	0.00	0.02	246	0.15
08/05/94	358					21			7.43	62	2810	0.12	0	0.12	274	1.1
08/09/94	362					21			7.15	32	2730	0.04	0	0.04	242	1.6
08/16/94	369					19.5			7.79	42	2890	0	0	0	238	0.9
08/23/94	376					23			7.64	26	2490	0.02	0	0.02	273	0.8
09/01/94	385					21			7.54	56	2900	0.05	0	0.05	301	1.2
09/07/94	391					20			6.77	46	2770	0.02	0	0.02	322	1.5
09/29/94						17			7.84	51	2850	0.15	0	0.15	213	1.4
10/05/94						17			7.8	18	2470	0	0	0	258	1.5
10/20/94						13			7.36	18	2380	0	0	0	233	0.83
10/26/94						13.5			8.54	57	1670	0.03	0	0.03	183	0.78

Leachate N Data

Date	Day	Flow	Airpt. Precip.	Airpt. Temp	Air Temp	Temp	Cond.	Site pH	pH	TSS	Alk.	NO3-N	NO2-N	NOx-N	NHx-N	PO4-P
		m³/day	mm	°C	°C	°C	mS			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
	AVERAGE	2798	2.52	9.3	7.62	14.17	4.36	7.37	7.51	70	2380	0.38	0.03	1.11	199.5	0.32
	MAXIMUM	10278	19.20	19.2	22.00	25.50	6.74	7.67	8.02	308	3810	3.40	1.10	16.03	336.0	1.60
	MINIMUM	0	0.00	-2.5	-1.00	5.00	2.41	7.00	6.77	10	1005	0.00	0.00	0.00	83.3	0.00
	0-54	762	0.09	12.63	10.20	14.73	4.17	5.02	6.57	57	2487	0.16	0.01	2.95	258.5	0.46
	55-149	3124	3.61	6.57	8.23	10.70	4.39	7.40	7.34	78	2214	0.65	0.02	0.87	167.6	0.42
	150-170	4362	1.20	6.34	6.38	10.19	3.97	7.17	7.39	101	1531	0.22	0.55	0.95	128.9	0.21
	171-205	4579	4.58	4.09	5.28	8.34	4.03	7.33	7.76	58	1854	0.70	0.02	0.98	145.9	0.21
	206-240	3442	3.80	6.85	7.13	12.12	3.13	7.42	7.55	58	2172	0.20	0.00	1.01	169.1	0.16
	241-308	1837	1.64	13.03		18.28		7.50	7.74	80	2413	0.49	0.00	0.85	224.5	0.17
	309-352	1223		16.33		20.21			7.63	62	2606	0.01	0.00	0.15	233.3	0.25
	352-391					20.92			7.39	44	2765	0.04	0.00	0.04	275.0	1.18
	HRT Ex.					15.12			7.885	36	2342.	0.045	0	0.045	221.7	1.127
	Loading Period															
	AVERAGE	2798	2.5	9.3	7.6	14.2	4.4	7.4	7.5	70	2380	0.4	0.0	1.1	199.5	0.3
	MAXIMUM	10278	19.2	19.2	22.0	25.5	6.7	7.7	8.0	308	3810	3.4	1.1	16.0	336.0	1.6
	MINIMUM	0	0.0	-2.5	-1.0	5	2	7	7	10	1005	0	0	0	83	0
	0-54	762	63.5	15.5	17.9	18.0	6.26	7.5	7.4	71	3109	0.2	0.0	3.4	298.2	0.5
	55-130	2476	87.8	6.6	8.8	11.1	4.65	7.4	7.4	76	2214	0.4	0.0	0.7	177.9	0.5
	131-157	6124	23.3	7.2	7.4	9.6	3.38	7.1	7.2	72	1005	1.3	0.4	1.5	109.6	0.0
	158-189	3339	33.0	4.0	5.0	8.8	4.43	7.3	7.7	92	1809	0.7	0.0	1.0	149.8	0.2
	190-213	5537	30.2	5.5	6.3	9.6	3.65	7.3	7.5	51	1697	0.3	0.0	1.4	142.0	0.2
	214-301	2254	107	11.0		16.3		7.5	7.7	76	2406	0.4	0.0	0.8	208.2	0.2
	302-350	1244	331	15.7		19.8			7.6	62	2485	0.0	0.0	0.1	234.5	0.2
	351-376		580			20.5			7.5	45	2810	0.1	0.0	0.1	251.3	1.2

RBC Nitrogen Data

Date	Day	Fill Time min	Flow L/Cyc	Flow L/d	Nut. Flow L/d	HRT days	Alk mg/L	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L	NHx-N +NOx-N mg/L	NHx-N Ldg. g/m²/d	NHx-N Removal g/m²/d	NHx-N Rem. %	NHx-N +NOx-N Removal %	Alk: NHx-N Removal
08/12/93	0	59	2.0	48	0	5.10	214	0.2	2.9	0.30	335.3	338.2	0.31	0.31	99.0	-11	8.8
08/24/93	12	59	2.0	48	0	5.10	179	0.1	0.3	0.02	318.02	318.3	0.34	0.34	99.9	5	7.6
08/31/93	19	59	1.5	36	0	6.81	160	3.6	0.2	0.06	352.05	352.2	0.22	0.22	99.9	-20	10.2
09/02/93	21	59	1.5	36		6.81		0.0	18.4		294.00	312.4	0.24	0.23	94.2	5	
09/08/93	27	59	1.9	44	4	5.06	190	1.4	0.5	0.00	351	351.5	0.27	0.27	99.8	-21	10.4
09/09/93	28	59	1.9	44	3.3	5.14		1.4	5.2		323	328.5	0.26	0.26	98.1	-16	
09/10/93	29	59	1.9	44	3.3	5.14		1.4	0.2		275	275.6	0.26	0.26	99.9	2	
09/15/93	34	59	2.0	48	4.2	4.69	183	2.8	0.3	0.00	277.00	277.3	0.34	0.34	99.9	16	8.4
09/16/93	35	59	2.0	48	2.25	4.88			0.8				0.31	0.31	99.7		
09/21/93	40	59	2.8	66	1.99	3.59	185	1.4	16.7	0.023	290.02	306.7	0.43	0.40	94.5	-1	12.1
09/29/93	48	59	1.8	43	1.2	5.52	165	1.0	0.3	0.02	350.02	350.3	0.27	0.27	99.9	-21	9.5
10/01/93	50	59	1.9	46	1.305	5.22		1.3	0.4		322	322.3	0.24	0.24	99.8	-21	
10/05/93	54	59	2.0	48	0	5.10	151	1.0	0.2	0.03	384.03	384.2	0.31	0.31	99.9	-25	10.7
10/12/93	61	29	2.0	96	4.9	2.43	188	1.4	0.2	0.00	333.00	333.2	0.61	0.61	99.9	-11	8.0
10/19/93	68	29	1.7	82	0	3.00	129	0.9		0.01	317.01	317.0	0.47	0.47	100.0	-16	8.6
10/27/93	76	29	2.2	106	0.091	2.32	137	0.8	0.3	0.01	246.01	246.3	0.46	0.46	99.9	-20	15.8
11/02/93	82	29	2.3	108	1.2	2.24	176	0.3	0.4	0.00	198.00	198.4	0.44	0.44	99.8	-3	19.1
11/05/93	85	29	2.3	110		2.22			0.957		180.4	181.4	0.41	0.40	99.4	-4	
11/09/93	89	29	2.5	118	0.125	2.08	135	2.9	0.4	0.01	192.01	192.4	0.48	0.48	99.8	-0	9.0
11/12/93	92	29	2.5	118	0	2.08											
11/16/93	96	29	1.9	91	0	2.69	188	1.5	0.4	0.08	176.08	176.5	0.37	0.37	99.8	7	8.3
11/18/93	98	29	1.9	91	2	2.63			17.729		153.9	171.6	0.30	0.27	88.6	-9	
11/30/93	110	14															
12/08/93	118	29	2.70	130		1.89	598	0.4	14.2	2.00	102.00	116.2	0.28	0.24	85.8	-16	12.9
12/14/93	124	29	2.70	130	1.48	1.87	475	0.4	0.2	0.14	96.94	97.1	0.24	0.24	99.8	-13	9.1
12/21/93	131	29	2.80	134		1.82	581	0.1	2.7	0.38	137.38	140.1	0.42	0.41	98.2	5	7.8
12/29/93	139	29	2.30	110	0	2.22	532	0.5	0.2	0.01	164.01	164.2	0.43	0.43	99.9	10	
01/04/94	145	29	2.40	115	0	2.13	400	0.1	1.9	0.13	110.13	112.0	0.25	0.24	98.1	-7	
01/05/94	146	29	2.45	118		2.08			0.4				0.21	0.21	99.5		
01/11/94	152	14	3.80	365	2.77	0.67	483	0.2	1.0	0.59	101.59	102.6	0.75	0.74	99.0	-5	5.5
01/13/94	154	14	2.85	274	3.65	0.88			2.2		97.319	99.5	0.48	0.47	97.4	-18	
01/17/94	158	14	3.00	288	4.24	0.84		0.4	2.8		116.50	119.3	0.86	0.85	98.0	16	
01/18/94	159	14	3.10	298	1.5	0.82	583	0.1	7.2	3.20	126.20	135.4	0.94	0.89	95.1	9	9.6
01/20/94	161	14	3.10	298	1.04	0.82	476	0.3	2.8		136.17	139.0	0.97	0.95	98.2	10	7.3
01/24/94	165	14	3.10	298	1.55	0.82	357	0.4	0.1		128.13	128.3	0.80	0.80	99.9	0	6.6
01/25/94	166	14	3.10	298	0.58	0.82	466	0.1	0.4	0.50	139.50	139.9	0.77	0.76	99.7	-16	12.3
01/27/94	168	14	3.20	307		0.80			2.2		134.0	136.2	0.96	0.95	98.5	8	
01/28/94	169	14	3.30	317	11	0.75			8.5		130.2	138.7	0.98	0.92	94.1	5	
02/01/94	173	8	3.60	576	0	0.43	1060	0.1	59.7	13.00	257.00	316.7	1.88	1.14	61.0		12.4
02/03/94	175	8	2.11	338	1.04	0.72			14.7		164.84	179.5	1.27	1.17	91.7	-1	
02/08/94	180	8	4.30	688	2.06	0.36	947	0.1	48.6	14.60	139.60	188.2	2.62	1.91	72.8	-5	10.5
02/09/94	181	8	4.45	712	0	0.34			71.8		131.00	202.8	2.60	1.51	58.2	-17	
02/11/94	183	8	3.30	528	2.75	0.46			55.4		159.76	215.2	1.77	1.15	64.9	-36	
02/13/94	185	8	1.93	309	2.75	0.79			1.6	19.00	160.00	161.6	0.91	0.90	98.8	-17	
02/14/94	186	8	2.00	320	3	0.76			0.4		163.67	164.0	1.04	1.04	99.8	-5	
02/15/94	187	8	2.20	352	3	0.69	412	0.2	1.6	1.20	164.20	165.8	0.96	0.95	98.8	-28	8.4
02/18/94	190	8	2.30	464	2.89	0.52			0.1		100.35	100.4	0.91	0.91	99.9	-8	
02/21/94	193	8	1.83	293	2.83	0.83			0.3		137.73	138.1	0.87	0.87	99.8	2	
02/22/94	194	8	1.90	304	2.75	0.80	473	0.1	17.0	0.95	139.95	157.0	0.85	0.74	87.1	-19	10.8
02/23/94	195	8	1.78	285	2.75	0.85			0.3		143.77	144.0	0.80	0.80	99.8	-8	
02/25/94	197	8	2.00	320	1.5	0.76			1.0		159.29	160.3	0.90	0.90	99.2	-19	
02/26/94	198	8	2.00	320	2.5	0.76			0.8	1.72	149.72	150.5	0.95	0.95	99.5	-7	
02/28/94	200	8	2.00	320	1.88	0.76			0.1		136.44	136.5	0.67	0.67	99.9	-38	
03/03/94	203	8	2.40	384	0.9	0.64	355	0.2	0.1	1.00	85.90	86.0	1.97	1.97	100.0	64	4.9
03/04/94	204	8	2.60	416	1.8	0.59			0.2		107.46	107.7	1.01	1.01	99.8	6	
03/07/94	207	4	2.35	677	2.4	0.36			10.7		130.73	141.5	1.87	1.71	91.7	-9	
03/08/94	208	4	2.40	691	2	0.35	676	0.0	17.1	19.00	119.00	136.1	2.47	2.22	89.8	19	7.6
03/09/94	209	4	2.50	720	2.29	0.34			1.5		153.19	154.7	2.19	2.17	99.0	-3	

KBC Nitrogen Data

Date	Day	Fill Time min	Flow L/Cyc	Flow L/d	Nut. Flow L/d	HRT days	Alk mg/L	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L	NHx-N +NOx-N mg/L	NHx-N Ldg. g/m²/d	NHx-N Removal g/m²/d	NHx-N Rem. %	NHx-N +NOx-N Removal %	Alk: NHx-N Removal
03/10/94	210	4	2.40	691	2.5	0.35			6.8		164.22	171.1	1.95	1.85	94.8	-28	
03/14/94	214	4	2.25	648	2.75	0.38			0.7		175.68	176.3	2.20	2.19	99.6	-10	
03/15/94	215	4	2.70	778	2.4	0.31	798	0.2	33.5	6.60	139.60	173.1	2.91	2.36	81.0	2	9.8
03/16/94	216	4	2.28	657	2.5	0.37			2.3		165.30	167.6	2.53	2.50	98.7	8	
03/17/94	217	4	2.20	634	2.29	0.39			21.613		133.93	155.5	2.24	1.95	87.0	6	
03/21/94	221	4	1.85	533	2.25	0.46			4.3		163.76	168.0	2.03	1.98	97.6	6	
03/22/94	222	4	1.70	490	0	0.50	509	0.1	1.4	1.20	177.20	178.6	2.04	2.03	99.3	9	7.6
03/23/94	223	4	1.83	527	2.12	0.46			0.2				1.82	1.82	99.9		
03/24/94	224	4	1.83	527	2.82	0.46			1.3				1.89	1.88	99.2		
03/30/94	230	4	1.55	446	2.38	0.55			0.942		208.94	209.9	1.73	1.72	99.5	-15	
03/31/94	231	4	2.50	720	2.5	0.34	654	0.2	9.3	6.37	190.37	199.7	3.16	3.01	95.5	3	8.5
04/05/94	236	4	1.80	518	2.3	0.47	603	0.1	3.7	4.08	194.08	197.8	2.21	2.17	98.2	1	9.7
04/06/94	237	4	1.95	562	2.7	0.43			0.12		191.51	191.6	1.79	1.79	99.9	-27	
04/07/94	238	4	1.91	551		0.44			0.439		163.01	163.4	2.05	2.05	99.7	7	
04/12/94	243	2	1.66	797	2.6	0.31	618	0.1	6.4	7.30	154.30	160.7	2.97	2.86	96.3	8	8.6
04/13/94	244	2	1.10	528	2.86	0.46			0.072		176.84	176.9	1.93	1.93	100.0	-2	
04/14/94	245	2	2.06	989	2	0.25			47.269		112.49	159.8	3.68	2.68	73.0	9	
04/19/94	250	2	2.20	1056		0.23	1060	0.2	64.3	4.80	141.80	206.1	4.40	2.96	67.2	-5	10.2
04/20/94	251	2	2.20	1056	2.86	0.23			32.184		129.32	161.5	3.94	3.22	81.7	8	
04/21/94	252	2	1.05	504	2.5	0.48			0.04		198.81	198.9	1.80	1.80	100.0	-18	
04/26/94	257	2	3.50	1680	2.6	0.15	1300	0.2	115.0	4.80	106.80	221.8	8.69	4.58	52.7	9	8.9
04/27/94	258	2	2.64	1267	2.5	0.19			31.25		169.69	200.9	6.22	5.38	86.5	13	
04/28/94	259	2	2.43	1166		0.21			59.068		120.06	179.1	4.39	2.92	66.6	-1	
05/03/94	264	2	2.50	1200	2.5	0.20	1330	0.2	109.0	10.20	135.20	244.2	6.20	3.42	55.1	1	8.7
05/04/94	265	2	2.41	1157	2.5	0.21			38.145		224.69	262.8	5.75	4.82	83.7	-12	
05/05/94	266	2	0.60	288	2.5	0.84			2.686		214.93	217.6	1.19	1.17	98.6	-12	
05/10/94	271	2	0.00	0	2.5		371	0.5	0.9	0.13	233.13	234.0	0.00	0.00		17	8.0
05/17/94	278	2	2.40	1152	2.6	0.21	956	0.0	65.0	58.10	183.10	248.1	6.91	5.32	77.0	12	5.4
05/18/94	279	2	2.50	1200	2.4	0.20			62.45		181.3	243.8	6.75	5.15	76.4	8	
05/19/94	280	2	2.35	1128	2.5	0.22			54.787		186.99	241.8	5.86	4.54	77.5	1	
05/24/94	285	2	2.60	1248	2.5	0.20	1580	0.2	128.0	19.10	111.00	239.0	7.06	3.66	51.9	10	8.5
05/26/94	287	2	2.52	1210	2.25	0.20			28.342		184.22	212.6	5.67	4.94	87.1	5	
05/30/94	291	2	2.31	1109	2.4	0.22			38.905		159.83	198.7	5.06	4.15	81.9	8	
05/31/94	292	2	2.18	1046	2.7	0.23	1200	0.0	73.8	48.00	160.00	233.8	5.83	4.19	71.8	11	8.3
06/06/94	298	2	2.27	1088		0.23			33.56		203.55	237.1	5.51	4.73	85.9	1	
06/07/94	299	2	2.22	1066		0.23	1100	0.0	66.8	94.30	183.00	249.8	5.83	4.31	74.0	3	7.8
06/08/94	300	2	2.21	1061		0.23			37.736		199.69	237.4	5.29	4.44	83.9	-1	
06/14/94	306	2	2.53	1212		0.20	12	1.0	120.0	5.23	114.23	234.2	6.27	3.17	50.6	4	15.2
06/17/94	309	1	0.00	0					0.115		241.9	242.0	0.00	0.00		-17	
06/21/94	313	1	2.45	1764		0.14	1600	0.7	142.0	13.50	110.00	252.0	9.87	4.54	46.0	4	8.1
06/24/94	316	1	2.20	1584		0.15			113.32		123.19	236.5	7.17	3.35	46.7	-11	
06/28/94	320	1	3.90	2808		0.09	1730	0.1	170.0	50.30	73.70	243.7	14.58	4.42	30.3	0	11.6
07/05/94	327	1	0.00	0			546	0.8	1.8	0.40	216.40	218.2	0.00	0.00		9	8.2
07/12/94	334	1	1.84	1327		0.18	953	1.0	60.7	4.20	169.20	229.9	6.21	4.50	72.4	-5	10.0
07/19/94	341	1	1.15	828		0.30	1410	1.3	121.0	4.43	116.43	237.4	4.33	2.20	50.8	3	11.1
08/05/94	358	3	2.00	720		0.34	818	4.7	7.2	11	220	227.2	4.20	4.09	97.4	17	7.5
08/09/94	362	3	1.78	642		0.38	739	5.7	1.9	4.5	219.5	221.4	3.30	3.28	99.2	9	8.3
08/16/94	369	3	2.10	756		0.32	1000	1.9	25.4	13.8	181.8	207.2	3.83	3.42	89.3	13	8.9
08/23/94	376	3	2.30	828		0.30	867	1.5	19.7	28.4	182.4	202.1	4.81	4.46	92.8	26	6.4
09/01/94	385	3	2.18	783		0.31	783	1.7	22.9	40.1	202.1	225	5.01	4.63	92.4	25	7.6
09/07/94	391	3	1.52	547		0.45	580	1.6	1.9	34.8	220.8	222.7	3.75	3.73	99.4	31	6.8
09/29/94		3	2.15	774	33.6	0.30	1750	0.42	108	224	341	449	8.03	6.18	76.9		
10/05/94		3	2.10	756	38.4	0.31	946	0.55	17.4	245	490	507.4	8.49	8.19	96.5		
10/20/94		3	2.40	864	38.4	0.27	2080	0.6	249	71.7	172.7	421.7	9.43	4.65	49.3		
10/26/94		3	2.35	846	37.2	0.28	1100	1.9	159	23	205	364	8.75	5.76	65.8		

RBC Nitrogen Data

Date	Day	Fill Time	Flow	Flow	Nut. Flow	HRT	Alk	PO4-P	NHx-N	NO2-N	NOx-N	NHx-N +NOx-N	NHx-N Ldg.	NHx-N Removal	NHx-N Rem.	NHx-N +NOx-N Removal	Alk: NHx-N Removal
		min	L/Cyc	L/d	L/d	days	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	g/m²/d	g/m²/d	%	%	
AVERAGE						1.18	694	0.92	27.99	22.3	181.83	209.71	2.76	2.04	87.1	-1.23	9.25
MAXIMUM						6.81	1750	5.70	170.00	224.0	384.03	449.00	14.58	6.18	100.0	64.33	19.06
MINIMUM						0.09	12	0.00	0.04	0.00	73.70	85.99	0.00	0.00	30.3	-37.52	4.92
	0-54	1.92	46	1.80	5.24	178	1.29	3.6	0.06	322.7	326.5	0.29	0.29	98.8	-8.917	9.695	
	55-149	2.30	110	0.89	2.25	322	0.84	3.1	0.25	185.1	188.2	0.38	0.38	97.7	-5.957	10.938	
	150-170	3.17	305	3.29	0.80	473	0.26	3.0	1.43	123.5	126.5	0.83	0.81	97.8	0.907	8.274	
	171-205	2.55	408	2.02	0.65	649	0.12	16.1	7.35	147.1	163.2	1.29	1.09	90.1	-8.457	9.419	
	206-240	2.12	610	2.26	0.41	648	0.11	6.8	7.45	164.7	172.3	2.18	2.08	95.9	-1.971	8.666	
	241-308	2.10	1009	2.52	0.27	953	0.24	50.7	25.20	166.0	216.7	4.88	3.60	77.4	3.217	8.961	
	309-352	1.65	1187		0.17	1248	0.78	87.0	14.57	150.1	237.1	6.02	2.72	49.3	-2.176	9.815	
	352-391	1.98	713		0.35	798	2.85	13.2	22.10	204.4	217.6	4.15	3.93	95.1	20.111	7.585	
	HRT Ex.	2.25	810	36.90	0.29	1469	0.87	133.4	140.9	302.2	435.5	8.67	6.20	72.1			
	Loading Period																

SBR Nitrogen Data

Date	Day	Flow	Nut. Flow	ML Wasting	HRT	Alk	PO4-P	NHx-N	NO2-N	NOx-N	NHx-N +NOx-N	NHx-N Loading	NHx-N Loading	NHx-N Removal	NHx-N Removal	NHx-N Removal	NHx-N +NOx-N Removal	Alk:NHx-N Removal
		L/d	L/d	L/day	days	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	g/m³/d	g/g/d	g/m³/d	g/g/d	%	%	
AVERAGE					2.85	816	1.64	44.1	30.24	155.0	195.9	126.1	0.68	86.9	0.54	77.0	4.6	7.5
MAXIMUM					4.69	2400	11.7	325.0	199.0	318.3	328.3	743.7	1.99	482.2	1.32	100.0	100.0	99.1
MINIMUM					0.43	144	0.00	0.0	0.00	0.9	35.7	17.8	0.09	-6.9	-0.00	-10.9	-162.7	-96.0
	0-54				4.64	382	3.44	13.84	5.18	276.9	290.8	63.52	0.77	60.80	0.72	95.99	3.05	9.42
	55-130				1.94	612	1.69	59.93	7.70	119.3	173.7	92.46	0.91	66.88	0.69	64.70	8.95	-1.31
	131-157				4.66	1030	0.19	106.18	0.97	35.0	145.2	24.68	0.13	2.05	0.01	7.30	-4.43	16.23
	158-189				4.63	610	0.76	1.00	0.88	186.6	187.5	32.98	0.21	32.82	0.21	99.47	12.56	5.39
	190-213				4.60	495	5.50	5.78	0.21	113.5	119.3	29.42	0.28	28.19	0.27	95.42	4.87	7.23
	214-301				2.00	938	0.83	43.70	6.13	153.0	188.2	104.65	0.91	82.27	0.69	76.75	5.34	8.37
	302-350				0.71	797	0.30	21.35	143.2	210.8	232.1	330.86	0.55	300.73	0.49	90.73	0.40	7.32
	351-376				0.43	1202	0.05	67.23	175.7	185.0	252.2	580.48	0.63	425.20	0.44	73.06	-0.44	8.75
	Loading Period																	

SBR Nitrogen Data

Date	Day	Flow	Nut.	ML	HRT	Alk	PO4-P	NHx-N	NO2-N	NOx-N	NHx-N +NOx-N	NHx-N Loading	NHx-N Loading	NHx-N Removal	NHx-N Removal	NHx-N Removal	NHx-N +NOx-N Removal	Alk:NHx-N Removal
		L/d	Flow Wasting L/d	L/day	days	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	g/m³/d	g/g/d	g/m³/d	g/g/d	%	%	
08/12/93	0	78	0.0	21.9	4.69	584	0.00	22.9	0.00	197.0	220	65.0	1.05	60.1	0.97	92.5	28.0	8.10
08/24/93	12	78		21.9	4.69	816	3.10	75.2	11.00	205.0	280	71.6	0.81	55.6	0.63	77.6	16.6	7.30
08/31/93	19	78		21.9	4.69	281	0.23	9.8	1.70	303.7	314	62.4		60.3		96.7	-6.9	10.10
09/02/93	21	78		21.9	4.69			22.9		245.4	268	67.0		62.2		92.7	18.6	
09/08/93	27	78	0.0	21.9	4.69	233	4.70	0.3	0.31	318.3	319	61.8	0.70	61.7	0.70	99.9	-9.8	10.27
09/09/93	28	78	0.8	21.9	4.65			0.2		271.9	272	58.8		58.8		99.9	4.1	
09/10/93	29	78		21.9	4.69			0.1		263.2	263	59.7		59.7		100.0	6.3	
09/15/93	34	78	4.1	21.9	4.46	233	5.20	1.8	1.60	309.6	311	70.5	0.78	70.1	0.77	99.5	6.0	8.25
09/16/93	35	78	2.0	21.9	4.58							64.0		64.0		100.0		
09/21/93	40	78	2.2	21.9	4.56	377	2.70	17.0	8.90	298.9	316	64.8	0.60	61.1	0.57	94.4	-3.7	11.40
09/29/93	48	78	2.0	21.9	4.58	215	8.40	1.1	0.54	307.5	309	61.6	0.70	61.3	0.70	99.6	-6.8	9.36
10/01/93	50	78		21.9	4.69			0.6		298.1	299	53.3		53.2		99.8	-12.1	
10/05/93	54	78	1.9	21.9	4.58	317	3.20	14.2	17.40	304.4	319	65.4		62.4		95.4	-3.8	10.60
10/12/93	61	187	2.6	21.9	1.93	991	2.40	103.0	0.10	193.1	296	153.2	1.36	100.4	0.89	65.6	1.2	8.16
10/19/93	68	187	0.0	21.9	1.95	226	0.93		55.30	310.3	310	139.9	0.91	139.9	0.91	100.0	-13.5	8.22
10/27/93	76	187	0.9	21.9	1.94	330	5.90	16.4	3.75	206.8	223	104.5	0.78	96.1	0.72	92.0	-8.7	16.15
11/02/93	82	187	4.6	21.9	1.91	256	0.29	10.9	0.62	152.6	164	97.9	0.87	92.3	0.82	94.3	14.7	19.73
11/05/93	85	187	5.0	21.9	1.90			6.5		156.7	163	88.8		85.4		96.2	6.4	
11/09/93	89	187	0.0	21.9	1.95	571	2.10	42.1	1.01	123.0	165	98.4	0.76	76.8	0.59	78.1	14.0	8.53
11/12/93	92	187	0.0	21.9	1.95			78.6		60.3	139	81.4		41.1		50.5	13.3	
11/16/93	96	187	2.8	21.9	1.92	678	1.70	120.0	0.07	50.5	170	97.3	0.80	35.9	0.29	36.8	10.6	15.46
11/18/93	98	187		21.9	1.95			99.5		52.4	152	79.5		28.5		35.9	3.7	
11/30/93	110	187		0	1.95							73.6		73.8				
12/08/93	118	187		0	1.95	1070	0.11	31.7	0.25	4.0	36	51.2	0.89	34.9	0.61	68.3	64.3	9.24
12/14/93	124	187	0.3	0	1.95	770	0.06	90.5	0.54	2.2	93	43.8		-2.6		-5.8	-7.6	-96.00
12/21/93	131	78		0	4.69	1070	0.15	125.0	0.42	1.9	127	31.3		4.7		15.0	13.7	28.64
12/29/93	139	78	1.5	0	4.61	1100	0.12	160.0	0.05	0.9	161	39.0		4.9		12.6	12.1	-47.83
01/04/94	145	78		0	4.69	1090	0.00	112.0	0.39	1.3	113	21.5		-2.3		-10.9	-8.5	99.09
01/05/94	146	78		0	4.69			86.4				18.0	0.12	-0.4	-0.00	-2.2	100.0	0.00
01/11/94	152	78	1.0	0	4.63	858	0.48	87.6	3.00	169.0	257	20.4		1.8		8.8	-162.7	17.50
01/13/94	154	78		0				66.1		2.1	68	17.8	0.14	3.7	0.03	20.6	18.9	0.00
01/17/94	158			0				59.4		53.5	113							
01/18/94	159			0														
01/20/94	161			0		144												
01/24/94	165			0		152												
01/25/94	166			0														
01/27/94	168	78	0.5	0	4.65							31.5		31.5		100.0	100.0	0.00
01/28/94	169	78		0	4.68							31.0	0.09	31.0	0.09	100.0	100.0	0.00
02/01/94	173	78	1.2	0	4.62	713	0.85	1.0	0.31			32.6	0.10	32.4	0.10	99.4		9.91
02/03/94	175	78		0	4.69			1.2				37.7		37.5		99.3		
02/08/94	180	78	1.6	0	4.60	588	0.92	0.1	0.08	216.1	216	38.1	0.43	38.1	0.43	99.9	-20.8	9.63
02/09/94	181	78	0.0	0	4.69			0.2		174.8	175	36.5	0.16	36.5	0.16	99.9	-1.4	
02/11/94	183	78	2.5	0	4.55													
02/13/94	185	78	0.0	0	4.69			4.3	2.30	182.3	187	29.4		28.5		96.9	-35.2	
02/14/94	186	78	2.5	0	4.55			0.0		173.8	174	32.7	0.30	32.7	0.30	100.0	-10.9	
02/15/94	187	78	2.4	0	4.55	530	0.51	0.2	0.84	185.8	186	27.3	0.20	27.2	0.20	99.9	-43.7	7.43
02/18/94	190	78	1.0	0	4.63			0.0		131.0	131	19.6	0.14	19.5	0.14	100.0	-41.3	
02/21/94	193	78	1.3	0	4.62			0.8		123.7	125	29.9	0.20	29.7	0.20	99.4	11.6	
02/22/94	194	78	2.3	0	4.56	540	11.7	3.5	0.51	133.5	137	28.1	0.23	27.4	0.22	97.3	-3.6	9.18
02/23/94	195	78	1.0	0	4.63			5.8		122.1	128	28.1	0.23	26.9	0.22	95.6	4.0	
02/25/94	197	78	2.3	0	4.56			11.0		120.5	132	28.3	0.25	25.9	0.23	91.7	2.4	
02/26/94	198	78	0.0	0	4.69			30.5	0.27	109.3	140	29.8		23.3		78.2	0.7	
02/28/94	200	78	0.0	0	4.69			18.3		109.1	127	20.9	0.21	17.0	0.17	81.4	-28.3	
03/03/94	203	78	2.3	0	4.56	431	0.99	1.1	0.01	94.7	96	51.3	0.73	51.1	0.72	99.5		4.62
03/04/94	204	78	1.8	0	4.59			0.1		91.9	92	24.3	0.34	24.2	0.34	99.9	19.7	
03/07/94	207	78	2.4	0	4.55			0.3		96.9	97	27.6	0.16	27.6	0.15	99.8	25.3	
03/08/94	208	78	2.5	0	4.55	515	3.80	1.3	0.05	109.1	110	35.8	0.37	35.5	0.36	99.2	34.4	7.89
03/09/94	209	78	2.2	0	4.56			2.2		116.6	119	30.5		30.0		98.5	21.2	

SBR Nitrogen Data

Date	Day	Flow	Nut.	ML	HRT	Alk	PO4-P	NHx-N	NO2-N	NOx-N	NHx-N +NOx-N	NHx-N Loading	NHx-N Loading	NHx-N Removal	NHx-N Removal	NHx-N Removal	NHx-N +NOx-N Removal	Alk:NHx-N Removal
		L/d	Flow Wasting L/d	L/day	days	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	g/m³/d	g/g/d	g/m³/d	g/g/d	%	%	
03/10/94	210	78	2.5	0	4.55			0.1		117.1	117	28.2	0.22	28.2	0.22	99.9	12.3	
03/14/94	214	78	3.0	0	4.51			0.1		138.1	138	34.1	0.29	34.1	0.29	100.0	13.7	
03/15/94	215	187	2.6	0	1.93	714	0.88	17.9	4.70	126.7	147	90.2		81.0		89.8	16.7	9.40
03/16/94	216	187	3.1	0	1.92			15.2		149.7	165	92.7	0.77	84.9	0.71	91.6	9.6	
03/17/94	217	187	2.3	0	1.93			34.4		126.0	160	85.1	0.78	67.4	0.62	79.3	3.5	
03/21/94	221	187	2.3	0	1.93			48.7		85.6	134	91.6	1.02	66.6	0.74	72.7	24.9	
03/22/94	222	187	2.8	0	1.92	1270	0.60	131.0	2.10	79.7	211	100.4		33.3		33.2	-7.2	11.08
03/23/94	223	187	2.8	0	1.92			38.8			39	83.2	1.00	63.3	0.76	76.1		
03/24/94	224	187	2.8	0	1.92			37.1			37	86.4	1.05	67.4	0.82	78.0		
03/30/94	230	187	2.6	0	1.92			45.2		132.8	178	93.1	1.51	69.9	1.13	75.1	2.1	
03/31/94	231	187	2.0	0	1.93	1240	1.00	46.2		126.6	173	105.5	1.04	81.9	0.81	77.6	16.2	6.82
04/05/94	236	187	2.8	0	1.92	1460	2.30	95.0	3.55	90.6	186	102.5	0.92	53.8	0.48	52.5	7.2	10.00
04/06/94	237	187	2.5	0	1.93			64.2		80.6	145	76.6	1.22	43.7	0.70	57.1	4.3	
04/07/94	238	187	2.5	0	1.93			58.7		80.2	139	89.8	1.99	59.7	1.32	66.5	21.3	
04/12/94	243	187	2.4	0	1.93	1300	0.67	170.0	5.10	90.7	261	89.7	0.72	2.6	0.02	2.9	-48.9	
04/13/94	244	187	2.9	0	1.92			52.6		97.7	150	88.2	1.31	61.3	0.91	69.5	13.3	
04/14/94	245	187	2.5	0	1.93			70.4		84.0	154	89.6	0.82	53.5	0.49	59.7	12.5	
04/19/94	250	187		0	1.95	1530	0.98	102.0	0.39	98.1	200	100.4		48.2		48.0	-2.1	9.26
04/20/94	251	187	2.9	0	1.92			104.8		70.5	175	89.9	0.71	36.2	0.29	40.3	0.5	
04/21/94	252	187	2.5	0	1.93			83.8		102.7	186	85.9	0.81	43.0	0.41	50.0	-10.7	
04/26/94	257	187	2.6	0	1.93	1120	0.62	77.0	14.00	140.0	217	124.5	1.30	85.0	0.89	68.3	10.7	7.95
04/27/94	258	187	2.8	0	1.92			65.8		145.4	211	118.2	1.11	84.5	0.80	71.5	8.7	
04/28/94	259	187	2.5	0	1.93			51.1		171.8	223	90.6	0.83	64.4	0.59	71.1	-25.7	
05/03/94	264	187	2.5	0	1.93	890	0.43	40.5	25.20	192.2	233	124.5	1.47	103.7	1.22	83.3	5.3	7.95
05/04/94	265	187	2.3	0	1.93			36.4		189.4	226	119.8	1.02	101.1	0.86	84.4	3.6	
05/05/94	266	187	2.5	0	1.93			14.6		204.2	219	99.4	0.74	91.9	0.69	92.5	-12.5	
05/10/94	271	187	2.5	0	1.93	529	1.30	0.4	0.17	208.2	209	144.0	0.59	143.7	0.59	99.8	26.0	7.42
05/17/94	278	187	2.6	0	1.93	463	0.44	0.2	15.10	228.1	228	144.5	1.01	144.4	1.01	99.9	19.1	5.91
05/18/94	279	187	2.4	0	1.93			51.6		175.0	227	135.4		109.0		80.5	14.8	
05/19/94	280	187	2.5	0	1.93			17.9		209.3	227	125.0	0.93	115.8	0.86	92.7	7.3	
05/24/94	285	187	2.6	0	1.93	574	0.60	0.5	1.20	221.2	222	136.3	0.88	136.0	0.87	99.8	16.6	8.20
05/26/94	287	187	2.5	0	1.93			0.0		224.2	224	112.9	0.55	112.8	0.55	100.0	-0.3	
05/30/94	291	187	2.5	0	1.93			0.2		211.0	211	110.0	0.65	109.9	0.65	99.9	2.1	
05/31/94	292	187	2.3	0	1.93	554	0.29	0.4	0.58	205.6	206	134.2	0.69	134.0	0.68	99.9	21.6	8.47
06/06/94	298	187		0	1.95			0.1		231.6	232	121.9	0.38	121.9	0.38	100.0	3.0	
06/07/94	299	187		0	1.95	546	0.69	0.5	1.50	252.5	253	131.7	0.38	131.4	0.38	99.8	1.5	7.97
06/08/94	300	187		0	1.95			0.2		229.2	229	120.1	0.48	120.0	0.48	99.9	2.8	
06/14/94	306	515		0	0.71	1200	0.68	81.3	43.80	140.8	222	342.9	0.53	228.2	0.35	66.5	8.6	4.21
06/17/94	309	515		0	0.71			0.3		200.6	201	291.1	0.44	290.6	0.44	99.8	2.8	
06/21/94	313	515		0	0.71	625	0.96	4.1	49.30	275.3	279	371.1	0.55	365.3	0.55	98.4	-6.2	7.55
06/24/94	316	515		0	0.71			67.7		244.5	312	300.0	0.76	204.5	0.52	68.2	-46.3	
06/28/94	320	515		0	0.71	886	0.14	15.9	187.0	194.0	210	344.3	0.59	321.8	0.55	93.5	14.0	7.47
07/05/94	327	515		0	0.71	610	0.00	0.3	199.0	206.0	206	340.0	0.51	339.6	0.51	99.9	14.4	7.89
07/12/94	334	515		0	0.71	593	0.00	0.7	194.0	223.0	224	310.4	0.48	309.5	0.48	99.7	-1.7	8.92
07/19/94	341	515		0	0.71	867	0.00	0.4	186.0	202.0	202	347.1	0.51	346.5	0.51	99.8	17.7	7.87
08/05/94	358	843		0	0.43	987	0.10	65.2	189.0	202.0	267	632.8	0.53	482.2	0.41	76.2	2.5	8.73
08/09/94	362	843		0	0.43	1080	0.00	48.5	196.0	210.0	259	558.9	0.43	446.9	0.35	80.0	-6.8	8.53
08/16/94	369	843		0	0.43	1540	0.05	88.0	142.0	143.0	231	549.7	0.92	346.4	0.58	63.0	2.9	9.00
08/23/94	376	843		0	0.43	2250	2.10	276.0	1.30	1.3	277	630.5		-6.9		-1.1	-1.6	
09/01/94	385	843		0	0.43	2360	4.80	278.0	0.00	1.8	280	695.2		53.1		7.6	7.1	
09/07/94	391	843		0	0.43	2400	3.50	325.0	0.01	3.3	328	743.7		-6.9		-0.9	-2.0	

RBC P and Misc. Data

Date	Day	Nutrient Flow L/day	Nutrient Addition (g/20 L)	Nutrient Addition (mg/L)	Influent PO4-P (mg/L)	NHx-N :PO4-P mg/L	HRT days	DO mg/L	Temp °C	Cond. mS	Site pH	pH	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L
08/12/93	0		40				5.10					6.8	0.2	2.9	0.30	335.3
08/24/93	12		40				5.10					7.6	0.1	0.3	0.02	318.0
08/31/93	19		40				6.81					7.3	3.6	0.2	0.06	352.1
09/02/93	21		40				6.81						0.0	18.4		294.0
09/08/93	27	4	40	13.47	14.15	22.71	5.06	8.5	20	5.1	8	7.3	1.4	0.5	0.00	351.0
09/09/93	28	3.3	40	11.27	11.66	26.30	5.14	8.8	22	5.12	8		1.4	5.2		323.3
09/10/93	29	3.3	40	11.27	11.60	27.51	5.14		20				1.4	0.2		275.4
09/15/93	34	4.2	40	13.11	13.77	30.14	4.69	8.1	16	5.04	8	7.9	2.8	0.3	0.00	277.0
09/16/93	35	2.25	40	7.30			4.88	8.9	15.5	4.67	7.8			0.8		
09/21/93	40	1.99	40	4.75	5.59	68.52	3.59	10.4	13.5	4.09	8	7.35	1.4	16.7	0.023	290.0
09/29/93	48	1.2	40	4.40			5.52	8.6	19	4.45	7.9	7.6	1.0	0.3	0.02	350.0
10/01/93	50	1.305	40	4.53	4.72	72.73	5.22		15				1.3	0.4		321.9
10/05/93	54	0	40	0.00	0.88		5.10	11.6	11.6	4.18	8	7.2	1.0	0.2	0.03	384.0
10/12/93	61	4.9	40	7.91	8.64	41.24	2.43	9.6	17	4.72	7.9	7.2	1.4	0.2	0.00	333.0
10/19/93	68	0	40	0.00	0.58		3.00	10.2	14	4.82	7.9	7.9	0.9		0.01	317.0
10/27/93	76	0.091	40	0.14	0.79		2.32	11.4	12.5	3.82	8	7.3	0.8	0.3	0.01	246.0
11/02/93	82	1.2	40	1.79	2.18	100.28	2.24		11	3.56	7.9	7.5	0.3	0.4	0.00	198.0
11/05/93	85		40	0.00			2.22						1.134	0.957		180.4
11/09/93	89	0.125	40	0.17	0.48		2.08		6.75	3.42	7.9	7.1	2.9	0.4	0.01	192.0
11/12/93	92	0	40	0.00	0.36		2.08		5.5	3.12	7.7					
11/16/93	96	0	40	0.00	0.80		2.69		8.5	3.21	7.9	7.5	1.5	0.4	0.08	176.1
11/18/93	98	2	40	3.50	3.72	52.63	2.63		5	3.42	7.8		1.106	17.72		153.9
11/30/93	110		40						6.75	3.31	8.1					
12/08/93	118		40	0.00			1.89		6	2.76	8.6	8.0	0.4	14.2	2.00	102.0
12/14/93	124	1.48	40	1.84	1.94	54.79	1.87		8.5			7.9	0.4	0.2	0.14	96.9
12/21/93	131		40	0.00			1.82		4	3.31	8.3	7.8	0.1	2.7	0.38	137.4
12/29/93	139	0	40	0.00	0.00		2.22		4.5	3.47		8.0	0.5	0.2	0.01	164.0
01/04/94	145	0	40	0.00	0.00		2.13		8.75	2.42		8.2	0.1	1.9	0.13	110.1
01/05/94	146		40	0.00			2.08		6.5	2.57				0.4		
01/11/94	152	2.77	40	1.23	1.28	90.29	0.67		8.5	2.7	8.3	7.9	0.2	1.0	0.59	101.6
01/13/94	154	3.65	40	2.15	2.27	46.47	0.88		10.5	2.57			0.524	2.2		97.3
01/17/94	158	4.24	40	2.36	2.65	60.95	0.84		9	3.06			0.4	2.8		116.5
01/18/94	159	1.5	40	0.82	0.85	189.43	0.82		7	3.16	8.4	7.7	0.1	7.2	3.20	128.2
01/20/94	161	1.04	40	0.57	0.89	251.69	0.82		5	3.56	8.3		0.3	2.8		136.2
01/24/94	165	1.55	40	0.84	1.12	183.49	0.82		10.5		7.9		0.4	0.1		128.1
01/25/94	166	0.58	40	0.32	0.53		0.82		8.5	2.95	8.3	8.2	0.1	0.4	0.50	139.5
01/27/94	168		40	0.00			0.80		9	3.17			0.311	2.2		134.0
01/28/94	169	11	40	5.47	5.81	25.21	0.75		6	3.75	8.1		0.391	8.5		130.2
02/01/94	173	0	40	0.00	0.06		0.43		5.5	4.04	8.1	8.2	0.1	59.7	13.00	257.0
02/03/94	175	1.04	40	0.50	0.81	271.42	0.72		5				0.213	14.7		164.8
02/08/94	180	2.06	40	0.49	0.61	238.61	0.36		0	3.92	8.5	8.1	0.1	48.6	14.60	139.6
02/09/94	181	0	40	0.00	0.30		0.34		2.5	3.84	8.7		0.061	71.8		131.0
02/11/94	183	2.75	40	0.84	1.16	105.95	0.46		5.5				0.195	55.4		159.8
02/13/94	185	2.75	40	1.44			0.79		6.5	3.25	8.3			1.6	19.00	160.0
02/14/94	186	3	40	1.51	1.86	96.45	0.76		5.5				0.278	0.4		163.7
02/15/94	187	3	40	1.38	1.41	104.71	0.69		7.5	3.17		8.18	0.2	1.6	1.20	164.2
02/18/94	190	2.89	40	1.01	1.26	99.39	0.52		7.5	2.45			0.334	0.1		100.4
02/21/94	193	2.83	40	1.56	1.88	76.19	0.83		5.5	3.13			0.039	0.3		137.7
02/22/94	194	2.75	40	1.46	1.51	83.27	0.80		4.75	3.55		7.59	0.1	17.0	0.95	140.0
02/23/94	195	2.75	40	1.56	1.82	73.18	0.85		5				0.02	0.3		143.8
02/25/94	197	1.5	40	0.76	1.03	133.49	0.76		2	3.35			0.04	1.0		159.3
02/26/94	198	2.5	40	1.26			0.76		5	2.41				0.8	1.72	149.7
02/28/94	200	1.88	40	0.95	1.21	84.89	0.76		9.5				0.051	0.1		136.4
03/03/94	203	0.9	40	0.38	0.45		0.64		11.5	2.03	8.13	8.22	0.2	0.1	1.00	85.9
03/04/94	204	1.8	40	0.70	0.91	187.88	0.59		10	2.42	8.4		0.306	0.2		107.5
03/07/94	207	2.4	80	1.15	1.44	65.72	0.36		7				0.051	10.7		130.7
03/08/94	208	2	80	0.94	0.99	152.37	0.35		11		8.2	7.68	0.0	17.1	19.00	119.0
03/09/94	209	2.29	80	1.03	1.11	197.07	0.24		9	2.74	8.2		0.291	1.5		152.2

RBC P and Misc. Data

Date	Day	Nutrient Flow L/day	Nutrient Addition (g/20 L)	Nutrient Addition (mg/L)	Influent PO4-P (mg/L)	NHx-N :PO4-P mg/L	HRT days	DO mg/L	Temp °C	Cond. mS	Site pH	pH	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L
03/10/94	210	2.5	80	1.17	1.26	111.00	0.35		10.5				0.13	6.8		164.2
03/14/94	214	2.75	80	1.38	1.66	118.11	0.38		11				0.318	0.7		175.7
03/15/94	215	2.4	80	1.00	1.04	161.40	0.31		12		8.3	7.93	0.2	33.5	6.60	139.6
03/16/94	216	2.5	80	1.24	1.39	161.52	0.37		11				0.28	2.3		165.3
03/17/94	217	2.29	80	1.17	1.29	148.48	0.39		7		8.38		0.32	21.61		133.9
03/21/94	221	2.25	80	1.37	1.54	151.92	0.46		6		8		0.39	4.3		163.8
03/22/94	222	0	80	0.00			0.50		10.5		8.28	7.66	0.1	1.4	1.20	177.2
03/23/94	223	2.12	80	1.31	1.59	116.76	0.46		7.5				0.201	0.2		
03/24/94	224	2.82	80	1.73	2.00	86.78	0.46		10		8.24		0.071	1.3		
03/30/94	230	2.38	80	1.73	1.97	117.92	0.55		14				0.434	0.942		208.9
03/31/94	231	2.5	80	1.13	1.20	189.54	0.34		12		8.2	7.95	0.2	9.3	6.37	190.4
04/05/94	236	2.3	80	1.44	1.48	146.53	0.47		11.5		8.11	7.8	0.1	3.7	4.08	194.1
04/06/94	237	2.7	80	1.56	1.72	123.25	0.43		10				0.508	0.12		191.5
04/07/94	238		80	0.00			0.44		9		8.46		0.145	0.439		163.0
04/12/94	243	2.6	80	1.06	1.11	173.80	0.31		13		8.2	7.91	0.1	6.4	7.30	154.3
04/13/94	244	2.86	80	1.76	2.09	176.22	0.46		9.5				1.111	0.072		176.8
04/14/94	245	2	80	0.66	0.94	192.74	0.25		10				0.277	47.26		112.5
04/19/94	250		80	0.00			0.23		18.5			7.96	0.2	64.3	4.80	141.8
04/20/94	251	2.86	80	0.88	1.08	163.53	0.23		16.5				0.2	32.18		129.3
04/21/94	252	2.5	80	1.61	1.82	103.81	0.48		13	3.79	8.4		0.205	0.04		198.8
04/26/94	257	2.6	80	0.50	0.57	302.14	0.15		16		8.28	7.88	0.2	115.0	4.80	106.8
04/27/94	258	2.5	80	0.64	0.84	253.82	0.19		15				0.05	31.25		169.7
04/28/94	259		80	0.00			0.21		15				0.26	59.06		120.1
05/03/94	264	2.5	80	0.68	0.74	236.07	0.20		15		8.31	7.7	0.2	109.0	10.20	135.2
05/04/94	265	2.5	80	0.70	1.29	152.03	0.21		14.5				0	38.14		224.7
05/05/94	266	2.5	80	2.80	3.13	66.03	0.84		15.7		7.8		0.233	2.686		214.9
05/10/94	271	2.5	80						19		8.6	7.77	0.5	0.9	0.13	233.1
05/17/94	278	2.6	80	0.73	0.77	280.38	0.21		19.5		8.16	7.93	0.0	65.0	58.10	183.1
05/18/94	279	2.4	80	0.65	0.83	343.38	0.20		16.5				0.239	62.45		181.3
05/19/94	280	2.5	80	0.72	0.77	259.58	0.22		18.7		8.13		0.04	54.78		187.0
05/24/94	285	2.5	80	0.65	0.76	264.57	0.20		22.5		8.17	7.86	0.2	128.0	19.10	111.0
05/26/94	287	2.25	240	1.82	1.82	105.72	0.20		15.5				0	28.34		184.2
05/30/94	291	2.4	240	2.11	2.50	71.29	0.22		14.5		8.22		0.03	38.90		159.8
05/31/94	292	2.7	240	2.52	2.64	71.38	0.23		17.5		8.23	8.05	0.0	73.8	48.00	160.0
06/06/94	298	2.38	240	2.13	2.29	89.36	0.22		17.5				0	33.56		203.6
06/07/94	299	2.5	240	2.29	2.43	78.32	0.23		18			7.97	0.0	66.8	94.30	183.0
06/08/94	300	2.5	240	2.30	2.40	81.96	0.23		16.7				0	37.73		199.7
06/14/94	306	2.5	240	2.01	2.05	116.83	0.20		14.5			7.91	1.0	120.0	5.23	114.2
06/17/94	309	1.87	240						18.5				0.102	0.115		241.9
06/21/94	313	2.5	240	1.38	1.57	138.47	0.14		22			8.19	0.7	142.0	13.50	110.0
06/24/94	316	2	480	2.47	2.80	35.41	0.15		17				0	113.3		123.2
06/28/94	320	2.75	480	1.91	2.14	36.94	0.09		19			7.9	0.1	170.0	50.30	73.7
07/05/94	327	2.4	480						17.5			7.9	0.8	1.8	0.40	216.4
07/12/94	334	2.5	960	7.35	7.40	24.84	0.18		22.5			7.87	1.0	60.7	4.20	169.2
07/19/94	341	2.3	960	10.83	10.98	12.91	0.30		22.5			8.1	1.3	121.0	4.43	116.4
08/05/94	358	2.6	150	2.20	3.30	-190.4	0.34		19.5			7.85	4.7	7.2	11	220.0
08/09/94	362	2.35	150	2.23	3.83	-128.4	0.38		21			7.8	5.7	1.9	4.5	219.5
08/16/94	369	2.61	150	2.10	3.00	192.82	0.32		21			8.02	1.9	25.4	13.8	181.8
08/23/94	376	2.65	150	1.95	2.75	202.69	0.29		22			7.94	1.5	19.7	28.4	182.4
09/01/94	385	2.6	150	2.02	3.22	182.65	0.31		20			7.86	1.7	22.9	40.1	202.1
09/07/94	391	2.08	150	2.31	3.81	144.57	0.45		19.5			7.72	1.6	1.9	34.8	220.8

RBC P and Misc. Data

Date	Day	Nutrient Flow L/day	Nutrient Addition (g/20 L)	Nutrient Addition (mg/L)	Influent PO4-P (mg/L)	NHx-N :PO4-P mg/L	HRT days	DO mg/L	Temp °C	Cond. mS	Site pH	pH	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L
			AVERAGE	1.98	2.42	121.1		9.6	12.2	3.48	8.16	7.78	0.60	22.70	10.07	180.8
			MAXIMUM	13.47	14.15	343.4		11.6	22.5	5.12	8.70	8.22	5.70	170.0	94.30	384.0
			MINIMUM	0.00	0.00	-190.4		8.1	0.0	2.03	7.70	7.06	0.00	0.04	0.00	73.7
	0-54	298.22		0.29	7.79	6.24	41.32	5.24	9.3	17.0	4.66	7.96	7.37	1.29	3.56	0.06	322.7
	55-149	167.58		0.38	1.02	1.77	62.24	2.25	10.4	8.4	3.42	8.00	7.66	0.89	3.07	0.25	185.1
	150-170	128.92		0.83	1.53	1.92	121.08	0.80		8.2	3.12	8.22	7.92	0.31	3.02	1.43	123.5
	171-205	145.86		1.29	0.93	1.08	129.62	0.65		5.8	3.13	8.36	8.05	0.14	16.09	7.35	147.1
	206-240	169.07		2.18	1.14	1.45	137.89	0.41		9.9	2.74	8.25	7.80	0.22	6.82	7.45	164.7
	241-308	223.81		4.88	1.27	1.56	170.62	0.27		15.9	3.79	8.23	7.89	0.21	50.65	25.20	166.0
	309-352	237.77		6.02	4.79	4.98	49.71	0.17		19.9			7.99	0.57	86.99	14.57	150.1
	352-391	275.00		4.15	2.14	3.32	67.32	0.35		20.5			7.87	2.85	13.17	22.10	204.4

Loading Period	Leachate NHx-N	NHx-N Loading

SBR P and Misc. Data

Date	Day	Nut. Flow L/day	Nut. Add. g/20 L	Nut. Add. mg/L	Inf. PO4-P mg/L	NHx-N :PO4-P	HRT days	DO mg/L	Temp °C	Cond. mS	Site pH	pH	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L	MLSS mg/L	MLVSS mg/L	Eff TSS mg/L
			AVERAGE	2.8	3.0	108.5							1.45	44.1	30.2	155.0	343	181	84
			MAXIMUM	8.2	8.8	847.9							11.70	325.0	199.0	318.3	2080	674	605
			MINIMUM	0.0	0.3	-114							0.00	0.0	0.0	0.9	7	27	13
	0-54	298	63.5	3.8	2.8	127.9	4.64		17.1				2.78	13.8	5.2	276.9	129	100	150
	55-130	178	87.8	1.5	2.0	81.3	2.15		8.2				1.82	65.8	6.9	109.5	159	27	78
	131-157	110	23.3	2.6	2.6	6.4	4.66		6.6				0.28	102.4	1.1	43.3	227		22
	158-189	150	33.0	2.7	3.0	61.0	4.63		12.5				0.92	1.0	0.9	186.6	425	216	124
	190-213	142	30.2	3.5	4.0	55.4	4.59		5.8				2.49	6.3	0.2	112.0	172	123	64
	214-301	208	107	2.4	2.6	165.3	1.93		13.4				1.02	44.9	6.1	153.4	214	125	72
	302-350	234	331	3.2	3.4	70.9	0.71		19.6				0.42	21.3	143.2	210.8	1023	600	85
	351-376	251	580	3.9	5.1	36.5	0.43		22.2				1.76	180.1	88.1	93.6	855	ERR	66

Ldg. Period	Leachate NHx-N	NHx-N Ldg.

SBR P and Misc. Data

Date	Day	Nut. Flow L/day	Nut. Add. g/20 L	Nut. Add. mg/L	Inf. PO4-P mg/L	NHx-N :PO4-P	HRT days	DO mg/L	Temp °C	Cond. mS	Site pH	pH	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L	MLSS mg/L	MLVSS mg/L	Eff TSS mg/L	Eff VSS mg/L
08/12/93	0		40		0.3		4.7					7.25	0	22.9	0.002	197.0	100		144	
08/24/93	12		40		0.3		4.7					7.78	3.1	75.2	11	205.0	142		112	
08/31/93	19		40		0.5		4.7					7.03	0.23	9.8	1.7	303.7				
09/02/93	21		40				4.7						0.064	22.9		245.4				
09/08/93	27	0.0	40	0.0	0.7		4.7	5.8	19	4.75	7.5	7.37	4.7	0.26	0.31	318.3	142		13	
09/09/93	28	0.8	40	1.6	1.9		4.6	4.4	22	5	7.4		1.708	0.196		271.9				
09/10/93	29		40				4.7						2.41	0.128		263.2				
09/15/93	34	4.1	40	8.2	8.8	90.9	4.5	6	16.5	4.76	7.4	7.5	5.2	1.8	1.6	309.6	146	100	17.	
09/16/93	35	2.0	40	4.1			4.6	6.3	15	4.37	7.4									
09/21/93	40	2.2	40	4.6	5.4	106.2	4.6	7	13	3.92	7.6	7.34	2.7	17	8.9	298.9	174		130	
09/29/93	48	2.0	40	4.1			4.6	6.2	21.5	4.34	8	7.48	8.4	1.1	0.54	307.5	141		27	
10/01/93	50		40				4.7						1.608	0.564		298.1				
10/05/93	54	1.9	40	3.9	4.8	186.8	4.6	8.3	12.5	3.78	7.6	6.91	3.2	14.2	17.4	304.4	58		605	
10/12/93	61	2.6	40	2.2	3.0	347.0	1.9	4.4	16.5	5.1	7.8	7.55	2.4	103	0.1	193.1	182		46	
10/19/93	68	0.0	40	0.0	0.6		2.0	.4	14	4.66	7.5	7.18	0.93		55.3	310.3	248		42.	
10/27/93	76	0.9	40	0.8	1.4		1.9	9.3	10.5	3.47	7.6	7.68	5.9	16.4	3.75	206.8	215		54	
11/02/93	82	4.6	40	3.9	4.3	44.9	1.9		9.7	3.25	7.7	7.13	0.29	10.9	0.62	152.6	182		29	
11/05/93	85	5.0	40	4.2	4.6	-114	1.9						6.059	6.526		156.7				
11/09/93	89	0.0	40	0.0	0.3		2.0		5.25	3.29	8.1	7.47	2.1	42.1	1.01	123.0	210		205	
11/12/93	92	0.0	40	0.0	0.4		2.0		4.5	3.34	8.1		0.285	78.61		60.3				
11/16/93	96	2.8	40	2.4	3.2	47.9	1.9		5.5	3.6	8.2	8.09	1.7	120	0.065	50.5	197		88	
11/18/93	98		40				2.0		8	3.5	8.4			99.54		52.4				
11/30/93	110		40				2.0		6	3.5	8.5									
12/08/93	118		40				2.0		8	3.2	8.2	7.93	0.11	31.7	0.25	4.0	93		138	
12/14/93	124	0.3	40	0.2	0.3		1.9		7.75			7.74	0.064	90.5	0.54	2.2	49		50	
12/21/93	131		40				4.7		3	3.76	8.5	7.98	0.15	125	0.42	1.9	52	27	52	
12/29/93	139	1.5	40	3.1	3.1	7.8	4.6		3	3.85		7.75	0.12	160	0.05	0.9				
01/04/94	145		40				4.7		8.5	2.72		7.91	0	112	0.39	1.3				
01/05/94	146		40				4.7		6.5	2.95				86.4			251		22	
01/11/94	152	1.0	40	2.1	2.1	5.0	4.6		6.5	2.66	8.8	8.19	0.48	87.6	3	169.0				
01/13/94	154		40						8.5	2.71			0.515	66.1		2.1	203			
01/17/94	158		40						8	2.87			1.061	59.4		53.5				
01/18/94	159		40						13	4.68	8.6									
01/20/94	161		40						14.5	3.83	7.08						828			
01/24/94	165		40						16.5		5.8						699			
01/25/94	166		40						15.5	7.23	8.3									
01/27/94	168	0.5	40	1.0	1.3		4.6		17	6.75				0			551		284	
01/28/94	169		40				4.7		15	6.02	7.7			0			545	352		
02/01/94	173	1.2	40	2.5	2.5	90.1	4.6		11	5.8	7.7	8.24	0.85	0.96	0.31		513		156	
02/03/94	175		40				4.7						1.431	1.209			273	172	115	71
02/08/94	180	1.6	40	3.2	3.3	75.0	4.6		11	4.67	8.78	8.32	0.92	0.13	0.079	216.1	144		50	
02/09/94	181	0.0	40	0.0	0.3		4.7		11.5	3.97	8.6		1.275	0.206		174.8	315	233		
02/11/94	183	2.5	40	5.1			4.5		13.5											
02/13/94	185	0.0	40	0.0			4.7		12	3.3	8.1			4.3	2.3	182.3				
02/14/94	186	2.5	40	5.1	5.4	49.7	4.5		13				2.345	0.048		173.8	165	108	74	55
02/15/94	187	2.4	40	4.9	4.9	29.1	4.6		11.5	3.36		8.35	0.51	0.17	0.84	185.8	219		62	
02/18/94	190	1.0	40	2.1	2.3	66.6	4.6		12.5	2.75			0.94	0.029		131.0	233	139	66	36
02/21/94	193	1.3	40	2.7	3.1	86.4	4.6		5.5	3.01			1.443	0.82		123.7	224	146	62	38
02/22/94	194	2.3	40	4.6	4.6	-18.2	4.6		3.5	3.38		8.07	11.7	3.5	0.51	133.5	200		78	
02/23/94	195	1.0	40	2.1	2.3	59.1	4.6		4				0.196	5.825		122.1	198	123	64	40
02/25/94	197	2.3	40	4.6	4.8	26.5	4.6		0.5	3.06			0.256	11.04		120.5	167	115	67	45
02/26/94	198	0.0	40	0.0			4.7		3	2.41	8.9			30.5	0.27	109.3				
02/28/94	200	0.0	40	0.0	0.3		4.7		8.5				0.211	18.30		109.1	155	99	63	43
03/03/94	203	2.3	40	4.7	4.8	63.8	4.6		9.5	2.23	8.37	8.26	0.99	1.1	0.007	94.7	114		49	
03/04/94	204	1.8	40	3.7	3.9	53.6	4.6		9.5	2.32	8.4		1.773	0.102		91.9	111	72	56	35
03/07/94	207	2.4	40	4.9	5.2	43.9	4.6		3.5				2.217	0.298		96.9		178		
03/08/94	208	2.5	40	5.1	5.1	125.6	4.5		8.5		7.8	7.77	3.8	1.3	0.053	109.1	158		70	

SBR P and Misc. Data

Date	Day	Nut. Flow L/day	Nut. Add. g/20 L	Nut. Add. mg/L	Inf. PO4-P mg/L	NHx-N :PO4-P	HRT days	DO mg/L	Temp °C	Cond. mS	Site pH	pH	PO4-P mg/L	NHx-N mg/L	NO2-N mg/L	NOx-N mg/L	MLSS mg/L	MLVSS mg/L	Eff TSS mg/L	Eff VSS mg/L
03/10/94	210	2.5	40	5.1	5.2	44.5	4.5		8				2.189	0.121		117.1	220	126	54	35
03/14/94	214	3.0	40	6.0	6.3	36.3	4.5		9.5				1.922	0.068		138.1	184.	118.1	65.	36.1
03/15/94	215	2.6	40	2.2	2.3	113.4	1.9		10		8.2	7.84	0.88	17.9	4.7	128.7				
03/16/94	216	3.1	40	2.6	2.8	104.1	1.9		10				1.19	15.22		149.7	177.	120.3		
03/17/94	217	2.3	40	2.0	2.1	125.3	1.9		6		8.47		1.04	34.4		126.0	170.	108.4	57.	35.1
03/21/94	221	2.3	40	1.9	2.1	179.2	1.9		6		8.49		1.39	48.72		85.6	148.	89.5	64.	35.4
03/22/94	222	2.8	40	2.4			1.9		9.5		8.54	7.87	0.6	131	2.1	79.7				
03/23/94	223	2.8	40	2.4	2.7	123.5	1.9		6				1.705	38.82			131.	83.4		
03/24/94	224	2.8	40	2.4	2.7	847.9	1.9		8.5		8.7		2.53	37.13			136.	82.2	59	32.7
03/30/94	230	2.6	40	2.3	2.5	82.8	1.9		12				0.849	45.15		132.8	112.	61.7		
03/31/94	231	2.0	40	1.7	1.8	201.2	1.9		12			8.09	1	46.17		126.6	163		76	
04/05/94	236	2.8	40	2.4	2.4	728.4	1.9		12			7.84	2.3	95	3.55	90.6	180		55	
04/06/94	237	2.5	40	2.1	2.3	193.2	1.9		9				1.869	64.16		80.6	121.	62.9		
04/07/94	238	2.5	40	2.1	2.4	379.7	1.9		7		9.14		2.118	58.68		80.2	82.5	45.1	76.	39.3
04/12/94	243	2.4	40	2.0	2.1	3.6	1.9		13		8.5	8.07	0.67	170	5.1	90.7	201		61	
04/13/94	244	2.9	40	2.5	2.8	84.6	1.9		9.5				1.372	52.6		97.7	124.	67.2	74.	42.1
04/14/94	245	2.5	40	2.1	2.4	89.7	1.9		9.5				1.266	70.39		84.0	209.	108.8		
04/19/94	250		40				2.0					7.51	0.98	102	0.39	98.1	71		84	
04/20/94	251	2.9	40	2.5	2.7	83.1	1.9		17		7.8		1.8	104.7		70.5	205			
04/21/94	252	2.5	40	2.1	2.4	68.7	1.9		13		8.74		1.140	83.83		102.7	170.		60.	
04/26/94	257	2.6	40	2.2	2.3	98.5	1.9		14.5			7.9	0.62	77	14	140.0	154		264	
04/27/94	258	2.8	40	2.4	2.6	82.2	1.9		15				0.55	65.76		145.4	166.	106.2		
04/28/94	259	2.5	40	2.1	2.4	64.1	1.9		16		8.09		0.4	51.09		171.8	169.	109.2	46.	28.1
05/03/94	264	2.5	40	2.1	2.2	113.8	1.9		14.5		7.94	7.73	0.43	40.5	25.2	192.2	137		56	
05/04/94	265	2.3	40	1.9	2.5	98.2	1.9		14				0.511	36.41		189.4	183.	117.9		
05/05/94	266	2.5	40	2.1	2.5	108.9	1.9		14		8.3		0.827	14.57		204.2	210.	133.7	58.	34.8
05/10/94	271	2.5	40	2.1	2.2	301.7	1.9		18.5		8.97	8.31	1.3	0.43	0.17	208.2	392		38	
05/17/94	278	2.6	40	2.2	2.3	153.6	1.9		18.5		8.97	7.98	0.44	0.15	15.1	228.1	230		46	
05/18/94	279	2.4	40	2.1	2.2	147.8	1.9		18				0.802	51.55		175.0				
05/19/94	280	2.5	40	2.1	2.2	124.0	1.9		20.5		7.7		0.374	17.85		209.3	221.	135.1	49.	28.3
05/24/94	285	2.6	40	2.2	2.3	152.1	1.9		22		7.6	7.81	0.6	0.54	1.2	221.2	251		44	
05/26/94	287	2.5	40	2.1	2.1	149.4	1.9		17.5				0.676	0.027		224.2	322.	203.6	64.	38.1
05/30/94	291	2.5	40	2.1	2.5	108.3	1.9		15.25		8.15		0.553	0.189		211.0	244	169		
05/31/94	292	2.3	40	2.0	2.1	144.5	1.9		17		8.42	7.85	0.29	0.37	0.58	205.6	316		70	
06/06/94	298	2.63	80	4.5	4.7	64.3	1.9		16				0.973	0.076		231.6	507.	322.2		
06/07/94	299	2.5	80	4.3	4.4	68.4	1.9		17			8.12	0.69	0.53	1.5	252.5	565		102	
06/08/94	300	2.5	80	4.3	4.4	67.3	1.9		17				0.921	0.161		229.2	385.	247.7	77.	44.6
06/14/94	306	2.5	160	3.1	3.2	64.4	0.7		14.5			7.55	0.68	81.3	43.8	140.8	1050		81	
06/17/94	309	2.4	160	3.0	3.3	70.0	0.7		20				0.377	0.344		200.6	1168	658.1		
06/21/94	313	2.7	160	3.4	3.6	98.5	0.7		22			7.42	0.96	4.1	49.3	275.3	1080		103	
06/24/94	316	2.33	160	2.9	3.3	65.1	0.7		17.5				1.047	67.70		244.5	702.	395.5		
06/28/94	320	2.75	160	3.5	3.7	64.2	0.7					7.65	0.14	15.9	187	194.0	948		73	
07/05/94	327	2.4	160	3.0	3.5	71.7	0.7		18			7.4	0.142	0.33	199	206.0	1064	671.6	85	
07/12/94	334	2.5	160	3.1	3.2	68.6	0.7		22			7.76	0	0.68	194	223.0	1040		82	
07/19/94	341	2.9	160	3.7	3.8	64.6	0.7		23			7.74	0	0.44	186	202.0	1130	674		
08/05/94	358	2.6	320	4.0	5.1	41.7	0.4		22			7.44	0.1	65.2	189	202.0	1920		63	
08/09/94	362	2.35	320	3.6	5.2	37.0	0.4		22			7.56	0	48.5	196	210.0	2080		67	
08/16/94	369	2.61	320	4.0	4.9	30.8	0.4		22.5			7.94	0.05	88	142	143.0	965		116	
08/23/94	376	2.65	320	4.1	4.9	-1.1	0.4		21			8.26	2.1	276	1.3	1.3	116			
09/01/94	385	2.6	320	4.0	5.2	56.3	0.4		20			8.42	4.8	278	0	1.8	7		32	
09/07/94	391	2.6	320	4.0	5.5	-1.5	0.4		20			8.3	3.5	325	0.007	3.3	40		51	

Comparison of Different Phosphate Measurements

Date	RAW				RBC			SBR		Ratio RAW	RBC	SBR
	Preserved	Normal	Membrane	Pres/Dil	Normal	Membrane	Pres/Dil	Normal	Membrane			
03/09	0.076		1.007	0.391		1.637	2.592		11.606			
04/13	0.332	0.208	0	0.293	1.111	0.121	1.263	1.372	0.712	0	0.108910	0.518950
05/18	0.068	0.176	0.011	0	0.239	0.048	0.37	0.802	0.644	0.0625	0.200836	0.802992
08/05		1.1	0.17		4.7	2.9		0.1	0.02	0.154545	0.617021	0.2
08/09		1.6	0.16		5.7	2.9		0.05	0	0.1	0.508771	0
08/16		0.9	0.14		1.9	1		0.05	0	0.155555	0.526315	0
08/23		0.8	0		1.5	0.8		2.1	1	0	0.533333	0.476190
09/01		1.2	0.04		1.7	0		4.8	1.6	0.033333	0	0.333333
09/07		1.5	0.1		1.6	0.31		3.5	1.3	0.066666	0.19375	0.371428
									AVERAGE	0.085	0.397	0.230
									MAXIMUM	0.156	0.617	0.476
									MINIMUM	0.000	0.000	0.000

OVERALL AVERAGE	EFFLUENT AVERAGE
0.249	0.337

Preserved = preserved with phenyl mercuric acetate and stored for a week.
Pres/Dil = diluted 1:10 or 1:20 then preserved
Normal = unpreserved, undiluted, filtered through Whatman 934AH, measured immediately
(Preserved and Pres/Dil were Whatman 934AH filtered first.
Membrane = filtered through 0.45 micro-m membrane filter, undiluted, measured immediately

Leachate TKN

Date	Day	Alk	NO3-N	NO2-N	NOx-N	NHx-N	TKN	TKN Diss.	TKN:NHx
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
09/15	34	2950	0.33	0.00	0.33	331	392		1.184
10/19	68	2470	0.36	0.00	0.36	273	273		1.000
11/04	84				0.86	188.68	149.51	160.26	0.792
11/04	84				0.863	171.48	168.94	167.4	0.985
11/05	85				1.276	159.76	163.44	146.38	1.023
11/12	92				1.488	158.79	183.6	157.05	1.156
11/30	110	1650	0.02	0.01	0.03	144	156		1.083
12/21	131	1700	0.03	0.00	0.03	147	151		1.027
01/25	166	1950	0.05		0.05	121	136		1.124
02/22	194	1720	0.15	0.15	0.30	132	185		1.402
03/14	214				0.448	159.68	188.66	177	1.181
03/15	215	2200	0.03	0.00	0.03	176	196		1.114
03/21	221				0.033	178.75	166.01	153.26	0.929
04/19	250	2400	0.06	0	0.06	196	218		1.112
05/17	278	2130	0.27	0	0.27	282	285		1.011
05/19	280				1.12	243.96	269.18	209.25	1.103
05/26	287				3.272	220.28	231.6	232.28	1.051
06/08	300				1.579	234.45	268.24	228.45	1.144
06/21	313	2580	0.03	0	0.03	263	264		1.004
07/19	241	2800	0.02	0	0.02	246	250		1.016
					AVERAGE	201.3	214.8	181.3	1.072
					MAXIMUM	331.0	392.0	232.3	1.402
					MINIMUM	121.0	136.0	146.4	0.792

RBC TKN

Date	Day	Fill Time	NHx N	TKN	TKN Diss.	Organic N Removed	TKN: NHx N	NO3 N	NO2 N	NOx N	Total N	NHx N Ldg	NHx N Rem	NHx N Rem	TKN Rem	NHx-N Rem :TKN Rem	Lost N	Total N Rem
		(min)	mg/L	mg/L	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	g/m²/d	g/m²/d	%	g/m²/d		%	%
09/15	34	59	0.3	13.4		47.85	53.60	277	0.00	277	277.3	0.34	0.34	100	0.39	0.87	26.0	16
10/19	68	29		7.2				317	0.01	317	317.0	0.47	0.47	100	0.46	1.03	-18.6	-16
11/04	84	29	0.4	10.88	8.38		28.94			180	180.8	0.44	0.44	100	0.33			
11/04	84	29	15.4	11.63	9.27	1.21	0.76			180	195.9	0.40	0.37	91	0.37	0.99	-13.1	-14
11/05	85	29										0.38						
11/12	92	29	78.6	96.17	84.7	7.252	1.22			60	138.9	0.40	0.20	50	0.22	0.92	15.4	13
11/30	110	14																
12/21	131	29	2.7	9.3		-2.6	3.44	137	0.38	137	140.1	0.42	0.41	98	0.41	1.02	2.9	5
01/25	166	14	0.4	6.5		8.92	15.48	139	0.50	140	139.9	0.77	0.76	100	0.82	0.93	-7.3	-16
02/22	194	8	17.0					139	0.95	140	157.0	0.85	0.74	87				-19
03/14	214	4	0.7	12.99	9.58	16.646	19.80			176	176.3	2.25	2.24	100	2.48	0.91	0.2	-10
03/15	215	4	33.5	46.7		6.8	1.39	133	6.60	140	173.1	2.91	2.36	81	2.47	0.95	5.0	2
03/21	221	4	4.3	14.1	23.4	-22.58	3.32			164	168.0	2.08	2.03	98	1.77	1.15	-7.1	6
04/19	250	2	64.3	74.5		11.8	1.16	137	4.80	142	206.1	4.40	2.96	67	3.22	0.92	0.8	-5
05/17	278	2	65.0	68.4		-0.4	1.05	125	58.10	183	248.1	7.20	5.54	77	5.53	1.00	11.8	12
05/19	280	2	54.8	44.37	57.6	35.637	0.81			187	241.8	6.48	5.02	78	5.97	0.84	14.4	1
05/26	287	2	28.3	68.21	63.0	-28.54	2.41			184	212.6	5.62	4.90	87	4.17	1.17	-7.5	5
06/08	300	2	37.7	51.53	56.3	19.996	1.37			200	237.4	5.27	4.42	84	4.87	0.91	6.9	-1
06/21	313	1	142.0	176		-33	1.24	97	13.50	110	252.0	9.87	4.54	46	3.30	1.37	-8.3	4
07/19	341	1	121.0	129		-4	1.07	112	4.43	116	237.4	4.33	2.20	51	2.13	1.03	1.8	3
	AVERAGE		39.2	49.5	39.1	4.3	8.6				205.5	2.9	2.2	83.0	2.3	1.0	1.5	-0.7
	MAXIMUM		142.0	176.0	84.7	47.9	53.6				317.0	9.9	5.5	100	6.0	1.4	26.0	16.3
	MINIMUM		0.3	6.5	8.4	-33.0	0.8				138.9	0.3	0.2	46.0	0.2	0.8	-18.6	-19

SBR TKN

Date	Day	HRT	NHx N	TKN	TKN Diss.	Organic N Removed	TKN: NHx N	NO3 N	NO2 N	NOx N	Total N	NHx N Ldg	NHx N Rem	NHx N Rem	TKN Rem	NHx-N Rem :TKN Rem	Lost N	Total N Rem
		days	mg/L	mg/L	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	g/m^3/d	g/m^3/d	%	g/m^3/d		%	%
09/15	34	4.5	1.8	22.7		40.1	12.61	308	1.6	310	311.4	71	70	99	79	0.89	15.3	6.0
10/19	68	4.7		20.4				255	55.3	310		58			54		-21.0	
11/04	84	1.9										97						
11/04	84	1.9										88						
11/05	85	1.9	6.526	13.7	14.1	-3.557	2.108			157	163.2	82	79	96	77	1.02	-3.5	-1.4
11/12	92	2.0	78.61	96.1	84.7	7.252	1.223			60	138.9	81	41	50	45	0.92	15.4	13.3
11/30	110	2.0										74						
12/21	131	4.6	125	143		-14	1.144	1.5	0.42	2	126.9	31	5	15	2		4.0	13.7
01/25	166																	
02/22	194	4.6	3.5					133	0.51	134	137.0	28	27	97				-3.6
03/14	214	4.5	0.068	11.5	8.46	17.538	169.2			138	138.1	34	34	100	38	0.90	20.9	13.7
03/15	215	1.9	17.9	31.4		6.5	1.754	124	4.7	129	146.6	90	81	90	84	0.96	18.3	16.7
03/21	221	1.9	48.72	61.5	79.6	-25.51	1.262			86	134.3	92	67	73	54	1.24	11.4	24.9
04/19	250	1.9	102	110		14	1.078	97.7	0.39	98	200.0	100	48	48	55	0.87	4.6	-2.1
05/17	278	1.9	0.15	6.8		-3.65	45.33	213	15.1	228	228.2	144	144	100	143	1.01	17.7	19.1
05/19	280	1.9	17.85	31.1	29.1	11.948	1.743			209	227.1	125	116	93	122	0.95	11.1	7.3
05/26	287	1.9	0.027	8.76	11.1	2.587	324.4			224	224.2	113	113	100	114	0.99	0.8	-0.3
06/08	300	2.0	0.161	8.13	15.4	25.821	50.49			229	229.3	120	120	100	133	0.90	12.0	2.8
06/21	313	0.7	4.1	4.2		0.9	1.024	226	49.3	275	279.4	371	365	98	367	1.00	-5.9	-6.2
07/19	341	0.7	0.44	12.4		-7.96	28.18	16	186	202	202.4	347	346	100	335	1.03	14.2	17.7
	AVERAGE		27.1	38.8	34.7	5.1	45.8				192.5	113.0	110.4	84.0	113.4	1.0	7.7	8.1
	MAXIMUM		125.0	143	84.7	40.1	324.4				311.4	371.1	365.3	100	366.6	1.2	20.9	24.9
	MINIMUM		0.0	4.2	8.5	-25.5	1.0				126.9	28.1	4.7	15.0	1.7	0.9	-21.0	-6

Miscellaneous Leachate Data

Date	Day	Flow	Precip.	Airprt Temp	Air Temp	Temp	Conduct.	Site pH	pH	Colour	TSS	NOx-N	COD	NHx-N	PO4-P	BOD5	BOD:COD
		m³/day	mm	°C	°C	°C	mS	Units	Units	Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
08/12/93	0	0	0	17.6					7.4	500	70	0.32	438	305	0.31		
08/24/93	12	0	0	15.7		20			7.8	700	50	0.02	413	336	0.33		
08/31/93	19	946	0	15.4		20			7.2	800	60	0.26	336	293	0.52		
09/08/93	27	893	0	18.6		20			7.2	800	125	0.04	407	290	0.68		
09/15/93	34	854	0	13.9		17.25			7.4	850	43	0.33	392	331	0.66	37	0.09
09/21/93	40	962	0	10.9	14.5	16	5.9	7.6	7.43	1000	62	0.64	413	304	0.84		
09/29/93	48	978	0	14.3		16.5			7.4	1000	50	0.08	400	289			
10/05/93	54	938	1.4	11.4	18.4	14.75	6.1	7.5	7.3	600	109	0.04	385	307	0.88		
10/12/93	61	956	1.5	14.6	17.5	17.5	6.34	7.6	7.9	800	58	0.83	324	299	0.73		
10/19/93	68	957	0	11	16	17.5	6.04	7.5	7.5	800	56	0.36	341	273	0.58	38	0.11
10/27/93	76	1470	0	7.5		14			7.7	500	103	1.33	268	204	0.65		
11/02/93	82	2095	11.9	9.9	11	12	4.6	7.5	7.2	600	74	0.68	344	191	0.39		
11/09/93	89	1724	0	3.6	8	9.5	4.75	7.4	7.1	500	73	0.03	370	192	0.31		
11/16/93	96	1997	0	4.3	12	11	4.72	7.3	7.2	500	82	0.63	410	190	0.80	70	0.17
11/30/93	110	2655	6.8	4.5	6	8.5	3.69	7.3	7.3	500	46	0.03	473	144	0.99	89	0.19
12/08/93	118	5192	14.7	6.4	7.5	10	3.73	7.4	7.2	400	173	0.03	299	100	0.69		
12/14/93	124	6343	4.4	7.3	9	11			7.1	700	37	0.68	320	85.5	0.10		
12/21/93	131	3486	0	1.6	0.5	7	4.11	7.23	7.5	500	54	0.03	295	147	0.13	37	0.13
12/29/93	139	3316	4.6	4.9	3	9	4.98		7.3	500	79	0.03	412	183	0.00		
01/04/94	145	8359	13.4	8.5	8.75	9.5	2.41		7.3	200	106	3.41	289	101	0.00		
01/11/94	152	5772	3	7.4	8	10	3.27	7.1	7.1	200	31	1.67	236	96	0.05		
01/18/94	159	4009	0.8	5.1	6	10	4.18	7.3	7.1	150	174	0.03	280	148	0.04		
01/25/94	166	3724	0	7	7.5	10.5	4.11	7.2	8.0	400	99	0.05	250	121	0.21	45	0.18
02/01/94	173	2977	0	-0.7	5	8.5	5.1	7.0	8.0	800	64	0.66	330	153	0.06		
02/08/94	180	2600	1.2	-2.5	-1	5.5	5.51	7.4	7.8	800	56	0.03	330	179	0.12		
02/15/94	187	4382	5.2	8.2	8	9	3.7		7.6	500	67	1.41	198	128	0.03		
02/22/94	194	4353	3.2	3.9	4.5	7.5	4.4		7.4	300	50	0.30	300	132	0.05	46	0.15
03/03/94	203	10278	6.2	7.6	9.5	12	3.64	7.2	8.0	800	53	0.04	223	241	0.07		
03/08/94	208	4779	0	5.2	9.5	13		7.2	7.2	600	49	0.33	300	168	0.05		
03/15/94	215	3568	0.6	8.7		14		7.5	7.6	500	64	0.03	324	176	0.04	27	0.08
03/22/94	222	3011	10.6	3.8		16		7.3	7.5	550	55	0.54	257	196	0.06		
03/31/94	231	2411	0	9.8		19.5		7.5	7.8	575	71	0.04	311	206	0.07		
04/05/94	236	2932	1.2	8.9		14		7.5	7.6	600	53	0.05	357	200	0.04		
04/12/94	243	2415	9.4	9.6		17		7.5	7.8	600	53	0.05	308	175	0.05		
04/19/94	250	2000	1.8	14.4					7.4	600	53	0.06	320	196	0.06	20	0.06
04/26/94	257	1755	1.2	12.7					7.9	550	30	0.02	361	243	0.07		
05/03/94	264	1710	0	9.8					7.7	550	40	2.70	360	243	0.06		
05/10/94	271	5391	0.2	16.5					7.6	700	18	0.95	408	281	0.08		
05/17/94	278	1432	0	14.2					7.9	450	107	0.27	385	282	0.04	36	0.09
05/24/94	285	1133	0	17.4					8.0	750	75	0.02	418	266	0.11		
05/31/94	292	1179	4.6	14.2					7.8	600	57	0.79	384	262	0.12		
06/07/94	299	1136	0	12.6					7.8	700	308	0.00	333	257	0.14		
06/14/94	306	1388	5.4	13.1					7.5	400	61	0.04	383	243	0.04		
06/21/94	313	1394	0	16.9					7.5	800	10	0.03	437	263	0.19	49	0.11
06/28/94	320	1204	0	18.9					7.7	800	74	0.00	411	244	0.23		
07/05/94	327	1496							7.7	600	48	0.00	424	241	0.00		
07/12/94	334	1132							7.7	600	106	0.00	411	220	0.05		
07/19/94	341	0							7.6	700	70	0.02	483	246	0.15	52	0.11
08/05/94	358								7.43	800	62	0.12	443	274	1.1		
08/09/94	362								7.15	800	32	0.04	480	242	1.6		
08/16/94	369								7.79	800	42	ND	448	238	0.9		
08/23/94	376								7.64	800	26	0.02	465	273	0.8		
09/01/94	385								7.54	800	56	0.05	532	301	1.2		
09/07/94	391								6.77	800	46	0.02	146	322	1.5		
								MINIMUM	7	150	10		198		0.00	20	0.06
								MAXIMUM	8	1000	308		483		1.10	89	0.19
								AVERAGE	8	617	69		353		0.35	44	0.12

Rotating Biological Contactor Organics

Date	Day	Fill Time (min)	Flow L/day	HRT days	COD mg/L	BOD mg/L	Colour mg/L	COD Loading g/m²/d	BOD Loading g/m²/d	COD Removal g/m²/d	BOD Removal g/m²/d	COD Removal %	BOD Removal %	COD:BOD Removal	Colour Removal %	TSS mg/L	TSS Stld. mg/L
08/12/93	0	59	48	5.10	327		400	0.447		0.113		25.3			20.0	26	
08/24/93	12	59	48	5.10	239		500	0.422		0.178		42.1			28.6	29.6	6.8
08/31/93	19	59	36	6.81	251		500	0.257		0.065		25.3			37.5	26.5	19
09/08/93	27	59	44	5.52	271		600	0.384		0.128		33.4			25.0	41	6
09/15/93	34	59	48	5.10	277	10	500	0.400	0.038	0.117	0.028	29.3	73.0	4.259	41.2	14.5	2
09/21/93	40	59	66	3.70	271		550	0.582		0.200		34.4			45.0	21.5	12.5
09/29/93	48	59	43	5.67	248		500	0.368		0.140		38.0			50.0	16.5	13.5
10/05/93	54	59	48	5.10	230		400	0.393		0.158		40.3			33.3	21.5	10.5
10/12/93	61	29	96	2.55	235		500	0.662		0.182		27.5			37.5	54	44
10/19/93	68	29	82	3.00	226	12	450	0.592	0.066	0.200	0.045	33.7	68.4	4.423	43.8	30	12
10/27/93	76	29	106	2.32	630		300	0.602		-0.813					40.0	30.5	15
11/02/93	82	29	108	2.27	199		500	0.790		0.333		42.2			16.7	19	1.5
11/09/93	89	29	118	2.08	380		1000	0.926		-0.025		-2.7			-100.0	48	7
11/16/93	96	29	91	2.69	250	19	500	0.796	0.136	0.310	0.099	39.0	72.9	3.137	0.0	33	9
11/30/93	110	14															
12/08/93	118	29	130	1.89	223		400	0.824		0.210		25.4			0.0	86	43
12/14/93	124	29	130	1.89	146		300	0.882		0.480		54.4			57.1	19	7
12/21/93	131	29	134	1.82	191	43	300	0.844	0.106	0.297	-0.017	35.3	-16.2		40.0	31	16
12/29/93	139	29	110	2.22	237		350	0.968		0.411		42.5			30.0	8	8
01/04/94	145	29	115	2.13	267		150	0.708		0.054		7.6			25.0	18	
01/11/94	152	14	365	0.67	162		200	1.832		0.574		31.4			0.0	22	20
01/18/94	159	14	298	0.82	143		300	1.773		0.867		48.9			-100.0	18	11
01/25/94	166	14	298	0.82	130	34	300	1.583	0.285	0.760	0.070	48.0	24.4	10.909	25.0	10	6
02/01/94	173	8	576	0.43	230		500	4.044		1.226		30.3			37.5	28	1
02/08/94	180	8	688	0.36	240		500	4.831		1.317		27.3			37.5	15	2
02/15/94	187	8	352	0.70	198		400	1.483		-0.000		-0.0			20.0	15	3
02/22/94	194	8	304	0.81	200	33	200	1.940	0.298	0.647	0.084	33.3	28.3	7.692	33.3	65	9
03/03/94	203	8	384	0.64	121		300	1.822		0.833		45.7			62.5	32	8
03/08/94	208	4	691	0.35	244		400	4.412		0.824		18.7			33.3	29	9
03/15/94	215	4	778	0.32	255	153	320	5.360	0.447	1.142	-2.085	21.3	-466.7		36.0	46	9
03/22/94	222	4	490	0.50	236		350	2.677		0.219		8.2			36.4	45	15
03/31/94	231	4	720	0.34	288		350	4.764		0.352		7.4			39.1	113	21
04/05/94	236	4	518	0.47	249		400	3.938		1.191		30.3			33.3	38	36
04/12/94	243	2	797	0.31	242		350	5.222		1.119		21.4			41.7	40	14
04/19/94	250	2	1056	0.23	303	111	550	7.190	0.449	0.382	-2.045	5.3	-455.0		8.3	93	23
04/26/94	257	2	1680	0.15	322		500	12.904		1.394		10.8			9.1	64	22
05/03/94	264	2	1200	0.20	356		550	9.191		0.102		1.1			0.0	74	18
05/10/94	271	2	0		302		450								35.7	336	9
05/17/94	278	2	1200	0.20	370	255	500	9.830	0.919	0.383	-5.591	3.9	-608.3		-11.1	67	24
05/24/94	285	2	1248	0.20	379		400	11.099		1.036		9.3			46.7	69	16
05/31/94	292	2	1046	0.23	369		550	8.549		0.334		3.9			8.3	28	12
06/07/94	299	2	1066	0.23	410		550	7.550		-1.746		-23.1			21.4	123	29
06/14/94	306	2	1214	0.20	296		400	9.896		2.248		22.7			0.0	35	23
06/21/94	313	1	1764	0.14	398	189	650	16.401	1.839	1.464	-5.254	8.9	-285.7		18.8	49	18
06/28/94	320	1	2808	0.09	396		600	24.555		0.896		3.6			25.0	117	27
07/05/94	327	1	0		311		400	0.000		0.000		26.7			33.3	73	3
07/12/94	334	1	1325	0.18	316		500	11.585		2.678		23.1			16.7	35	6
07/19/94	341	1	828	0.30	347	198	400	8.509	0.916	2.396	-2.572	28.2	-280.8		42.9	18	9
06/05/94	358	3	720	0.34	417		600	6.786		0.398		5.9			25.0	189	
08/09/94	362	3	641	0.38	361		550	6.544		1.622		24.8			31.3	147	
08/16/94	369	3	756	0.32	371		600	7.206		1.239		17.2			25.0	118	14
08/23/94	376	3	828	0.30	448		600	8.192		0.299		3.7			25.0	221	48
09/01/94	385	3	785	0.31	489		700	8.883		0.718		8.1			12.5	192	34
09/07/94	391	3	547	0.45	468		700	1.700		-3.749					12.5	170	21
				MINIMUM	121	10	150	0.00	0.04	-1.75	-5.59	-23.1	-608.3	3.1	-100.0	8.0	1.0
				MAXIMUM	630	255	1000	24.56	1.84	2.68	0.10	54.4	73.0	10.9	62.5	*****	44.0
				AVERAGE	289	89	453	4.57	0.46	0.47	-1.90	21.2	-204.5	5.6	20.1	62.7	15.2

Activated Sludge Organics

Date	Day	Flow	HRT	COD	BOD	Colour	COD Loading	BOD Loading	COD Removal	BOD Removal	COD Removal	BOD Removal	COD:BOD Removal	Colour Removal
		L/day	days	mg/L	mg/L	mg/L	g/m³/day	g/m³/day	g/m³/day	g/m³/day	%	%		%
08/12/93	0	78	4.7	518		800	93.3		-17.0		-18.3			-60.0
08/24/93	12	78	4.7	341		600	88.0		15.3		17.4			14.3
08/31/93	19	78	4.7	326			71.6							
09/08/93	27	78	4.7	284		500	86.7		26.2		30.2			37.5
09/15/93	34	78	4.5	299	0	600	83.5	7.9	19.8	7.9	23.7	100.0	2.514	29.4
09/21/93	40	78	4.6	359		600	88.0		11.5		13.1			40.0
09/29/93	48	78	4.6	310		800	85.2		19.2		22.5			20.0
10/05/93	54	78	4.6	279		800	82.0		22.6		27.5			-33.3
10/12/93	61	187	1.9	331		600	166.0		-3.6		-2.2			25.0
10/19/93	68	187	2.0	289	70	750	174.7	19.5	26.6	-16.4	15.2	-84.2	-1.625	6.3
10/27/93	76	187	1.9	224		400	137.3		22.5		16.4			20.0
11/02/93	82	187	1.9	253		400	176.2		46.6		26.5			33.3
11/09/93	89	187	2.0	330		800	189.6		20.5		10.8			-60.0
11/16/93	96	187	1.9	300	67	800	210.1	35.9	56.4	1.5	26.8	4.3	36.667	-60.0
11/30/93	110	187	2.0											
12/08/93	118	187	2.0	288		500	153.2		5.6		3.7			-25.0
12/14/93	124	187	1.9	267		600	163.9		27.2		16.6			14.3
12/21/93	131	78	4.7	263	13	250	62.8	7.9	6.8	5.1	10.8	64.9	1.333	50.0
12/29/93	139	78	4.6	332			87.8							
01/04/94	145	78	4.7	279			61.6							
01/11/94	152	78	4.6	242			50.3							
01/18/94	159			143			0.0							
01/25/94	166						0.0							
02/01/94	173	78	4.6	260		600	70.3		14.9		21.2			25.0
02/08/94	180	78	4.6	250		400	70.3		17.0		24.2			50.0
02/15/94	187	78	4.6	235		500	42.2		-7.9		-18.7			0.0
02/22/94	194	78	4.6	260	31	150	63.9	9.8	8.5	3.2	13.3	32.6	2.667	50.0
03/03/94	203	78	4.6	179		400	47.5		9.4		19.7			50.0
03/08/94	208	78	4.5	231		500	63.9		14.7		23.0			16.7
03/15/94	215	187	1.9	253	71		166.0	13.8	36.4	-22.5	21.9	-163.0	-1.614	
03/22/94	222	187	1.9	198			131.7		30.2		23.0			
03/31/94	231	187	1.9	228		450	159.3		42.5		26.7			21.7
04/05/94	236	187	1.9	257		400	182.9		51.2		28.0			33.3
04/12/94	243	187	1.9	258		350	157.8		25.6		16.2			41.7
04/19/94	250	187	2.0	303	40	550	163.9	10.2	8.7	-10.2	5.3	-100.0	-0.850	8.3
04/26/94	257	187	1.9	152		450	185.0		107.1		57.9			18.2
05/03/94	264	187	1.9	300		400	184.4		30.7		16.7			27.3
05/10/94	271	187	1.9	310		450	209.0		50.2		24.0			35.7
05/17/94	278	187	1.9	293	36	400	197.2	18.4	47.1	0.0	23.9	0.0		11.1
05/24/94	285	187	1.9	317		400	214.2		51.7		24.2			46.7
05/31/94	292	187	1.9	263		400	196.7		62.0		31.5			33.3
06/07/94	299	187	2.0	296		550	170.6		19.0		11.1			21.4
06/14/94	306	515	0.7	395		600	540.4		-16.9		-3.1			-50.0
06/21/94	313	515	0.7	455	94	650	616.6	69.1	-25.4	-63.5	-4.1	-91.8	0.400	18.8
06/28/94	320	515	0.7	512		600	579.9		-142.5		-24.6			25.0
07/05/94	327	515	0.7	505		600	598.2		-114.3		-19.1			0.0
07/12/94	334	515	0.7	485		700	579.9		-104.4		-18.0			-16.7
07/19/94	341	515	0.7	654	246	650	681.5	73.4	-241.3	-273.7	-35.4	-373.1	0.881	7.1
08/05/94	358	843	0.4	495		800	1023.1		-120.1		-11.7			0.0
08/09/94	362	843	0.4	459		700	1108.6		48.5		4.4			12.5
08/16/94	369	843	0.4	452		700	1034.7		-9.2		-0.9			12.5
08/23/94	376	843	0.4	461		700	1074.0		9.2		0.9			12.5
09/01/94	385	843	0.4	486		700	1228.7		106.2		8.6			12.5
09/07/94	391	843	0.4	468		800	337.2							0.0
			MINIMUM	143.0	0.0	150.0	0.0	7.9	-241.3	-273.7	-35.4	-373.1	-1.625	-60.0
			MAXIMUM	654.0	246.0	800.0	1023.1	73.4	107.1	7.9	57.9	100.0	36.667	50.0
			AVERAGE	317.9	60.7	547.7	273.3	24.9	1.7	-58.4	11.0	-89.4	2.875	12.9

Leachate Total Metals - Both Data Sets

Date	Cr	Fe	Pb	Mn	Ni	Zn
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
09/15	ND	16.8	ND	1.07	0.041	0.1
10/19	ND	19.2	ND	1.11	0.029	0.067
11/30	ND	14.9	ND	1.03	ND	0.31
12/21	ND	17.3	ND	1.31	ND	0.23
01/25	ND	20.2	ND	1.54	0.029	0.2
02/22	0	14.2	0	1.48	0	0.27
03/09	0.01	19.1			0.028	0.417
03/15	0	13.8	0	1.36	0	0.07
04/13	0.005	13			0.042	0.18
04/19	0	13.4	0	1.38	0	0.062
05/17	0	14.4	0	1	0.028	0.092
05/18	0.005	18.2			0.042	0.186
06/21	0	12.4	0	1.29	0.025	0.06
07/19	0	13.2		0.82	0.033	0.079
08/03	0.009	10.9			0.051	0.111
08/23	0	14.6	0	1.03	0.037	0.035
city dl	0.03	0.03	0.08	0.003	0.025	0.015
ay dl	0.01	1			0.02	0.02
AVERAGE	0.002	15.350	0.000	1.202	0.024	0.154
MAXIMUM	0.01	20.2	0	1.54	0.051	0.417
MINIMUM	0	10.9	0	0.82	0	0.035

KBC Total Metals - Both Data Sets

Date	Cr	Fe	Pb	Mn	Ni	Zn	Cr Removal	Fe Removal	Pb Removal	Mn Removal	Ni Removal	Zn Removal
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	%	%	%	%	%	%
09/15	ND	3.02	ND	0.21	0.043	0.053	-	82.0	-	80.4	-4.9	47.0
10/19	ND	2.31	ND	0.053	0.031	0.039	-	88.0	-	95.2	-6.9	41.8
11/30												
12/21	ND	5.77	ND	0.36	ND	0.12	-	66.6	-	72.5	-	47.8
01/25	ND	4.44	ND	0.34	ND	0.13	-	78.0	-	77.9	>16	35.0
02/22												
03/09		7			0.04	0.493	-	63.4			-42.9	-18.2
03/15	0	7.27	0	1.28	0	0.075	-	47.3	-	5.9	-	-7.1
04/13		9.1			0.04	0.376	-	30.0			4.8	-108.9
04/19	0	11.7	0	1.46	0	0.084	-	12.7	-	-5.8	-	-35.5
05/17	0	11	0	1.09	0.026	0.057	-	23.6	-	-9.0	7.1	38.0
05/18		19			0.05	0.198	-	-4.4			-19.0	-6.5
06/21	0	9.96	0	0.65	0.031	0.072	-	19.7	-	49.6	-24.0	-20.0
07/19	0	5.85	0	0.31	0.041	0.042	-	55.7	-	62.2	-24.2	46.8
08/03												
08/23	0	25.7	0	1.08	0.037	0.078	-	-76.0	-	-4.9	0.0	-122.9
city my dl	0.03	0.03	0.08	0.003	0.025	0.015						
AVE	0.000	9.394	0.000	0.683	0.026	0.140	0.0	37.4	0.0	42.4	-8.5	-4.8
MAX	0	25.7	0	1.46	0.05	0.493	0.0	88.0	0.0	95.2	7.1	47.8
MIN	0	2.31	0	0.053	0	0.039	0.0	-76.0	0.0	-9.0	-42.9	-122.9

SBR Total Metals - Both Data Sets

Date	Cr	Fe	Pb	Mn	Ni	Zn	Cr Removal	Fe Removal	Pb Removal	Mn Removal	Ni Removal	Zn Removal
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	%	%	%	%	%	%
09/15	ND	6.67	ND	0.96	0.043	0.11	-	60.3	-	10.3	-4.9	-10.0
10/19	ND	13.5	ND	1.03	0.032	0.59	-	29.7	-	7.2	-10.3	-780.6
11/30												
12/21	ND	10.2	ND	0.22	ND	0.25	-	41.0	-	83.2	-	-8.7
01/25												
02/22												
03/09		2.9			0.034	0.27	-	84.8			-21.4	35.3
03/15	0	10.8	0	1.23	0	0.36	-	21.7	-	9.6	-	-414.3
04/13		13.9			0.036	0.1	-	-6.9			14.3	44.4
04/19	0	11.6	0	1.15	0	0.082	-	13.4	-	16.7	-	-32.3
05/17	0	5.76	0	1.01	0	0.5	-	60.0	-	-1.0	>12	-226.1
05/18		8.5			0.04	0.198	-	53.3			4.8	-6.5
06/21	0	11.9	0	0.98	0.029	0.11	-	4.0	-	24.0	-16.0	-83.3
07/19	0	13.6	0	1.17	0.039	0.074	-	-3.0	-	-42.7	-18.2	6.3
08/03												
08/23	0	10.3	0	0.064	0.037	0.054	-	29.5	-	93.8	0.0	-54.3
city my dl	0.03	0.03	0.08	0.003	0.025	0.015						
AVE	0.000	9.969	0.000	0.868	0.024	0.208	0.0	32.3	0.0	22.3	-4.3	-127.5
MAX	0	13.9	0	1.23	0.043	0.59	0.0	84.8	0.0	93.8	14.3	44.4
MIN	0	2.9	0	0.064	0	0.054	0.0	-6.9	0.0	-42.7	-21.4	-780.6

METAL AND TOXICITY DATA

Note: "2" under date indicates measurements on samples left in control beakers during Daphnia LC50 tests.

Cr

	Totals		Dissolved	EC50-5			EC50-15			Daph LC50		
Date	Raw		Raw	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS
03/09	0.010			12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	0.010											
04/13	0.005			45.4	100	100	46.6	100	100	11	100	28.5
2	<.001											
05/11	0.005			50.0	100	100	50	100	100			
08/03	0.009		0.012									

Susan says best to say all less than 0.01.
due to strange double peak response on raw samples.

Fe

	Totals			Dissolved			EC50-5			EC50-15			Daph LC50		
Date	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS
03/09	19.1	7.0	2.9	1.2	2.0	24.8	12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	10.7	4.0	4.4	ND	1.5	1.7									
04/13	13.0	9.1	13.9	0.2	1.5	1.2	45.4	100	100	46.6	100	100	11	100	28.5
2	9.6	6.8	8.7	1.2	1.3	<1.0									
05/11	18.2	19.0	8.5	2.8	1.8	1.1	50.0	100	100	50	100	100			
08/03	10.9			0.5											

Due to dilution/noise, detection limit is about 1.0 mgsome samples lower due to subtraction of non zero blank
sometimes good removals
no clear trend
usually get pption

Diss less than total
no clear trend

Zn

	Totals			Dissolved			EC50-5			EC50-15			Daph LC50		
Date	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS
03/09	0.417	0.493	0.270	0.018	0.292	0.728	12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	0.183	0.112	0.100	0.032	0.071	0.063									
04/13	0.180	0.376	0.100	0.061	0.077	0.030	45.4	100	100	46.6	100	100	11	100	28.5
2	0.099	0.251	0.093	0.054	0.100	0.020									
05/11	0.186	0.198	0.198	0.028	0.038	0.033	50.0	100	100	50	100	100			
08/03	0.111			0.033											

Detection limit = .02 (SD = 0.1)
some sig removals by always less than tot (except P)
usually sig ppte

no sig removal
sometimes pptes, sometimes dissolves

Cu

	Totals			Dissolved			EC50-5			EC50-15			Daph LC50		
Date	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS
03/09	0.010	0.019	0.048	0.117	0.501	1.019	12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	0.025	0.020	0.039	0.022	0.225	0.214									
04/13	<.01	0.017	0.031	0.021	0.166	0.041	45.4	100	100	46.6	100	100	11	100	28.5
2	0.019	0.019	0.012	0.020	0.035	0.034									
05/11	0.017	0.022	0.032	0.029	0.332	0.036	50.0	100	100	50	100	100			
08/03	0.036			0.046											

Detection limit is .01 mg/L (SD = .01 to .05)

Diss samples contaminated

no sig removal

results probably unreliable

Co

	Totals			Dissolved			EC50-5			EC50-15			Daph LC50		
Date	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS
03/09	0.03	0.04	0.03	0.03	0.04	0.05	12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	0.02	0.04	0.03	<.02	0.03	0.03									
04/13	0.03	0.04	0.05	0.04	0.03	0.03	45.4	100	100	46.6	100	100	11	100	28.5
2	0.03	0.04	0.04	0.00	0.04	0.03									
05/11	0.04	0.05	0.04	0.04	0.04	0.04	50.0	100	100	50	100	100			
08/03	0.03			0.04											

some samples lower due to subtraction of non zero blank

Detection limit is about 0.02 mg/L (SD = 0.1)

diss about same as total

no sig removals

no sig removals

no sig precip

no sig precip

Cd

	Totals			Dissolved			EC50-5			EC50-15			Daph LC50		
Date	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS	Raw	RBC	AS
03/09	0.006	0.008	0.007	0.007	0.007	0.010	12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	0.004	0.008	0.007	<.004	0.006	0.008									
04/13	0.006	0.008	0.007	0.006	0.009	0.006	45.4	100	100	46.6	100	100	11	100	28.5
2	0.006	0.007	0.007	0.004	0.008	0.008									
05/11	0.008	0.008	0.008	0.010	0.006	0.007	50.0	100	100	50	100	100			
08/03	0.006			0.008											

Detection limit is about 0.004 (SD of measurements = 0.01 to 0.02)

no sig removal or pptdiss same as total

no sig removal or pption

Ni

Date	Totals Raw	Totals RBC	Totals AS	Dissolved Raw	Dissolved RBC	Dissolved AS	EC50-5 Raw	EC50-5 RBC	EC50-5 AS	EC50-15 Raw	EC50-15 RBC	EC50-15 AS	Daph LC50 Raw	Daph LC50 RBC	Daph LC50 AS
03/09	0.028	0.040	0.034	0.480	0.745	1.039	12.0	80.15	88.2	13.38	45	31	18.1	100	100
2	0.022	0.038	0.028	0.079	0.330	0.900									
04/13	0.042	0.040	0.036	0.044	0.130	0.063	45.4	100	100	46.6	100	100	11	100	28.5
2	0.038	0.033	0.037	0.041	0.144	0.065									
05/11	0.042	0.050	0.040	0.041	0.184	0.074	50.0	100	100	50	100	100			
08/03	0.051			0.076											

Detection limit = .02 mg/L (SD = 0.1)

no sig removal Diss > total probably contaminated
no sig pption

AMMONIA TOXICITY DATA

Date	Sample	EC50-5 (%)	EC50-15 (%)	Daph LC50 (%)	Fish LC50 (%)	Total Phenol.	Total Oil/ Grease	Total Extr. HC	before pH	before NHx N (mg/L)	before NH3 N (mg/L)	after pH	after NHx N (mg/L)	after NH3 N (mg/L)
02/09	raw	20	18	12	13	ND	13	3	7.5	171.5	3.33	8.3	218.2	21.42
	rbc	52	27	20					8.2	71.8	5.83	8.3	75.8	8.08
	ase	100	100	100					8.4	0.2	0.03	8.6	1.5	0.30
03/09	raw	12	13	18	13	0.02	2	0.5	7.3	143.0	1.61	8.2	122.4	10.17
	rbc	80	45	100					8.0	1.5	0.08	8.3	0.5	0.05
	as	88	31	100					7.7	2.2	0.07	8.4	0.6	0.08
04/13	raw	45	47	11	13	0.13	ND	ND	7.6	172.2	4.01	8.1	142.0	9.95
	rbc	100	100	100					8.1	0.1	0.01	8.5	0.3	0.04
	ase	100	100	29					8.0	52.6	2.91	8.2	40.0	3.69
05/18	raw	50	50			ND	14	ND	7.5	264.2	5.13			
	rbc	100	100						7.9	62.5	3.03			
	ase	100	100						7.7	51.6	1.47			

Notes: "100" indicates > 100 % (i.e. non-toxic)
"EC50-5" indicates Microtox EC50 after 5 minutes
"EC50-15" indicates Microtox EC50 after 15 minutes
"Total Phenol." indicates total phenolics
"Total Extr. HC" indicates total extractable hydrocarbons
"before" indicates the beginning of Daphnia LC50 tests
"after" indicates the end of Daphnia LC50 tests

NH3-N = NHx-N/(1 + 10^(-pH)/Ka)
Ka = 5.848 x 10^(-10) (20° C) Source: [65]

RAINBOW TROUT TOXICITY DATA

Date	LC50 (%)	NHx-N (mg/L)	pH	NH3-N (mg/L)	Cu (mg/L)	Zn (mg/L)	Ni (mg/L)	Mn (mg/L)	Fe (mg/L)
77/03/01	33	66							
77/04/18	42	63							
77/06/12	10	237							
93/01/26	24	83	7.66	2.23	0.08	0.35	0.03	1.28	15.4
93/03/03	7	224	7.86	9.41	0.08	0.25	0.03	1.18	27.2
93/03/17	23	113	7.96	5.91	0.07	0.38	0.03	1.46	36.6
93/04/14	13	189	7.81	7.11	0.07	0.11	0.02	1.18	14.8
93/05/12	10	174.5	7.71	5.25	0.07	0.1	0.02	1.07	15.7
93/06/16	9	182	7.94	9.11	0.07	0.19	0.02	0.88	15.9
93/07/13	7	224	7.92	10.74	0.09	0.16	0.02	1.11	17.7
93/08/18	7	279	7.92	13.37	0.07	0.08	0.03	0.98	13.9
93/09/16	13	267	7.6	6.75	0.08	0.08	0.04	1.15	13.6
93/10/13	12	277	7.94	13.87					
93/11/19	13	160	7.73	5.04					
93/12/28	13	164	7.65	4.32					
94/01/27	24	97.2	7.53	1.95					
94/02/09	13	171.5	7.54	3.53					
94/03/09	13	144	7.7	4.24					
94/04/13	13	188	7.69	5.41					
94/07/13	7	222	7.56	4.77					
94/12/14	13	161	7.44	2.64					

ka = 6.053E-10 (15°C)
(For NH3-N Calculations)

MICROTOX EC50 DATA

Date	Sample	EC50-5 (%)	D-Conf (%)	EC50-15 (%)	D-Conf (%)	EC50-25 (%)	D-Conf (%)	EC50-35 (%)	D-Conf (%)	Daph LC50 (%)	D-Conf (%)	Fish LC50 (%)	D-Conf (%)	NHx N (mg/L)	2259/N
02/09	raw	20.26	25.8	17.8	27.1					11.8	?	13	8	171.5	13.2
	rbc	51.6	49.3	27.2	15.2					20.0	16.1			71.8	31.5
	ase	100	-	100	-					100	-			0.2	10966.0
03/09	raw	12.04	8.479	13.38	10.01					18.1	112.1	13	8	143.0	15.8
	rbc	80.15	97	45	?					100	-			1.5	1531.5
	as	88.2	28.4	31	85					100	-			2.2	1030.6
03/23	raw	49.82	99.93	50	large									162.4	13.9
	rbc	100		100										0.2	10130.0
	ase	100		100										38.8	58.2
	asi	100		100										41.1	55.0
03/24	raw	32.95	20.9	26.93	5.71									168.6	13.4
	rbc	100		100										1.3	1737.7
	ase	100		100										37.1	60.8
	asi	100		100										35.3	63.9
04/06	raw	?		24.48	3.06									149.6	15.1
	rbc	100		100										0.1	18825.0
	ase	100		100										64.2	35.2
	asi	100		100										65.8	34.3
04/07	raw	25.36	25.2	14.84	7.4									175.2	12.9
	rbc	68	13	76	20									0.4	5145.8
	ase	100		100										59.7	37.8
	asi	100		100										65.2	34.7
04/13	raw	45.4	20	46.6	23.5					11		13	8	172.2	13.1
	rbc	100		100						100				0.1	31375.0
	ase	100		100						28.5				52.6	42.9
04/14	raw	44.2	?	39.9	25.9									174.9	12.9
	rbc	77.7	57.7	90.9	150.2									47.3	47.8
	ase	100		100										70.4	32.1
	asi	100		100										82.3	27.5
04/20	raw	76	?	83	?									175.5	12.9
	rbc	100		100										32.2	70.2
	ase-basic	63		63										104.8	21.6
	ase-100	100		88.6	11	48.2	10.4	38	8.6					104.8	21.6
	asi-basic	100		100										93.8	24.1
	asi-100	100		100										93.8	24.1
04/21	raw	53.1	48.6	52.27	37.7									167.7	13.5
	rbc	100		100										0.0	56475.0
	ase-basic	91		95.5										83.8	26.9
	ase-100	100		79.4		79	463	73.1	400.04					83.8	26.9
	asi-basic	79		68										97.8	23.1
	asi-100	100		100		89.4	109.8	69.7	40.1					97.8	23.1
05/18	raw	50	?	50	?									264.2	8.6
	rbc	100		100										62.5	36.2
	ase	100		100										51.6	43.8
												33		66.0	34.2

Note: D-Conf" indicates 95% confidence interval