

PILOT SCALE STRUVITE RECOVERY TRIALS FROM A FULL-SCALE
ANAEROBIC DIGESTER SUPERNATANT AT THE CITY OF PENTICTON
ADVANCED WASTEWATER TREATMENT PLANT

by

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ABSTRACT

Pilot-testing of a fluidized bed reactor used to recover phosphate in the form of struvite from a full-scale anaerobic digester supernatant was conducted on site, at the City of Penticton Advanced Wastewater Treatment Plant (AWWTP). The main objective of this study was to demonstrate the ability of the reactor, developed by the UBC phosphate recovery team, to remove at least 70 % of the phosphate in the supernatant from a full-scale digester fed with a combination of primary and secondary sludge, from a biological nutrient removal wastewater treatment plant.

Results showed that the reactor was capable of removing over 80 % of the phosphate from the digester supernatant. The operation of the reactor could easily be controlled to achieve any desired level of phosphorus removal up to 90%. Reactor operation was relatively trouble free after an initial commissioning period. By the end of the experiment, it was possible to leave the reactor unattended for periods of up to 5 days without incident.

Analysis of the recovered struvite crystals showed essentially pure struvite (>99 % by weight) with small amounts of calcium (<0.5 % by weight) and traces of potassium and iron. The recovered crystals had mean diameters increasing from 0.5 to 1.8 mm over the course of the study. This increasing diameter is believed to be due to changes in the crystal structure that caused them to become stronger over the course of the study. The causes of this change in crystal structure remain unknown, and require further investigation.

A model was developed which was able to predict the effluent quality of the reactor based on the concentrations of magnesium, ammonia and phosphate in the reactor influent and the operating pH of the reactor. The model is based on the assumptions that the reactor effluent is at equilibrium with respect to struvite, and that magnesium, ammonia and phosphate are removed in equimolar amounts. The system equilibrium was described by an equilibrium conditional solubility product curve, developed for a sample of digester supernatant taken during the study.

Phosphate release from the anaerobic digestion of waste activated sludge was found to be 13% of the total phosphorus load to the treatment plant, when digesting only 40% of the secondary sludge, significantly lower than predicted in a previous study (Niedbala, 1995). This is probably due to the recent practice of discharging aluminum-rich sludge from the city drinking water treatment plant to the wastewater treatment plant. Changing this practice could result in the production of significantly greater masses of product at similar costs, thus increasing the economic viability of the process.

Further studies at larger scale and of longer duration would be required to determine the steady state struvite product qualities produced by this process. The market that the product will target will also be important in order to produce a desirable and profitable product.

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1. INTRODUCTION

Phosphorus recovery is an important area of research in the environmental engineering field. There are a variety of reasons for this, including the gradual depletion of global reserves of mined phosphate deposits, the degradation of the quality the remaining phosphate ore and operational problems encountered in biological nutrient removal (BNR) wastewater treatment plants. The piping and equipment in the sludge treatment processes of these plants is increasingly prone to fouling and encrustation with struvite, which can dramatically increase pumping and maintenance costs. Another important factor in driving this research was the increased opportunity for phosphate recovery derived from the increased use of biological nutrient removal technology around the world. The use of BNR in wastewater treatment leads to the creation of an enriched phosphate stream in the sludge handling liquors. This enriched stream was the focus of most investigations into the recovery of phosphorus from municipal wastewaters.

In this study, a pilot scale phosphorus recovery reactor, developed at the University of British Columbia, was tested at a full-scale BNR treatment plant in the city of Penticton, British Columbia, Canada. The reactor was used to recover phosphate in the form of struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) from an anaerobic digester supernatant stream, through the addition of magnesium chloride and pH adjustment in a fluidized bed. The study was carried out over a four-month period in the fall of 2001, during which time the anaerobic digester was fed with a blend of primary and secondary sludge. The following section outlines the reasons for undertaking this research.

1.1. Global Phosphorus Supply Depletion

Studies have shown that the global supply of phosphate rock may be exhausted within the next 50-100 years (Steen, 1998; Driver et al., 1999). The quality of this mined phosphate rock is also decreasing as lower grade ore deposits are used; these contain less phosphorus and more contaminants, such as heavy metals (Driver et al., 1999). For these reasons, the processing of mined phosphate rock is becoming more costly and the phosphate industry is searching for more

sustainable and lower cost sources of phosphorus: A study conducted in Europe has found that the phosphate recovered from wastewater was likely to be of better quality than commercially available phosphate rock, but the full economic impact of phosphorus recovery from wastewater still requires further investigation and appears to be site specific (Jeanmaire and Evans, 2001).

1.2. Recoverable Phosphorus Sources In British Columbia

In British Columbia the two major sources of phosphorus recovery being considered are municipal wastewater treatment plants and large livestock farms. The main emphasis thus far has been on the municipal wastewater, since there is currently centralized treatment for large volumes of wastewater and commercially exploitable masses of phosphorus can be recovered from single sources. Many wastewater treatment plants are ideal locations for phosphorus recovery since the required pre-treatment and stream concentration to make phosphorous recovery most feasible are already in place. Although the bulk of potentially recoverable phosphate in British Columbia will likely come from agricultural sources in the long run, until regulation are put into place to limit nutrient discharges from farms, it is unlikely that the agricultural industry will invest in the necessary infrastructure to support phosphorus recovery. It is currently estimated that about 1900 tonnes of phosphorus are amenable for recovery per year from municipal sewage in British Columbia and about 10,000 tonnes of phosphorus are recoverable from agricultural wastes (Yu, 2001).

1.3. Site Selection

The City of Penticton Advanced Wastewater Treatment Plant (AWWTP) was selected as the site for this experiment. This site was selected because it was one of the nearest BNR plants to the University of British Columbia and has previously been used in successful collaborative research efforts between UBC, the City of Penticton and Stantec Consultants. The AWWTP is also one of the best performing cold climate BNR plants in North America, and the staff has been extremely helpful in previous research conducted on site. The City of Penticton has also expressed an interest in being one of the pioneering municipalities in Canada with regards to implementing innovative and sustainable waste management strategies.

1.4. City of Penticton Advanced Wastewater Treatment Plant

The City of Penticton AWWTP consists of preliminary treatment including screening and degritting, primary clarifiers, two parallel modified UCT design BNR secondary treatment trains, sand filters for secondary effluent polishing and chlorine disinfection. The city of Penticton is located in the Okanagan Valley in south central British Columbia, between Lake Okanagan and Lake Skaha. This is a region of intense fruit growing and irrigation and an environment sensitive to excessive nutrient input. For this reason the wastewater treatment plant is subject to very low effluent phosphorus standards (0.25 mg/L). The sludge treatment train for this plant consists of primary sludge fermenters, to provide the required volatile fatty acids for the BNR system, and a two stage anaerobic digester for the fermented primary sludge. The primary sludge is then dewatered on a belt press after being combined with thickened waste activated sludge from the BNR trains. The secondary sludge is not digested on site, since this practice would lead to the release of the excess phosphorus stored in the secondary sludge from the BNR system (Niedbala, 1995). Instead, the combined dewatered sludge is windrow composted off site at the municipal landfill, and the composted sludge is sold to local landscaping and agricultural operations, as a soil conditioner, known as City of Penticton Compost.

During the course of this study, from September to December 2001, the operation of the sludge treatment system was modified to transfer a portion of the secondary sludge to the digester, in order to obtain a digester supernatant stream rich in phosphate and ammonia.

2. RESEARCH OBJECTIVES

The purpose of this study was to provide the transition for the UBC phosphate recovery team from using synthetic supernatant to using real supernatant at a full-scale BNR wastewater treatment plant. The research team at UBC had successfully demonstrated a reactor design used to recover struvite from synthetic supernatants with Mg, NH₄ and PO₄ concentrations similar to those expected in the digester supernatant at the City of Penticton AWWTP; however, some doubts still remained as to the effects of dissolved constituents, as well as suspended solids, in the real supernatant on the control and operation of the reactor. Both bench scale and pilot scale experiments had been conducted at UBC prior to this study, and the expected operating parameters were determined from this work prior to setting up the pilot plant at the City of Penticton AWWTP (Dastur, 2001).

The objectives of this study were to determine the operational parameters that would allow successful operation of the pilot-scale reactors treating real anaerobic digester supernatant from a full-scale BNR wastewater treatment plant. Successful operation was defined as the controlled removal of at least 70 % of the ortho-phosphate from the digester supernatant, and the recovery of this phosphorus in the form of large (>1mm) and easily separable struvite crystals.

This study also aimed to develop a mathematical model which could be used to predict the pilot-scale reactor performance with respect to treated effluent quality based on an analysis of the untreated supernatant.

Other aims of this study were to estimate the impacts of a full-scale struvite recovery plant on nitrogen and phosphorus loads from the digester supernatant, to estimate the production of struvite and to determine the associated costs.

3. BACKGROUND

3.1. Struvite Chemistry

Struvite is a sparingly soluble compound composed of equimolar amounts of magnesium, ammonia and phosphate, as well as six waters of hydration ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$). Several studies have been aimed at determining the equilibrium solubility product of this compound in water; however, the results of these studies vary greatly.

Dastur (2001) gives a good overview of the work completed on this subject to date. In general, the mixing conditions and assumed times to reach equilibrium vary considerably in these studies, as do the number and complexity of the compounds included in the equilibrium calculations (Ohlinger, 1999). Some studies do not account for the ionic strength of the solutions, while others do, and some studies include varying numbers of magnesium phosphate compounds, while others assume that different forms of phosphate are involved in the formation of struvite (Ohlinger *et al.*, 1998, Dastur, 2001). Overall, the published values for the thermodynamic solubility product (K_{sp}) of struvite range from $3.8 \cdot 10^{-10}$ to $5.1 \cdot 10^{-15}$ (Dastur, 2001).

Uncertainty about the thermodynamic solubility product for struvite has led investigators to develop a surrogate parameter referred to as the conditional solubility product (P_s) which represents the product of the measured total concentrations of the three species involved in the formation of struvite. This simplified analysis only requires the results from the chemical analysis of the sample, but the equilibrium value varies with pH, temperature and possibly other factors (Dastur, 2001). It is, however, simple to develop an equilibrium P_s curve for a given sample matrix, that should be applicable in the operation of a struvite crystallizing reactor.

The advantage of the use of this P_s curve over a true thermodynamic equilibrium constant is that the P_s curve is much simpler to develop and use. Only measurements for magnesium, ammonia, ortho-phosphate and pH are required, and no other equilibrium constants or activity corrections are needed. The conditional solubility product curves developed by Dastur (2001)

and Ohlinger (1999) are easily regressed, using second or fourth order polynomial functions, and are therefore easily incorporated in a model to predict the formation of struvite or the operation of a struvite recovery reactor.

The main disadvantage of using the P_s values for describing a struvite crystallizing system is that comparison between studies becomes more difficult due to differing matrix effects in each wastewater analyzed. A very close agreement was found however between the results of Ohlinger (1999) and a study performed at UBC using distilled water and relatively pure crystalline struvite (Dastur, 2001).

3.2. Struvite Crystallography

Several studies have been conducted in order to determine the effects of various environmental conditions on the morphology of struvite crystals. This include the effects of turbulence, struvite supersaturation ratio in the solution, molar ratios of Mg:N:P, presence of impurities, reactor seeding conditions and pH, among others. Overall the morphologies of the crystals vary as widely as the conditions under which they are grown. An attempt is presented here to summarize some of the more important factors that are thought to affect the shape and size of the produced struvite crystals.

Generally, the distinction between precipitation and crystallization reactions is vague. Precipitation is generally used to describe processes that produce small amorphous solids while crystallization is used to describe processes that produce solids with defined structure and crystalline facets. Mersmann (1999) shows that in continuous crystallizers such as the one used in this study, the conditions necessary to produce large particles (which he defines as $> 100 \mu\text{m}$) is to use low concentration reactants, to encourage agglomeration, to have good macro-mixing in the reactor, and to have low supersaturation ratios. Mersmann also shows that, in crystallizers producing large particles, the primary factor influencing formation of new crystal nuclei tends to be attrition (or breakage of existing crystals) due to impact with reactor components or other crystals.

Spontaneous struvite crystal accumulation in sludge piping and pumping equipment is a problem in wastewater treatment plants, especially those with biological phosphorus removal. This phenomenon was first reported by Borgerding (1972). Struvite accumulation is preferentially formed on rough surfaces, in areas of high turbulences, and in areas that undergo pressure drops (Ohlinger *et al.*, 1999). This is due to ease of surface attachment, bulk chemical transport limitations to the growth of struvite, and pH increases in low pressure areas due to degassing of carbon dioxide. The degree of turbulence in which crystals are grown also has been shown to affect the shape of the crystals. Large, elongated crystals are typically found in quiescent environments whereas small, tightly packed crystals are found in higher mixing energy environments (Ohlinger *et al.*, 1999).

In other studies on struvite crystallization, several authors have found interesting relations between various factors and crystal morphology. Particle size uniformity and distribution has been reported to vary with operating pH as well as Mg:P molar ratio for particles in the 1-150 μm range, with lower pH and magnesium dosages leading to more uniform and smaller particles (Shin and Lee, 1997). Another study found that the electrical surface charge (zeta potential) of the struvite particles grown varies with the solution pH and magnesium concentration (Bouropoulos and Koutsoukos, 2000). The particles were found to have lower zeta potentials at lower pH (< 9.2) and reach an isoelectric point at an Mg concentration of approximately 10^{-2} molar. This indicates that crystal agglomeration could be encouraged at lower pH and higher Mg dosing rates.

Hirasawa *et al.* (1997), found that the shape of the struvite crystals changed from orthorhombic to agglomerated rosettes to needle-like when the Mg:P molar ratio in solution was changed from 1:1 to 2:1 to 4:1. Fine crystals were also observed to be forming in the 4:1 Mg:P molar ratio sample. This makes it unclear whether the change in crystal morphology is due to changes in the molar ratios or in the initial supersaturation of the solution.

The settling characteristics and chemical composition of struvite containing precipitates have been found to change based on the order in which Mg, N, and P containing reagents are added to a solution, as well as the pH at which the reaction takes place, and the changes in pH of the solution during the precipitation reaction (Dempsey, 1997)

Individual struvite crystals have been described as having an orthorhombic (Doyle *et al.*, 2000), hexagonal/rectangular (Munch and Barr, 2001), coffin lid or arrow-head (Wierzbicki *et al.*, 1997) shape, depending on the conditions in which they are grown and the presence of inhibiting compounds.

Other studies conducting pilot or full-scale fluidized bed crystallization of struvite from anaerobic digester liquors have reported widely varying crystal size distributions. Battistoni *et al.* (2001) report that 0.35mm crystals containing struvite, hydroxyapatite and calcium carbonate are grown on 0.26 mm sand grain seed material. Crystals of sizes ranging from 0-3 mm consisting of nearly pure struvite were grown in studies spanning up to 2 months in a pilot-scale struvite recovery operation in Fukuoka City, Japan (Abe, 1995). Nearly pure struvite crystals, with diameters ranging from 0.5-1mm, were produced in a full-scale struvite recovery operation in the Shimane Prefecture, Japan (Ueno and Fujii, 2001). Using a similar process as that used by Ueno and Fujii at pilot scale, 0.11 mm crystals consisting of greater than 90% struvite were grown in Brisbane, Australia (Munch and Barr, 2001). The growth rate of the crystal diameter reported by Abe (1995) ranged from 0.061-0.173 mm per day and their data shows that a steady state crystal size was not reached during their studies. Takiyama *et al.* (1997) suggest that the lag time between startup and reaching the steady-state crystal size distribution can be shortened (from approximately 7 to 2 crystal residence times) by seeding the reactor with product from a reactor operating at steady-state. This indicates that using product from another installation to seed the reactor could significantly shorten the startup time.

3.3. Struvite Formation Models

Several models have been developed and used to predict the possibility and rate of formation of struvite in sludge digestion equipment, as well as in dedicated struvite crystallizers. These range from simple empirical and equilibrium chemistry models to complex 3 phase, dynamic physical-chemical models.

Battistoni *et al.* (1998) have developed a double saturation model, based on pH and contact time, to describe the operation of a sand-seeded, fluidized bed crystallizing reactor recovering a mixed crystal of struvite, hydroxyapatite and calcium carbonate. This model was

further refined to describe the operation of a long term pilot study (Battistoni *et al.*, 2002). Unfortunately this model does not take the entire equilibrium chemistry into account and relates supersaturation only to pH. This makes direct application of this model to other reactors and other wastewaters unlikely, since the composition of anaerobic digestion liquors can be quite variable from site to site.

In the United Kingdom, several studies have been performed to determine the potential for struvite formation in various streams at wastewater treatment plants, using the commercially available Struvite version 3.1 model developed by Loewenthal and Morrison of the University of Cape Town, South Africa. These studies have shown that, in general, the highest potential for phosphate recovery as struvite from wastewater treatment plants occurs in the anaerobic sludge handling liquors of treatment plants that do not use chemical phosphorus precipitation (Doyle *et al.*, 2000; Parsons *et al.*, 2001; Jaffer *et al.*, 2002). Generally the Struvite 3.1 model was found to under-predict struvite formation at high pH values, indicating that further calibration of the model may be needed for accurate prediction of struvite formation in each particular wastewater.

Ohlinger (1998) has used a P_s equilibrium curve to predict the struvite formation from supernatants from the Sacramento Regional Wastewater Treatment Plant with good success. This model is simply based on the equilibration of a sample through the formation of struvite crystals. This model will also likely require calibration for each wastewater treated, since it is not based on a thermodynamic equilibrium.

A three phase dynamic model has been developed by Wentzel *et al.* (2001) to predict the behavior of a solution in which carbon dioxide is being stripped by aeration to increase the pH while struvite and/or calcium phosphates are being formed. This model seems to have great potential to be generally applicable to phosphorus recovery reactors, where pH adjustment is accomplished with air stripping; however, this model also requires calibration in order to be successfully applied to each different solution matrix.

Overall, it appears that the chemistry of struvite crystallization is not sufficiently well understood to create a model that would be widely applicable to a variety of solutions without parameter calibration. Models have been developed that accurately describe the crystallization of struvite from anaerobic digester liquors, given that they are calibrated to that particular liquor.

3.4. Operating Problems at Wastewater Treatment Plants

One of the main reasons for the research being conducted on phosphate recovery is the increasing occurrence of operational problems related to phosphorus removal in treatment plants. The three main problems being addressed in the literature are the re-release of excess biologically removed phosphate during anaerobic digestion, the encrustation or scaling of process piping and equipment in anaerobic sludge handling facilities treating BNR sludges, and the production of excess sludge volumes due to chemical and biological phosphorus removal.

3.4.1. *Phosphorus Release During Anaerobic Digestion*

Recent discoveries have shown that a very large part of the phosphorus removed in BNR plants is re-released under anaerobic conditions in sludge digestion systems, and that this release can often lead to supersaturation conditions with respect to struvite in the sludge treatment process (Jardin and Popel, 1994; Niedbala, 1995; Mavinic et al. 1998; Ohlinger et al., 1998). This research has also shown that, in order to maintain very low effluent phosphate concentrations, these BNR plants need to find a way to isolate, and remove the excess phosphate accumulated by the biomass.

In a pilot study conducted on site at the City of Penticton AWWTP, it was found that about 80% of the phosphorus removed in the BNR process would be re-released to the digester supernatant and returned to the headworks of the plant, should the phosphate rich secondary sludge be digested anaerobically with the primary sludge (Niedbala, 1995). This study suggested that ferric chloride be used to precipitate the phosphorus from the digester supernatant, to eliminate the possibility of excessive phosphorus loads re-entering the BNR system.

Jardin and Popel (2001) have found that, in some cases, much of the phosphorus released in anaerobic digestion is rapidly re-precipitated in the digester, as either struvite or aluminum phosphates, thus preventing excessive feedback of phosphorus to the headworks of the treatment plant. This only occurs if sufficient quantities of magnesium, aluminum or presumably iron, are present to carry out the precipitation. If these metals are absent or if phosphorus content of the supernatant is in excess of these metal ions, significant phosphorus feedback to the headworks is probable.

In many cases, and as is current practice in Penticton, the waste activated sludge is dewatered and transported off-site without digestion. In this case, the sludge can be landfilled directly or composted and used as a soil conditioner. Another option is to use chemical phosphorus precipitation with alum or ferric chloride on the digester supernatant return, if the sludge is digested on site, such as in the Phostrip process. The main problem with this technique is that it can be expensive and creates a relatively large volume of chemical sludge containing either aluminum or iron bound phosphates. These metal phosphate complexes can only be used in a very limited number of phosphorus processing plants in the phosphate industry. These metal bound phosphates are usually landfilled at a significant cost, since it is rarely economically feasible to recover the nutrient value from this type of sludge (Booker *et al.*, 1999; Jeanmaire, 2001).

All these methods of phosphorus removal are designed to eliminate the excess load of phosphorus to the liquid treatment train of a BNR treatment plant, in order to allow the treatment plant to successfully meet stringent effluent guidelines for phosphorus. Since phosphate is a conservative substance within wastewater treatment systems (i.e. phosphorus does not exist in a volatile or gaseous phase), all of the phosphorus in the wastewater must exit either in the effluent or in the sludge, unless phosphorus accumulates in deposits within the treatment plant or a deliberate attempt is made to recover the phosphorus in a separate process.

3.4.2. *Struvite Encrustation*

High concentrations of ammonia and phosphate have led to increasing operational problems with struvite encrustation of the sludge, supernatant, centrate, and filtrate conveyance systems in the sludge handling systems of wastewater treatment plants. These problems are especially evident in areas of high turbulence, such as pump impellers and pipe bends (Jaffer *et al.*, 2002; Ohlinger *et al.*, 1999). Struvite encrustation problems were first noticed at the Hyperion wastewater treatment plant in Los Angeles in the 1960's (Borgerding, 1972). Since then, the increased use of biological phosphorus removal technologies has led to an increased prevalence of these encrustation problems because these systems lead to higher soluble ammonia, phosphate and magnesium concentrations in the sludge treatment train. In some cases, the conditions for struvite formation are so favorable that piping systems become completely

plugged with struvite within the first year of operation, such as those at the Slough WWTP in England (Williams, 1999). This results in costly and time-consuming maintenance programs in order to prevent failure of the sludge treatment processes.

Prevention of these struvite deposition and encrustation problems has been one of the leading driving forces behind phosphorus recovery research, since the removal of phosphorus in the form of struvite in a controlled reactor should drastically reduce or eliminate the encrustation problem in undesirable locations. This would potentially eliminate the cost of the maintenance programs, while producing a valuable by-product.

3.4.3. Excess Sludge Production for P Removal

Both chemical and biological phosphorus removal have the effect of increasing the sludge production of wastewater treatment plants. Paul *et al.* (2001) estimate that the average increase in sludge production from biological and chemical phosphorus removal in France is 3 kg of solids per kg of phosphorus removed, or 5 percent of the total sludge production. The increase in sludge production was also found to be dependent on the BOD:P ratio in the wastewater being treated. It was also estimated that this excess sludge production costs 15 million Euros per year in France. Woods *et al.* (1999) estimate that sludge volumes can be reduced by up to 49% by implementing phosphorus recovery, depending on the current sludge handling operations at wastewater treatment plants.

Another study conducted by Jeanmaire and Evans (2001) concluded that a decrease in sludge mass of 2-8% could be expected if phosphorus recovery was undertaken at an operating BNR facility with anaerobic sludge digestion.

In a case where the secondary sludge is not being digested on site in order to avoid phosphorus feedback and struvite encrustation, significantly larger sludge volume reduction could be expected since approximately 30 to 40% of total solids are destroyed during anaerobic digestion (Metcalf and Eddy Inc., 1991). According to Niedbala (1995), 80% of the sludge produced at the Penticton AWWTP is secondary, and therefore digestion of this sludge would lead to an approximate reduction of 24 to 32 % in total sludge mass being trucked off site.

3.5. Feasibility of Struvite Recovery from Wastewater

Since wastewater treatment plants are often large centralized sources of nutrient discharges to the environment, they have been identified as one of the most promising sources for recovery of phosphorus (Yu, 2001; Woods et al., 1999). The fact that BNR technologies have become more widely used for municipal wastewater treatment over the last two decades has led to an acceleration of this field of research, since the recovery of phosphorus is more technologically and economically feasible when combined with BNR.

Momberg and Oellermann (1992) found that phosphorus recovery, as either struvite or hydroxyapatite from various wastewater streams, appears to be a feasible route for nutrient removal, either as a tertiary treatment or as a side stream process in a BNR plant. This led to further research by several other authors on the ideal placement of a nutrient recovery facility in wastewater treatment plants.

Driver *et al.* (1999) found that up to 80 percent of the phosphate in sewage in the UK could be recycled via precipitation as hydroxyapatite for reuse in the phosphate industry, or for direct reuse as a fertilizer. They also find that animal wastes should be considered as an important source of recoverable phosphorus. Woods *et al.* (1999) found that phosphorus recovery would be most feasible in treatment plants with high phosphate loads relative to BOD, and high sludge handling costs since they see sludge volume reduction as being a major driving force behind phosphate recovery in the wastewater industry. Social and legislative pressures are also seen as an incentive for implementing phosphate recovery (Jeanmaire and Evans, 2001).

Several authors have found that the use of biological phosphorus removal in wastewater treatment makes the recovery of phosphate as struvite more feasible by providing a concentrated phosphate stream in the sludge digestion and dewatering liquors. This allows phosphate recovery to be carried out at minimal cost, while providing other operational benefits such as reduced struvite encrustation, reduced sludge volumes and reduced phosphate feedback through digester supernatants (Stratful *et al.*, 1999; Williams, 1999; Edge, 1999; Booker *et al.* 1999; Jeanmaire and Evans, 2001; Munch and Barr, 2001; Paul *et al.*, 2001). However, it has been found that the recovery of phosphorus is economically and technically non-feasible when chemical

precipitation with aluminum or iron salts is used (Parsons *et al.*, 2001; Paul *et al.*, 2001). Sludge from chemical precipitation processes has also been found to provide little phosphorus value when spread on agricultural land (Edge, 1999).

Other waste streams such as piggery waste, abattoir wastewater and other manures have been found to show great potential for future phosphate recovery (Momborg and Oellermann, 1992; Webb and Ho, 1999). Livestock waste streams in British Columbia have been found to account for more than 80% of recoverable phosphorus, with municipal sewage accounting for the remainder (Yu, 2001).

Several potential markets have been suggested for use of the recovered phosphorus. These include a sustainable source of high grade material for phosphate industry (Jeanmaire and Evans, 2001), although this would require high retrofit cost for the phosphate processing industry if the phosphorus is recovered as struvite (Durrant *et al.*, 1999). The more likely market for struvite would be direct use as a slow release fertilizer (Booker *et al.*, 1999). In the UK, struvite was found to be a potential replacement for di-ammonium phosphate fertilizers, especially if local fertilizer needs in the area of the recovery operation could be met (Gaterell *et al.*, 2000). In Japan, struvite is already being successfully marketed as a premium slow-release fertilizer additive for rice paddy and household use (Ueno and Fujii, 2001).

Since nutrient discharges from wastewater treatment plants are increasingly being seen as an important contributor to the degradation of water quality, regulatory agencies are imposing more and more stringent effluent criteria for both nitrogen and phosphorus. These criteria have led to the widespread use of nutrient removal techniques in the wastewater treatment industry, but it is not until recently that the possibility of recovering these nutrients for subsequent reuse in the fertilizer or phosphate industries has been investigated. Essentially, the recovery of phosphorus from wastewater will provide some closure to the mass balance on phosphorus, while allowing for low effluent concentrations and eliminating the need to dispose of this resource in a non-sustainable manner.

3.6. Pilot and Full-scale Struvite Recovery Studies

Stratful *et al.* (1999) provide a good overview of various processes that have been studied to recover phosphorus, as either struvite or calcium phosphate. These include the DHV Crystalactor calcium phosphate fluidized bed process, the Rim-Nut ion exchange process, the Unitika Phosnix struvite recovery process, the Kurita fixed bed calcium phosphate process, and the CSIR fluidized bed process.

Previous research at UBC has led to the development of a novel reactor design used to recover phosphate from real and synthetic supernatants at the bench scale. The bench scale equipment was found to be prone to plugging problems and low recoveries of phosphorus. These problems were largely rectified with the scale-up to pilot scale. The pilot-scale reactors allowed for higher phosphate recoveries (up to 90%) from a synthetic supernatant similar to that expected at the Penticton AWWTP (Dastur, 2001).

Since the chemical costs of struvite formation have been found to be a major contributor to the total costs of the process, several researchers have attempted to develop processes whereby no chemicals are used (Battistoni, *et al.*, 1997; Battistoni, *et al.*, 1998; Kumashiro *et al.*, 2001). Battistoni *et al.* (1997 and 1998) de-gassed carbon dioxide from digester supernatant by air stripping, in order to increase the solution pH to ranges where struvite and calcium phosphates are less soluble; they used the magnesium and calcium present in the wastewater as cation sources for the crystallization of phosphate materials. This approach is feasible in the case of the wastewater treatment plants in these investigations, but would be less feasible in regions with softer waters containing less magnesium and calcium. Another drawback of this technique is that the product is relatively impure, containing a combination of struvite, calcium phosphate, and calcium carbonate. Kumashiro *et al.* (2001) used sea water as a source of magnesium and produced essentially pure struvite crystals, at operating costs of \$0.70 per kg of struvite produced.

Ammonia is often present in significantly higher molar concentrations than phosphate in digester supernatants. For this reason, several authors have investigated the possibility of recovering both ammonia and phosphate from supernatants as struvite. In two studies,

magnesium and phosphoric acid are added to digester supernatant in dosages sufficient to remove 85 to 90 % of the ammonia (Siegrist *et al.*, 1992; Celen and Turker, 2001). The costs for this process ranged from \$12 to \$20 per kg of ammonia removed. Shin and Lee (1997) found that the addition of sea water and bittern both worked well as magnesium sources for the precipitation of struvite, in order to remove ammonia and phosphorus from a synthetic wastewater.

Japan has been the global leader in the recovery of phosphorus as struvite. Several full-scale installations are already in operation. Abe (1995) reports that over 80% phosphorus recovery was possible, when treating supernatant from the Seibu treatment plant in Fukuoka City. This study also found that the struvite could be recovered as grains of diameters exceeding 2 mm. In order to accomplish this, the pH was adjusted by a combination of air stripping of CO₂ and addition of sodium hydroxide, and magnesium chloride was added to ensure that phosphate was the limiting reagent in the formation of struvite. It was found that in order to grow large crystals, re-circulation of the reactor effluent was required when treating supernatants with high concentrations of phosphate. A study conducted by Munch and Barr (2001) in Brisbane, Australia found that struvite crystals with an average diameter of 0.11 mm were grown in a similar reactor where magnesium hydroxide was used for both magnesium dosage and pH adjustment, and no effluent re-circulation was used.

Ueno and Fujii (2001) presented results from the full-scale operation of three struvite recovery reactors treating BNR sludge dewatering filtrate at the Shimane Prefecture Lake Shinji East Clean Center. These reactors use a magnesium hydroxide solution for magnesium dosing and some pH adjustment, with the remainder of the pH adjustment being carried out by air stripping of CO₂ and addition of sodium hydroxide. In this reactor, the air blower also acts as an air lift pump, to re-circulate the reactor contents in order to dilute the feed in a double-jacketed column design. A ten day crystal retention time is sufficient to grow crystals of 0.5 to 1 mm in this reactor. This facility produces between 500 and 550 kg of struvite per day and sells the product for \$340 per metric ton to a fertilizer company, which also pays for the shipping costs. The fertilizer company blends the struvite with other components to produce an enhanced fertilizer that is claimed to improve the flavour of paddy rice.

Several phosphorus recovery reactor designs, process configurations, and treatment objectives have been successfully tested around the world over the past decade. The optimal configuration appears to be dependent on the characteristics of the waste stream to be treated, the local cost of chemicals, and the potential market for the product. In general, it appears that significant cost reductions can be achieved by reducing the chemical usage at these plants by using air stripping for pH adjustment and using sea water or other inexpensive magnesium sources for dosing magnesium to the reactor. It also appears that in order to grow large (>1 mm) struvite crystals, recirculation of the reactor effluent is often necessary to dilute the waste stream being treated, and that long crystal retention times are required (> 10 days). Overall, the fluidized bed crystallizer, without heterogeneous carrier material, seems to be the most widely used and successful design for these reactors.

4. MATERIALS AND METHODS

Based on previous experiments at the bench scale, a pilot scale reactor was designed and tested at the UBC Environmental Engineering Pilot Plant using a synthetic feed. Two identical reactors based on this design were operated in parallel over a four month period, from September to December of 2001, at the City of Penticton AWWTP, and were housed in a heated chemical storage building on site as shown in Figure 4.1.

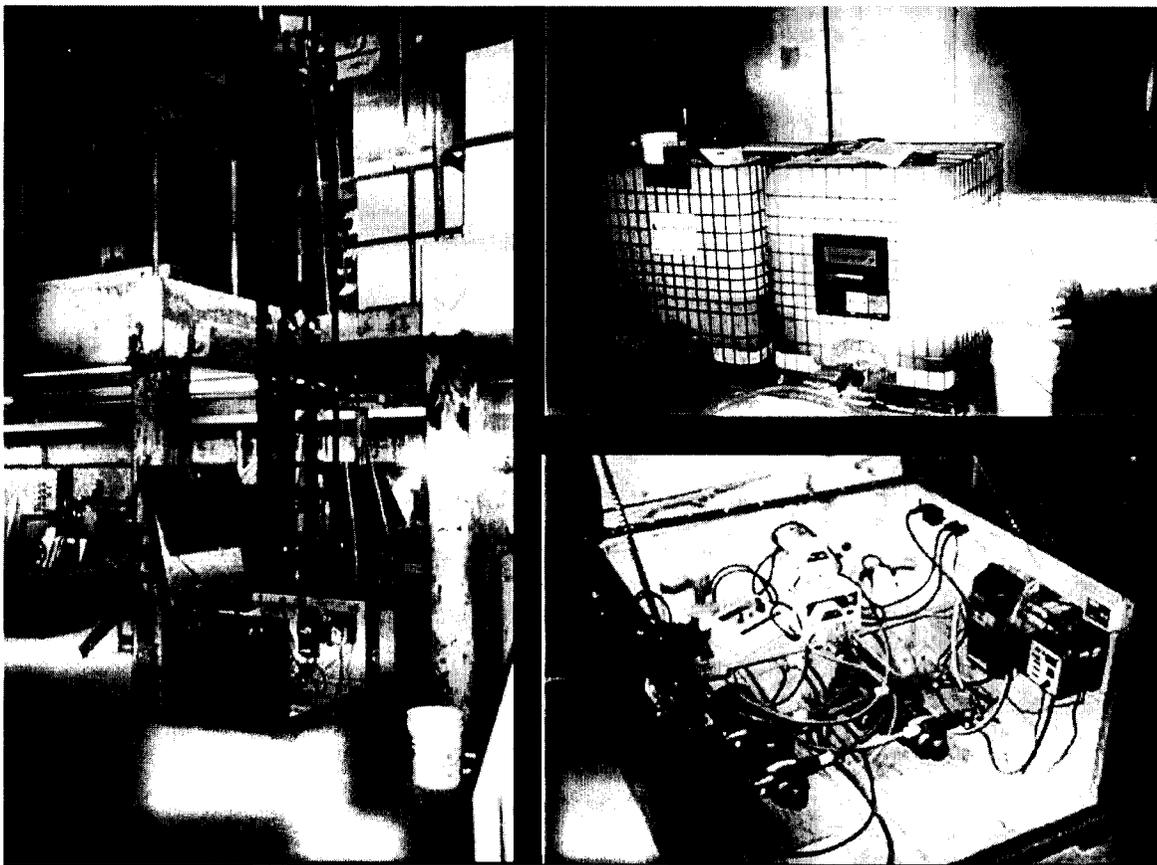


Figure 4.1: Pilot-scale reactor setup at the City of Penticton AWWTP. Left: two parallel fluidized bed reactors; top right: magnesium chloride, sodium hydroxide (in foreground) and supernatant storage tanks (in background); bottom right: close-up of one reactor control box, with feed, recycle and magnesium dosing pumps and pH controller.

During the test period at the UBC Pilot Plant, the analytical techniques to be used in this study were developed and evaluated. In most cases, the methods developed for use with the synthetic feed proved to be successful with the real supernatant; however, some changes were necessary.

4.1. Reactor Design

The reactor used in this study was based on a 3X linear scale up of the bench scale reactor, designed by the UBC phosphate recovery team (Dastur, 2001). Figure 4.2 shows the basic design of the reactor and associated equipment. The reactor itself was a fluidized bed reactor with sections of increasing diameter and a settling zone at the top. The diameter changes caused turbulent eddies above each transition, ensuring that sufficient mixing existed in the reactor and also helped to classify the fluidized particles by size; as such, only the largest crystals in the reactor were harvested.

The crystallizer was constructed of clear PVC piping connected with standard Schedule 40 or Schedule 80 PVC fittings. An attempt was made to keep the inside joints between piping and fittings as smooth as possible, to minimize dead zones where the fluidized particles could settle and struvite encrustation problems could occur. Clear piping was used in order to be able to monitor the behavior of the struvite crystals in the fluidized bed, and monitor for signs of plugging or encrustation. The clear piping also made it easier to monitor the expanded and collapsed bed heights of the struvite crystals.

For the pilot scale reactor used in this work, the inside diameters were 40 mm, 52 mm and 77 mm for the bottom, middle and top sections of the fluidized zone. The clarifier section at the top of the crystallizer was built out of 202 mm diameter clear acrylic pipe. The total liquid volume of each reactor was approximately 19 liters, 9 liters of which were in the three fluidized zones.

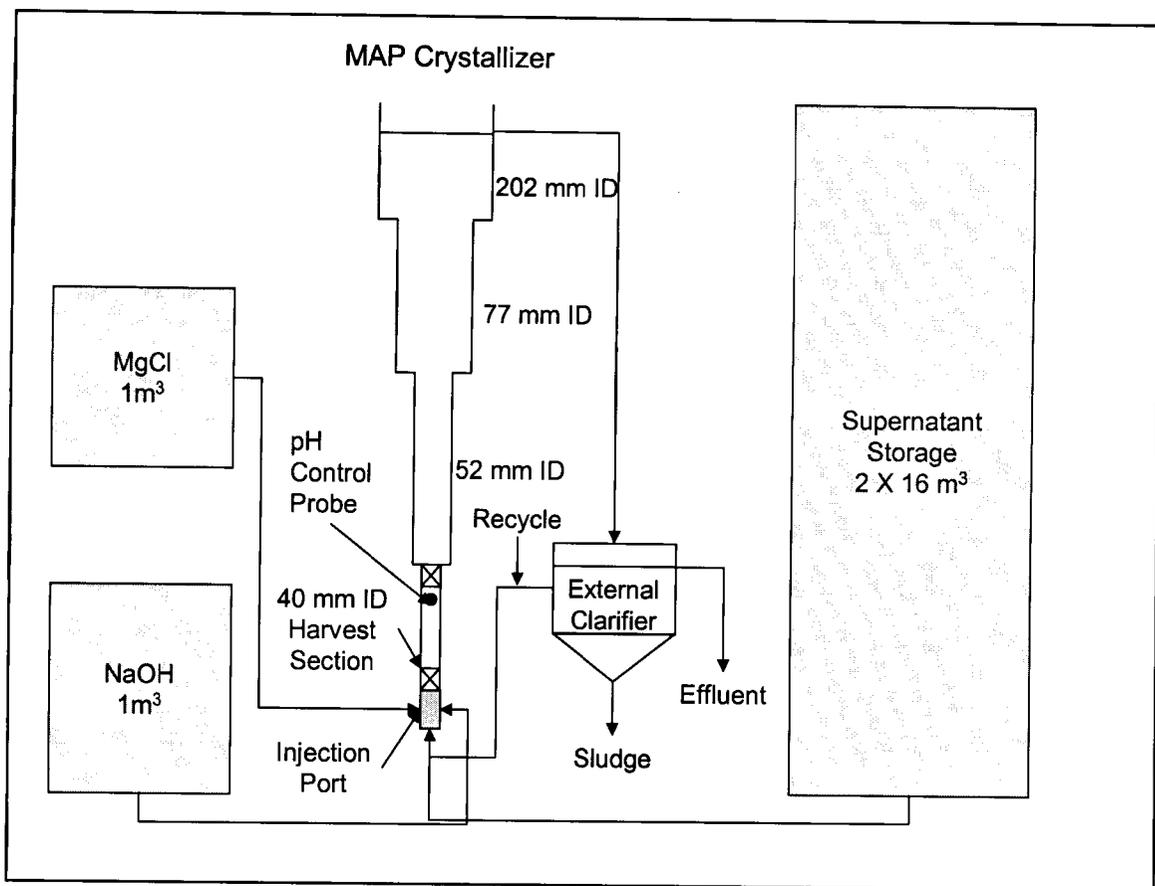


Figure 4.2: Pilot-scale struvite crystallizer reactor process design.

Each reactor was initially seeded with one liter of struvite crystals grown from synthetic supernatant at the UBC pilot plant. This was done in order to avoid problems encountered previously when trying to self seed the reactor at a high supersaturation ratio. The reactor does not use any carrier material such as sand for seeding, and therefore the product from the reactor is nearly pure struvite.

The total height of the reactors used in this study was approximately 4900 mm. The total liquid flow rates through each reactor for the duration of the study was 3.6 liters per minute. Each reactor was equipped with two pH probes, one in the top of the harvest zone and another in the external clarifier. The pH probe in the harvest zone was used for feedback control using a proportional flow pH controller. Magnesium was dosed to the reactor in the form of magnesium chloride solution to supply the desired magnesium to phosphorus molar ratio in the reactor.

4.1.1. Injection Port Design

The reactor injection port was designed to blend the supernatant feed stream with the recycle stream from the external clarifier, the magnesium chloride solution from the dosing pump and the sodium hydroxide solution from the pH controller. Figure 4.3 shows a simplified cross section of the injection port design. The injection port block itself was constructed out of stainless steel, as were the magnesium and caustic injection ports. These parts of the reactor were built out of stainless steel, in order to prevent corrosion and to withstand regular scouring from cleaning.

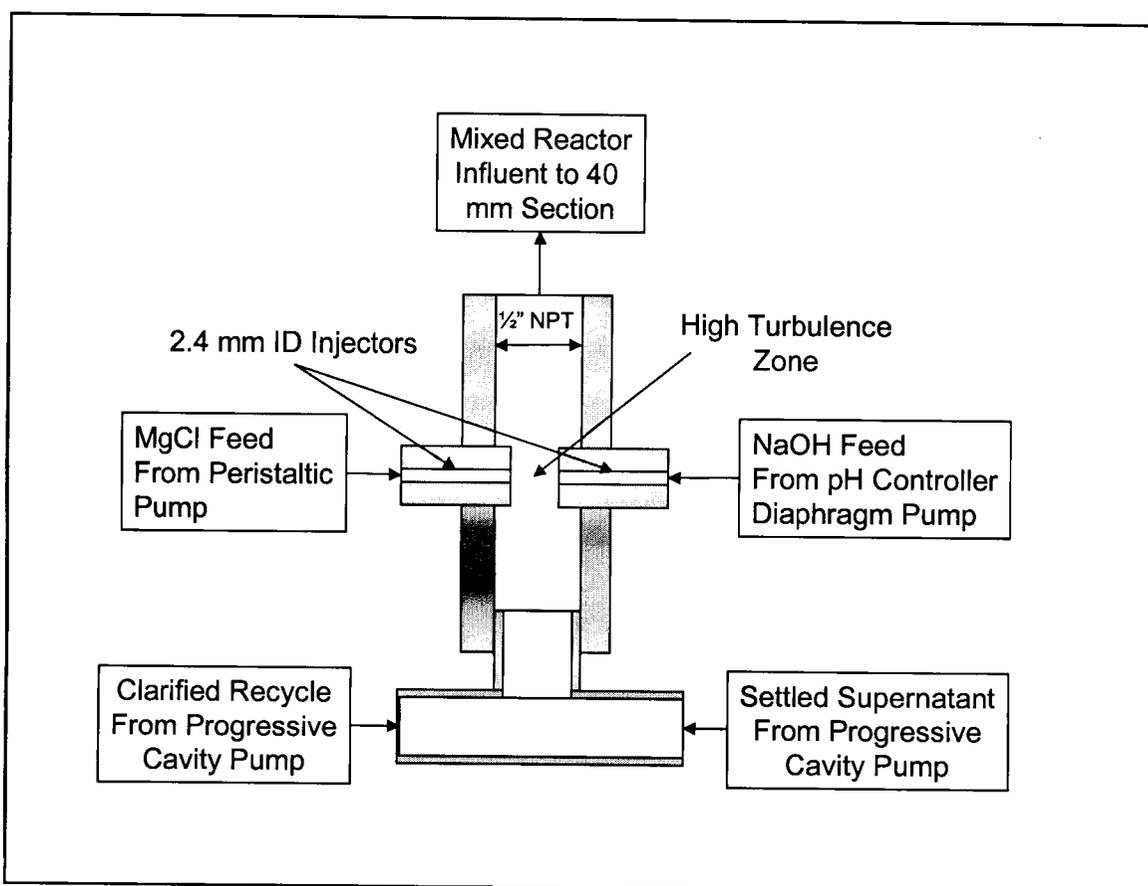


Figure 4.3: Pilot-scale struvite crystallizer injection port assembly.

The injection port assembly was easily disconnected from the reactor by means of quick release connectors, in order to be able to clean this section regularly. Since the magnesium chloride and sodium hydroxide (caustic) injection points are coincident, high local supersaturation ratios exist in this zone and some encrustation of the chemical feed ports occurred during the course of the experiment. The magnesium and caustic injection ports were

cleaned with a welding rod (approximate diameter 1.6 mm) every time the reactor was stopped for harvesting, or whenever decreased flow was observed. The injection ports were machined from stainless steel rods to have ¼ inch NPT threading on both ends, to connect to the injection port block and to quick release tubing connectors, and were bored out to 2.4 mm as shown in Figure 4.3.

There was some encrustation of the high turbulence area indicated in Figure 4.3 throughout the experiment, but complete blockage never occurred and cleaning was only performed every 2 to 7 days. The high turbulence area was cleaned using a length of threaded rod of similar diameter to the gap between the magnesium and caustic injection ports (approximately 10 mm). No struvite scaling was observed below the magnesium and caustic injection points, indicating that the solution remained undersaturated until it passed through the high turbulence area where struvite formation was initiated.

4.1.2. Harvest Zone Design

The harvest zone, located immediately above the injection port, had an internal diameter of 40 mm, held a volume of 1.1 liters and was 960 mm in length. Two ball valves (one at the top and one at the bottom as shown in Figure 4.2) were used to isolate the harvest zone when injection port cleaning or struvite harvesting was required. The harvesting procedure is described in Section 4.1.9 below. The empty reactor fluid upflow velocity in the harvest section was 2810 mm per minute and the Reynolds number for this condition was estimated at 2100. It is important to note that the fluid upflow velocities and Reynolds numbers during fluidized bed operation with a fully loaded reactor (i.e. 6-8 liters collapsed bed struvite crystal volume) will be quite different from these values.

4.1.3. Reaction Zone Design

Immediately above the harvest zone were two expanding sections with 52 and 77 mm inside diameters, and volumes of 3.6 liters and 4.3 liters respectively. The 52 mm inside diameter section had a length of 1770 mm and was equipped with an isolation ball valve at the top in order to be able to separately drain each section. The 77 mm inside diameter section was 940 mm in length and was mounted to the clarifier section above using a bulkhead fitting.

Empty reactor upflow velocities were 1690 mm per minute and 770 mm per minute for the 52 and 77 mm inside diameter sections respectively, which corresponds to Reynolds numbers of 1600 and 1100. Again the hydraulics of the reactor were significantly different from this when the reactor was fully loaded with struvite crystals and behaving as a fluidized bed reactor. The reactor diameter changes were accomplished using standard PVC expansion couplings with rounded transitions.

During the operation of the reactors, the fluidized bed of struvite crystals expanded to the top of the reaction zone and settled in the bottom of clarifier section mounted above. This causes the full 9 liters of reactor volume to be used for crystal growth, allowing maximal contact between the supersaturated solution and the struvite crystals.

4.1.4. Clarifier Zone Design

Mounted to the top of the reaction zone was a 202 mm inside diameter clarifier section with a height of approximately 380 mm and two side outlets for the overflow from the reactor. The main overflow was set at approximately 300 mm water depth in the clarifier section, while the backup overflow was set at approximately 350 mm water depth.

The main overflow was connected to the external clarifier (see Figure 4.2) by a vertical 25 mm inside diameter clear PVC pipe tipped with a length of 31 mm inside diameter flexible tubing. The flexible tubing was placed in the external clarifier in a U shape with the submerged exit in the upwards vertical position on the external clarifier wall opposite the recycle and effluent ports. The backup overflow was connected to the external clarifier by 12.7 mm outside diameter LDPE tubing (9.7 mm inside diameter) which was mounted to the top edge of the external clarifier with a horizontal exit above the water surface. Both overflows were equipped with siphon breakers, since they had a tendency to become vapour locked, causing the system to overflow.

The clarifier section was flat bottomed and equipped with a drain valve to remove accumulation of suspended solids. In practice, this valve was never used since the only accumulation observed was of small struvite crystals which settled and formed a cone shape in the bottom of the clarifier section with a side slope of approximately 60°. The normal operating

volume of the clarifier section was approximately 10 liters and the upflow velocity at design flow was 110 mm per minute. At this velocity, very few struvite crystals were observed to be escaping the reactor.

4.1.5. External Clarifier and Recycle Flow

Each reactor was equipped with an external clarifier to act as an effluent storage vessel for recycling to the injection port and to ensure that any remaining fine-suspended solids were not returned to the reactor. The external clarifiers were rectangular with surface dimensions of 365 mm by 400 mm and had a square pyramidal bottom, with a 45° slope. The external clarifiers were placed on the floor adjacent to each reactor as shown in Figure 4.4. The water level in the external clarifiers was maintained at a side water depth of approximately 305 mm, with a freeboard of 50 mm. The approximate external clarifier volume was 54 liters.

Each external clarifier had a surface area of 0.15 square meters which resulted in a surface overflow rate of between 2.7 and 8.2 mm per minute depending on the supernatant feed flow rate. This overflow velocity was independent of the recycle flow rate, since the recycle was withdrawn as an underflow from the external clarifier. It is important to note that hydraulic conditions in the external clarifiers were far from ideal; there was no inlet zone to dissipate the momentum generated by the 4500 mm fall to the clarifier from the top of the crystallizer, other than a bend in the tubing. Also, both exits from the clarifier were sharp orifices and were not equipped with any weirs or manifolds to distribute the flow. The clarifiers did however produce a relatively clear overflow stream and accumulated some sludge in the bottom, indicating that some solids did escape the clarifier section at the top of the crystallizers.

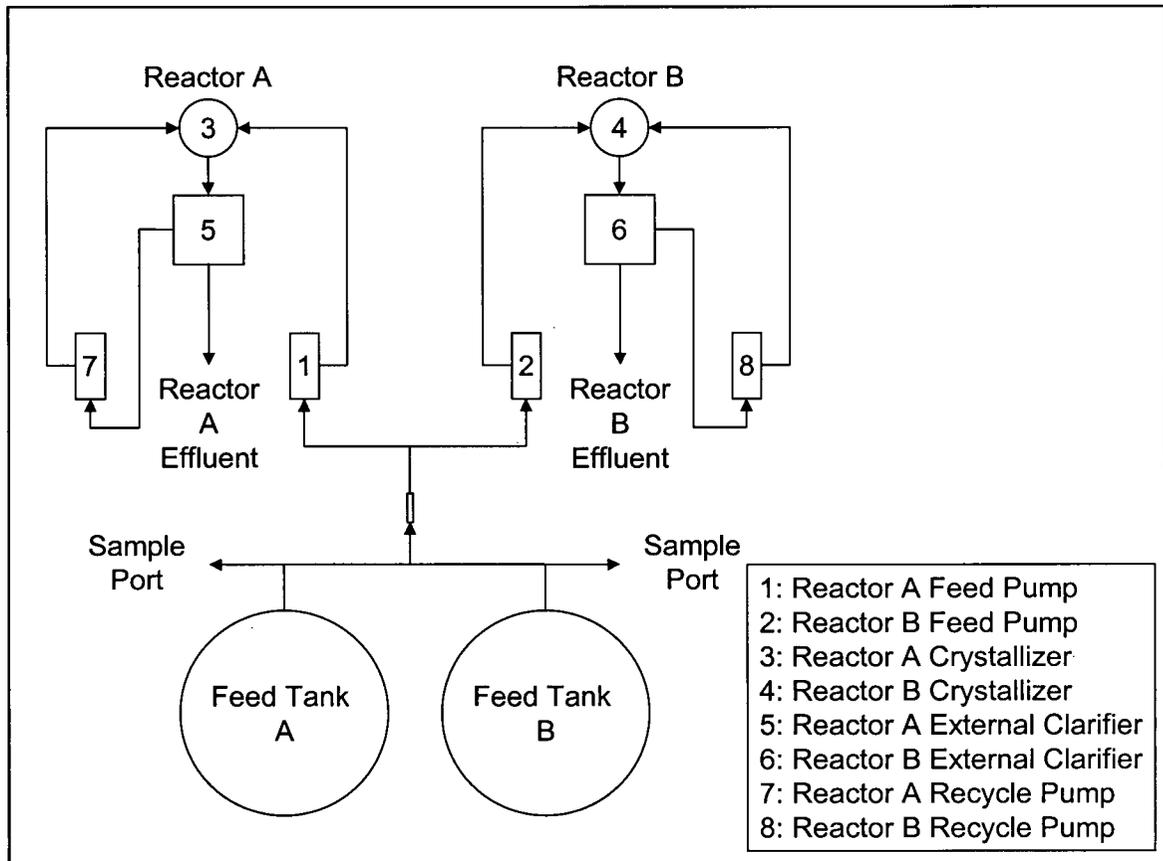


Figure 4.4: Pilot-scale schematic.

The recycle flow back to the fluidized bed reactor was withdrawn from a port on the side of the external clarifier approximately 150 mm below the water surface. The recycle was pumped using a Moyno Model 500 332 progressive cavity pump with a $\frac{1}{2}$ HP motor and variable frequency drive to allow precise flow control (capacity 0.8-18.9 L/min). The set point for the flow rate of the recycle to each reactor was varied between 2.4 and 3.2 liters per minute during the course of the experiment and verified daily.

The treated effluent from the external clarifier overflowed by gravity from a port near the top of the external clarifier to a floor drain which flowed back to the wastewater treatment plant headworks.. The effluent drain line was equipped with a 3 way valve to allow for collection of effluent samples and flow measurement. A sludge drain valve was placed on the external clarifier bottom in order to collect and remove any accumulated sludge from the clarifier. A small quantity of this sludge was wasted approximately weekly and consisted of a blend of small struvite crystals and suspended solids from the digester supernatant.

The total reactor flow rate was measured from in the 25 mm overflow pipe into the external clarifier using a graduated cylinder and stopwatch. All of the pumped and gravity flow tubing exiting the external clarifier, as shown in Figure 4.4, was 12.7 mm outside diameter LDPE tubing (9.7 mm inside diameter). Some encrustation of this tubing was noticed during the course of the study, but it was found that it could be easily removed by periodically flexing the tubing and complete blockage of these lines was never observed during this study. The fact that some encrustation did occur here indicates that the reaction taking place in the crystallizer was not 100% complete.

4.1.6. Supernatant Storage Tanks and Supernatant Feed Flow

The digester at the City of Penticton AWWTP is a two stage anaerobic digester, operated in the mesophilic temperature range. The first stage of the digester is gas mixed and the second stage is unmixed. Supernatant from the second stage of the digester was pumped from an overflow splitter box to two storage tanks for use in the pilot struvite crystallizer. The supernatant from the splitter box normally flowed by gravity back to the headworks of the treatment plant, but by plugging the exit and using a submersible pump, it was possible to intercept the needed amount of supernatant and fill one of the storage tanks within a few hours.

The two storage tanks each had a capacity of 16,000 liters and were equipped with overflows and drain valves. The supernatant to be used in the reactors was pumped out of the tanks from a fitting located approximately 500 mm above the tank bottom. This was done to allow any suspended solids in the supernatant to settle to the bottom of the tank and prevent excess suspended solids from entering the reactor. One full tank would typically last approximately seven days when feeding both reactors. It was therefore possible to fill each tank several days before it was needed, in order to allow settling time before withdrawing any supernatant. This was important since the supernatant collected occasionally contained high levels of suspended solids (over 2000 mg/L) when attempts were being made to increase the loading of secondary sludge to the digesters.

The residual sludge remaining in each tank was drained and returned to the treatment plant's headworks when the tank level approached the feed outlet. In this way, the settled solids were regularly removed from the tanks and no accumulation was observed.

The large volume of the storage tanks also allowed a constant feed strength to be maintained for several days at a time when the digester's operation was being drastically changed to increase the supernatant phosphate concentration. This was crucial during the initial months of the study, when the supernatant characteristics were changing significantly on a daily basis, in order to maintain relatively constant conditions within the crystallizers.

The piping from the feed tanks to the reactors was arranged so that both reactors were fed from the same line and so that supernatant could be drawn from either feed tank individually or both in parallel, as shown in Figure 4.4. During the course of the experiment, feed was always drawn from a single tank, while the other tank was being drained, refilled and allowed to settle.

Feed supernatant was pumped from the storage tanks using Moyno Model 500 331 progressive cavity pump with a ½ HP motor and variable frequency drive to allow precise flow control (capacity 0.3-7.6 L/min). Each reactor had its own independent pumping system, in order to ensure accurate flow control and to allow different types of operation to be evaluated in parallel. The set point for the flow rate of the feed to each reactor was varied between 0.4 and 1.2 liters per minute during the course of the experiment.

4.1.7. pH Control and Caustic Soda Dosing

Since the solubility of struvite is highly pH dependent, a pH control system is critical in maintaining the desired supersaturation conditions within the crystallizers. For this study, the pH within the reactors was adjusted using a sodium hydroxide (caustic soda) solution. The sodium hydroxide solution was made up on-site from industrial grade sodium hydroxide pellets delivered in 22.7 kg bags (PrairieChem Inc.). The solution was made up and stored in standard one cubic meter bulk liquid storage tanks, as shown in Figure 4.1. Since there were no means to block air access to the sodium hydroxide solution, it became slowly buffered by carbon dioxide from the air. This caused the solution to become less effective in raising the pH in the reactors over time; therefore, an attempt was made to keep a minimal volume of solution on hand in the storage tank. Once this problem was noticed, each batch of caustic solution was made up of 4 kilograms of sodium hydroxide pellets in approximately 500 liters of tap water. Each batch would typically last one week, when made up in this manner.

The sodium hydroxide solution was metered into the reactor through the injection port as described above in Section 4.1.1. The pH in the reactor was monitored at the top of the harvest zone as shown in Figure 4.2, using a Cole Parmer double junction in-line pH probe. The pH in the reactor was controlled based on this signal using a Cole Parmer model 56025-40 pH pump control system with proportional output. This pH control unit allowed pH control to within ± 0.1 pH units and could dose at a maximum rate of 20 liters per hour. In practice, the pH reading at the top of the harvest zone was observed to vary by up to ± 1 pH unit due to the lag time between the injection port and the pH probe. A previous design of the reactor had the pH probe located at the bottom of the harvest zone, but this caused severe encrustation problems on and around the pH probe, thus interfering with pH readings. The tubing between the sodium hydroxide solution storage tank and the pH controller, and between the pH controller and the reactor injection port, was 6.3 mm outside diameter LDPE tubing (4.3 mm inside diameter).

Using the concentration of sodium hydroxide described above (8 g/L), the metering pump operated at a rate well within its maximum capacity, and the pH was maintained at or slightly below (-0.2 pH units) the pH controller setpoint in the reactor effluent. Although significant variations in the pH were measured at the top of the harvest zone, the pH in the external clarifier remained constant within 0.1 pH units. This indicates that mixing and equalization between the harvest zone and the external clarifier lead to relatively homogeneous conditions in the effluent. The pH in the external clarifier was monitored using an Oakton continuous pH monitor, equipped with an Oakton gel filled, epoxy body pH probe.

The pH probes in the top of the harvest zone (the control probes) were calibrated whenever the reactor was shut down for harvesting, that is, whenever it was possible to remove these probes without losing the reactor contents. They were calibrated using standard pH 7 and pH 10 buffer solutions, as per manufacturer's instructions for two point calibration. The pH probes in the external clarifier (effluent monitoring probes) were calibrated every two to four days using the same method as the control probes. The calibration of the probes was periodically verified by measuring the pH of a solution and ensuring that all four pH meters displayed a pH that was within 0.1 pH units of each other. In general, the control probes responded much faster and maintained their calibration better than the effluent monitoring probes, probably due to their higher quality and industrial design.

4.1.8. Magnesium Chloride Dosing

Since magnesium was the limiting reagent in the formation of struvite from the Penticton digester supernatant, it was necessary to supplement the reactor with magnesium. Throughout this study, the objective was to keep a molar ratio of Mg:PO₄ equal to 1.3:1 within the reactor. This higher magnesium concentration causes the limiting reagent to be phosphate and thus allows for lower effluent phosphate concentrations than in magnesium limited systems.

In this study, the magnesium required to establish the excess Mg:PO₄ ratio was provided by using a solution of magnesium chloride hexahydrate. The magnesium chloride used was of commercial grade and was supplied in 50 kg bags (Thunder Sword Resources Inc.). The magnesium chloride solution was stored in a standard one cubic meter bulk liquid storage tank as shown in Figure 4.1. Typically, the solution was made up of four kilograms of magnesium chloride hexahydrate crystals in 1000 liters of tap water; however, this concentration was varied somewhat during the course of the experiment for convenience.

The magnesium chloride solution was pumped from the storage tank to the injection port of the reactor using a MasterFlex L/S variable speed peristaltic pump with Standard pump heads. The tubing used in the peristaltic pumps was 6.3 mm outside diameter neoprene tubing. All tubing used for conveying the magnesium chloride solution from the storage tank to the pump and from the pump to the reactor was 6.3 mm outside diameter LDPE tubing (4.3 mm inside diameter). Two peristaltic pumps were available in order to have independent control of the magnesium dosing rate in each reactor; however, during the first months of the experiment, both reactors were fed using two pump heads mounted on a single pump, in order to ensure that both reactors were dosed with the same amount of magnesium.

The flowrate of the magnesium solution into each reactor was measured by timing the drawdown in a graduated cylinder. Based on this flow measurement and the analysis of the magnesium concentration in the feed tank, it was possible to estimate the magnesium dosage applied to each reactor each day. These flow measurements were verified roughly against the total volume of magnesium solution used each day to ensure that the recorded flow rate was representative. The magnesium solution dosing rate varied between 20 and 60 milliliters per minute over the course of the study.

4.1.9. Crystal Harvest Procedure

Crystals were harvested from the reactor after the feed, recycle and chemical feed flows were stopped and the crystals are allowed to settle. The harvest zone was isolated using ball valves after the settling was complete and the settled bed volume of struvite crystals was measured. In order to remove the crystals for harvesting, the injection port section of the reactor was removed using quick disconnects and the crystals were allowed to fall into a bucket. The harvest zone was then rinsed with reactor effluent to ensure that all crystals were removed. The harvested crystals were then dried and analyzed as described below. Once the harvest was complete, the injector port section was reattached, the isolation valves were opened and the feed, recycle and chemical feed flows were restarted.

Occasionally it was necessary to apply compressed air to the top of the harvest zone (through the pH probe port after the probe was removed) in order to force the settled struvite crystals to fall from the reactor. This was necessary because the crystals were often highly irregular in shape and tended to agglomerate and bridge across the 40 mm section. This usually occurred when the crystals were of poorer quality (i.e. smaller size and more brittle).

4.1.10. Crystal Drying and Analysis

After the crystals were harvested from the reactor in a bucket, the remaining liquid was decanted off and the struvite crystals were spread over a 300 mm by 750 mm drying rack. The drying racks were made of a wooden frame supporting a standard plastic window screen. The size of the openings in this screen material was not measured. The crystals tended to agglomerate into clumps in the bucket upon decanting of the supernatant. For this reason, little crystal mass was lost through the screen.

Once the crystals were spread over the drying rack, it was suspended between two buckets and the crystals were left to dry for 24 hours with a 15 amp ceramic heater fan blowing warm air over them. The dried crystals were then removed from the drying rack and screened using standard sieves with nominal sieve sizes of 2 mm, 1 mm and 0.5 mm. The sieving apparatus was also equipped with a lid and a pan for collecting the portion of crystals with diameters of less than 0.5 mm. In this manner, it was possible to segregate the dried harvested

crystals into four size fractions: 0-0.5 mm, 0.5-1 mm, 1-2 mm and greater than 2 mm. The crystal mass collected in each size fraction from each harvest was measured using an analytical balance, and a sample of each size fraction was collected for further analysis.

It should be noted that the harvesting, drying and sieving process caused significant breakage of the crystals removed from the reactor. This was especially evident in the early stages of the experiment when the crystals were very brittle. In the later stages, the crystals became rounder, harder and denser, resulting in less breakage from handling. Even though this breakage was evident, it was assumed that the size distribution after handling was representative of what could be expected should the process be commercialized. In a commercial process, the harvested crystals would need to be screened, dried and bagged by a mechanized process, which would probably have a similar impact on the crystals as the handling procedure used here.

4.1.11. Daily Monitoring and Control

Each day, several operating parameters were monitored in order to characterize the operation of each reactor. In each reactor, the effluent flow rate, the total combined flow rate in the down pipe from the crystallizer to the external clarifier, and the flow rate of magnesium chloride solution into the reactor were monitored.

The tank levels in both the sodium hydroxide and magnesium chloride storage tanks were recorded daily, and the usage of each solution was calculated from by difference from the previous days reading. The mass of reagent added to the chemical storage tanks, as well as the volume of tap water added, was recorded whenever solutions were replenished.

The pH of the digester supernatant in the storage tank being used was measured and recorded daily as well as the pH of the effluent from each reactor. Samples of the digester supernatant and the effluent from each reactor were collected daily, and subsequently filtered and analyzed for magnesium, ortho-phosphate and ammonia nitrogen, as described in Section 4.4.

After all the other daily readings and samples were taken, the reactors were shut down and the struvite crystals were allowed to settle. Once the settling was complete, the collapsed bed volume of crystals was recorded. After all the required data was collected, crystals were

harvested as described in Section 4.1.9 and any required reactor maintenance, such as injector port cleaning and pH probe calibration, was performed. Once this maintenance was completed, the reactors were restarted and the flows were readjusted to match the desired set points.

4.2. Struvite Solubility Determination

For the purpose of the operation of the pilot struvite crystallization reactors at the City of Penticton AWWTP, a P_S curve developed at the University of British Columbia for bench scale crystallizer testing was used. This solubility curve was developed by melting struvite crystals in distilled water and analyzing the resulting solution at equilibrium for pH, dissolved magnesium, ammonia and ortho-phosphate (Dastur, 2001). From the experimental data collected in Penticton, it became apparent that the equilibrium P_S was significantly different in digester supernatant than in distilled water, and therefore a new solubility curve was developed for digester supernatant after the pilot scale trials in Penticton.

4.2.1. Apparatus

The apparatus used for determining the solubility of struvite was a six station paddle stirrer (Phipps and Bird). Square jars containing 1.5 liters of the solution being tested were immersed in a constant temperature bath at 20 ± 0.1 °C. The paddle stirrers were set to operate at 70 ± 2 RPM. A sufficient mass of struvite crystals, harvested from the reactors in Penticton, were placed in each jar to ensure that some solid phase struvite remained at equilibrium. Equilibrium was assumed to be reached 24 hours after conditions were changed in each jar, based on previous research at UBC (Ping Liao, Research Associate, UBC Department of Chemical Engineering, pers. comm.). The pH in each jar was adjusted using dilute hydrochloric acid and sodium hydroxide solutions, in order to determine the solubility of struvite over the expected operating range of struvite crystallization equipment (i.e. between pH values of 7 and 9). In a previous study, these conditions were found to be optimal to approximate equilibrium conditions while minimizing the volatilization of ammonia during the test (Ping Liao, pers. comm.).

Two sets of tests were conducted, one using distilled water and one using digester supernatant from the City of Penticton AWWTP. For each test, each beaker was filled with 1.5 liters of either distilled water or supernatant, then struvite crystals were added to the reactor and mixed in. For the tests using supernatant, a reagent grade magnesium chloride solution was dosed into the supernatant to result in an initial molar Mg:P ratio of 1.3:1 as used in the pilot-scale experiment. The pH of each jar was then adjusted as desired and the apparatus was left to equilibrate for 24 hours. At the end of the 24 hour period, the pH and conductivity in each jar were measured and samples of the equilibrated solution were filtered and analyzed for magnesium, calcium, ammonia and ortho-phosphate.

4.3. Crystal Product Analysis

In order to determine the composition and purity of the crystals grown from the supernatant in the pilot scale crystallizers at the City of Penticton AWWTP, samples of several of the harvested crystals were dissolved in a 0.5% nitric acid solution. These solutions were subsequently analyzed for the components of struvite, as well as calcium, aluminum, iron and potassium.

For each sample analyzed, approximately 0.03 g of crystals was dissolved in 50 ml of 0.5% nitric acid solution. In order to accelerate the crystal dissolution, the samples were submerged in an ultrasonic bath until no visible solids remained. The samples were then allowed to sit for 24 hours before being analyzed, in order to ensure that any invisible crystallites had time to dissolve and the solution had time to mix completely. Each sample was vortex mixed and inverted several times during this time to further accelerate the mixing. Trace amounts of solid residue were found at the bottom of some of the samples at the end of 24 hours. This was found to be fibrous material, possibly originating from the struvite crystals themselves, or from dust contamination either in the laboratory or in the crystal handling and drying process at the wastewater treatment plant. No attempt was made to quantify the mass of this fibrous residue or to identify its chemical makeup. It was simply observed under a microscope and identified as being fibrous material. An image of this material is presented in Figure 4.5

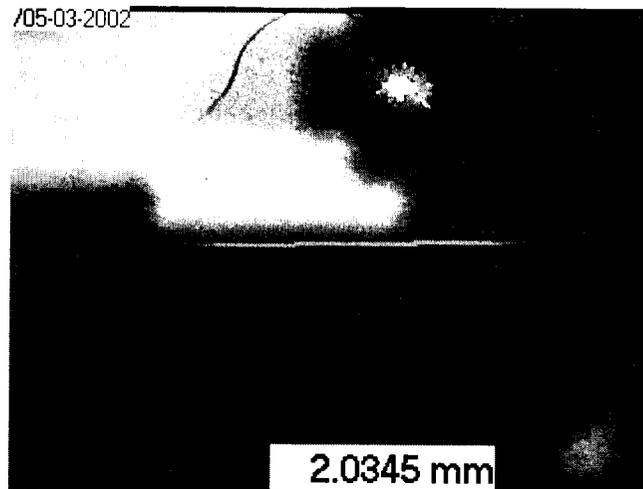


Figure 4.5: Fibrous residue from crystal dissolution tests.

4.4. Analytical Methods

Two general types of analyses were conducted during the course of this study: field analyses at the wastewater treatment plant and lab analyses performed in the UBC Environmental Engineering lab. The field tests were meant to be representative of analyses that could be performed routinely on-site by wastewater treatment plant staff, while the tests performed at the UBC lab were generally of a non routine nature and were only necessary for research purposes. The exception to this was the analysis for magnesium. Since there was no equipment available in the lab at the wastewater treatment plant to measure magnesium concentrations, samples were shipped from Penticton to the UBC lab for analysis. In the future a method of measuring magnesium on site at the wastewater treatment plant would be advisable to minimize analytical turnaround time and to be able to more accurately control the reactor operating conditions.

4.4.1. Magnesium

Magnesium results reported throughout this report were analyzed by atomic absorption. Most samples were analyzed for dissolved magnesium; however, some samples were analyzed for total magnesium, to determine if a large amount of magnesium was present in particulate form.

An attempt was made at determining the dissolved magnesium concentration in the digester supernatant matrix using EDTA titrations for total and calcium hardness. The assumption is that the difference between the total hardness and the calcium hardness is composed entirely of magnesium hardness. Unfortunately, this method gave results that were orders of magnitude different from the values determined by atomic absorption, and this technique was abandoned.

Magnesium analysis in the UBC lab was performed by flame atomic absorption spectrophotometry, using a Varian Inc. SpectrAA220 Fast Sequential Atomic Absorption Spectrophotometer. Instrument operational parameter details can be found in Appendix A.

4.4.2. Ortho-phosphate

Ortho Phosphate was measured on site at the wastewater treatment plant using the Stannous Chloride method as described in method number 4500-P D in Standard Methods for the Examination of Water and Wastewater (APHA, AWWA and WPCF, 1995), with the exception that sample sizes were 50 ml instead of 100ml. The absorbances of the samples were measured using a Milton Roy Spectronic 401 spectrophotometer.

Ortho phosphate samples analyzed at the UBC laboratory were analyzed using flow injection analysis on a LaChat QuikChem 8000 instrument configured as described in Appendix A. Flow injection analyses were performed on the samples from the crystal product analysis and struvite solubility determination experiments described in Sections 4.2 and 4.3 above.

Initially, on-site ortho-phosphate analysis was attempted using a Hach DR2000 spectrophotometer with the ammonia-molybdovanadate method. Unfortunately, the color of the supernatant interfered with the yellow color developed and measured in this method, and it proved to be unusable.

4.4.3. Ammonia

On-site ammonia tests were performed using a Hach DR2000 spectrophotometer using the salicylate method (Hach, Nitrogen, Ammonia, High Range Test'N Tube method 10031).

The relative standard deviation of this method was found to be 3.7%, with replicate analyses varying by as much as 30 mg/L.

Ammonia analyses performed at the UBC laboratory used flow injection analysis on the same LaChat instrument as the phosphate analysis described above. Instrument operational parameter details can be found in Appendix A.

4.4.4. pH

Field pH measurements were performed using the Oakton continuous pH monitors described above in the reactor design. Laboratory pH measurements were performed using a Beckman Φ 44 pH meter equipped with an Oakton pH probe. All pH meters were regularly calibrated by the two point method, using buffer solutions of pH 7 and pH 10.

4.4.5. Calcium, Aluminum and Iron

Calcium, aluminum and iron analysis was performed on the samples from the crystal product analysis. This analysis was performed by atomic absorption spectrophotometry using the same instrument as for the magnesium analysis described above. Instrument operational parameter details can be found in Appendix A.

4.4.6. Potassium

Potassium analysis was performed on the samples from the crystal product analysis. This analysis was performed by atomic emission spectrophotometry using the same instrument as for the magnesium analysis described above. Instrument operational parameter details can be found in Appendix A.

4.4.7. Total Phosphorus

Total phosphorus analysis for the estimation of full-scale phosphorus loads in the wastewater treatment plant were digested using the sulfuric acid-nitric acid digestion method (APHA, 1995, method 4500-P B.4) and analysed by flow injection analysis on the same LaChat instrument as the ortho-phosphate samples as described above.

4.4.8. Filtration

All field samples were filtered using Fisher Brand G6 filter papers with a nominal pore size of 1.5 microns to remove suspended solids from the samples.

4.4.9. Conductivity

Conductivity was measured using a Hanna Instruments HI9033 multi range conductivity meter for the struvite solubility tests described above.

4.5. Terminology

For ease of understanding in the following sections, several of the terms used to describe the operation and control of the struvite crystallizers are defined here.

4.5.1. Struvite Solubility Product

The solubility product or K_{sp} as defined in this study is the product of the ionic activities of the precise ionic forms involved in the formation of a precipitate. For the case of struvite, this relation is defined by Equation 1, where the {} brackets indicate ion activity in moles per liter. This involves the speciation of analytically determined concentrations using published acid and base dissociation constants, as well as an adjustment for activity. The result is theoretically a thermodynamic constant applicable under any conditions; however, for this to be true, all potential reactions that could be affecting the speciation of each compound must be accounted for and properly analyzed. This also requires accurate values for dissociation constants and solubility products for all related compounds. A rough attempt has been made here to quantify a K_{sp} value for the struvite crystals formed in the pilot plant in Penticton; however, due to a lack of analytical and experimental information, this value is not used to quantify the operation of the reactor.

$$K_{sp} = \{Mg^{2+}\} \{NH_4^+\} \{PO_4^{3-}\} \quad \text{Eq. 1}$$

The ionic strength of the solution was determined based on conductivity measurements using the conversion factor described in Equation 2 (Tchobanoglous and Schroeder, 1985).

$$\mu = 1.6 \times 10^{-5} EC \quad \text{Eq. 2}$$

Where μ = Ionic Strength

EC = Electric Conductivity ($\mu\text{S/cm}$)

From this value of ionic strength, the activity coefficients for each species of interest was calculated, based on the Güntelberg approximation of the Debye-Hückel equation shown in Equation 3 (Sawyer *et al.*, 1994).

$$\log \gamma = \frac{0.5z^2 \sqrt{\mu}}{1 + \sqrt{\mu}} \quad \text{Eq. 3}$$

Where: γ = the activity coefficient for the species of interest.

z = the ionic charge of the species of interest.

The second step in determining the solubility products of the produced struvite was to partition the analytically measured compounds into the specific ions present in the water. That is to partition the measured phosphate into PO_4^{3-} , HPO_4^{2-} , H_2PO_4^- , and H_3PO_4 , the measured ammonia into NH_3 and NH_4^+ , and the measured magnesium into Mg^{2+} and MgOH^+ . No forms of magnesium phosphate were included in these calculations. Equations 4 to 8 show the dissociation constants which were used for the partitioning at a temperature of 20°C (Ping Liao, pers comm.). These coefficients were adapted and interpolated to 20°C from literature values.

$$[\text{H}_2\text{PO}_4^-][\text{H}^+]/[\text{H}_3\text{PO}_4] = 7.81 \times 10^{-3} \quad \text{Eq. 4}$$

$$[\text{HPO}_4^{2-}][\text{H}^+]/[\text{H}_2\text{PO}_4^-] = 6.12 \times 10^{-8} \quad \text{Eq. 5}$$

$$[\text{PO}_4^{3-}][\text{H}^+]/[\text{HPO}_4^{2-}] = 5.00 \times 10^{-13} \quad \text{Eq. 6}$$

$$[\text{NH}_3][\text{H}^+]/[\text{NH}_4^+] = 6.05 \times 10^{-10} \quad \text{Eq. 7}$$

$$[\text{Mg}^{2+}][\text{OH}^-]/[\text{MgOH}^+] = 2.75 \times 10^{-3} \quad \text{Eq. 8}$$

These acid and base dissociation constants were then substituted into Equations 9-11 to solve for each individual species concentration. Since all samples were filtered prior to analysis, it was assumed that only dissolved species were present.

$$T\text{-PO}_4 = [\text{H}_3\text{PO}_4] + [\text{H}_2\text{PO}_4^-] + [\text{HPO}_4^{2-}] + [\text{PO}_4^{3-}] \quad \text{Eq. 9}$$

$$T\text{-NH}_3 = [\text{NH}_3] + [\text{NH}_4^+] \quad \text{Eq. 10}$$

$$T\text{-Mg} = [\text{Mg}^{2+}] + [\text{MgOH}^+] \quad \text{Eq. 11}$$

Once the activity of each individual species of interest was determined, the solubility product was calculated over a pH range similar to that expected to be encountered in an operating struvite crystallizer.

4.5.2. *Struvite Conditional Solubility Product*

The struvite conditional solubility product (P_S), as defined in this study, is the direct product of the analytical results for soluble magnesium, ammonia nitrogen and ortho-phosphate, as defined by Equation 12, where the [] brackets indicate concentration in moles per liter. There is no attempt to correct for ionic activity in this value; it was simply used as a “quick way” to determine the supersaturation ratio for reactor operation based on field analytical results.

$$P_S = [\text{Mg} - T][\text{NH}_4 - N][\text{PO}_4 - P] \quad \text{Eq. 12}$$

4.5.3. *Supersaturation Ratio*

The supersaturation ratio (SS ratio) represents the ratio of the conditional solubility product in a solution to the equilibrium conditional solubility product for the given conditions. The equilibrium conditional solubility product used in this study is the one developed using the digester supernatant from the City of Penticton AWWTP. Equation 13 is the relation used to determine the supersaturation ratio where $P_{S \text{ eq}}$ indicates the equilibrium conditional solubility product. A solution with a SS ratio greater than 1 is supersaturated with respect to struvite and struvite will be formed to bring the solution to equilibrium; a solution with a SS ratio of less than 1 is undersaturated and struvite crystals will melt to bring the solution to equilibrium.

$$\text{SS Ratio} = P_s/P_{s \text{ eq}} \quad \text{Eq. 13}$$

4.5.3.1. *Feed supersaturation ratio*

The feed or influent supersaturation ratio describes the hypothetical supersaturation ratio that would exist in an instantly mixed solution consisting of digester supernatant, magnesium chloride solution and sodium hydroxide solution, in proportions equal to those fed to the reactor. This also implies that this supersaturation ratio is for the solution at a pH equal to that in the reactor. This ratio is said to be hypothetical since these conditions never actually exist in the reactor. This supersaturation ratio is a good means of estimating the driving force for the overall crystallization reaction, but does not represent conditions inside the reactor.

4.5.3.2. *Effluent supersaturation ratio*

Assuming that the crystallization reaction has sufficient time to reach equilibrium, the supersaturation ratio in the reactor effluent should be 1.0. However, since the retention time in the reactor is quite short, it is expected that the reaction will not be 100% complete. The effluent supersaturation ratio is used as an indicator of this degree of reaction completion. This ratio is calculated based on analysis of reactor effluent samples.

4.5.3.3. *In-reactor supersaturation ratio*

The supersaturation ratio in the reactor is the factor that governs the actual reaction driving force, and this ratio determines to a certain degree the rate of crystal growth, compared with the rate of crystal nucleation. In essence, high supersaturation ratios in the reactor will lead to excess nucleation and eventually a precipitation reaction, rather than a crystallization reaction.

The supersaturation ratio in the reactor for this study has been calculated by combining the concentrations of magnesium, ammonia and ortho-phosphate in the reactor feed and recycle streams. It is therefore representative of the supersaturation ratio in a completely mixed sample drawn from immediately above the injection ports of the reactors. The local supersaturation ratios in the injector port section will undoubtedly differ from this value, due to micro-scale concentration gradients as the reagents mix; however, this value is thought to be representative of the bulk solution properties.

4.5.4. *Recycle Ratio*

The recycle ratio in this study is calculated using Equation 14.

$$\text{Recycle Ratio} = (Q_t - Q_e) / Q_e \quad \text{Eq. 14}$$

Where: Q_t = The total combined flow through the reactor.

Q_e = The effluent flow from the external clarifier (or the combined feed flows)

The recycle ratio therefore represents the ratio of the flow from the recycle pump to the combined flow from the supernatant feed pump and chemical dosing pumps. This recycle ratio is used to control the in-reactor supersaturation ratio by diluting the feed with treated effluent.

4.5.5. *Crystal Retention Time*

For this study, the crystal retention time (CRT) is used as a means of estimating the average amount of time a harvested crystal spends in the reactor. It is calculated by measuring the collapsed bed volume of struvite crystals in the reactor at the time of each harvest, and then calculating the approximate number of days that have passed since that volume of crystals have been removed from the reactor. For example, if the collapsed bed volume was measured to be 6.6 liters, and 1.1 liters of crystals were harvested from the reactor every two days, then the CRT would be 12 days. Since the crystals were harvested from the reactor at irregular intervals, the CRT was calculated using a log of each harvest date and volume.

4.5.6. *Mean Crystal Size*

The mean crystal size of each harvest was calculated from the sieve analysis. All the crystals in each size fraction were assumed to be of a diameter in the middle of the size fraction. That is the crystals that were of less than 0.5 mm were assumed to be 0.25 mm in diameter, the 0.5-1 mm crystals were assumed to have a diameter of 0.75 mm, the 1-2 mm crystals were assumed to have a diameter of 1.5 mm and the crystals that were greater than 2 mm were assumed to have a diameter of 2.5 mm. Based on this assumption the mean diameter by mass was calculated using Equation 15.

$$\text{MCD} = (\text{M1}(0.25) + \text{M2}(0.75) + \text{M3}(1.5) + \text{M4}(2.5))/(\text{M1}+\text{M2}+\text{M3}+\text{M4}) \quad \text{Eq. 15}$$

Where: MCD = Mean Crystal Diameter (mm)

M1 = mass of crystals of diameter less than 0.5 mm.

M2 = mass of crystals of diameter from 0.5 to 1 mm

M3 = mass of crystals of diameter from 1 to 2 mm

M4 = mass of crystals of diameter greater than 2 mm

4.5.7. *Percent Phosphate Removal*

Since the removal of phosphorus is a primary objective of this research, the percentage of phosphate removed from the digester supernatant stream was monitored. This value was calculated using Equation 16.

$$\%P \text{ removal} = ([P_i](Q_i) - [P_e](Q_e)) / ([P_i](Q_i)) * 100 \quad \text{Eq 16}$$

Where: $[P_i]$ = concentration of $\text{PO}_4\text{-P}$ in the feed supernatant.

$[P_e]$ = concentration of $\text{PO}_4\text{-P}$ in the reactor effluent.

Q_i = -the flow of supernatant into the reactor.

5. RESULTS AND DISCUSSION

The main result of this study was that the reactor design described in Section 3 was successful in recovering phosphate in the form of struvite from a full-scale digester supernatant at the City of Penticton AWWTP. After the initial commissioning and startup phase, the two reactors operated without failure and with little required operator intervention for the duration of the study. By the end of the study, it was possible to let the reactor operate for periods of up to 5 days without any operator intervention.

Crystalline product was recovered from the reactor as small pellets, with average diameters approaching 2 mm by the end of the study. These crystals were found to be nearly pure struvite and of a hardness adequate to allow easy separation and processing of the product.

The overall operation period of the reactors was from September 2nd, 2001 to December 13th, 2001. However due to the low phosphate content (7.8-18.8 mg/L PO₄-P) in the digester supernatant initially, the operation of the reactors prior to October 12th, 2002 was essentially a commissioning phase and little phosphorus recovery was possible. During this time, high chemical dosages of both magnesium chloride and sodium hydroxide were necessary to induce the crystallization of struvite and this data is therefore not presented here, other than to say that phosphate removal is possible even at these low concentrations, but at a high unit cost. The following discussion therefore relates to the results obtained during the period of October 12th to December 13th, 2001, except where explicitly noted.

5.1. Struvite Solubility Product Determination

Determination of the solubility of struvite in the digester supernatant used in this study will be discussed first, in order to set a baseline for discussions regarding various operational parameters in the reactors; these include supersaturation ratios and reaction completeness. Several authors have attempted to determine a solubility product for struvite, but there is a very wide range of reported solubility values (Dastur, 2001). It was therefore important for this study

to determine the equilibrium conditions that could be expected in our reactors, when treating real digester supernatant.

Using the procedure outlined in Section 4.2, two experiments were conducted; one to determine the struvite equilibrium conditions in distilled water, and the other to determine the equilibrium conditions in digester supernatant. Thermodynamically, there should be a single value of the solubility product (K_{sp}) that should apply to all solutions, as long as it is possible to determine the activity of each chemical species accurately. Unfortunately, it is difficult to determine the activity of individual compounds in digester supernatant with precision, due to the presence of a myriad of known and unknown compounds. The presence of these compounds also leads to a wide range of possible competing reactions which could skew the solubility product determination.

5.1.1. Struvite Solubility Product in Distilled Water

In order to simplify the solution chemistry involved in determining the solubility product of the struvite formed in the reactors in Penticton, a preliminary trial was conducted using distilled water as the solvent. Figure 5.1 shows the negative logarithm of struvite solubility product (pK_{SP}) calculated over a pH range from approximately 7.0 to 9.5 for distilled water. It can be seen that the solubility product calculated is relatively constant over this range. The mean value of the solubility product in this range was found to be 1.5×10^{-14} with a standard deviation of 3.6×10^{-15} . However, when subjected to a least squares regression, the trend line does, in fact, have a slope indicating that the solubility product does change with pH; the slope in the curve is relatively small and the variation in the data makes it difficult to ascertain whether this value is in fact a constant, or whether it varies with pH. In this study, the solubility product was only evaluated out of curiosity, and is not used as a control parameter for the reactor, but simply as a means of comparing results obtained in distilled water to those in digester supernatant. Detailed calculations and data for this determination can be found in Appendix B.

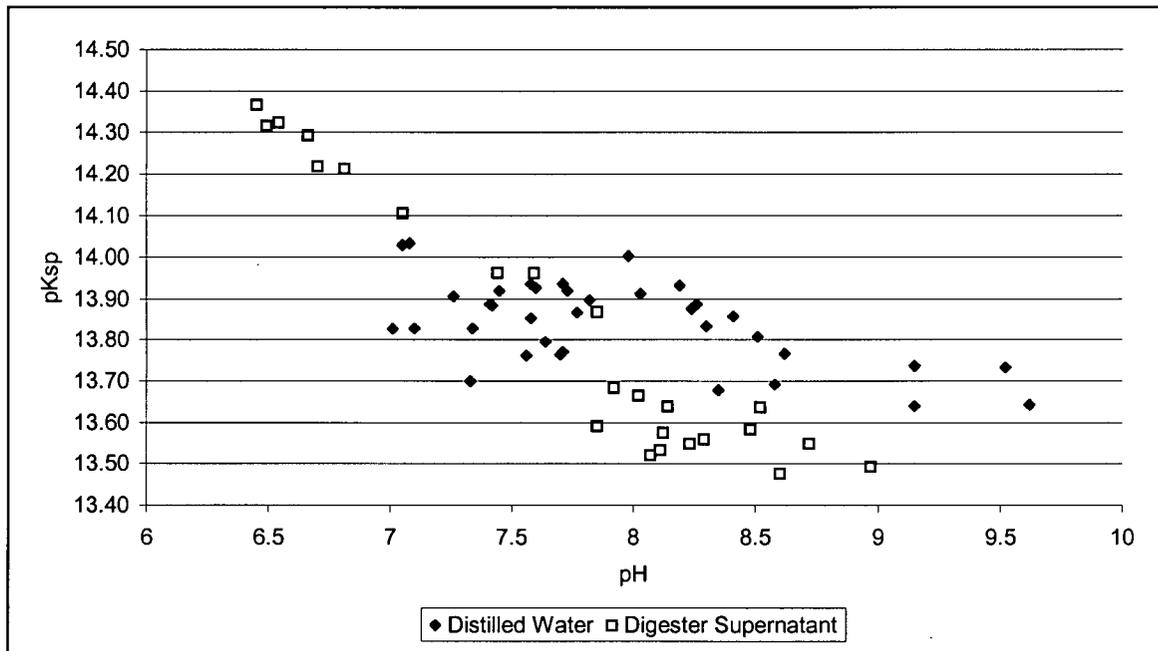


Figure 5.1: Struvite solubility product in distilled water and digester supernatant vs. sample pH.

5.1.2. Struvite Solubility Product in Digester Supernatant

Also shown in Figure 5.1 is the calculated struvite solubility product in digester supernatant from the City of Penticton AWWTP. This solubility product varied from 4.3×10^{-15} to 3.2×10^{-14} . There is an obvious change in this value with pH, indicating that there are probably some reactions taking place in the supernatant that were not accounted for in the simplified analysis performed here. Since it was not possible to determine a constant K_{sp} value for struvite in digester supernatant across a wide pH range, it was decided that using the P_S would be a more reasonable way of monitoring the reactor operation, since the calculation of the P_S is much simpler and requires fewer assumptions.

5.1.3. Struvite Conditional Solubility Product

As a simple means of determining the saturation state of the supernatant being treated, the conditional solubility product (P_S) was used. Figure 5.2 shows the experimentally determined struvite P_S curves for distilled water, as well as for digester supernatant. A second order polynomial curve was fitted to the data using Microsoft Excel software, and this curve was used subsequently to represent equilibrium conditions in the solutions. For the supernatant curve, Equation 17 describes this polynomial curve where pP_S is the negative logarithm of the

P_s . This curve fits the data with a R^2 value of 0.993, indicating that this is an accurate representation of the equilibrium conditions in this particular supernatant. There is a significant difference between the pP_s curves for supernatant and for distilled water, mainly due to the difference in ionic strength of the two solutions; however, other factors such as chemicals in the supernatant that may compete with the crystallization or inhibit it, are also at play. In order to eliminate these factors from the analysis, the curve developed using digester supernatant from the Penticton AWWTP was used.

$$pP_s = -0.203pH^2 + 4.09pH - 11.76$$

Eq. 17

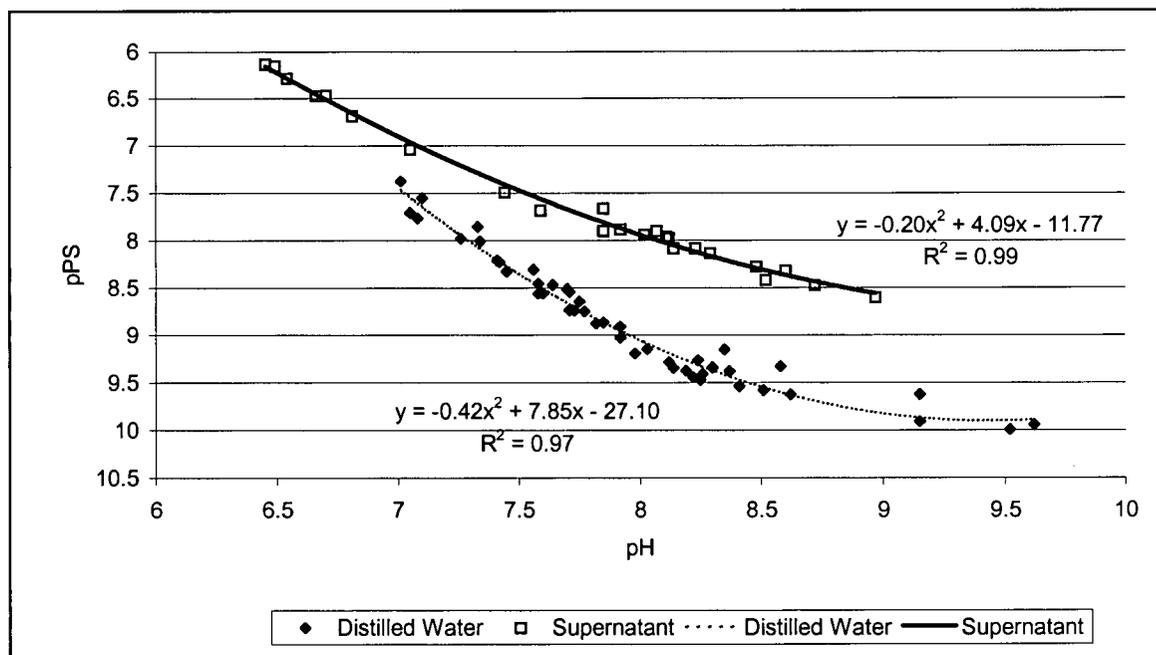


Figure 5.2: Struvite pP_s in digester supernatant and distilled water as a function of pH

5.2. Supernatant Characteristics During the Study

Since the operation of the digester at the City of Penticton AWWTP was modified during the course of this study, the composition of the supernatant from the digester changed significantly. Normal operation of the digester involved only the digestion of primary sludge, resulting in $PO_4\text{-P}$ concentrations of 5 to 15 mg/L in the digester supernatant. At the beginning

of the study (early September), the digester was supplemented with thickened waste activated sludge (WAS) from a thickener tank. This practice appeared to hydraulically overload the digester and it was therefore discontinued until a better solution could be found. During this period, the supernatant contained high suspended solids concentrations (up to 2000 mg/L) and this was causing operational problems for the treatment plant.

Following this period of instability, a method of transferring WAS from the gravity belt thickener was devised that allowed the transfer of much thicker sludge (approximately 5% solids). This practice allowed much more WAS to be transferred to the digester without hydraulic overloading and thus allowed the phosphate concentration to increase, without causing suspended solids problems in the supernatant. Once this practice was established in early October, it was possible to maintain much higher phosphate concentrations in the digester, as can be seen in Figure 5.3.

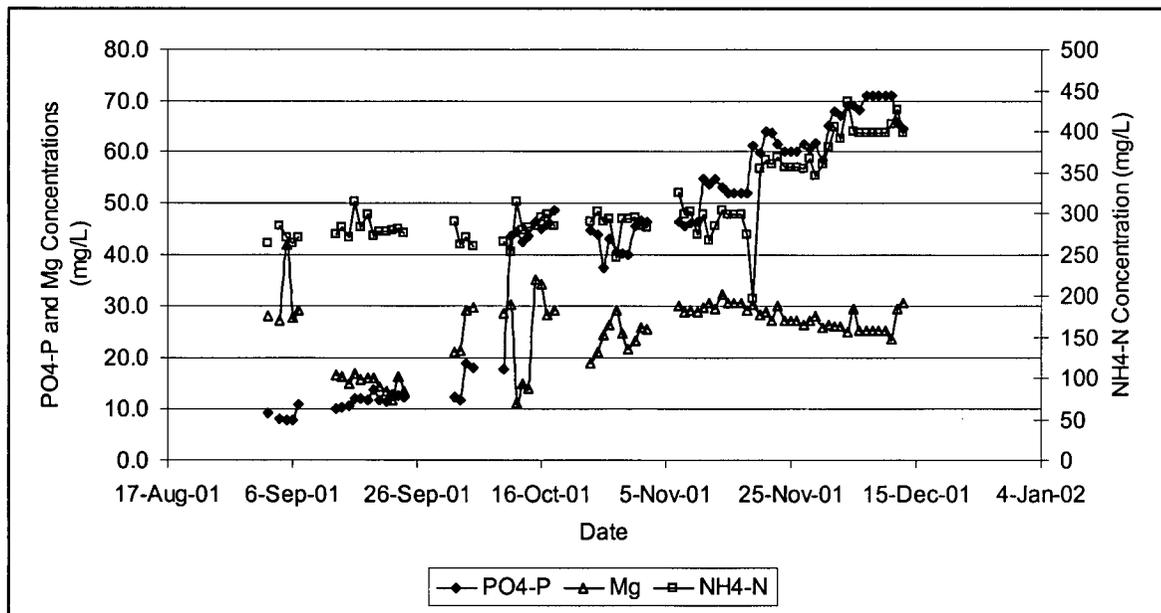


Figure 5.3: Digester supernatant composition during the course of the study.

The estimated hydraulic residence time of the digester was 28 days; therefore, there was some lag time between the change in operation and the resulting conditions in the supernatant. By adding thickened WAS to the digester on an average of 3 days per week, it was possible to maintain a PO₄-P concentration of greater than 50 mg/L. This also coincided with a concerted

attempt to keep the aluminum containing sludge from the water treatment plant out of the digester, thus allowing higher phosphate concentration to be maintained in the supernatant¹.

Once the aluminum sludge was eliminated from the digester feed (early October), the concentrations of ammonia and phosphate increase steadily as the WAS content in the digester was increased. The magnesium concentration, however, appeared to remain relatively constant and independent of the ammonia and phosphate concentrations; this is contrary to the belief that magnesium is released in conjunction with phosphate when BNR sludge is digested anaerobically (Doyle, et al 2000; Jardin and Popel 2001). The reasons for this different trend have not been investigated here.

During the period from October 12th to Dec 13th, the concentration of PO₄-P ranged from 37 to 71 mg/L, while the NH₄-N concentration ranged from 197 to 436 mg/L and the Mg concentration ranged from 11 to 35 mg/L. Due to the wide variation in the composition of the supernatant being fed to the crystallization reactors, the operation of the reactors was continually modified to maintain stable crystal growth conditions in the reactor.

5.3. Reactor Operation

This section describes the results obtained from the operation of the two struvite crystallization reactors at the City of Penticton AWWTP. In general it should be said that the reactors operated as expected and in a manner similar to the operation observed during previous trials with similar pilot-scale reactors using synthetic supernatant (Dastur, 2001). The crystals harvested from the reactor were generally of a darker color and of a smaller diameter than those harvested from synthetic supernatant, but removal and recovery of these crystals was easy and the product handling methods used in the previous trials worked well here. The detailed operational data collected during the study are found in Appendices C and D for reactors A and B respectively.

¹ In order to minimize the aluminum load to the digester, on days when the aluminum-rich drinking water treatment plant sludge was discharged to the wastewater treatment plant, sludge from the fermenters was sent directly to the sludge press, thus bypassing the digester.

5.3.1. *Mg/NH₄/PO₄ Forms and filtration*

Several samples were analyzed, both unfiltered and filtered, to determine what portion of the constituents of interest (Mg, NH₄-N, and PO₄-P) were associated with suspended solids. Table 5.1 shows the results of this analysis. The influent samples are for settled digester supernatant from the storage tanks, while the effluent samples are for reactor effluent from both reactors. The latter is a good indicator of the presence of small crystals of struvite in the effluent, as well as indicating any chemicals that are adsorbed to colloidal material in the supernatant. Since the dissolved forms of the ions are the ones taking part in the chemical equilibrium reactions within the supernatant, it was the dissolved concentrations that were of interest; therefore, the samples used for the analysis of the performance of the reactors were filtered.

Table 5.1: Supernatant filtration analysis and solid fraction determination for reactor influent and effluent.

Analyte	Unfiltered Influent Sample	Filtered Influent Sample	Influent Solid Fraction	Unfiltered Effluent Sample	Filtered Effluent Sample	Effluent Solid Fraction
Mg (mg/L)	25.4	25.5	-0.1	38.9	39.0	-0.1
NH ₄ -N (mg/L)	292	281	11	249	238	11
PO ₄ -P (mg/L)	42.8	40.8	2.0	8.0	6.9	1.1
n	4	4	4	8	8	8

In general, a relatively small fraction of all three analytes are associated with the suspended solids, and an equal amount is present in the influent and effluent samples; this indicates that the solid fraction is possibly associated with colloidal material that does not settle out and simply passes through the struvite crystallizing reactors without interacting with the crystals. The only exception is phosphate which has a slightly lower solid fraction in the effluent than the influent. This could be due to analytical error, or the low phosphate concentration in the effluent causing some dissolution of the phosphate associated with colloidal matter. In any case, the difference between the influent and effluent solid fractions was quite small (0.9 mg/L).

Interestingly, there was no magnesium present in solid form (with nominal size greater than 1.5 microns); in fact, the analysis shows that some magnesium was added to the solution

during the filtration process. The difference is quite small, however, and may have been due to sampling or analytical error.

5.3.2. *Removal efficiency*

One of the main objectives of this research was to remove phosphate from the digester supernatant stream, in a full-scale BNR plant. The performance of the two reactors, with respect to removal of phosphate and ammonia from the supernatant stream, is described herein. Magnesium removal was not evaluated, since it was supplemented to the reactor in order to ensure that it was not the limiting reagent in the formation of struvite. Suffice it to say that this dosing can be controlled so that the overall effect of the crystallization reactor can be to either add or remove magnesium from the supernatant. In this study, the magnesium concentration in the feed to the reactor was maintained at a 1.3:1 molar ratio with phosphate. Whether magnesium was added or removed in the process, therefore, depended on the removal of phosphate and the initial concentration of magnesium in the supernatant.

Overall, it was possible to control the phosphorus removal efficiency within the range of 30 to 90 %. This control was exerted either by setting the pH in the reactors or by setting the inlet supersaturation ratio. The original objective of the study was to demonstrate that it was possible to remove at least 70% of the phosphate from the digester supernatant stream. As can be seen in Figure 5.4, it was, in fact, possible to control the removal efficiency in the desired range. Variations from the target value were investigated to compare the economics of different removal efficiencies. The two reactors were operated in a parallel mode until November 7th, when the operation of Reactor B was modified to purposely achieve lower phosphate removal. With the exception of 1 day, when the magnesium feed to the reactor was accidentally interrupted (Oct 24th), the removal of phosphate in Reactor A was maintained above 70%. This shows that it is, in fact, possible to maintain the removal efficiency targeted in this study, and that it was possible to maintain a higher removal efficiency if desired (>80%) for a supernatant with a phosphate concentration of 40 mg/L or more. These results are consistent with results obtained in several other studies where struvite was being recovered from full-scale digester liquors (Abe, 1995; Munch and Barr, 2001; Ueno and Fujii, 2001)

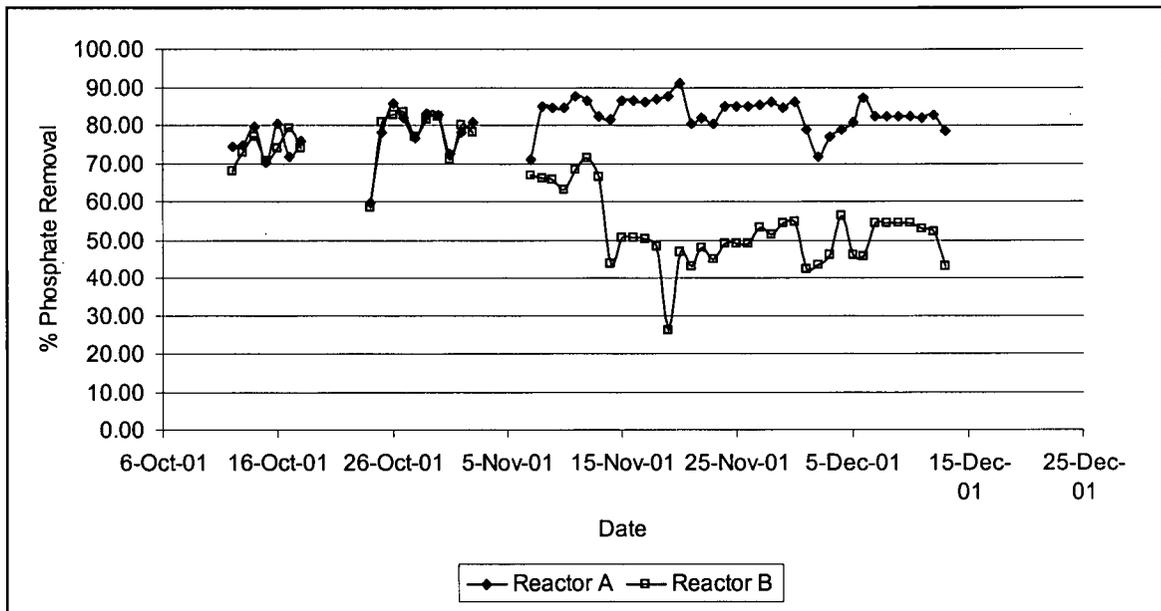


Figure 5.4. Percentage phosphate removal for each reactor during the study period.

For phosphate removal, two possible factors were evaluated to control the percentage removal; the operating pH of the reactor, and the inlet supersaturation ratio. The first assumes that the variation in the $Mg:NH_4:PO_4$ molar ratios in the supernatant is small and can therefore be ignored; also, the percentage of phosphorus removed will vary with the operating pH, simply because the solubility of struvite, as defined by the equilibrium P_s , varies with pH. This method of evaluation is by far the simplest and is useful for the day to day operation of the reactor, but would probably fail to accurately predict the performance of a reactor at a new site with different molar ratios. This relation is shown graphically in Figure 5.5. The wide range of removal efficiencies for a given pH (up to 31%) is due to the change in inlet concentrations and changes in the $Mg:NH_4:PO_4$ molar ratios over the duration of the study. That is to say, this method of prediction is useful, but simplistic, and will not be sufficient in a supernatant which is highly variable in composition if precise control of the phosphate removal is required.

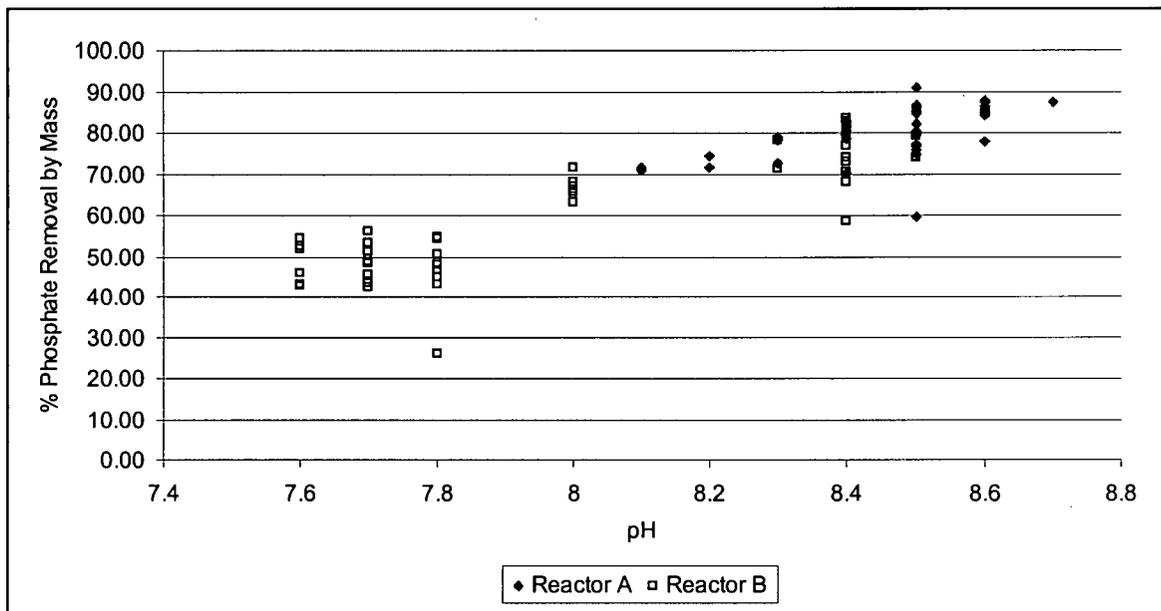


Figure 5.5: Phosphate removal vs. operating pH in the struvite crystallizing reactors.

In the second method of predicting the removal of phosphorus, the inlet supersaturation ratio is used. This method assumes that the effluent supersaturation ratio will be unity, indicating that equilibrium has been reached in the reactor. It is therefore possible to predict the effluent phosphate concentration by assuming equimolar removal of Mg and $\text{NH}_4\text{-N}$. Figure 5.6 shows the percentage of phosphorus removal versus the inlet supersaturation ratio for the operating period in both reactors. The important factors that contribute to the scatter in Figure 5.6 are the inaccuracies in the measurement of the Mg, $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ concentrations, as well as in the measurement of the pH. The fact that a supersaturation ratio is a function of all four of these measured values makes for a compounded error, but the advantage is that this method allows the prediction of removal efficiency in a widely-varying supernatant composition, with the same accuracy.

Overall, the best method to use to predict the phosphate removal from an operational point of view will depend on the degree of accuracy wanted and the available data. Basically, a reactor can be controlled to remove the desired amount of phosphate by varying the operating pH or the inlet supersaturation ratio. The difference between the two methods is that the first takes into account only one of the factors involved and is applicable only for a specific supernatant,

while the latter requires a more complete analysis of the situation and is more generally applicable.

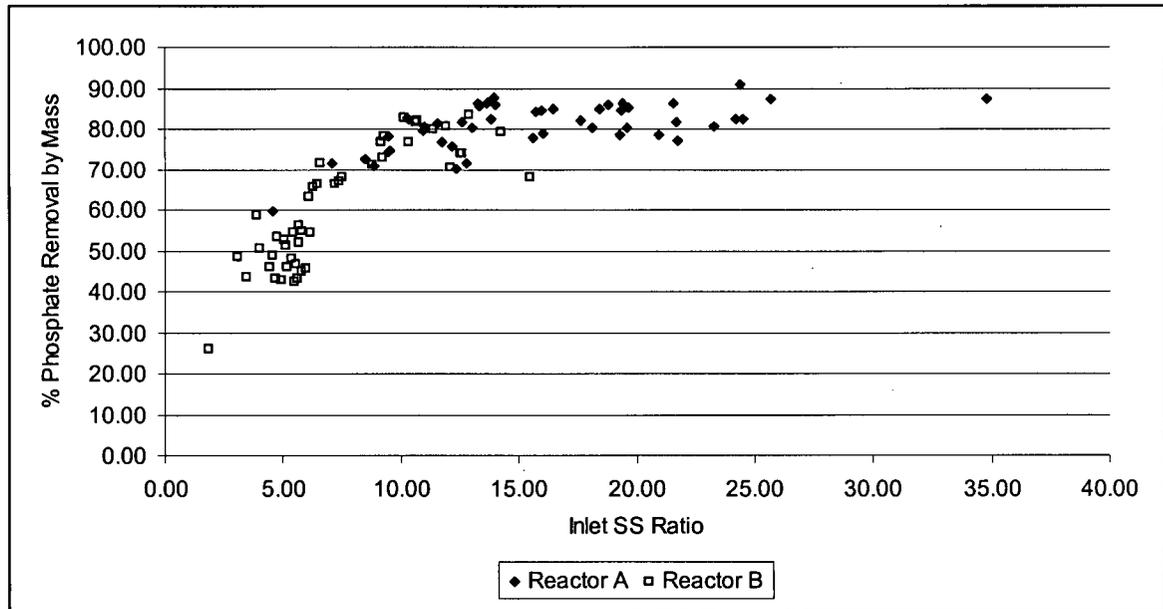


Figure 5.6: Phosphate removal vs. inlet supersaturation ratio in the struvite crystallizing reactors.

Ammonia concentrations in the digester supernatant in Penticton were several times higher than phosphorus. The average ammonia to phosphate molar ratio in the supernatant during the study period was 13.4:1, with a range of 7.1:1 to 17.2:1. For this reason, the removal of ammonia is not expected to be very high since ammonia and phosphate should be removed in equimolar amounts during the formation of struvite. The removal of ammonia is, however, expected to be slightly higher than phosphate since it is volatile, especially at a basic pH. Figure 5.7 shows the measured removal of ammonia during the course of the study for both reactors. On average, 5.0% and 3.5% of the ammonia was removed from the supernatant in reactors A and B, respectively. The large variation in the removal of ammonia is in part due to the relatively low precision of the analytical method used to determine $\text{NH}_4\text{-N}$ in the field; it is also due to the method of calculation requiring the measurement of several flows as well as the concentrations. On several days, negative removals were calculated for ammonia when evidently struvite was being formed, but this is probably due to analytical error. As discussed previously, replicate field analyses for ammonia were found to vary by as much as 30 mg/L. It is therefore not

unreasonable that the negative values calculated for ammonia removal could be due to analytical error.

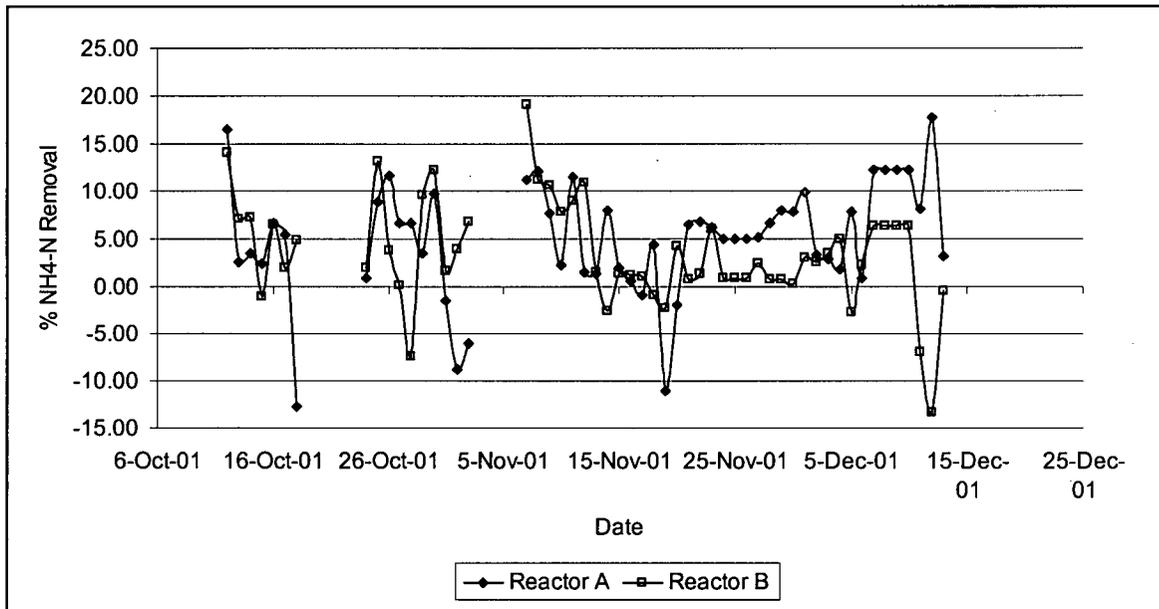


Figure 5.7: Percentage ammonia removal for each reactor during the study period.

5.3.3. *Struvite Recovery*

In order to ensure that the phosphate being removed from the supernatant was in fact being recovered, the dry weight of each harvest of struvite was recorded, and the final dry weight of struvite in each reactor was recorded at the end of the experiment. These masses are compared with the theoretical mass of struvite that should have been formed, based on the phosphate removed from the digester supernatant in Table 5.2. The struvite that is considered to be recovered in this analysis is the mass weighed after the drying and sieving of the harvested product. Some losses occurred during the process of harvesting, drying, transferring, sieving and weighing the product struvite crystals. Significant accumulation of fine struvite crystals could be seen on the floor around the reactors and the crystal processing areas; however, no attempt was made to quantify these losses. Some additional loss occurred in the sludge wasted from the external clarifier. This sludge mass was not analyzed or weighed, but it was visually observed to contain fine crystalline material which was periodically discarded. Another source of error is that this analysis assumes that the reactors were operating 24 hours a day, when in fact they were shut down daily to harvest crystals, monitor the collapsed bed depth of crystals, clean the injector

ports, and calibrate the pH probes. On average, these shutdown periods are estimated to be 1 hour per day or 4% of the time. Table 5.2 shows that between 86 and 87 percent of the phosphate removed was recovered. Correcting these values for the estimated shutdown time brings the recovery rates to between 90 and 91 percent. Taking into account the relatively small mass of struvite produced and the amount of handling and process losses over the course of 3 months of study, this recovery is higher than expected. In a full-scale crystallization installation, it is expected that the losses would represent a smaller fraction of the produced struvite due to the larger scale involved, and recovery of processing losses as they accumulate on floors.

Table 5.2: Comparison of theoretical struvite production and actual struvite recovery.

	Reactor A	Reactor B
Struvite Harvested (kg)	7.82	6.50
Struvite Left in Reactor (kg)	3.80	4.35
Total Struvite Recovered (kg)	11.62	10.85
Theoretical Struvite Produced (kg)	13.54	12.52
% Struvite Recovered	86	87

5.3.4. Reactor Struvite Loading

An attempt was made to operate the two reactors at the same struvite loading rate. The struvite loading rate is defined here as the theoretical mass of struvite that should be grown based on the daily mass of phosphate removed in each reactor. Figure 5.8 shows the struvite loading rates of both reactors during the study period. Generally, the struvite loading rates of the two reactors were similar, except for during two periods, November 11th to 12th, and November 21st to 28th. The differences in loading rates applied to the reactors were mostly due to difficulty in maintaining constant flow rates through the reactors, due to changing water levels in the storage tanks, but also partly due to the changes in the supernatant's composition.

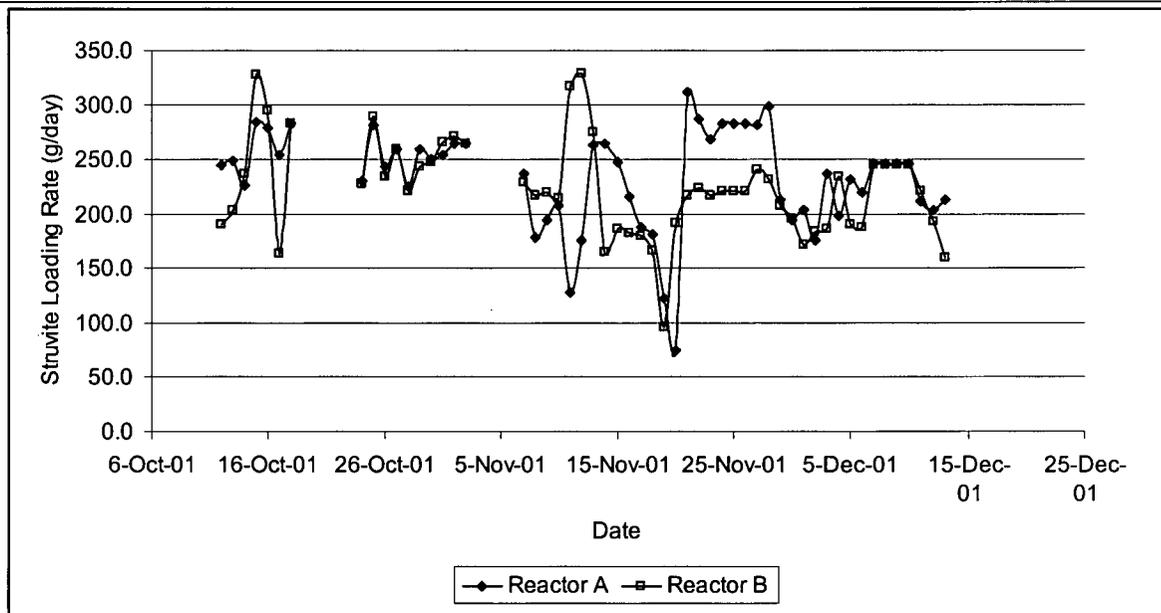


Figure 5.8: Reactor struvite loading during the study period.

5.3.5. Supersaturation Ratio

Figures 5.9 and 5.10 show the feed, in-reactor, and effluent supersaturation ratios for reactors A and B, respectively. The most notable difference between the supersaturation ratios in Figures 5.9 and 5.10 are in the influent supersaturation ratios. This is due to the lower targeted recovery in Reactor B. Since Reactor B was operated at a lower pH, while maintaining the same Mg:P molar ratio as Reactor A, the influent supersaturation ratio is lower in Reactor B. This allowed more supernatant to be pumped through the reactor at a lower recycle ratio, while maintaining the same struvite loading rate. Overall, by maintaining relatively constant struvite loading rates in both reactors, the in-reactor SS ratios and the effluent SS ratios remain quite similar in both reactors. It can be seen from Figures 5.9 and 5.10 that the in-reactor SS ratio varies independently of the inlet SS ratio. This is attributed to the fact that the inlet SS ratio simply describes the potential for recovery from the supernatant at the operating conditions of the reactor, whereas the in-reactor SS ratio describes the actual conditions in the reactor, including the effect of the effluent recycle stream.

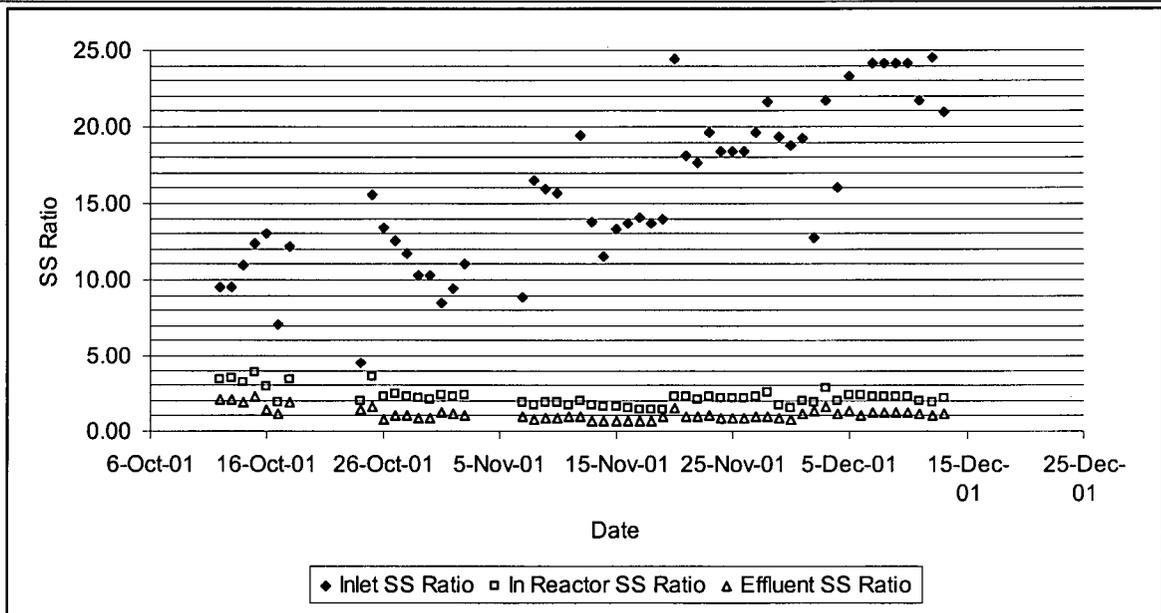


Figure 5.9: Reactor A supersaturation ratios during the study period.

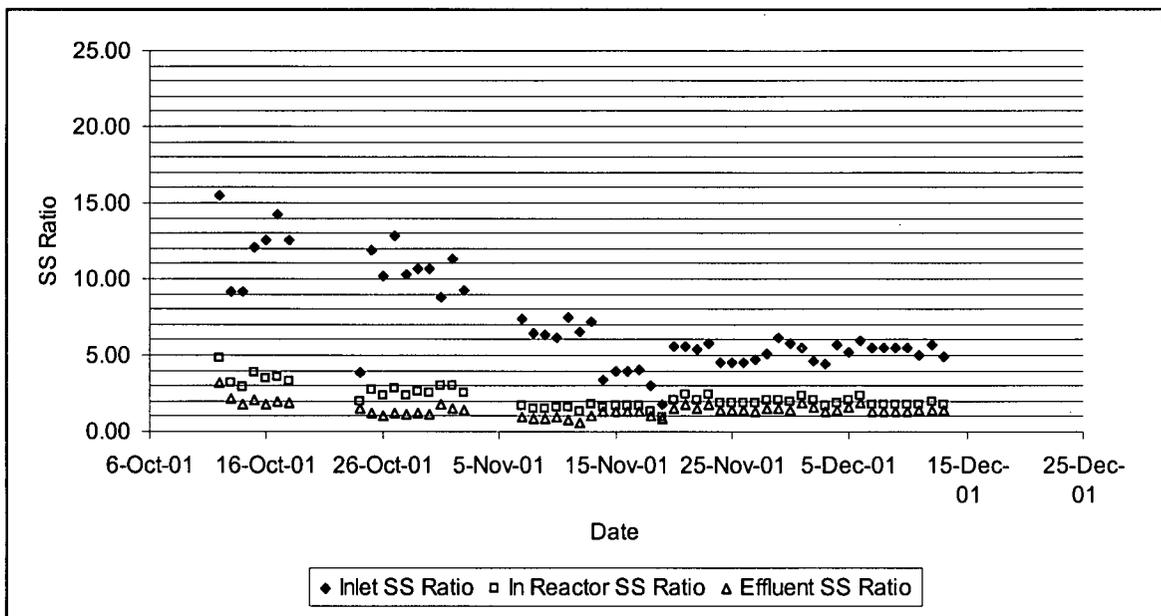


Figure 5.10: Reactor B supersaturation ratios during the study period.

5.3.5.1. Relation between in-reactor and effluent SS ratios

For greater clarity, the in-reactor and effluent supersaturation ratios for Reactors A and B are shown again in Figures 5.11 and 5.12, respectively. In these figures, it is easier to see that these two values appear to be correlated.

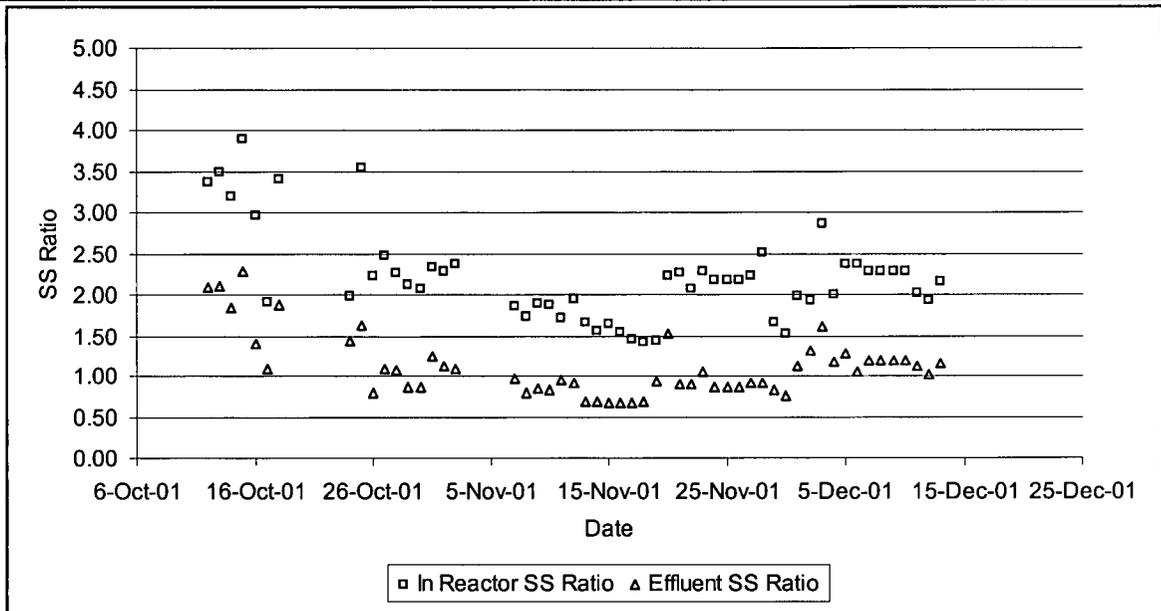


Figure 5.11: Comparison of in-reactor SS ratio with effluent SS ratio for Reactor A.

There are two possible reasons for the correlation between in-reactor and effluent SS ratios. The first is that the bulk of the variation in these SS ratios may come from errors in the measurement of pH and the dissolved constituents of the effluent. Since these values are all used in the computation of both SS ratios, an error in any or all of these values will affect both the in-reactor and effluent SS ratios.

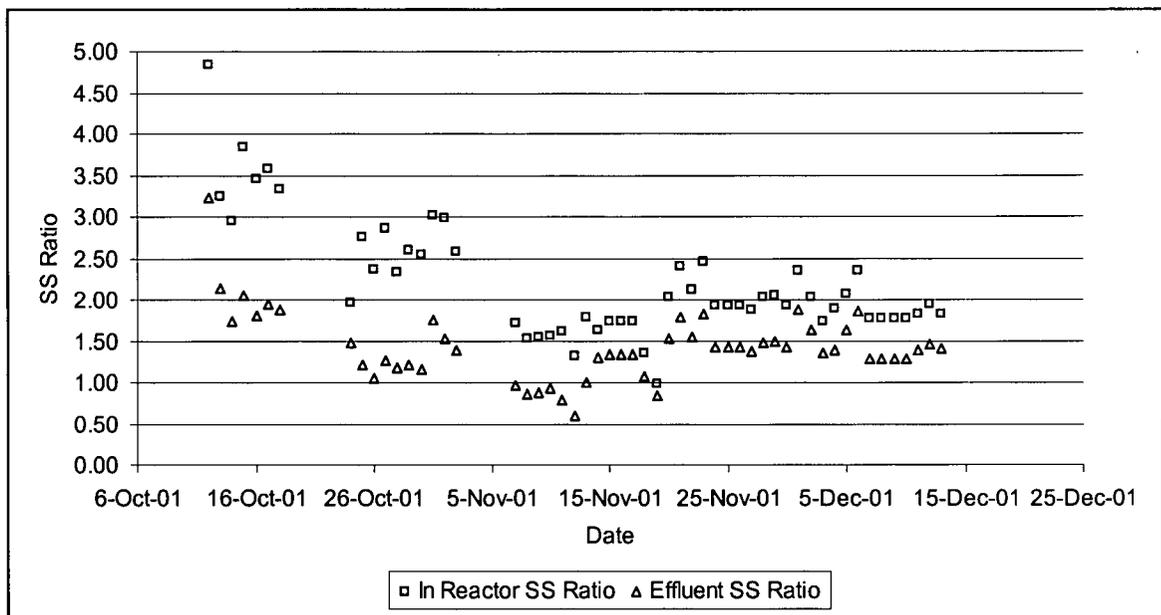


Figure 5.12: Comparison of in-reactor SS ratio with effluent SS ratio for Reactor B.

The second explanation is that the reactors are operating near their kinetic limit for struvite loading and that any increase in struvite loading will result in an increased effluent supersaturation. In an under-loaded reactor, it is expected that equilibrium will have time to establish itself and the effluent should therefore have a supersaturation ratio approaching unity. In this case the reactor loading rate will have little effect on the effluent supersaturation ratio. In an overloaded reactor, however, the solution will not have time to reach equilibrium and therefore the higher the reactor loading, the higher the effluent supersaturation ratio will be.

In order to determine whether the correlation between in-reactor and effluent SS ratios are due to analytical error, or due to the reactor loading exceeding its kinetic limit, the effluent SS ratios are plotted against the in-reactor SS ratios and against the struvite loading rate in Figures 5.13 and 5.14, respectively.

Figure 5.13 shows that there is an evident correlation between the supersaturation ratio in the reactor and in the effluent. This is as expected from general observation of Figures 5.11 and 5.12 and the previous discussion. This shows that an increased supersaturation in the effluent occurs concurrently with an increased supersaturation in the reactor, but does not necessarily show that one is the cause of the other. Both possible causes (increased loading, or measurement error) could be responsible for the correlation. In order to evaluate the possibility of increased loading causing the increased effluent supersaturation ratio, the effluent supersaturation ratio is plotted against the struvite loading rate of each reactor in Figure 5.14.

From Figure 5.14, it can be seen that there is, in fact, no correlation between the struvite loading rate of each reactor and the effluent supersaturation ratio. This would tend to indicate that the reactor is under-loaded, since the effluent supersaturation does not respond to an increased struvite loading. This also infers that the changes in effluent supersaturation ratios are probably due mainly to the compounded measurement error in each individual reading of pH, Mg, $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$. This also implies that the effluent supersaturation should, in fact, always be approaching unity and that the differences between the measured values and unity could be corrected for. Further investigation, involving more meticulous analysis of replicate samples, could be useful in determining this with more certainty.

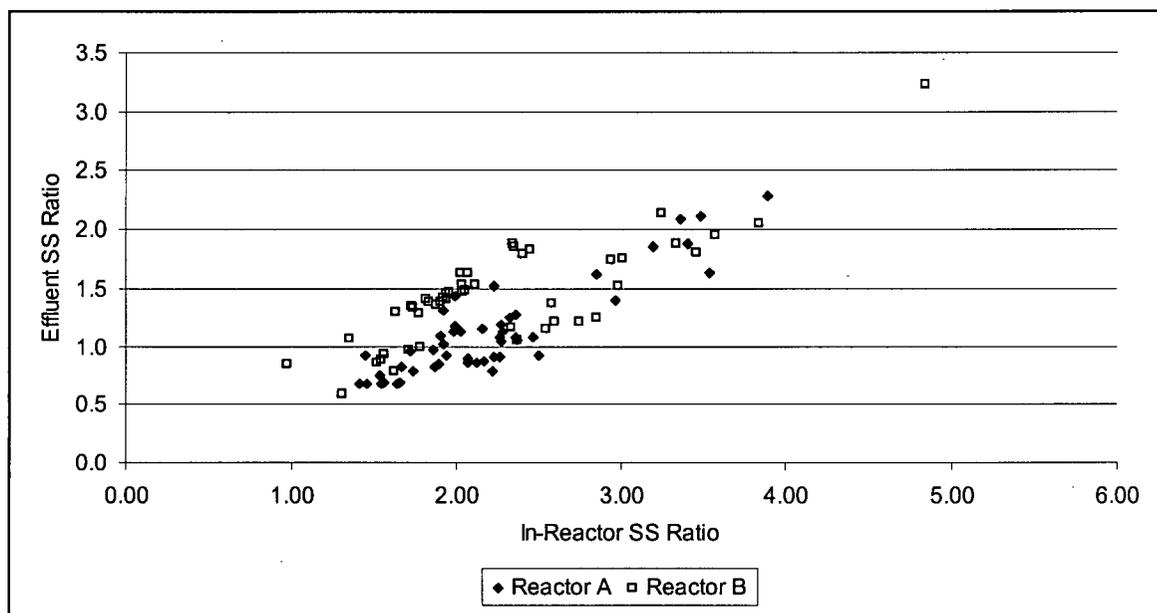


Figure 5.13: The relationship between the in-reactor and effluent supersaturation ratios.

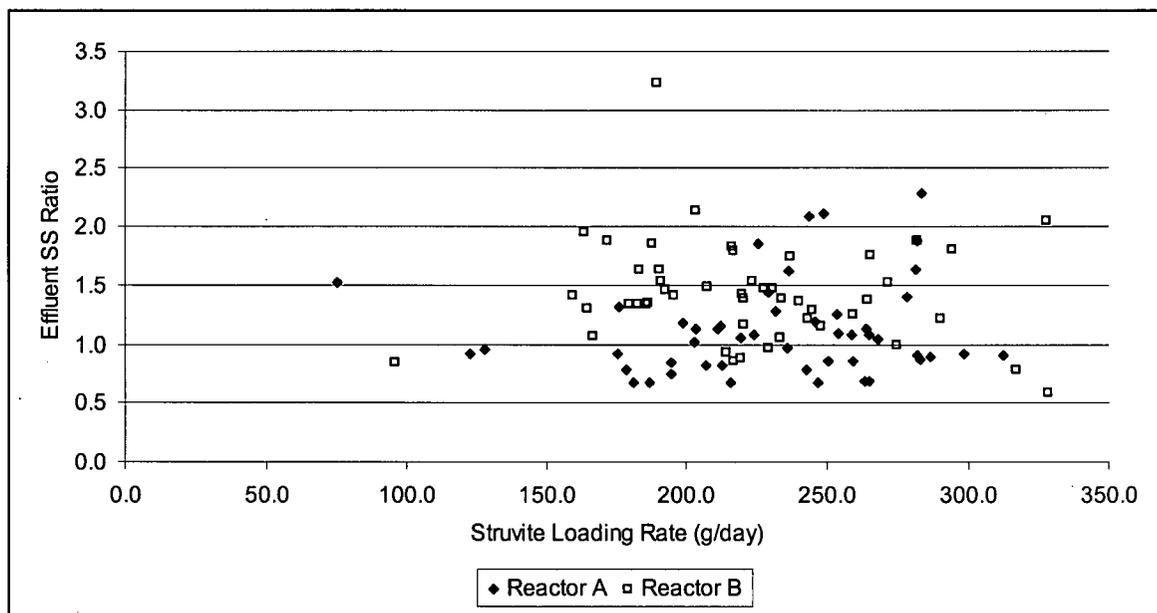


Figure 5.14: The relationship between reactor struvite loading rate and effluent supersaturation ratio.

In any case, the effluent supersaturation ratio in reactors A and B average 1.11 and 1.43, respectively. One interesting factor is that an error of 0.1 in the pH reading can cause a change of over 0.3 in the SS ratio. Considering that the accuracy of the pH meters used was ± 0.1 and that these probes were observed to drift significantly over time, the measurement of pH may be

the main source or error in the determination of the SS ratios. Statistically, the effluent SS ratio in Reactor A is not different from 1.0 at the 99% confidence level, while the effluent SS ratio is greater than 1 in Reactor B at the 99% confidence level.

It is difficult to explain why the effluent SS ratios in both reactors are different. Since both reactors were constructed in the same manner and were operated in a similar manner, it was expected that both reactors would have a similar effluent SS ratio. The most likely cause for this difference would be a drift in the pH reading from one of the reactors, since the SS ratio is so sensitive to pH. It is unlikely that this is due to excess loading as previously discussed, and because there was little struvite encrustation in the reactors effluent piping. It is believed therefore that the effluent SS ratios were, in fact, approaching unity in both reactors.

5.3.6. *Crystal Retention Time*

Crystal Retention Time (CRT) was developed as a means of monitoring the mean time that a struvite crystal spends in the reactor. It was expected that this factor could be correlated to crystal size, since longer growing times should lead to larger crystals. The CRT in the reactors varied from 12 to 47 days using the method of calculation described in Section 4.5.5.

Figure 5.15 shows the calculated CRT for each harvest from the two reactors. The increasing trend at the beginning of each curve results from the low feed phosphate concentration at the beginning of the study, causing slow growth rates. Due to these slow growth rates, the CRT of the early crystals was quite high, since harvesting of the reactor only occurred once the reactor was fully loaded.

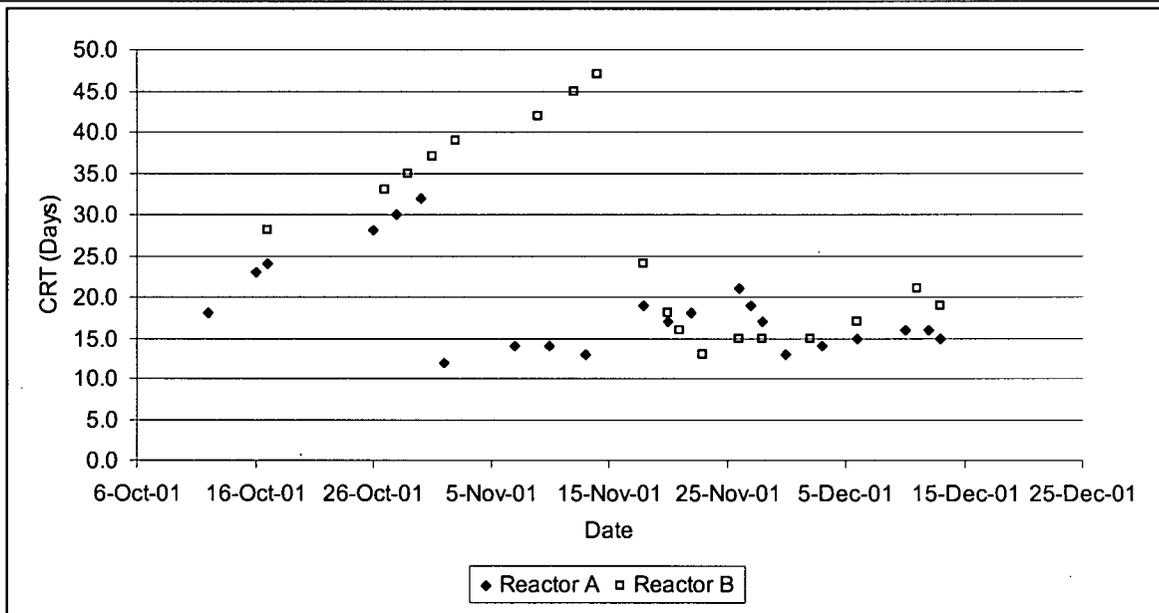


Figure 5.15: CRT calculated for all harvested crystals during the study period.

Since the CRT of the early crystals were not thought to be representative of the actual age of the harvested crystals until one full CRT had elapsed, the subsequent analysis of the crystals in Section 5.5 is focused on the crystals harvested after at least one full reactor volume was harvested. This means that the CRT range analyzed in this study effectively ranges from 12 to 21 days. A longer term study with more regular harvesting intervals would be necessary in order to fully examine the effect of CRT on product size, but a preliminary investigation is completed in Section 5.5.

5.3.7. Operational Problems

This section describes several of the day to day operational problems that were encountered during the study and the solutions that were found to mitigate these problems. Overall, most of these problems were quite minor and several of them were due to the small scale of the equipment and the temporary nature of the installation.

5.3.7.1. Plugging of tubing

On several occasions, the tubing leading from the external clarifier to the recycle pump and to the drain was found to be encrusted with struvite. This encrusted layer would sometimes break away from the tubing walls and accumulate in low spots in the tubing. These

accumulations occasionally resulted in flow reductions or overflow of the external clarifier. This problem was solved by simply flexing the tubing at the point of obstruction; this broke up the obstruction and allowed normal flow to be resumed. To prevent this type of obstruction, the tubing was regularly flexed or impacted at the points where the accumulation was observed and the problem did not recur.

5.3.7.2. *Reactor fouling*

Encrustation of the reactor walls with struvite was also observed. This caused the clear piping used in the reactors to become coated with an opaque layer and prevented the observation of the particle movement and the monitoring of the collapsed and expanded crystal bed heights. A stiff brush on a telescoping pole was used periodically to clean the interior walls of the reactor. It was found that this was only necessary in the harvest section of the reactor, once the reactor was fully loaded with crystals. Although the reactor walls in the upper sections of the reactor did slowly accumulate a struvite crust, it typically broke off by itself before completely obstructing the view into the reactor. Even in the harvest section of the reactor, this cleaning was only required a few times per month.

5.3.7.3. *Injector port fouling*

The injector port was the section of the reactor most prone to struvite encrustation, since the highest local supersaturation ratios occurred there. Although this section was regularly cleaned, occasionally the encrustation obstructed the flow through this section. The flow was never stopped completely due to encrustation, but the flow of magnesium chloride solution and sodium hydroxide was occasionally dramatically reduced. The feed and recycle flows through the reactor were also occasionally reduced, due to the reduction in diameter of the injector port section.

5.3.7.4. *Feed flow regulation*

Even though positive displacement pumps were used, the change in pump head between the full level and the empty level in the supernatant feed tanks caused variations in supernatant feed flow of up to 25%. This was partially due to the fact that the feed pumps were operated

near their minimum flow capacities. This problem was minimized by adjusting the pump speed daily. In a full-scale process, it is expected that this problem would be minimal with the use of on line flow control.

5.3.7.5. *Suspended solids control*

Due to the variable suspended solids content of the digester supernatant, it was necessary to allow sufficient settling time for the supernatant in the feed tanks to prevent solids carryover into the crystallization reactors. The settling of the suspended solids in the supernatant was always rapid, and there was never much residual solids in the settled supernatant. In general, the settling was easy due to the presence of excess storage capacity; however, in a full-scale installation, it would be important to have a sedimentation tank installed between the digester and the crystallizing reactors, in order to prevent the solids from entering the reactors.

5.3.7.6. *Caustic solution storage and strength depletion*

With the passage of time, the caustic solution was observed to decrease in strength; that is, a larger volume of caustic was needed to maintain a given pH in the reactors as the solution aged. This was probably due to the contamination of the solution with carbon dioxide from the air since the chemical storage tanks were not isolated from the atmosphere. This led to an increased use of sodium hydroxide beyond what would normally be expected if a properly designed storage tank was used; however, no attempt to estimate this over-consumption was made in this study. This correction would reduce the chemical usage costs somewhat from the values discussed in Section 5.7.

5.3.7.7. *Magnesium chloride dosing rate*

The magnesium chloride dosing rate measured in this study was overestimated due to a faulty method of measurement. The flow rate of magnesium chloride into each reactor was measured by inserting the end of the feed tubing into the bottom of a graduated cylinder and recording the change in volume over a minute. Unfortunately, the presence of the tubing in the graduated cylinder displaces a significant portion of the volume and therefore the actual volume

pumped was overestimated. This may explain why the calculated amount of magnesium removed in the reactor exceeds the amount of phosphate removed on a molar basis.

5.4. Reactor Performance Model

A model was developed to predict the effluent magnesium, ammonia and ortho-phosphate concentrations from a struvite crystallizing reactor, such as the one used in this study. The model inputs are the operating pH of the reactor, as well as the magnesium, ammonia and ortho-phosphate concentrations in the combined feed to the reactor. The model assumes that pure struvite is being formed (i.e. that magnesium, ammonia and ortho-phosphate are removed in equimolar amounts), and that the reactor effluent is at equilibrium as described by pP_S in Equation 17.

Equation 18 is the general equation used by the model, where Δ represents the molar reduction in the concentrations of Mg, NH_4 -N and PO_4 -P; $[Mg]_{in}$, $[NH_4]_{in}$ and $[PO_4]_{in}$ represent the concentrations of magnesium, ammonia and ortho-phosphate in the combined influent to the reactor; and $P_{S\ eq}$ is the equilibrium P_S as described by Equation 17. This equation is solved iteratively for Δ , and the resulting effluent concentrations from the reactor are then predicted as the combined influent concentrations minus Δ .

$$([Mg]_{in} - \Delta)([PO_4]_{in} - \Delta)([NH_4]_{in} - \Delta) = P_{Seq} \quad \text{Eq. 18}$$

In order to verify the model, it was used to predict the effluent concentrations of both reactors during the course of the experiments at the City of Penticton AWWTP. The model was used to predict the effluent concentrations of magnesium, ammonia and phosphate, based on the collected data for the combined influent and the operating pH of each reactor. Figures 5.16 to 5.21 show the comparison of the model results to the measured effluent concentrations. The detailed model calculations and the analysis of the model results can be found in Appendix E.

Figures 5.16 and 5.17 compare the modeled and measured concentrations for phosphate in the effluents from Reactor A and Reactor B, respectively. In general, the model predicts the effluent phosphate concentrations quite well. The average absolute error in the modeled effluent phosphate concentration for Reactors A and B were 1.8 mg/L and 4.6 mg/L, respectively. The

model appears to under-predict the effluent phosphate concentration at lower pH values, which is the reason for the larger absolute error in Reactor B, especially later in the experimental run. This may be due to an error in pH reading or due to the fact that the effluent from Reactor B averaged an SS ratio of 1.4 and the model assumes that this value is 1.0. As discussed previously, these two factors are related and the error in pH reading could be the cause of the elevated effluent SS ratio.

Figures 5.18 and 5.19 compare the modeled and measured concentrations for ammonia in the effluents from Reactor A and Reactor B, respectively. Both of these graphs show very good correlation between the modeled and measured values. The average absolute error in the modeled effluent ammonia concentration for Reactors A and B were 13.1 mg/L and 12.8 mg/L, respectively. This error is approximately equal to the relative standard deviation found in the analytical determination of ammonia.

Figures 5.20 and 5.21 compare the modeled and measured concentrations for magnesium in the effluents from Reactor A and Reactor B, respectively. Considering that the influent magnesium concentration is calculated using the combination of the magnesium concentrations in the feed supernatant and feed magnesium chloride solution, as well as the measured flows of these two, the predicted effluent concentrations match the actual values quite closely. The average absolute error in the modeled effluent magnesium concentration for reactors A and B were 7.1 mg/L and 6.1 mg/L, respectively.

The error measurements described above are the averages of the absolute value of the error between the predicted and measured values. Since the measured values are, themselves, expected to contain some experimental error, a more representative value of the model error may be the average of the errors between the predicted and measured values, without taking the absolute values. Table 5.3 shows the comparison between the error as calculated by absolute values, and by actual values in mg/L and in percentage of the measured values.

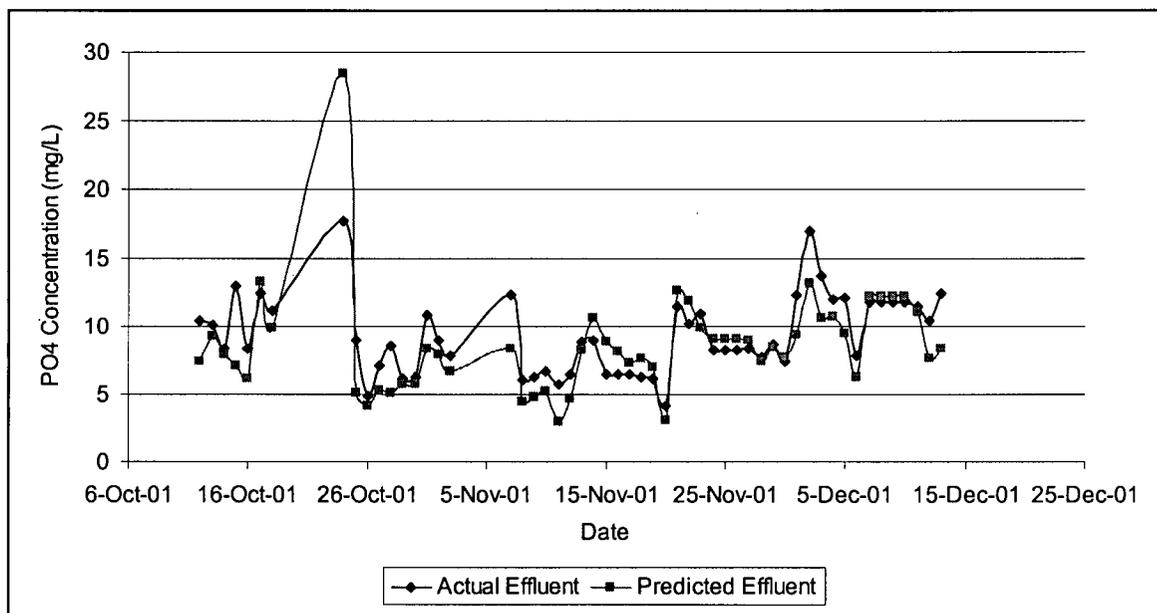


Figure 5.16: Modeled and actual effluent phosphate concentrations for Reactor A.

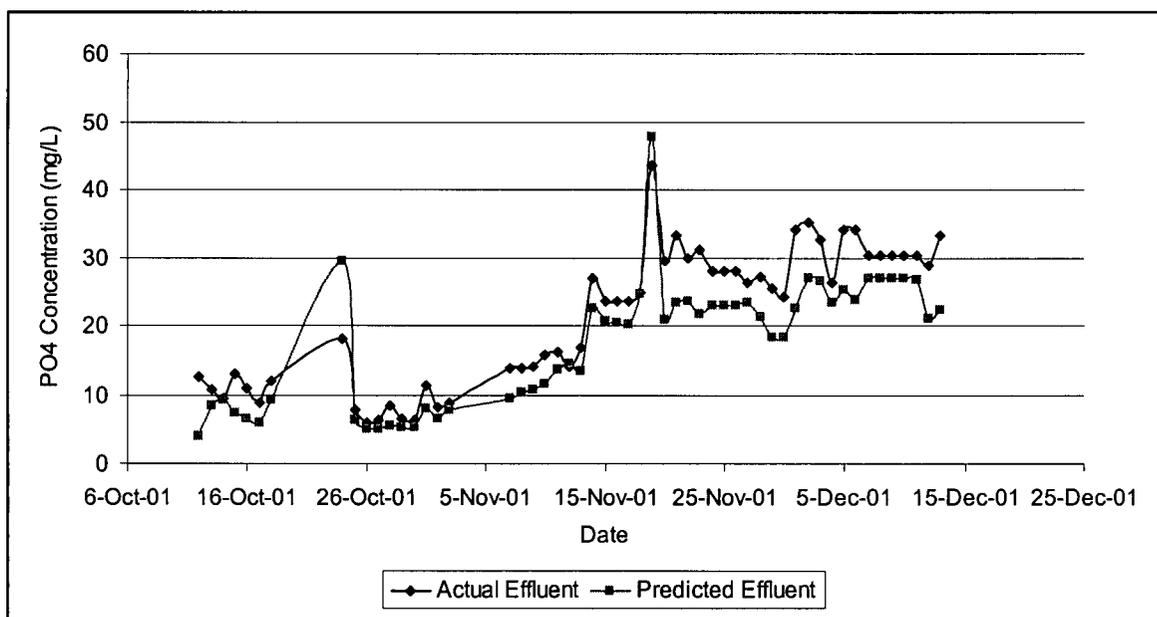


Figure 5.17: Modeled and actual effluent phosphate concentrations for Reactor B

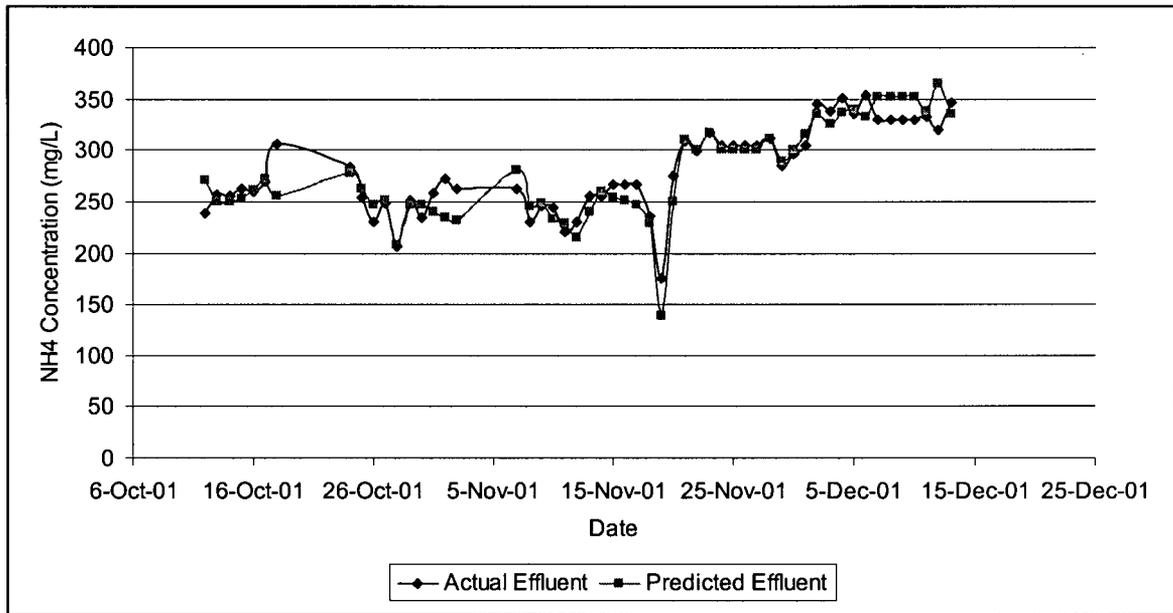


Figure 5.18: Modeled and actual effluent ammonia concentrations for Reactor A.

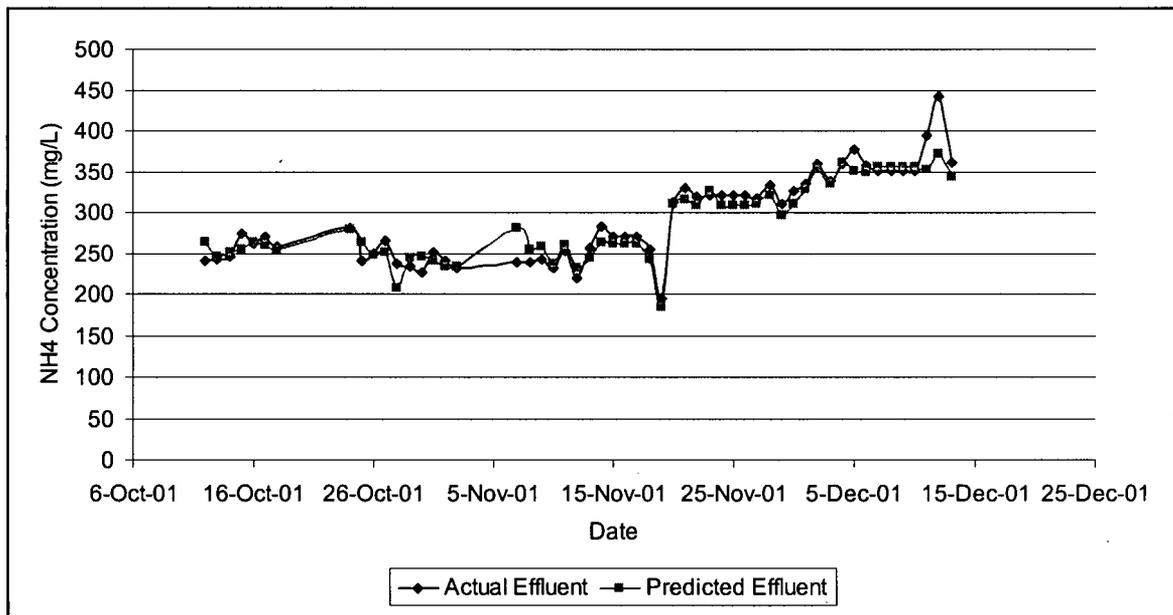


Figure 5.19: Modeled and actual effluent ammonia concentrations for Reactor B

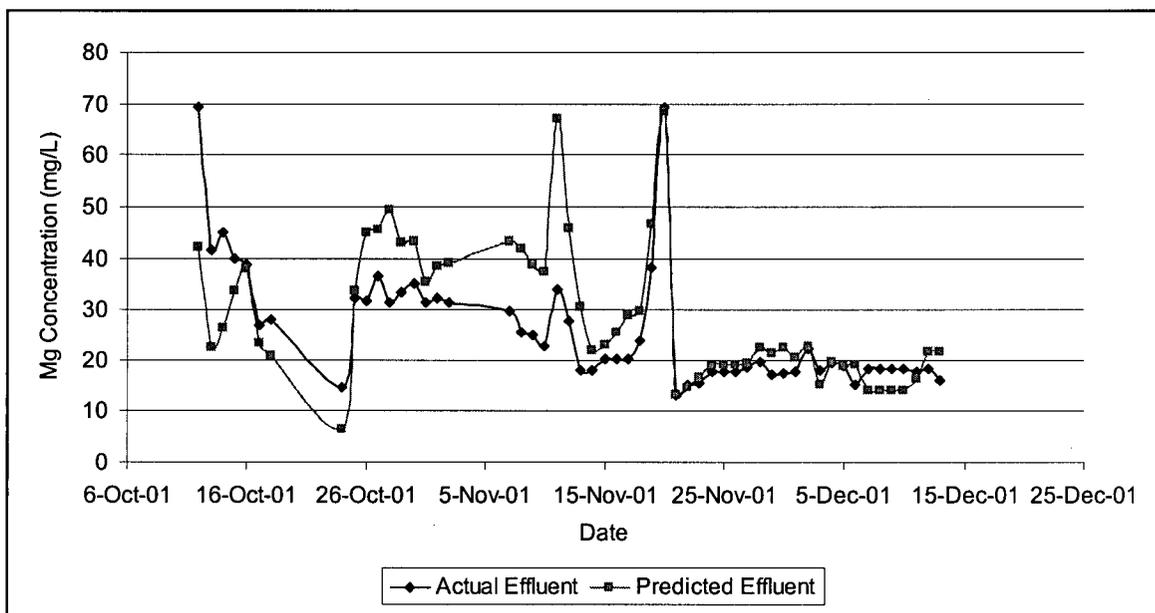


Figure 5.20: Modeled and actual effluent magnesium concentrations for Reactor A.

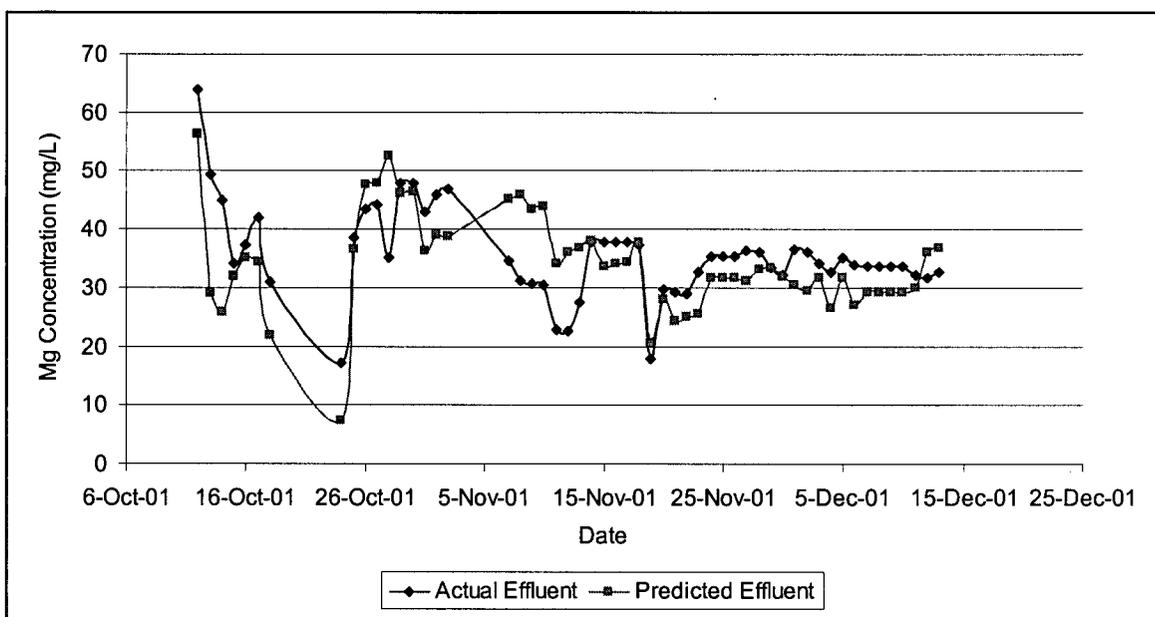


Figure 5.21: Modeled and actual effluent magnesium concentrations for Reactor B.

Table 5.3: Comparison of average model error absolute and actual values.

Criteria	Average Absolute Error (mg/L)	Relative Absolute Error (%)	Average Actual Error (mg/L)	Relative Actual Error (%)
Reactor A Mg	7.1	26.1	2.9	12.7
Reactor A NH ₄	13.1	4.8	-2.3	-0.9
Reactor A PO ₄	1.8	18.8	-0.7	-8.2
Reactor B Mg	6.1	18.2	-1.5	-2.8
Reactor B NH ₄	12.8	4.4	-4.8	-1.2
Reactor B PO ₄	4.6	22.0	-4.0	-19.3

The use of the actual error values, rather than the absolute error values, tends to reduce the reported relative error if the error is not systematic; that is, if the error is normally distributed. In this study, all of the relative errors were reduced dramatically when actual errors are considered as compared with absolute errors, with the exception of the error in phosphate prediction in Reactor B. This is attributed to the fact that the predicted phosphate concentration in Reactor B is systematically lower than the actual value, especially at lower pH's.

5.5. Struvite Product Characteristics

Another important factor to investigate in this study was the characteristics of the harvested struvite crystals. Three major factors were investigated in this regard: the size of the harvested crystals, the apparent density of the crystals in the reactor and the chemical composition of the harvested crystals. The crystals were also examined under an optical microscope and a scanning electron microscope (SEM).

5.5.1. Struvite Crystal Size

In general, it was found that the size of the harvested crystals was continuously increasing during the course of the study, even after several complete reactor volumes had been harvested. Figure 5.22 shows the mean crystal diameter of each harvest from both reactors, during the course of the study. With time, the crystals grew stronger and larger. One of the most important factors in determining the final diameter of the crystals was their structural strength, since the early crystals tended to break easily during the harvesting, drying and sieving

operations. The crystals harvested late in the study, on the other hand, did not tend to break much during these handling processes.

These results imply that several complete CRT's must have elapsed before a steady state crystal size will be reached, as suggested by Takiyama *et al.* (1997). In fact, the mean crystal diameters shown in Figure 5.22 do not appear to be approaching their steady state values, even after two months of operation. Similar results are reported by Abe (1995). Further studies of longer term would be necessary to determine the final steady state size the struvite crystals can be expected to reach. From the data collected in this study, the mean crystal diameter grew by an average of 0.016 mm per day.

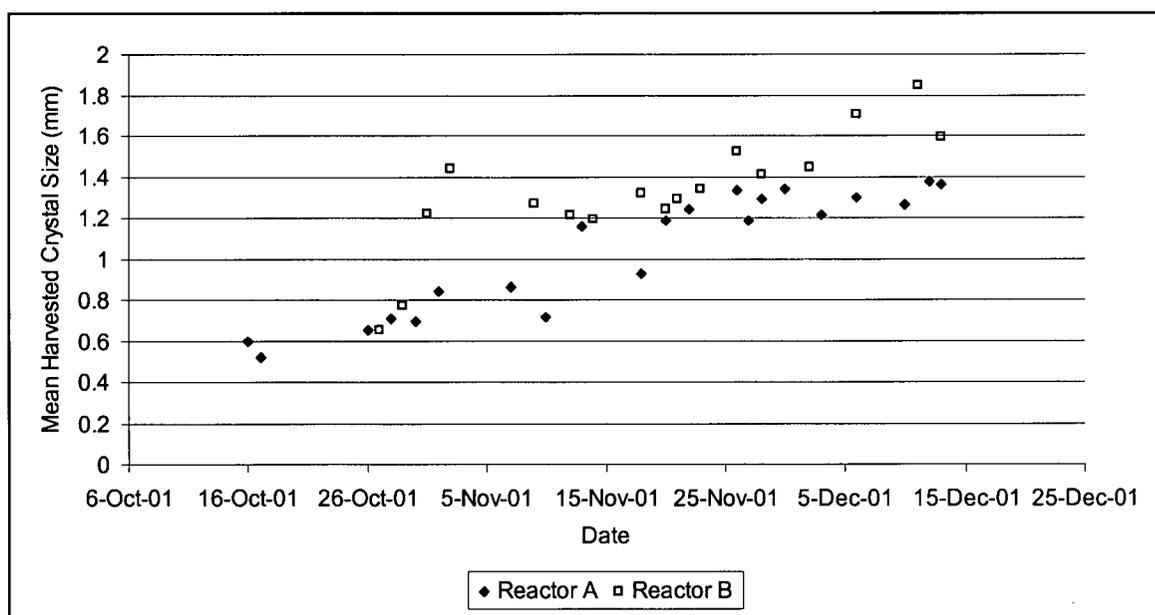


Figure 5.22: Mean crystal diameter of struvite crystals harvested during the study.

Other factors that were evaluated to determine their effect on mean crystal diameter were the CRT and the SS ratio in the reactor. Figures 5.23 and 5.24 show the relation between these two factors and the mean crystal size. In general, the trends in these two graphs are much less definite (as evidenced by the low R^2 values); however, the theoretically expected trends do appear.

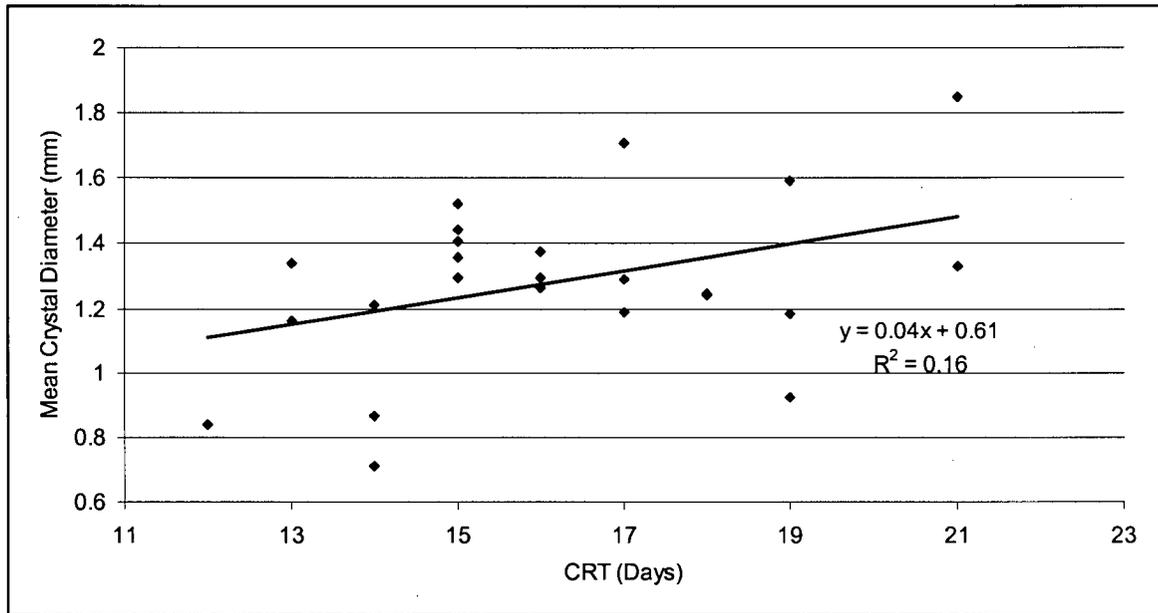


Figure 5.23: Mean harvested crystal diameter vs. CRT for each harvest.

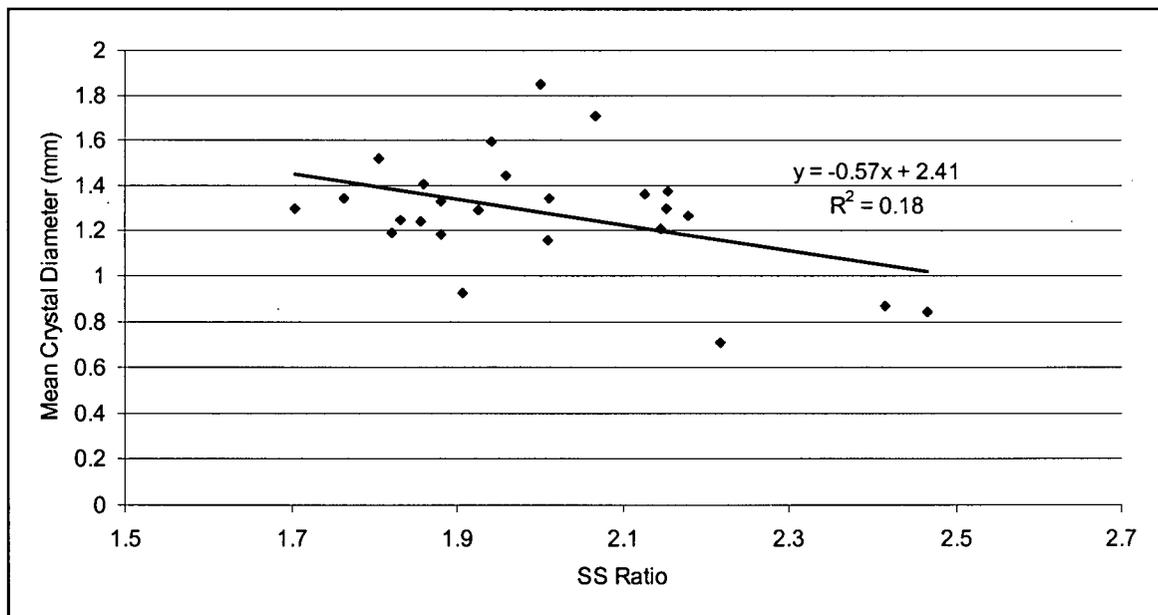


Figure 5.24: Mean harvested crystal diameter vs. average in-reactor SS ratio.

It is expected that the longer the CRT, the larger the crystals will get. On average, it was found that the crystals grew by 0.04 mm per day of CRT, as shown in Figure 5.23. This trend is quite variable, indicating that the CRT may not be the most important factor in determining the final size of the harvested crystals. It is, however, expected that there is a certain minimum CRT that will be required to get a given size of crystals. Since several other factors including the supernatant composition, the operating pH, the in-reactor SS ratio and the harvesting frequency

were all varied at the same time as the CRT, further studies which maintain all other factors constant would be necessary to determine the exact effect of CRT on mean crystal diameter.

The generally accepted theory in crystallizer engineering is that the average size of the produced crystals varies inversely with the supersaturation ratio at which the crystallizing solution is maintained. Figure 5.24 shows that an inverse relationship between SS ratio and crystal size did seem to exist in this study. The mean crystal diameter was found to decrease by 0.56 mm for a unit increase in in-reactor SS ratio. As with the analysis of crystal size vs. CRT, however the SS ratio was not varied independently from the other factors and further studies would be required to assess the exact role of the SS ratio on the crystal size.

5.5.2. *Struvite Crystal Bulk Density*

Although the density of the crystals was not measured directly in this study, an interesting trend was observed in the mass of crystals removed from the harvest section of the reactor with time. For each harvest, the flow through the reactor was stopped and the fluidized crystals were allowed to settle before the harvest zone was isolated with the ball valves and the crystals were withdrawn from the reactor. In this manner, a constant volume of 1.1 liters of crystals was harvested each time. It was noticed throughout the study that the crystal mass harvested from this volume was consistently increasing with time. Figure 5.25 shows this trend.

The first harvests in the study had a total mass of approximately 200 g, while the final harvests had a mass of approximately 600 g. This increasing trend did not appear to be reaching a maximum by the end of the study. In general, the crystal mass harvested was increasing by approximately 7 grams per day of reactor operation. This increase in mass harvested coincided with the increase in diameter of the harvested crystals. Visual analysis of the crystals, presented in Section 5.5.4, shows that this increased bulk density of the crystals was probably due to the change in shape of the crystals over the course of the study, from friable plate like aggregates, to harder rounded crystal roses.

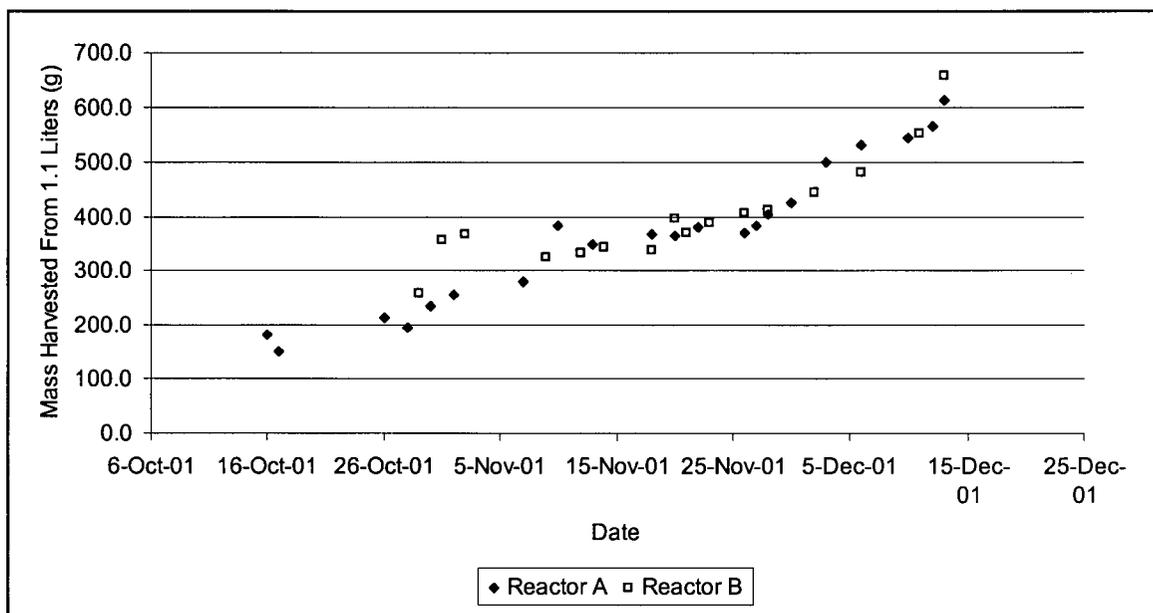


Figure 5.25: Harvested crystal mass from the 1.1L harvest zone over the course of the study.

5.5.3. Struvite Crystal Composition

In order to verify the composition of the crystals grown in this study, 29 samples of crystals were analyzed as described in Section 4.3. Each size fraction (<0.5 mm, 0.5-1mm, 1-2mm and >2mm) of harvests, from 3 dates, from each reactor, were analyzed. The detailed data from this analysis is shown in Appendix F. Table 5.4 shows the average crystal compositions as compared to the expected theoretical composition of pure struvite and the estimated struvite content of the crystals. The estimated struvite content was calculated by averaging the ratios of measured to theoretical composition of Mg, N, and P for each sample.

Table 5.4: Average results of crystal composition analysis.

% Composition by Mass	Mean	Standard Deviation	Theoretical Value for Pure Struvite
Mg	9.9	0.4	9.9
N	5.6	0.3	5.7
P	12.8	0.6	12.6
Struvite (est.)	99.8	4.0	100.0

The results in Table 5.4 show that the crystals harvested from the reactors were essentially pure struvite. The crystal samples were also analyzed for content of Fe, Al, K, and

Ca. These were thought to be the most likely metals that would be found in the struvite crystals as impurities. Table 5.5 shows the average results of the crystal analysis for impurities. Again, the detailed data is presented in Appendix F. The main impurity found in the crystals was calcium, and it was only present at an average of 0.5% by weight. Based on this limited analysis, the produced crystals are therefore believed to be composed mostly of pure struvite. Further analysis of the crystals should be performed for heavy metals and pathogens, to determine if the product is appropriate for direct use as an agricultural fertilizer.

Table 5.5: Struvite crystal impurity content.

% Content By Weight	Mean	Standard Deviation
Ca	0.49	0.32
K	0.04	0.01
Fe	0.03	0.02
Al	*	*

* Most Al analyses were below the detection limit of the method used.

5.5.4. *Microscope and SEM Crystal Examination*

In order to better understand reasons for the observed changes in harvested crystal sizes and densities, samples of the crystals were observed, first under a microscope at 40X magnification, and then by SEM. A preliminary microscope observation was used as a method of screening the samples and finding general trends, in order to be able to select representative samples for further analysis by SEM.

In general, it was found that the appearance of the crystals changed significantly with time. The early crystals appeared to be a loose aggregation of plate like crystals, which explains why the crystals tended to break apart during the drying and screening processes. Over the course of the study, the crystals grew more rounded and more solidly aggregated. In the crystals from the final harvests, the crystals are very rounded and appeared to be monolithic under microscope examination at 40X. SEM analysis of these crystals shows that all of the crystals are, in fact, aggregates of smaller crystals; the later crystals are simply more solidly aggregated.

Figure 5.26 shows SEM images of crystals which were retained on a 1 mm sieve, but passed a 2 mm sieve. The images on the left are of crystals harvested from Reactor A, while

those on the right are from Reactor B. All images are at 50X magnification and the bar in the bottom right of each image represents 1 mm. The top row of images are of crystals harvested in October, the middle row of images are of crystals harvested in November and the bottom row of images are of crystals harvested in December.

The progression in the crystal morphology is quite striking when looking at these images. The crystals appear to progress from loosely aggregated crystals in October, to tightly packed, and more solidly bound crystal balls in December, especially in Reactor B. The crystal from December in Reactor A appears to be similar to the crystal from November in Reactor B. The outside faces of these crystals (Reactor B November and Reactor A December) appear to be similar to the crystal from December in Reactor B; however, their cores appear to be weaker. This may have caused the clumps of hard surface crystals to break away, either due to turbulence and impacts in the reactor, or during the drying and sieving operations.

These images seem to indicate that the strength and shape of the crystal aggregate change slowly with each complete CRT, since the broken pieces of the older crystals appeared to form the core of the new crystals. These images can also be used to explain the difference in the bulk densities of the harvested crystals, as discussed previously. The later crystals appear to be much rounder and more filled in, thus allowing the crystals to pack in more tightly to the harvest zone, when flow through the reactor is stopped. This, in turn, would cause the harvested mass to increase as observed.

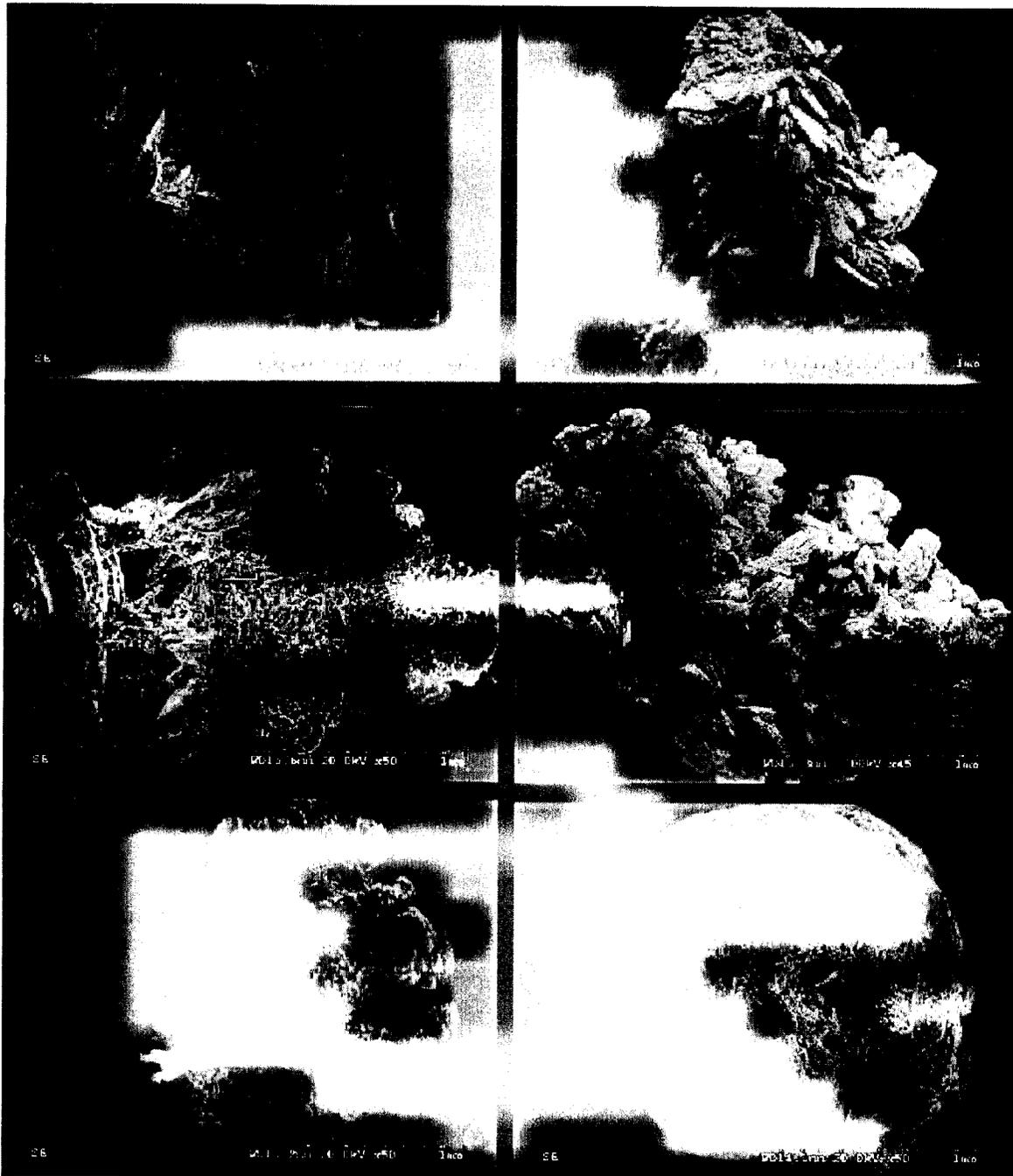


Figure 5.26: SEM images of crystals retained on a 1 mm sieve, but passing a 2 mm sieve at 50X magnification. Top left: harvested October 28 from Reactor A; middle left: harvested November 18 from Reactor A; bottom left: harvested December 11 from Reactor A; top right: harvested October 17 from Reactor B; middle right: harvested November 18 from Reactor B; bottom right: harvested December 12 from Reactor B.

In Figure 5.27, crystals from the four size fractions collected on December 11 from Reactor B are shown. These images are interesting because they show that the crystals in the smaller size fractions appear to be broken pieces of larger crystals, as predicted by Mersmann (1999) for large crystal systems. Unfortunately, this does not show if this breakage occurs in the reactor, or during the drying and sieving process. It is quite likely that most of this breakage occurs in the sieving operation, since this operation involves some relatively strong abrasion. It is also unlikely that the smaller crystal particles would be found in the harvest zone of the reactor, due to the high fluid upflow velocity and their displacement by the larger particles in the fluidized bed.



Figure 5.27: SEM images of crystals harvested from Reactor B on December 11 at 50X magnification. Top left: crystal retained on 2 mm sieve; top right: crystal retained on 1 mm sieve; bottom left: crystals retained on 0.5 mm sieve; bottom right: crystals passing 0.5 mm sieve.

Close inspection of the bottom left image in Figure 5.27 reveals that the individual crystal surfaces on the inside of the crystal show an ortho-rhombic shape and are growing from the center of the crystal outwards. This could lead to the conclusion that the stripes observed on the surface of the whole crystals may in fact be the tips of these ortho-rhombic crystals, which are rounded off by the abrasion in the fluidized bed and in the sieving process.

The stripes described above can be more clearly seen under higher magnification, as shown in Figure 5.28. Under 300X magnification, the surface no longer appears as smooth as under 50X magnification, and it appears that the crystal is made up of tightly-agglomerated, smaller, brick-like crystals. If this image is considered in conjunction with the bottom left image in Figure 5.27, we can begin to appreciate that these square formations on the surface of the crystals may, in fact, be the tips of the plate like surfaces observed on the broken crystals.

Under 3000X magnification, the surface of each individual crystal tip becomes more resolved, and it becomes apparent that these crystal surfaces are covered with cracks and fissures (as shown in Figure 5.28). It is unclear if these cracks and fissures are inherent in the crystals, or if they are a product of the drying process. The crystals were dried using a ceramic space heater, which caused the temperature of the crystals to increase. Although the surface temperature of the crystals was never measured, they were observed to be quite warm to the touch at times. This heating, and the subsequent cooling, could lead to thermal cracking of the crystals, as well as to the expulsion of some of the ammonia or water molecules from the struvite crystal matrix.

The crystallography of the recovered crystals was not analyzed in depth, but simply observed visually, and since the crystals were grown under continually varying conditions, it is impossible to determine the exact cause of the changes in the appearance of the crystals. It would also be impossible to predict the appearance of crystals from future works based on this study, especially considering that the crystals grown in this study are very different from those grown in ongoing studies at UBC using synthetic supernatant in similar reactors (Ali Adnan, Masters Student, UBC Civil Engineering, pers. comm.). Further studies, under tightly controlled conditions, would probably be necessary to determine the cause and effect relationships leading to the final shape and size of the produced crystals. It may be sufficient to empirically determine

the conditions leading to the production of crystals with the desired characteristics for their final use.

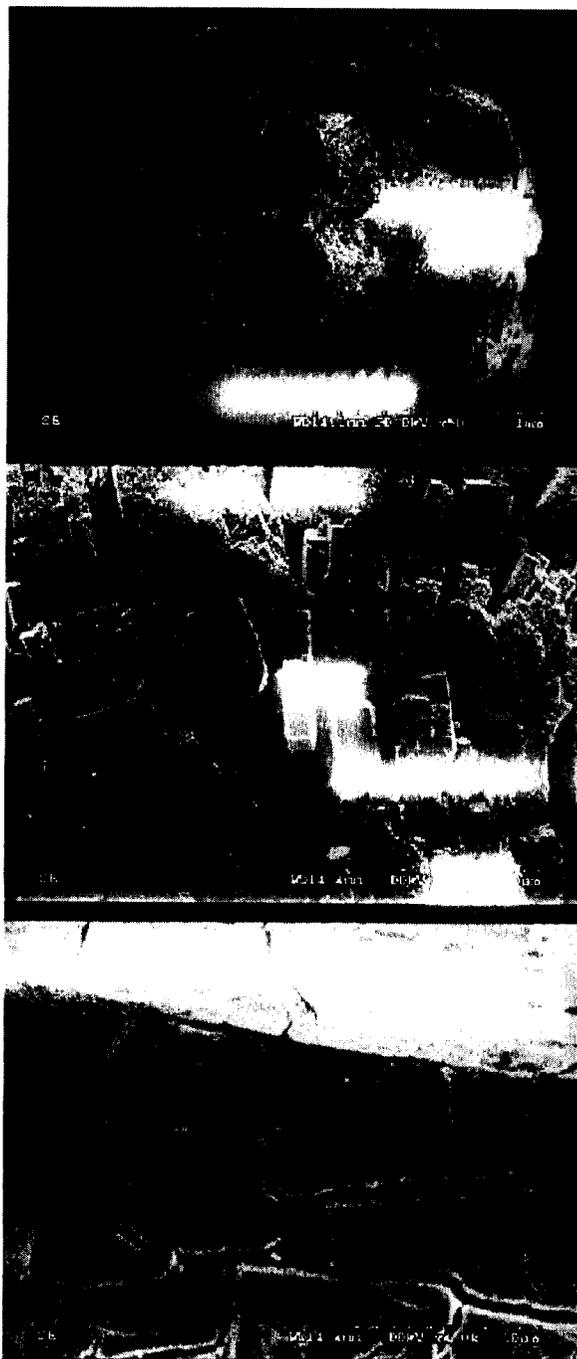


Figure 5.28: SEM images of a crystal retained on the 1 mm sieve, harvested from Reactor B on Dec 11. Magnified at 50X (top), 300X (middle), and 3000X (bottom).

5.6. Treated Supernatant Phosphate and Ammonia Reductions

A preliminary analysis was performed to determine the effect of installing a full-scale struvite crystallizing reactor on the phosphate and ammonia loads applied to the BNR treatment train at the City of Penticton AWWTP. In order to accomplish this, a preliminary mass balance was performed on total phosphorus through the treatment plant, based on data from the year 2000. The mass balance shows that 97.6% of the total phosphorus entering the plant is removed from the liquid stream, and thus transferred to the sludge stream. This represents 65.8 kg of total phosphorus per day.

Of this mass, only 8.9 kg per day were estimated to be released from the sludge and returned to the headworks of the treatment plant with the digester supernatant, during the course of this study. This return represents approximately 13% of the phosphorus load to the treatment plant. A rough estimate shows that the phosphorus load from the digester supernatant would increase to 33% of the influent phosphorus load, if 100% of the WAS was digested. This value is significantly lower than the 80% found by Niedbala (1995).

One of the main reasons for this discrepancy is probably the practice of disposing of aluminum-rich, drinking water treatment sludge to the wastewater treatment plant, which began after the study by Niedbala. This aluminum load appears to cause the treatment plant to operate as a combined biological/chemical phosphorus removal plant, where the removed phosphorus is much less susceptible to resolubilization under anaerobic digestion, as described by Jardin and Popel (2001).

If a full-scale struvite recovery reactor were to be installed, it may be beneficial to cease dumping the drinking water treatment plant sludge to the wastewater treatment plant, in order to maximize the amount of recoverable phosphorus in the digester supernatant stream. Also, maximizing the amount of secondary sludge that can be digested would allow for a maximum of phosphorus to be removed from the sludge stream.

The following discussion evaluates changes in ammonia and phosphorus loads that could be expected in the treatment plant, should a full-scale struvite recovery system be installed and

operated under conditions similar to those in this study; that is with the digestion of approximately 40% of the secondary sludge along with the primary sludge.

5.6.1. Ammonia Load form the Digester Supernatant

Digesting secondary sludge caused the digester supernatant ammonia concentration to increase from 270 mg/L as N to 400 mg/L as N. This concentration is then reduced by an average of 50 mg/L in the struvite crystallizing reactor. The net result of the process is, therefore, to increase the ammonia concentration by approximately 80 mg/L. Since the average daily digester supernatant flow was 80 m³, this increased ammonia concentration would represent an increased ammonia load of approximately 6.4 kg/day to the treatment plant.

5.6.2. Phosphorus Load From the Digester Supernatant

Digesting secondary sludge caused the digester supernatant phosphate concentration to increase from 10 mg/L as P to 70 mg/L as P. This concentration is then reduced to between 5 and 30 mg/L as P in the struvite crystallizing reactor depending on the desired percent recovery. Assuming that 80 % recovery is achievable, the net result of the process is, therefore, to increase the phosphorus concentration in the supernatant returned to the BNR process by approximately 4 mg/L. At the average daily digester supernatant flow, this increased phosphorus concentration represents an increased load of approximately 0.3 kg/day to the treatment plant. It would also reduce the phosphorus content of the sludge being shipped off site to the composting facility by approximately 4.5 kg/day, or 6.8%.

In order to improve the removal efficiency of this process, a larger portion of the phosphorus in the sludges would have to be released in the digester. In this study, only 8.5% of the phosphorus removed in the treatment plant was present in the form of ortho-phosphate in the digester supernatant. By increasing the portion of soluble ortho-phosphate in the digester supernatant, it would be possible to recover a larger amount of phosphorus and nitrogen in the struvite crystallizing reactors; thus reducing the loads on the treatment plant, and recovering a larger amount of product.

5.6.3. *Estimated Full-scale Struvite Production*

Based on the data collected in this study, it is estimated that a full-scale struvite recovery operation treating only 40% of the secondary sludge in conjunction with the primary in the City of Penticton AWWTP would produce between 25 and 45 kg of struvite per day, depending on the efficiency desired (50-90% P recovery). This amounts to between 9.1 and 16.4 metric tons of struvite per year.

5.7. Financial Estimates

Based on the pilot scale work, some basic estimates of the operating costs and savings that could be expected in a full-scale operation are outlined here. It is important to note that these results are very rough estimates, and that capital costs are not included. In order to aid in the estimation of the expected capital costs, an equipment list for full-scale implementation is included, but estimated prices have not been obtained for this equipment. The operating costs outlined in this section assume that the wastewater treatment plant is operated in the same manner as during the later part of this study (i.e. November and December of 2001). All cost estimates are in Canadian dollars.

5.7.1. *Capital Infrastructure Requirements*

A significant investment in equipment and piping would be required in order to implement a full-scale struvite recovery system at the City of Penticton AWWTP. Although no attempt was made to quantify this cost, a summary of the required equipment is listed in the following section for reference, along with available information relating to the sizing of this equipment.

5.7.1.1. *Digester upgrade*

Digester upgrade requirements depend on the quantity of WAS that will be treated and the current excess capacity of the digester. Alternatives include modifying the digester for operation in the thermophilic temperature range to reduce the required HRT, or building a new digester to handle the increase in hydraulic and organic load. Further study of this aspect would

be required to determine the exact needs. A study by Niedbala (1995) found that a reduction in the HRT of the digesters from 20 days to 10 days had little impact on the digesters performance. Current common design practice is to design for 15 day retention time in digesters. Since the existing digesters have a retention time of approximately 28 days, digester upgrades may not be required.

5.7.1.2. *WAS dewatering and transfer to digester*

Some modification to the WAS thickening and dewatering equipment would be required to allow trouble free transfer of thickened WAS to the digester. Transfer pumps and piping will also be required for a permanent installation since the current piping does not allow for this.

5.7.1.3. *Supernatant transfer to settling and storage*

A permanent method of transferring the digester supernatant to a settling and equalization tank will be required for the full-scale installation, since no permanent winterized system currently exists. This would include a pump and piping capable of transferring and estimated intermittent flow of 90 m³/day.

5.7.1.4. *Supernatant settling and storage*

Since the supernatant occasionally contains high solids concentrations, a facility to remove these solids is required. Also, since the digester flow is intermittent, a storage/equalization tank is required to allow a continuous feed to the struvite crystallizer. A volume of at least 90 m³ would be advisable to allow storage of supernatant during maintenance shutdowns. A typical secondary clarifier design, with a floating decanter, should be adequate to allow storage, settling and sludge withdrawal. Sizing would depend on a study of the settling characteristics of the solids, as well as desired equalization volume. Existing decommissioned clarifiers on site would be likely candidates for this role.

5.7.1.5. *MgCl storage, batch dilution and dosing*

Storage for concentrated MgCl solution would be required. Volume would be decided based on desired shipping frequency. A batch dilution system would be desirable to avoid

excessive concentration gradients in the injection port area of the reactor. Variable flow dosing pumps would also be required to control the Mg dosing to the reactor. The estimated usage of magnesium chloride would be 15 metric tons per year as magnesium chloride hexahydrate. The existing unused chemical storage tanks on site could be used for this purpose, if the magnesium chloride was delivered in bulk tanker trucks in liquid form.

5.7.1.6. NaOH storage, batch dilution and dosing

Storage for concentrated NaOH solution would be required. Volume would be decided based on desired shipping frequency. The storage tank should be properly designed for sodium hydroxide storage and isolated from the carbon dioxide in the atmosphere, to avoid depletion of the caustic strength. A batch dilution system would be desirable to avoid excessive pH gradients in the injection port area of the reactor. Variable flow dosing pumps with a pH controller would also be required to control reactor pH. The estimated usage of sodium hydroxide would be between 5 and 12 metric tons per year, depending on the desired operating pH of the reactor. A purpose-built tank would be required for this task, since no existing tanks have the required safety precautions and carbon dioxide traps for sodium hydroxide storage.

5.7.1.7. Reactor feed and recycle pumps with flow control

A feed pump capable of delivering 90 m³/day of supernatant at 20 feet of head with low shear is required. This pump should be equipped with a variable frequency drive and a flow meter, to be able to control the feed flow rate. A recycle pump capable of delivering 1-10 times the feed flow with low shear, variable frequency drive and flow meter for flow control is also required. This pump would be subjected to a low head difference (piping head loss only). The requirement for low shear pumps is due to the potential for the formation of struvite deposits on the pump impellers if high shear conditions induce pH increases due to the degassing of CO₂. Alternatively, the pumps should be equipped with easily cleaned impellers that are not prone to excessive wear when scaled.

5.7.1.8. *Struvite crystallizing reactor*

Depending on the phosphate removal efficiency desired, the full-scale reactor will have diameters between 10 to 12.5 times those of the pilot reactor. The heights of the reactor zones could remain the same as those of the pilot reactor, and the valves in the harvest zone can probably be eliminated and replaced with an online crystal withdrawal system. The external clarifier can probably also be eliminated, since it serves a redundant purpose if the recycle is drawn from the top clarifier. This practice would also reduce the overflow velocities in the top clarifier, making settling more efficient there.

The full-scale reactor could fit comfortably in the existing chemical storage building on site in Penticton, where a lime silo was originally designed to fit. This lime silo was never constructed since chemical phosphorus removal was never needed at the treatment plant.

5.7.1.9. *Chemical injector section*

The injection port section would need to be redesigned to allow for the larger chemical flows while, maintaining rapid mixing characteristics and allowing easy removal for cleaning and maintenance. Multiple injection points should be considered for both magnesium and caustic, to minimize supersaturation gradients in the injector section. For supernatants with higher phosphate concentrations, it may be beneficial to separate the magnesium and caustic injection points to further decrease the supersaturation gradient in each injector zone. This should lead to more uniform crystal growth conditions and less injector scaling problems.

5.7.1.10. *Product screening and drying*

Facilities to separate the product crystals from the liquid stream and dry them are required. Either a rotating drum screen or a parabolic screen could be used for this purpose. Testing of these devices would be required to determine the optimum configuration.

The product crystals can either be air dried or heat dried, depending on the time allowed for the drying to occur; further investigation at larger scale would be required to determine the optimum configuration. In this study, the harvested crystals were heat dried in under 24 hours in a 10 mm deep static pile.

5.7.1.11. Product packaging and shipping

Once the product is dried, a decision has to be made as to whether the product will be shipped in bulk containers or packaged on site. This would depend on the targeted market and whether a central product processing facility, such as a fertilizer producer, is anticipated. Regardless, an area to store the produced struvite will be required until a sufficient quantity is accumulated for economical shipping to market or further processing. Roll-off bins similar to those used to haul dewatered sludge off site could easily be used for this purpose.

5.7.2. Operating Costs

The operating costs outlined here are based on information gathered during the course of the pilot study. Detailed calculations of these costs can be found in Appendix G. Operating costs are provided for two scenarios, one for 80 % phosphate removal and one for 60% phosphate removal from a supernatant containing 70 mg/L of ortho-phosphate and approximately 400 mg/L of ammonia. These scenarios are comparable to the operation of Reactors A and B, respectively, during the course of this study. For easy reference, the scenarios are identified as Scenario A and B, to represent 80% and 60 % removal, respectively.

5.7.2.1. Chemical costs

A significant portion of the operating costs for this type of struvite recovery operation would come from the chemical costs for magnesium chloride and sodium hydroxide. Prices for sodium hydroxide and magnesium chloride hexahydrate were assumed to be \$500 and \$200 per metric ton of solid, respectively. The dosing of magnesium chloride for this cost estimation was assumed to be equimolar to the phosphate concentration in the supernatant; the excess molar ratio of magnesium to phosphate is assumed to come from the magnesium already present in the supernatant.

For sodium hydroxide the usage was estimated for each reactor over an 18 day operating period. The difference between the requirements for each reactor is due to the difference in operating pH's. Table 5.6 shows the estimated chemical usage costs for the two scenarios.

Table 5.6: Chemical costs.

Scenario	MgCl Cost (\$/day)	NaOH Cost (\$/day)	Struvite Produced (kg/day)	Chemical Costs (\$/kg struvite)
A	8.26	16.57	40	0.62
B	8.26	7.44	30	0.53

5.7.2.2. Labour costs

Labor requirements for the operation of this reactor are estimated at 0.63 persons per day; compared with 0.7 persons per day as found by Kumashiro *et al.* (2001). The details of the estimated labor requirement calculations can be found in Appendix G. Assuming a labor cost of \$50 000 per year for a five day work week, the cost of labor for the facility would be \$44 000 per year. This amounts to a cost of \$3.03 and \$4.04 per kg of struvite produced for Scenarios A and B, respectively. This shows that the labor requirement may be the largest cost associated with the production of the struvite. It should be noted that this cost is expected to stay relatively constant for a larger facility, therefore reducing the unit labor cost of struvite in larger facilities.

5.7.3. Savings and Revenues

Sources of savings and revenues expected from the operation of a full-scale struvite recovery facility in Penticton include the sale of the product struvite, the reduction in shipping costs for dewatered sludge and the reduction in polymer usage for dewatering the sludge.

Current estimates of the market value of struvite vary widely from country to country and are therefore difficult to identify with any accuracy. This study assumes that the price of struvite product will be \$730 per metric ton. Table 5.7 shows the estimated cost savings expected from Scenarios A and B; detailed calculations can be found in Appendix G.

Table 5.7: Cost savings and revenues.

Scenario	Sale of Product (\$/kg struvite)	Reduction in Sludge Shipping (\$/day)	Reduction in polymer use (\$/day)	Savings and revenues (\$/kg struvite)
A	0.73	18.34	100	3.69
B	0.73	18.34	100	4.67

5.7.4. Net Process Savings

The overall operating savings expected from the operation of a full-scale struvite recovery process similar to the one described in this report at the City of Penticton AWWTP is shown in Table 5.8. These values translate into a total annual savings of \$580 and \$1090 for Scenarios A and B, respectively. The bulk of the costs come from the labor to run the reactor, while the bulk of the savings come from the reduction in polymer usage to dewater WAS.

Table 5.8: Overall process savings for full-scale struvite recovery.

Scenario	Chemical Costs (\$/kg struvite)	Labor Costs (\$/kg struvite)	Savings and Revenues (\$/kg struvite)	Net Savings and Revenues (\$/kg struvite)
A	0.62	3.03	3.69	0.04
B	0.53	4.04	4.67	0.10

Several process changes could be implemented to improve the cost-benefit ratio. These include increasing the mass of struvite recovered by increasing the percentage of WAS digested, reducing the aluminum load to the wastewater treatment plant from the drinking water treatment plant. These modifications would cause the concentration of phosphate in the supernatant to increase, thus allowing more struvite to be produced. This in turn would reduce the unit cost of labor and caustic, as well as increasing the benefit from reduced sludge hauling, and product sale. The effect of this on polymer usage would need to be investigated. Further cost reductions could be achieved by using air stripping for pH adjustment, thus reducing or eliminating the need for caustic; however, this would cause an increase in electrical cost to operate a blower, and the reactor design would need to be modified and tested.

Another important factor to consider is that by recovering phosphate from our wastewaters, we would be reducing our dependence on the limited global supply of phosphate rock, and extending the availability of this essential non-renewable resource. The ultimate social cost of the depletion of our phosphate reserves has yet to be determined; however, suffice it to say that should our phosphate reserves be exhausted, intensive agriculture as we know it today would cease to exist and the global food supply would, therefore, diminish significantly.

6. SUMMARY AND CONCLUSIONS

Based on the results obtained from this pilot-scale study on struvite recovery from a full-scale anaerobic digester supernatant at the City of Penticton AWWTP in British Columbia, Canada, the following conclusions can be drawn:

- The pilot-scale struvite recovery reactor developed at UBC was effective in removing phosphate from anaerobic digester supernatant stream, under controlled conditions and produced a product consisting of nearly pure struvite.
- By controlling the operating pH of the reactors and the inlet supersaturation ratio, the percentage removal of ortho-phosphate in the reactor was varied between 42% and 91%. The study's target ortho-phosphate reduction of at least 70% was easily achieved.
- A model was developed which predicts effluent magnesium, ammonia and ortho-phosphate concentrations from the reactor, based on the influent concentrations of these ions and the operating pH of the reactor. The model assumptions are that the effluent from the reactor is at equilibrium and that the reductions in magnesium, ammonia and ortho-phosphate are equimolar.
- During the course of the study, 90 to 91% of the removed phosphorus was recovered after harvesting, drying and screening operations. Most of the loss of mass is expected to be due to sludge wasted from the external clarifier and processing losses during the harvesting, drying and screening operations.
- A preliminary analysis of the costs and savings associated with the operation of a full-scale struvite recovery reactor, operating in the same manner as the pilot reactors in the last months of this study, shows that the process savings slightly exceed the process costs. This analysis only included chemical costs, labor costs and savings associated with product sale, reduced sludge shipping and reduced polymer usage. Further savings could be realized with the processing of more secondary sludge and better phosphorous recovery. If a larger portion of the WAS from the treatment plant was digested, a larger amount of struvite could potentially

be recovered; also by reducing the aluminum input (water treatment sludge is currently processed in the anaerobic digester) to the treatment plant, a larger portion of the phosphorus entering the plant could be recovered.

- A preliminary solubility product determination for the produced struvite crystals gave significantly different results for distilled water and digester supernatant. A conditional solubility product developed was useful in predicting reactor efficiency and in operating the reactor. In order to accurately predict the operational efficiency of the reactor, measurements of pH, conductivity, magnesium, ammonia and ortho-phosphate are required.
- Although present, scaling on the reactor and piping walls was not problematic during the course of this study. The use of flexible walled tubing allowed the accumulated scale deposits in the piping to be easily removed, and frequent (bi-weekly) cleaning of the injection port section of the reactor prevented complete blockage of the chemical injection points.
- After an initial commissioning period, the operation of the reactors was trouble free and they could be operated without intervention for periods of up to five days. The main requirements for labor were for filling chemical dosing tanks and harvesting the product.
- The produced struvite crystals were easily separated from the liquor, and were composed of nearly pure struvite (99.8%), with small amounts of calcium, and traces of potassium and iron. The mean diameter, and bulk density of the harvested crystals increased continuously over the course of the study. The mean diameter of the harvested crystals varied from 0.5 to 1.8 mm. SEM examination of the crystals suggested that this was due to changes in the structure of the crystal aggregates over the course of the study; however, it was not clear whether these changes were due to a crystal maturation process, or to changes in the operating conditions of the crystallizers.
- The size and hardness of the struvite crystals were affected by the crystal retention time in the reactor, the supersaturation ratio in the reactor and the elapsed time from reactor startup. It was not possible to determine the exact effect of each of these parameters from this study, since they were not varied independently.

7. RECOMMENDATIONS

Based on the experience gained from this pilot-scale study on struvite recovery from a full-scale anaerobic digester supernatant, the following recommendations are put forth:

- Longer-term studies would be needed to determine the steady-state struvite crystal size and morphology, since a steady state was not reached during this study. This study should also attempt to keep reactor conditions, such as in-reactor SS ratio and CRT, constant and harvest crystals at regular intervals.
- The desired size, density, strength and composition of the product crystals, based on the expected market for the crystals, should be determined. This information would allow the evaluation of the effects of various reactor conditions relative to a target product quality.
- A study of the effect of the SS ratio in the reactor on the harvested crystal size and morphology would be useful in determining the optimum operating range for crystal growth.
- A study of the effect of the CRT on the harvested crystal size and morphology would be useful in determining the optimum operating range for crystal growth.
- Air stripping of carbon dioxide shows much promise as a means of cheaply adjusting the pH in the reactor. A reactor design incorporating an air stripping component should be investigated.
- In order to gain a better understanding of the hydraulics in the reactor, an investigation into the struvite crystal bed porosity and fluidization characteristics would be useful. This increased knowledge of the hydraulics could be used to develop a kinetic model of the crystallization reactions occurring in the reactor.
- A tracer test should be conducted on a fully loaded (i.e. full of struvite crystals) reactor to accurately determine the hydraulic residence time distribution of the reactor. This information would also help in the development of a kinetic model of the crystallization reactions.

- Further studies varying the hydraulic residence time in the reactor, as well as the fluidization velocities, would be useful in determining the minimum reactor volumes and maximum flow rates that can be achieved without sacrificing reactor performance.
- A full-scale study would be necessary to examine the impacts that struvite recovery will have on the process performance and stability of a BNR treatment plant.
- A full-scale struvite recovery study at a wastewater treatment plant experiencing excessive struvite scaling in the sludge handling piping would be needed to accurately determine the impact of struvite recovery on the scaling problem.
- An investigation into the possibility of digesting a larger portion of the WAS and reducing the processing of aluminum-rich sludges to the City of Penticton AWWTP would be useful in evaluating the potential for increased P and N recovery.
- A permanent, full-scale installation would be the ideal way to evaluate many of the long-term questions raised by this study and would allow a more thorough investigation into the actual costs and savings.

8. REFERENCES

- Abe, Shizuo (1995), Phosphate removal from dewatering filtrate by MAP process at Seibu treatment plant in Fukuoka City. *Sewage Works in Japan*, 1995, pp. 59-64.
- APHA, AWWA and WPCF (1995) *Standard methods for the examination of water and wastewater*, 19th ed., American Public Health Association, Washington, DC.
- Battistoni P., A. De Angelis, M. Prisciandaro, R. Boccadoro and D. Bolzonella (2002). P removal from anaerobic supernatants by struvite crystallization: long term validation and process modeling. *Water Research*, Vol. 36, pp 1927-1938.
- Battistoni, P., A. De Angelis, P. Pavan, M. Prisciandaro, and F. Cecchi (2001). Phosphorus removal from a real anaerobic supernatant by struvite crystallization. *Water Research*, Vol. 35, No. 9, pp. 2161-2178.
- Battistoni, P., G. Fava, P. Pavan, A. Musacco and F. Cecchi (1997). Phosphate removal in anaerobic liquors by struvite crystallization without addition of chemicals: preliminary results. *Water Research*, Vol. 31, No. 11, pp. 2925-2929.
- Battistoni, P., P. Pavan, F. Cecchi and J. Mata-Alvarez (1998). Phosphate removal in real anaerobic supernatants: modeling and performance of a fluidized bed reactor. *Water Science and Technology*, Vol. 38, No. 1, pp. 275-283.
- Booker, N.A., A.J. Priestley and I.H. Fraser (1999). Struvite formation in wastewater treatment plants: opportunities for nutrient recovery. *Environmental Technology*, Vol. 20, pp. 777-782.
- Borgerding, J. (1972). Phosphate deposits in digestion systems. *Journal Water Pollution Control Federation*, Vol. 44, pp. 813-819.
- Bouropoulos, Nicolaos and Petros Koutsoukos (2000). Spontaneous precipitation from aqueous solutions. *Journal of Crystal Growth*, Vol. 213, pp. 381-388.
- Celen, I. and M. Turker (2001). Recovery of ammonia as struvite from anaerobic digester effluents. *Environmental Technology*, Vol. 22, pp. 1263-1272.
- Dastur, Mahazareen Behram (2001), *Investigation into the factors affecting controlled struvite crystallization at the bench-scale*. MASc Thesis, University of British Columbia, Canada

- Dempsey, Brian A. (1997). Removal and re-use of ammonia and phosphate by precipitation of struvite. *Proceedings from the 1997 Purdue Industrial Waste Conference*, 5-7 May. 1997, Purdue, USA.
- Doyle, J.D., R. Phillip, J. Churchley and S.A. Parsons (2000). Analysis of Struvite Precipitation in real and synthetic liquors. *Trans IChemE*, Vol 78, Part B, pp. 480-488.
- Driver, J., D. Lijmbach and I. Steen (1999). Why recover phosphorus for recycling and how? *Environmental Technology*, Vol. 20, pp. 651-662.
- Durrant, A.E., M.D. Scrimshaw, I. Stratful and J.N. Lester (1999). Review of the feasibility of recovering phosphate from wastewater for use as a raw material by the phosphate industry. *Environmental Technology*, Vol. 20, pp. 749-758.
- Edge, D. (1999). Perspectives for nutrient removal from sewage and implications for sludge strategy. *Environmental Technology*, Vol.20, pp. 759-763.
- Gaterell, M.R., R. Gay, R. Wilson, R.J. Gochin, and J.N. Lester (2000). An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertilizer markets. *Environmental Technology*, Vol. 21, pp. 1067-1084.
- Hirasawa, I., H. Nakagawa, O. Yosikawa, and M. Itoh (1997). Phosphate recovery by reactive crystallization of magnesium ammonium phosphate: application to wastewater. In *Separation and Purification By Crystallization*. ACS Symposium Series. Vol. 667, pp. 267-276.
- Jaffer, Y., T.A. Clark, P. Pearce and S.A. Parsons (2002). Potential phosphorus recovery by struvite formation. *Water Research*, Vol. 36, pp. 1834-1842.
- Jardin, N. and H.J. Popel (1994). Phosphate release of sludges from enhanced biological P-removal during digestion. *Water Technology*, Vol. 30, pp 281-292.
- Jardin, N. and H.J. Popel (2001). Refixation of Phosphates Released During Bio-P Sludge Handling as Struvite or Aluminum Phosphate. *Environmental Technology*, Vol. 22, pp. 1253-1262.
- Jeanmaire, N. (2001). Recycling of removed phosphorus: analysis of the potential interest in wastewater treatment plants. Downloaded from the World Wide Web on June 15th 2002. http://www.nhm.ac.uk/mineralogy/phos/Jeanmaire_report.doc

- Jeanmaire, N. and T. Evans (2001). Technico-economic feasibility of P-Recovery from municipal wastewaters. *Environmental Technology*, Vol 22, pp. 1355-1361.
- Kumashiro, K, H. Ishiwatari and Y. Nawamura (2001). A pilot plant study on using seawater as a magnesium source for struvite precipitation. *In proceedings from Second International Conference On the recovery of phosphorus from sewage and animal wastes*, Noordwijkerhout, Holland, March 2001.
- Mavinic, D.S., F.A. Koch, E.R. Hall, K. Abraham and D. Niedbala (1998). Anaerobic co-digestion of combined sludges from a BNR wastewater treatment plant. *Environmental Technology*. Vol. 19, pp 35-44.
- Mersmann, A. (1999). Crystallization and precipitation. *Chemical Engineering and Processing*, Vol. 38, pp. 345-353.
- Metcalf and Eddy, Inc. (1991) *Wastewater engineering: treatment, disposal, and reuse*. Third Edition. McGraw-Hill, Inc., New York.
- Momberg, G.A. and R. A. Ollermann (1992). The removal of phosphate by hydroxyapatite and struvite crystallization in South Africa. *Water Science and Technology*. Vol. 26, No. 5-6, pp. 987-996.
- Munch, Elisaveth v. and Keith Barr (2001). Controlled struvite crystallization for removing phosphorus from anaerobic digester sidestreams. *Water Research*, Vol. 35, No. 1, pp. 151-159.
- Niedbala, Dyanne (1995). *Pilot-scale studies of the anaerobic digestion of combined wastewater sludges and mitigation of phosphorus release*. MSc Thesis, University of British Columbia, Canada.
- Ohlinger, K.N., T.M. Young and E.D. Schroeder (1998). Predicting struvite formation in digestion. *Water Research*, Vol. 32, No. 12, pp 3607-3614.
- Ohlinger, K.N., T.M. Young and E.D. Schroeder (1999). Kinetic effects on preferential struvite accumulation in wastewater. *Journal of Environmental Engineering*, Vol. 125, No. 8, pp. 730-737.
- Ohlinger, Kurt N. (1999). *Struvite Controls in Anaerobic Digestion and Post-digestion Wastewater Treatment Processes*. Ph.D. Thesis, University of California – Davis, USA.

- Parsons, S.A., F. Wall, J. Doyle, K. Oldring, J. Churchley (2001). Assessing the potential for struvite recovery at sewage treatment works. *Environmental Technology*, Vol. 22, pp. 1279-1286.
- Paul, E., M.L. Laval and M. Sperandio (2001). Excess sludge production and costs due to phosphorus removal. *Environmental Technology*. Vol. 22, pp. 1363-1371.
- Sawyer, C., P. McCarty, G. Parkin (1994). *Chemistry for Environmental Engineers*. McGraw-Hill Series in Water Resources and Environmental Engineering, New York.
- Shin, H.S. and S.M. Lee (1997). Removal of nutrients in wastewater by using magnesium salts. *Environmental Technology*, Vol. 19, pp. 283-290.
- Siegrist, H., D. Gajcy, S. Sulzer, P. Roeleveld, R. Oswald, H. Frischkecht, D. Pfund, B. Morgeli, E. Hungerbuhler (1992). Nitrogen elimination from digester supernatant with magnesium-ammonium-phosphate precipitation. In *Chemical Water and Wastewater Treatment II*. Proceedings of the 5th Gothenburg Symposium, Sept 28-30, 1992, Nice, France, 457-466.
- Steen, I. (1998). Phosphorus availability in the 21st century: Management of a non-renewable resource. *Phosphorus & Potassium*, September – October 1998, pp. 25-31.
- Stratful, I., S. Brett, M.B. Scrimshaw, and J.N. Lester (1999). Biological phosphorus removal, its role in phosphorus recycling. *Environmental Technology*, Vol. 20, pp. 681-695.
- Takiyama, H., H. Yamauchy, M. Matsuoka (1997). Effects of seeding on start-up operation of a continuous crystallizer. In *Separation and Purification By Crystallization*. ACS Symposium Series. Vol. 667, pp. 172-186.
- Tchobanoglous, G. and E.D. Schroeder (1985). *Water Quality*. Addison Wesley Publishing Company, USA.
- Ueno, Y and M. Fujii (2001). Three years experience of operating and selling recovered struvite from full-scale plant. *Environmental Technology*, Vol. 22, No. 11, pp 1373-1381.
- Webb, K.M. and G.E. Ho (2001). Characterization of waste solutions to determine optimized P recovery. *Environmental Technology*, Vol. 22, pp. 1303-1312.
- Wentzel, M.C., E.V. Musvoto, and G.A. Ekama (2001). Application of integrated chemical-physical modeling to aeration treatment of anaerobic liquors. *Environmental Technology*, Vol. 22, pp. 1287-1293.

-
- Wierzbicki, A., J.D. Sallis, E.D. Stevens, M. Smith and C.S. Sikes (1997). Crystal growth and molecular modeling studies of inhibition of struvite by phosphocitrate. *Calcified Tissue International*, Vol. 61, pp. 216-222.
- Williams, S. (1999). Struvite precipitation in the sludge stream at Slough wastewater treatment plant and opportunities for phosphorus recovery. *Environmental Technology*, Vol. 20, pp. 743-747.
- Woods, N.C., S.M. Sock and G.T. Daigger (1999). Phosphorus recovery technology modeling and feasibility evaluation for municipal wastewater treatment plants. *Environmental Technology*, Vol. 20, No. 7, pp 663-680.
- Yu, Jing (2001). *Phosphorus inventory in British Columbia*. MEng Report, Department of Civil Engineering, University of British Columbia, Canada.

APPENDIX A: INSTRUMENT OPERATIONAL PARAMETER DETAILS

Table A-1 Instrument operational parameters for flame atomic absorption spectrophotometer.

Element Analyzed	Magnesium	Iron	Calcium	Aluminum	Potassium
Concentration Units	mg/L	mg/L	mg/L	mg/L	Mg/L
Instrument Mode	Absorbance	Absorbance	Absorbance	Absorbance	Emission
Sampling Mode	Autonormal	Autonormal	Autonormal	Autonormal	Autonormal
Calibration Mode	Concentration	Concentration	Concentration	Concentration	Concentration
Measurement Mode	Integrate	Integrate	Integrate	Integrate	Integrate
Replicates Standard	3	3	3	3	3
Replicates Sample	3	3	3	3	3
Wavelength	202.6	248.3 nm	422.7 nm	309.3 nm	766.5 nm
Range	0-100 mg/L	0-10 mg/L	0-60 mg/L	0-20 mg/L	0-10 mg/L
Flame Type	N ₂ O/C ₂ H ₂	Air/C ₂ H ₂	N ₂ O/C ₂ H ₂	N ₂ O/C ₂ H ₂	Air/C ₂ H ₂
Calibration Algorithm	New Rational	New Rational	New Rational	New Rational	New Rational

Table A-2 Instrument operational parameters for flow injection analysis.

Ion Analyzed	PO ₄ -P	NH ₃ -N
Concentration Units	mg/L	Mg/L
Range	0-100 mg/L	0-100 mg/L
Temperature	63°C	63°C
Method	Ammonia Molybdate	Phenate
Reference	1	2

1: LaChat Instruments Methods Manual for the QuikChem Automated Ion Analyzer (1990). QuikChem method number 10-115-01-1Z

2: APHA, AWWA, WPCF (1995). Method 4500-NH₃-F. Phenate Method

**APPENDIX B: KSP DETERMINATION DATA AND
CALCULATIONS**

Solubility Trials Using Digester Supernatant and Struvite grown in Penticton

Sample	pH	Conductivity μS/cm	Sample data					
			Mg mg/L	NH ₄ -N mg/L	PO ₄ -P mg/L	Mg mol/L	NH ₄ -N mol/L	PO ₄ -P mol/L
S1	6.45	5060	129.6	378	158.5	0.00533	0.027	0.00512
S2	6.49	5060	130.0	363	156.1	0.00535	0.026	0.00504
S3	6.54	4830	113.9	333	144.8	0.00469	0.024	0.00468
S4	6.66	4810	86.9	383	106.9	0.00358	0.027	0.00345
S5	6.7	4800	89.1	369	109.0	0.00367	0.026	0.00352
S6	6.81	4550	74.7	333	87.4	0.00307	0.024	0.00282
S7	7.05	4090	53.1	283	64.7	0.00218	0.020	0.00209
S8	7.44	3920	30.9	304	36.2	0.00127	0.022	0.00117
S9	7.59	3970	27.5	244	32.8	0.00113	0.017	0.00106
S10	7.85	3710	23.6	384	25.4	0.00097	0.027	0.00082
S11	7.85	3980	21.0	274	23.1	0.00086	0.020	0.00075
S12	7.92	3380	17.9	355.0	21.7	0.00074	0.025	0.00070
S13	8.02	3630	18.6	369	17.8	0.00077	0.026	0.00057
S14	8.07	3280	20.1	368	18.0	0.00083	0.026	0.00058
S15	8.11	3270	18.2	363	17.7	0.00075	0.026	0.00057
S16	8.12	3490	19.4	363	15.9	0.00080	0.026	0.00051
S17	8.14	3320	14.5	356	16.9	0.00059	0.025	0.00055
S18	8.23	3320	16.7	364	14.3	0.00069	0.026	0.00046
S19	8.29	3460	14.8	353	14.9	0.00061	0.025	0.00048
S20	8.48	3850	15.4	220	16.5	0.00063	0.016	0.00053
S21	8.52	3490	11.3	327	10.9	0.00046	0.023	0.00035
S22	8.6	3560	12.1	341	12.4	0.00050	0.024	0.00040
S23	8.72	3650	11.1	225	14.2	0.00046	0.016	0.00046
S24	8.97	3620	9.3	289	9.8	0.00038	0.021	0.00032

Sample	Mg:P	N:P	Struvite P_s	Struvite pP_s	Phosphate Dissociation Constants		
	Molar Ratio	Molar Ratio			ka_1	ka_2	ka_3
S1	1.0	5.3	7.4E-07	6.1	7.81E-03	6.12E-08	5E-13
S2	1.1	5.1	7.0E-07	6.2	7.81E-03	6.12E-08	5E-13
S3	1.0	5.1	5.2E-07	6.3	7.81E-03	6.12E-08	5E-13
S4	1.0	7.9	3.4E-07	6.5	7.81E-03	6.12E-08	5E-13
S5	1.0	7.5	3.4E-07	6.5	7.81E-03	6.12E-08	5E-13
S6	1.1	8.4	2.1E-07	6.7	7.81E-03	6.12E-08	5E-13
S7	1.0	9.7	9.2E-08	7.0	7.81E-03	6.12E-08	5E-13
S8	1.1	18.6	3.2E-08	7.5	7.81E-03	6.12E-08	5E-13
S9	1.1	16.5	2.1E-08	7.7	7.81E-03	6.12E-08	5E-13
S10	1.2	33.4	2.2E-08	7.7	7.81E-03	6.12E-08	5E-13
S11	1.2	26.2	1.3E-08	7.9	7.81E-03	6.12E-08	5E-13
S12	1.1	36.2	1.3E-08	7.9	7.81E-03	6.12E-08	5E-13
S13	1.3	45.9	1.2E-08	7.9	7.81E-03	6.12E-08	5E-13
S14	1.4	45.2	1.3E-08	7.9	7.81E-03	6.12E-08	5E-13
S15	1.3	45.4	1.1E-08	8.0	7.81E-03	6.12E-08	5E-13
S16	1.6	50.5	1.1E-08	8.0	7.81E-03	6.12E-08	5E-13
S17	1.1	46.6	8.3E-09	8.1	7.81E-03	6.12E-08	5E-13
S18	1.5	56.3	8.2E-09	8.1	7.81E-03	6.12E-08	5E-13
S19	1.3	52.4	7.4E-09	8.1	7.81E-03	6.12E-08	5E-13
S20	1.2	29.5	5.3E-09	8.3	7.81E-03	6.12E-08	5E-13
S21	1.3	66.4	3.8E-09	8.4	7.81E-03	6.12E-08	5E-13
S22	1.2	60.8	4.8E-09	8.3	7.81E-03	6.12E-08	5E-13
S23	1.0	35.1	3.4E-09	8.5	7.81E-03	6.12E-08	5E-13
S24	1.2	65.2	2.5E-09	8.6	7.81E-03	6.12E-08	5E-13

Sample	Ammonia ka	MgOH kb	[H ⁺] mol/L	[OH] mol/L	[Mg ⁺⁺] mol/L	[NH ₄ ⁺] mol/L	[PO ₄ ⁻⁻⁻] mol/L
S1	6.05E-10	2.75E-03	3.5E-07	2.8E-08	5.3E-03	2.7E-02	1.1E-09
S2	6.05E-10	2.75E-03	3.2E-07	3.1E-08	5.4E-03	2.6E-02	1.2E-09
S3	6.05E-10	2.75E-03	2.9E-07	3.5E-08	4.7E-03	2.4E-02	1.4E-09
S4	6.05E-10	2.75E-03	2.2E-07	4.6E-08	3.6E-03	2.7E-02	1.7E-09
S5	6.05E-10	2.75E-03	2.0E-07	5.0E-08	3.7E-03	2.6E-02	2.1E-09
S6	6.05E-10	2.75E-03	1.5E-07	6.5E-08	3.1E-03	2.4E-02	2.6E-09
S7	6.05E-10	2.75E-03	8.9E-08	1.1E-07	2.2E-03	2.0E-02	4.8E-09
S8	6.05E-10	2.75E-03	3.6E-08	2.8E-07	1.3E-03	2.1E-02	1.0E-08
S9	6.05E-10	2.75E-03	2.6E-08	3.9E-07	1.1E-03	1.7E-02	1.5E-08
S10	6.05E-10	2.75E-03	1.4E-08	7.1E-07	9.7E-04	2.6E-02	2.4E-08
S11	6.05E-10	2.75E-03	1.4E-08	7.1E-07	8.6E-04	1.9E-02	2.1E-08
S12	6.05E-10	2.75E-03	1.2E-08	8.3E-07	7.4E-04	2.4E-02	2.4E-08
S13	6.05E-10	2.75E-03	9.5E-09	1.0E-06	7.7E-04	2.5E-02	2.6E-08
S14	6.05E-10	2.75E-03	8.5E-09	1.2E-06	8.3E-04	2.5E-02	3.0E-08
S15	6.05E-10	2.75E-03	7.8E-09	1.3E-06	7.5E-04	2.4E-02	3.3E-08
S16	6.05E-10	2.75E-03	7.6E-09	1.3E-06	8.0E-04	2.4E-02	3.0E-08
S17	6.05E-10	2.75E-03	7.2E-09	1.4E-06	5.9E-04	2.3E-02	3.4E-08
S18	6.05E-10	2.75E-03	5.9E-09	1.7E-06	6.9E-04	2.4E-02	3.6E-08
S19	6.05E-10	2.75E-03	5.1E-09	1.9E-06	6.1E-04	2.3E-02	4.3E-08
S20	6.05E-10	2.75E-03	3.3E-09	3.0E-06	6.3E-04	1.3E-02	7.6E-08
S21	6.05E-10	2.75E-03	3.0E-09	3.3E-06	4.6E-04	1.9E-02	5.6E-08
S22	6.05E-10	2.75E-03	2.5E-09	4.0E-06	5.0E-04	2.0E-02	7.7E-08
S23	6.05E-10	2.75E-03	1.9E-09	5.2E-06	4.6E-04	1.2E-02	1.2E-07
S24	6.05E-10	2.75E-03	1.1E-09	9.3E-06	3.8E-04	1.3E-02	1.5E-07

Sample	{Mg ⁺⁺ } mol/L	{NH ₄ ⁺ } mol/L	{PO ₄ ⁻ } mol/L	K _{sp}	pK _{sp}	Ionic Strength
S1	1.9E-03	2.1E-02	1.1E-10	4.3E-15	14.4	0.08
S2	1.9E-03	2.0E-02	1.2E-10	4.8E-15	14.3	0.08
S3	1.7E-03	1.8E-02	1.5E-10	4.7E-15	14.3	0.08
S4	1.3E-03	2.1E-02	1.8E-10	5.1E-15	14.3	0.08
S5	1.3E-03	2.0E-02	2.2E-10	6.0E-15	14.2	0.08
S6	1.2E-03	1.9E-02	2.9E-10	6.1E-15	14.2	0.07
S7	8.5E-04	1.6E-02	5.8E-10	7.8E-15	14.1	0.07
S8	5.1E-04	1.7E-02	1.3E-09	1.1E-14	14.0	0.06
S9	4.5E-04	1.4E-02	1.8E-09	1.1E-14	14.0	0.06
S10	3.9E-04	2.1E-02	3.1E-09	2.6E-14	13.6	0.06
S11	3.4E-04	1.5E-02	2.7E-09	1.4E-14	13.9	0.06
S12	3.1E-04	1.9E-02	3.4E-09	2.1E-14	13.7	0.05
S13	3.1E-04	2.0E-02	3.5E-09	2.2E-14	13.7	0.06
S14	3.5E-04	2.0E-02	4.3E-09	3.0E-14	13.5	0.05
S15	3.2E-04	1.9E-02	4.7E-09	2.9E-14	13.5	0.05
S16	3.3E-04	1.9E-02	4.2E-09	2.7E-14	13.6	0.06
S17	2.5E-04	1.9E-02	4.8E-09	2.3E-14	13.6	0.05
S18	2.9E-04	1.9E-02	5.1E-09	2.8E-14	13.5	0.05
S19	2.5E-04	1.8E-02	6.0E-09	2.8E-14	13.6	0.06
S20	2.5E-04	1.1E-02	9.7E-09	2.6E-14	13.6	0.06
S21	1.9E-04	1.6E-02	7.7E-09	2.3E-14	13.6	0.06
S22	2.0E-04	1.6E-02	1.0E-08	3.3E-14	13.5	0.06
S23	1.9E-04	9.7E-03	1.6E-08	2.8E-14	13.5	0.06
S24	1.6E-04	1.1E-02	1.9E-08	3.2E-14	13.5	0.06

Solubility Trials Using Distilled Water and Struvite grown in Penticton

Sample	pH	Conductivity μS/cm	Sample data					
			Mg mg/L	NH ₄ -N mg/L	PO ₄ -P mg/L	Mg mol/L	NH ₄ -N mol/L	PO ₄ -P mol/L
D1	7.01	889	81.6	48.8	111.9	0.00336	0.00349	0.00361
D2	7.05	721	63.0	37.5	87.7	0.00259	0.00268	0.00283
D3	7.08	709	61.9	36.2	81.2	0.00255	0.00258	0.00262
D4	7.1	798	71.3	42.1	98.4	0.00294	0.00301	0.00318
D5	7.26	551	52.6	28.2	74.2	0.00216	0.00201	0.00240
D6	7.33	598	58.0	33.0	77.4	0.00239	0.00235	0.00250
D7	7.34	576	51.8	29.0	69.0	0.00213	0.00207	0.00223
D8	7.41	480	43.6	24.3	61.0	0.00179	0.00174	0.00197
D9	7.42	466	44.9	23.1	59.7	0.00185	0.00165	0.00193
D10	7.45	426	42.4	20.7	56.2	0.00175	0.00148	0.00181
D11	7.56	440	42.1	21.8	56.6	0.00173	0.00156	0.00183
D12	7.58	356	36.8	16.9	46.9	0.00151	0.00121	0.00152
D13	7.58	388	39.1	17.7	53.4	0.00161	0.00126	0.00172
D14	7.6	384	34.5	18.4	46.0	0.00142	0.00131	0.00149
D15	7.64	397	38.7	18.0	51.6	0.00159	0.00128	0.00167
D16	7.7	395	36.6	19.0	46.6	0.00151	0.00136	0.00151
D17	7.71	374	36.2	17.9	46.6	0.00149	0.00128	0.00150
D18	7.71	330	32.7	14.0	42.0	0.00134	0.00100	0.00136
D19	7.73	334	30.7	15.9	39.0	0.00126	0.00114	0.00126
D20	7.77	319	33.4	13.0	43.3	0.00137	0.00093	0.00140
D21	7.82	264	30.0	12.0	38.8	0.00124	0.00086	0.00125
D22	7.98	225	22.8	10.2	29.1	0.00094	0.00073	0.00094
D23	8.03	235	25.6	9.1	32.1	0.00105	0.00065	0.00103
D24	8.19	191	20.0	8.9	25.2	0.00082	0.00063	0.00081
D25	8.24	315	26.0	7.6	28.6	0.00107	0.00055	0.00092
D26	8.26	177	20.0	8.5	24.2	0.00082	0.00061	0.00078
D27	8.3	236	20.6	8.0	29.0	0.00085	0.00057	0.00094
D28	8.35	353	25.8	7.6	37.7	0.00106	0.00055	0.00122
D29	8.41	160	17.7	7.7	22.4	0.00073	0.00055	0.00072
D30	8.51	158	17.1	7.3	22.2	0.00070	0.00052	0.00072
D31	8.58	420	19.6	6.8	37.1	0.00081	0.00048	0.00120
D32	8.62	165	13.7	8.2	22.1	0.00056	0.00059	0.00071
D33	9.15	227	7.8	9.4	17.8	0.00032	0.00067	0.00057
D34	9.15	527	9.9	7.2	35.0	0.00041	0.00052	0.00113
D35	9.52	329	5.5	10.6	18.6	0.00023	0.00075	0.00060
D36	9.62	310	4.8	12.4	19.9	0.00020	0.00088	0.00064

Sample	Mg:P	N:P	Struvite P _s	Struvite pP _s	Phosphate Dissociation Constants		
	Molar Ratio	Molar Ratio			ka ₁	ka ₂	ka ₃
D1	0.9	1.0	4.2E-08	7.4	7.81E-03	6.12E-08	5E-13
D2	0.9	0.9	2.0E-08	7.7	7.81E-03	6.12E-08	5E-13
D3	1.0	1.0	1.7E-08	7.8	7.81E-03	6.12E-08	5E-13
D4	0.9	0.9	2.8E-08	7.6	7.81E-03	6.12E-08	5E-13
D5	0.9	0.8	1.0E-08	8.0	7.81E-03	6.12E-08	5E-13
D6	1.0	0.9	1.4E-08	7.9	7.81E-03	6.12E-08	5E-13
D7	1.0	0.9	9.9E-09	8.0	7.81E-03	6.12E-08	5E-13
D8	0.9	0.9	6.1E-09	8.2	7.81E-03	6.12E-08	5E-13
D9	1.0	0.9	5.9E-09	8.2	7.81E-03	6.12E-08	5E-13
D10	1.0	0.8	4.7E-09	8.3	7.81E-03	6.12E-08	5E-13
D11	0.9	0.9	4.9E-09	8.3	7.81E-03	6.12E-08	5E-13
D12	1.0	0.8	2.8E-09	8.6	7.81E-03	6.12E-08	5E-13
D13	0.9	0.7	3.5E-09	8.5	7.81E-03	6.12E-08	5E-13
D14	1.0	0.9	2.8E-09	8.6	7.81E-03	6.12E-08	5E-13
D15	1.0	0.8	3.4E-09	8.5	7.81E-03	6.12E-08	5E-13
D16	1.0	0.9	3.1E-09	8.5	7.81E-03	6.12E-08	5E-13
D17	1.0	0.8	2.9E-09	8.5	7.81E-03	6.12E-08	5E-13
D18	1.0	0.7	1.8E-09	8.7	7.81E-03	6.12E-08	5E-13
D19	1.0	0.9	1.8E-09	8.7	7.81E-03	6.12E-08	5E-13
D20	1.0	0.7	1.8E-09	8.7	7.81E-03	6.12E-08	5E-13
D21	1.0	0.7	1.3E-09	8.9	7.81E-03	6.12E-08	5E-13
D22	1.0	0.8	6.4E-10	9.2	7.81E-03	6.12E-08	5E-13
D23	1.0	0.6	7.1E-10	9.1	7.81E-03	6.12E-08	5E-13
D24	1.0	0.8	4.2E-10	9.4	7.81E-03	6.12E-08	5E-13
D25	1.2	0.6	5.4E-10	9.3	7.81E-03	6.12E-08	5E-13
D26	1.1	0.8	3.9E-10	9.4	7.81E-03	6.12E-08	5E-13
D27	0.9	0.6	4.5E-10	9.3	7.81E-03	6.12E-08	5E-13
D28	0.9	0.4	7.0E-10	9.2	7.81E-03	6.12E-08	5E-13
D29	1.0	0.8	2.9E-10	9.5	7.81E-03	6.12E-08	5E-13
D30	1.0	0.7	2.6E-10	9.6	7.81E-03	6.12E-08	5E-13
D31	0.7	0.4	4.7E-10	9.3	7.81E-03	6.12E-08	5E-13
D32	0.8	0.8	2.4E-10	9.6	7.81E-03	6.12E-08	5E-13
D33	0.6	1.2	1.2E-10	9.9	7.81E-03	6.12E-08	5E-13
D34	0.4	0.5	2.4E-10	9.6	7.81E-03	6.12E-08	5E-13
D35	0.4	1.3	1.0E-10	10.0	7.81E-03	6.12E-08	5E-13
D36	0.3	1.4	1.1E-10	9.9	7.81E-03	6.12E-08	5E-13

Sample	Ammonia ka	MgOH kb	[H ⁺] mol/L	[OH] mol/L	[Mg ⁺⁺] mol/L	[NH ₄ ⁺] mol/L	[PO ₄ ⁻] mol/L
D1	6.05E-10	2.75E-03	9.8E-08	1.0E-07	3.4E-03	3.5E-03	7.1E-09
D2	6.05E-10	2.75E-03	8.9E-08	1.1E-07	2.6E-03	2.7E-03	6.5E-09
D3	6.05E-10	2.75E-03	8.3E-08	1.2E-07	2.5E-03	2.6E-03	6.7E-09
D4	6.05E-10	2.75E-03	7.9E-08	1.3E-07	2.9E-03	3.0E-03	8.7E-09
D5	6.05E-10	2.75E-03	5.5E-08	1.8E-07	2.2E-03	2.0E-03	1.1E-08
D6	6.05E-10	2.75E-03	4.7E-08	2.1E-07	2.4E-03	2.3E-03	1.5E-08
D7	6.05E-10	2.75E-03	4.6E-08	2.2E-07	2.1E-03	2.0E-03	1.4E-08
D8	6.05E-10	2.75E-03	3.9E-08	2.6E-07	1.8E-03	1.7E-03	1.5E-08
D9	6.05E-10	2.75E-03	3.8E-08	2.6E-07	1.8E-03	1.6E-03	1.6E-08
D10	6.05E-10	2.75E-03	3.5E-08	2.8E-07	1.7E-03	1.5E-03	1.6E-08
D11	6.05E-10	2.75E-03	2.8E-08	3.6E-07	1.7E-03	1.5E-03	2.3E-08
D12	6.05E-10	2.75E-03	2.6E-08	3.8E-07	1.5E-03	1.2E-03	2.0E-08
D13	6.05E-10	2.75E-03	2.6E-08	3.8E-07	1.6E-03	1.2E-03	2.3E-08
D14	6.05E-10	2.75E-03	2.5E-08	4.0E-07	1.4E-03	1.3E-03	2.1E-08
D15	6.05E-10	2.75E-03	2.3E-08	4.4E-07	1.6E-03	1.3E-03	2.6E-08
D16	6.05E-10	2.75E-03	2.0E-08	5.0E-07	1.5E-03	1.3E-03	2.8E-08
D17	6.05E-10	2.75E-03	1.9E-08	5.1E-07	1.5E-03	1.2E-03	2.9E-08
D18	6.05E-10	2.75E-03	1.9E-08	5.1E-07	1.3E-03	9.7E-04	2.6E-08
D19	6.05E-10	2.75E-03	1.9E-08	5.4E-07	1.3E-03	1.1E-03	2.6E-08
D20	6.05E-10	2.75E-03	1.7E-08	5.9E-07	1.4E-03	9.0E-04	3.2E-08
D21	6.05E-10	2.75E-03	1.5E-08	6.6E-07	1.2E-03	8.3E-04	3.3E-08
D22	6.05E-10	2.75E-03	1.0E-08	9.5E-07	9.4E-04	6.9E-04	3.8E-08
D23	6.05E-10	2.75E-03	9.3E-09	1.1E-06	1.1E-03	6.1E-04	4.8E-08
D24	6.05E-10	2.75E-03	6.5E-09	1.5E-06	8.2E-04	5.8E-04	5.7E-08
D25	6.05E-10	2.75E-03	5.8E-09	1.7E-06	1.1E-03	4.9E-04	7.3E-08
D26	6.05E-10	2.75E-03	5.5E-09	1.8E-06	8.2E-04	5.5E-04	6.5E-08
D27	6.05E-10	2.75E-03	5.0E-09	2.0E-06	8.5E-04	5.1E-04	8.6E-08
D28	6.05E-10	2.75E-03	4.5E-09	2.2E-06	1.1E-03	4.8E-04	1.3E-07
D29	6.05E-10	2.75E-03	3.9E-09	2.6E-06	7.3E-04	4.7E-04	8.7E-08
D30	6.05E-10	2.75E-03	3.1E-09	3.2E-06	7.0E-04	4.3E-04	1.1E-07
D31	6.05E-10	2.75E-03	2.6E-09	3.8E-06	8.1E-04	3.9E-04	2.2E-07
D32	6.05E-10	2.75E-03	2.4E-09	4.2E-06	5.6E-04	4.7E-04	1.4E-07
D33	6.05E-10	2.75E-03	7.1E-10	1.4E-05	3.2E-04	3.6E-04	4.0E-07
D34	6.05E-10	2.75E-03	7.1E-10	1.4E-05	4.1E-04	2.8E-04	7.9E-07
D35	6.05E-10	2.75E-03	3.0E-10	3.3E-05	2.2E-04	2.5E-04	9.9E-07
D36	6.05E-10	2.75E-03	2.4E-10	4.2E-05	2.0E-04	2.5E-04	1.3E-06

Sample	{Mg ⁺⁺ } mol/L	{NH ₄ ⁺ } mol/L	{PO ₄ ⁻ } mol/L	Ksp	pKsp	Ionic Strength
D1	2.1E-03	3.1E-03	2.4E-09	1.5E-14	13.8	0.014
D2	1.7E-03	2.4E-03	2.4E-09	9.4E-15	14.0	0.012
D3	1.6E-03	2.3E-03	2.5E-09	9.3E-15	14.0	0.011
D4	1.8E-03	2.7E-03	3.0E-09	1.5E-14	13.8	0.013
D5	1.5E-03	1.8E-03	4.7E-09	1.2E-14	13.9	0.009
D6	1.6E-03	2.1E-03	6.0E-09	2.0E-14	13.7	0.010
D7	1.4E-03	1.9E-03	5.6E-09	1.5E-14	13.8	0.009
D8	1.2E-03	1.6E-03	6.7E-09	1.3E-14	13.9	0.008
D9	1.3E-03	1.5E-03	6.9E-09	1.3E-14	13.9	0.007
D10	1.2E-03	1.3E-03	7.3E-09	1.2E-14	13.9	0.007
D11	1.2E-03	1.4E-03	1.0E-08	1.7E-14	13.8	0.007
D12	1.1E-03	1.1E-03	9.7E-09	1.2E-14	13.9	0.006
D13	1.1E-03	1.1E-03	1.1E-08	1.4E-14	13.9	0.006
D14	1.0E-03	1.2E-03	9.9E-09	1.2E-14	13.9	0.006
D15	1.1E-03	1.1E-03	1.2E-08	1.6E-14	13.8	0.006
D16	1.1E-03	1.2E-03	1.3E-08	1.7E-14	13.8	0.006
D17	1.1E-03	1.1E-03	1.4E-08	1.7E-14	13.8	0.006
D18	9.8E-04	9.0E-04	1.3E-08	1.2E-14	13.9	0.005
D19	9.2E-04	1.0E-03	1.3E-08	1.2E-14	13.9	0.005
D20	1.0E-03	8.3E-04	1.6E-08	1.4E-14	13.9	0.005
D21	9.3E-04	7.7E-04	1.8E-08	1.3E-14	13.9	0.004
D22	7.2E-04	6.5E-04	2.1E-08	9.9E-15	14.0	0.004
D23	8.1E-04	5.7E-04	2.6E-08	1.2E-14	13.9	0.004
D24	6.5E-04	5.5E-04	3.3E-08	1.2E-14	13.9	0.003
D25	7.9E-04	4.6E-04	3.7E-08	1.3E-14	13.9	0.005
D26	6.5E-04	5.1E-04	3.9E-08	1.3E-14	13.9	0.003
D27	6.5E-04	4.8E-04	4.7E-08	1.5E-14	13.8	0.004
D28	7.7E-04	4.4E-04	6.2E-08	2.1E-14	13.7	0.006
D29	5.8E-04	4.5E-04	5.3E-08	1.4E-14	13.9	0.003
D30	5.6E-04	4.1E-04	6.7E-08	1.6E-14	13.8	0.003
D31	5.7E-04	3.6E-04	9.9E-08	2.0E-14	13.7	0.007
D32	4.5E-04	4.4E-04	8.6E-08	1.7E-14	13.8	0.003
D33	2.4E-04	3.4E-04	2.2E-07	1.8E-14	13.7	0.004
D34	2.8E-04	2.5E-04	3.3E-07	2.3E-14	13.6	0.008
D35	1.6E-04	2.3E-04	4.9E-07	1.9E-14	13.7	0.005
D36	1.5E-04	2.3E-04	6.7E-07	2.3E-14	13.6	0.005

APPENDIX C: OPERATING DATA FOR REACTOR A

Date	MgCl Feed	Supernatant Lab results			Effluent Lab results			pH
	Mg (mg/l)	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	
2-Sep-01	1092	9.4	263	28.0	7.7	220	79.0	8.3
4-Sep-01	1092	8.3	284	27.3	11.3	263	83.0	8.4
5-Sep-01	1092	8.0	270	41.9	7.6	220	81.0	8.3
13-Sep-01	714	10.2	273	16.7	7.5	267	59.2	8.9
14-Sep-01	714	10.5	283	16.2	7.7	272	49.0	8.9
15-Sep-01	986	10.8	271	14.9	7.1	254	63.2	8.9
16-Sep-01	986	12.1	314	16.9	8.6	253	57.6	8.8
17-Sep-01	986	12.1	282	15.7	12.2	263	79.2	8.1
18-Sep-01	986	11.9	298	16.0	9.7	255	67.0	8.2
19-Sep-01	986	13.7	272	16.1	8.1	246	64.4	8.6
20-Sep-01	986	11.7	277	14.4	8.2	278	71.8	8.5
21-Sep-01	977	11.5	277	13.5	8.3	272	79.0	8.8
22-Sep-01	977	12.8	279	11.7	8.9	259	30.8	8.8
23-Sep-01	977	12.6	281	16.4	8.8	260	71.0	8.8
24-Sep-01	977	12.3	276	13.4	18.0	232	110.4	8.8
2-Oct-01	977	12.3	290	21.1	5.5	279	102.4	8.8
3-Oct-01	977	11.8	262	21.4	3.9	237	79.1	8.8
4-Oct-01	977	18.8	270	29.2	12.0	245	48.0	8.6
5-Oct-01	792	18.0	260	29.7	12.8	210	49.7	8.6
10-Oct-01	792	17.8	265	28.8	7.1	235	52.9	8.8
11-Oct-01	792	43.4	252	30.3	16.5	236	50.6	8.7
12-Oct-01	792	44.3	314	11.1	10.4	239	69.5	8.2
13-Oct-01	792	42.3	279	14.8	10.1	257	41.7	8.5
14-Oct-01	792	43.5	282	14.1	8.3	255	44.8	8.5
15-Oct-01	792	46.2	285	35.1	13.0	263	39.8	8.4
16-Oct-01	792	44.9	295	34.3	8.3	259	38.8	8.4
17-Oct-01	792	45.8	299	28.3	12.4	270	27.1	8.2
18-Oct-01	792	48.7	284	29.3	11.2	306	28.2	8.5
24-Oct-01	792	44.5	290	18.9	17.7	283	14.7	8.5
25-Oct-01	657	43.9	302	21.1	8.9	254	32.3	8.6
26-Oct-01	657	37.2	289	24.3	4.8	230	31.7	8.6
27-Oct-01	657	42.9	293	26.3	7.1	249	36.6	8.4
28-Oct-01	657	40.4	245	29.1	8.5	207	31.4	8.5
29-Oct-01	657	40.1	293	24.7	6.1	251	33.4	8.4
30-Oct-01	657	39.9	293	21.7	6.2	235	35.1	8.4
31-Oct-01	733	45.6	295	23.4	10.8	258	31.5	8.3

Date	MgCl Flow (mL/min)	Caustic Flow (l/day)	Total Influent Flow (mL/min)	Supernatant Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
2-Sep-01	47	103.5	950	831	2850	3800
4-Sep-01	52	100	900	779	2750	3650
5-Sep-01	47	75	950	851	2750	3700
13-Sep-01	48	10	1075	1020	2625	3700
14-Sep-01	46	7.5	1050	999	2600	3650
15-Sep-01	49	5	1000	948	2600	3600
16-Sep-01	60	7.5	1200	1135	2650	3850
17-Sep-01	62	80	1050	932	2650	3700
18-Sep-01	49	115	1000	871	2600	3600
19-Sep-01	52	150	925	769	2625	3550
20-Sep-01	50	5	950	897	2650	3600
21-Sep-01	50	7.5	1100	1045	2550	3650
22-Sep-01	0	2.5	1225	1223	2475	3700
23-Sep-01	51	15	1200	1139	2500	3700
24-Sep-01	52	5	1200	1145	2500	3700
2-Oct-01	52	15	1075	1013	2525	3600
3-Oct-01	52	20	1000	934	2500	3500
4-Oct-01	0	75	1350	1298	2500	3850
5-Oct-01	52	57.5	1325	1233	2425	3750
10-Oct-01	54	5	1125	1068	2525	3650
11-Oct-01	54	50	1225	1136	2525	3750
12-Oct-01	52	15	712	650	2938	3650
13-Oct-01	30	15	730	690	2820	3550
14-Oct-01	30	12.5	610	571	2940	3550
15-Oct-01	30	20	810	766	2940	3750
16-Oct-01	31	17.5	720	677	2830	3550
17-Oct-01	18	20	710	678	2865	3575
18-Oct-01	19	17.5	700	669	2900	3600
24-Oct-01	0	17.5	770	758	2880	3650
25-Oct-01	50	15	780	720	2820	3600
26-Oct-01	52	30	740	667	2860	3600
27-Oct-01	52	17.5	710	646	2890	3600
28-Oct-01	51	22.5	700	633	2900	3600
29-Oct-01	52	50	770	683	2830	3600
30-Oct-01	54	42.5	750	666	2825	3575
31-Oct-01	42	95	780	672	2870	3650

Date	Conditions at the inlet			Removal efficiency (%)		
	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	PO ₄ -P	NH ₄ -N	Mg
2-Sep-01	8.2	230	78.5	6	4	-1
4-Sep-01	7.1	246	86.7	-59	-7	4
5-Sep-01	7.1	242	91.6	-6	9	12
13-Sep-01	9.7	259	47.7	23	-3	-24
14-Sep-01	10.0	269	46.7	23	-1	-5
15-Sep-01	10.2	257	62.4	31	1	-1
16-Sep-01	11.4	297	65.3	25	15	12
17-Sep-01	10.7	250	72.1	-14	-5	-10
18-Sep-01	10.4	260	62.2	6	2	-8
19-Sep-01	11.4	226	68.8	29	-9	6
20-Sep-01	11.0	261	65.5	26	-6	-10
21-Sep-01	10.9	263	57.2	24	-3	-38
22-Sep-01	12.8	279	11.7	30	7	-164
23-Sep-01	12.0	267	57.0	26	2	-25
24-Sep-01	11.7	263	55.1	-53	12	-100
2-Oct-01	11.6	273	67.1	53	-2	-53
3-Oct-01	11.0	245	70.8	65	3	-12
4-Oct-01	18.1	260	28.1	34	6	-71
5-Oct-01	16.8	242	58.7	24	13	15
10-Oct-01	16.9	251	65.3	58	7	19
11-Oct-01	40.3	234	63.0	59	-1	20
12-Oct-01	40.4	286	67.9	74	17	-2
13-Oct-01	40.0	264	46.5	75	2	10
14-Oct-01	40.7	264	52.2	80	3	14
15-Oct-01	43.7	270	62.5	70	2	36
16-Oct-01	42.2	277	66.3	80	7	42
17-Oct-01	43.7	286	47.1	72	5	43
18-Oct-01	46.5	271	49.5	76	-13	43
24-Oct-01	43.8	285	18.6	60	1	21
25-Oct-01	40.5	279	61.6	78	9	48
26-Oct-01	33.5	261	68.1	86	12	53
27-Oct-01	39.0	267	72.1	82	7	49
28-Oct-01	36.6	222	74.2	77	7	58
29-Oct-01	35.6	260	66.3	83	3	50
30-Oct-01	35.5	260	66.6	83	10	47
31-Oct-01	39.3	254	59.6	73	-2	47

Date	Molar removal Inlet to outlet			Mg:P Removal Ratio	N:P Removal Ratio
	PO ₄ -P	NH ₄ -N	Mg		
2-Sep-01	1.6E-05	7.2E-04	-2.0E-05	-1.2	44.1
4-Sep-01	-1.4E-04	-1.2E-03	1.5E-04	-1.1	9.1
5-Sep-01	-1.3E-05	1.6E-03	4.4E-04	-32.7	-117.2
13-Sep-01	7.0E-05	-5.7E-04	-4.7E-04	-6.7	-8.1
14-Sep-01	7.4E-05	-2.0E-04	-9.5E-05	-1.3	-2.7
15-Sep-01	1.0E-04	2.0E-04	-3.6E-05	-0.4	2.0
16-Sep-01	9.2E-05	3.1E-03	3.2E-04	3.4	34.2
17-Sep-01	-4.7E-05	-9.0E-04	-2.9E-04	6.2	19.1
18-Sep-01	2.2E-05	3.3E-04	-2.0E-04	-9.1	15.3
19-Sep-01	1.1E-04	-1.4E-03	1.8E-04	1.7	-13.4
20-Sep-01	9.2E-05	-1.2E-03	-2.6E-04	-2.8	-12.9
21-Sep-01	8.5E-05	-6.4E-04	-9.0E-04	-10.6	-7.5
22-Sep-01	1.3E-04	1.4E-03	-7.9E-04	-6.3	11.2
23-Sep-01	1.0E-04	4.7E-04	-5.8E-04	-5.7	4.6
24-Sep-01	-2.0E-04	2.2E-03	-2.3E-03	11.2	-11.0
2-Oct-01	2.0E-04	-4.2E-04	-1.5E-03	-7.4	-2.1
3-Oct-01	2.3E-04	5.5E-04	-3.4E-04	-1.5	2.4
4-Oct-01	2.0E-04	1.0E-03	-8.2E-04	-4.2	5.3
5-Oct-01	1.3E-04	2.3E-03	3.7E-04	2.9	17.9
10-Oct-01	3.2E-04	1.2E-03	5.1E-04	1.6	3.7
11-Oct-01	7.7E-04	-1.6E-04	5.1E-04	0.7	-0.2
12-Oct-01	9.7E-04	3.4E-03	-6.3E-05	-0.1	3.5
13-Oct-01	9.6E-04	4.7E-04	2.0E-04	0.2	0.5
14-Oct-01	1.0E-03	6.5E-04	3.0E-04	0.3	0.6
15-Oct-01	9.9E-04	4.7E-04	9.3E-04	0.9	0.5
16-Oct-01	1.1E-03	1.3E-03	1.1E-03	1.0	1.2
17-Oct-01	1.0E-03	1.1E-03	8.2E-04	0.8	1.1
18-Oct-01	1.1E-03	-2.5E-03	8.8E-04	0.8	-2.2
24-Oct-01	8.4E-04	1.7E-04	1.6E-04	0.2	0.2
25-Oct-01	1.0E-03	1.8E-03	1.2E-03	1.2	1.7
26-Oct-01	9.3E-04	2.2E-03	1.5E-03	1.6	2.4
27-Oct-01	1.0E-03	1.3E-03	1.5E-03	1.4	1.2
28-Oct-01	9.1E-04	1.0E-03	1.8E-03	1.9	1.2
29-Oct-01	9.5E-04	6.4E-04	1.4E-03	1.4	0.7
30-Oct-01	9.4E-04	1.8E-03	1.3E-03	1.4	1.9
31-Oct-01	9.2E-04	-2.7E-04	1.2E-03	1.3	-0.3

Date	PO ₄ -P In-Reactor			NH ₄ -N In-Reactor		
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)
2-Sep-01	2.1	5.8	7.8	58	165	223
4-Sep-01	1.8	8.5	10.3	61	198	259
5-Sep-01	1.8	5.6	7.5	62	164	226
13-Sep-01	2.8	5.3	8.1	75	189	265
14-Sep-01	2.9	5.5	8.4	77	194	271
15-Sep-01	2.8	5.1	8.0	71	183	255
16-Sep-01	3.6	5.9	9.5	93	174	267
17-Sep-01	3.0	8.7	11.8	71	188	259
18-Sep-01	2.9	7.0	9.9	72	184	256
19-Sep-01	3.0	6.0	9.0	59	182	241
20-Sep-01	2.9	6.0	8.9	69	205	274
21-Sep-01	3.3	5.8	9.1	79	190	269
22-Sep-01	4.2	6.0	10.2	92	173	265
23-Sep-01	3.9	5.9	9.8	86	176	262
24-Sep-01	3.8	12.2	16.0	85	157	242
2-Oct-01	3.5	3.9	7.3	82	196	277
3-Oct-01	3.1	2.8	5.9	70	169	239
4-Oct-01	6.3	7.8	14.1	91	159	250
5-Oct-01	5.9	8.3	14.2	85	136	221
10-Oct-01	5.2	4.9	10.1	78	163	240
11-Oct-01	13.2	11.1	24.3	76	159	235
12-Oct-01	7.9	8.4	16.3	56	192	248
13-Oct-01	8.2	8.0	16.2	54	204	258
14-Oct-01	7.0	6.9	13.9	45	211	257
15-Oct-01	9.4	10.2	19.6	58	206	264
16-Oct-01	8.6	6.6	15.2	56	206	263
17-Oct-01	8.7	9.9	18.6	57	216	273
18-Oct-01	9.0	9.0	18.1	53	247	299
24-Oct-01	9.2	14.0	23.2	60	223	284
25-Oct-01	8.8	7.0	15.7	60	199	259
26-Oct-01	6.9	3.8	10.7	54	183	236
27-Oct-01	7.7	5.7	13.4	53	200	252
28-Oct-01	7.1	6.8	14.0	43	167	210
29-Oct-01	7.6	4.8	12.4	56	197	253
30-Oct-01	7.4	4.9	12.3	55	186	240
31-Oct-01	8.4	8.5	16.9	54	203	257

Date	Mg In-Reactor			In-Reactor Concentrations			In-Reacor Mg:P (molar ratio)	In-Reactor N:P (molar ratio)
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	PO ₄ -P (mol/L)	NH ₄ -N (mol/L)	Mg (mol/L)		
2-Sep-01	19.6	59.3	78.9	2.5E-04	1.6E-02	3.2E-03	12.8	62.9
4-Sep-01	21.4	62.5	83.9	3.3E-04	1.8E-02	3.5E-03	10.4	55.5
5-Sep-01	23.5	60.2	83.7	2.4E-04	1.6E-02	3.4E-03	14.3	67.0
13-Sep-01	13.9	42.0	55.9	2.6E-04	1.9E-02	2.3E-03	8.8	72.0
14-Sep-01	13.4	34.9	48.3	2.7E-04	1.9E-02	2.0E-03	7.4	71.8
15-Sep-01	17.3	45.7	63.0	2.6E-04	1.8E-02	2.6E-03	10.1	70.7
16-Sep-01	20.3	39.6	60.0	3.1E-04	1.9E-02	2.5E-03	8.1	62.2
17-Sep-01	20.5	56.7	77.2	3.8E-04	1.9E-02	3.2E-03	8.3	48.7
18-Sep-01	17.3	48.4	65.7	3.2E-04	1.8E-02	2.7E-03	8.5	57.4
19-Sep-01	17.9	47.6	65.5	2.9E-04	1.7E-02	2.7E-03	9.3	59.5
20-Sep-01	17.3	52.9	70.1	2.9E-04	2.0E-02	2.9E-03	10.0	67.6
21-Sep-01	17.2	55.2	72.4	2.9E-04	1.9E-02	3.0E-03	10.1	65.5
22-Sep-01	3.9	20.6	24.5	3.3E-04	1.9E-02	1.0E-03	3.1	57.7
23-Sep-01	18.5	48.0	66.5	3.2E-04	1.9E-02	2.7E-03	8.6	59.0
24-Sep-01	17.9	74.6	92.5	5.2E-04	1.7E-02	3.8E-03	7.4	33.5
2-Oct-01	20.0	71.8	91.9	2.4E-04	2.0E-02	3.8E-03	16.0	83.8
3-Oct-01	20.2	56.5	76.8	1.9E-04	1.7E-02	3.2E-03	16.5	89.2
4-Oct-01	9.9	31.2	41.0	4.6E-04	1.8E-02	1.7E-03	3.7	39.2
5-Oct-01	20.7	32.1	52.9	4.6E-04	1.6E-02	2.2E-03	4.7	34.5
10-Oct-01	20.1	36.6	56.7	3.3E-04	1.7E-02	2.3E-03	7.1	52.5
11-Oct-01	20.6	34.1	54.7	7.8E-04	1.7E-02	2.3E-03	2.9	21.5
12-Oct-01	13.3	55.9	69.2	5.2E-04	1.8E-02	2.8E-03	5.4	33.8
13-Oct-01	9.6	33.1	42.7	5.2E-04	1.8E-02	1.8E-03	3.3	35.2
14-Oct-01	9.0	37.1	46.1	4.5E-04	1.8E-02	1.9E-03	4.2	40.9
15-Oct-01	13.5	31.2	44.7	6.3E-04	1.9E-02	1.8E-03	2.9	29.8
16-Oct-01	13.5	30.9	44.4	4.9E-04	1.9E-02	1.8E-03	3.7	38.3
17-Oct-01	9.4	21.7	31.0	6.0E-04	2.0E-02	1.3E-03	2.1	32.4
18-Oct-01	9.6	22.7	32.3	5.8E-04	2.1E-02	1.3E-03	2.3	36.6
24-Oct-01	3.9	11.6	15.5	7.5E-04	2.0E-02	6.4E-04	0.9	27.0
25-Oct-01	13.3	25.3	38.6	5.1E-04	1.9E-02	1.6E-03	3.1	36.4
26-Oct-01	14.0	25.2	39.2	3.5E-04	1.7E-02	1.6E-03	4.7	48.8
27-Oct-01	14.2	29.4	43.6	4.3E-04	1.8E-02	1.8E-03	4.1	41.7
28-Oct-01	14.4	25.3	39.7	4.5E-04	1.5E-02	1.6E-03	3.6	33.3
29-Oct-01	14.2	26.3	40.4	4.0E-04	1.8E-02	1.7E-03	4.2	45.1
30-Oct-01	14.0	27.7	41.7	4.0E-04	1.7E-02	1.7E-03	4.3	43.1
31-Oct-01	12.7	24.8	37.5	5.5E-04	1.8E-02	1.5E-03	2.8	33.7

Date	Feed P _S	In-Reactor P _S	Equilibrium P _S	Feed S.S. ratio	In-Reactor S.S. Ratio	Effluent S.S. Ratio	Crystal Volume (l)	Harvest Volume (l)
2-Sep-01	1.4E-08	1.3E-08	6.7E-09	2.1	1.9	1.9		
4-Sep-01	1.4E-08	2.1E-08	5.7E-09	2.5	3.7	4.1		
5-Sep-01	1.5E-08	1.3E-08	6.7E-09	2.2	2.0	1.9		
13-Sep-01	1.1E-08	1.1E-08	3.0E-09	3.8	3.9	3.8	0.68	
14-Sep-01	1.2E-08	1.0E-08	3.0E-09	4.0	3.5	3.3	0.75	
15-Sep-01	1.6E-08	1.2E-08	3.0E-09	5.2	4.1	3.7	1.08	
16-Sep-01	2.1E-08	1.4E-08	3.3E-09	6.3	4.3	3.6	1.40	
17-Sep-01	1.8E-08	2.2E-08	9.5E-09	1.9	2.4	2.5	1.10	
18-Sep-01	1.6E-08	1.6E-08	8.0E-09	2.0	2.0	2.0	1.20	
19-Sep-01	1.7E-08	1.3E-08	4.3E-09	3.9	3.1	2.8	1.30	
20-Sep-01	1.8E-08	1.6E-08	4.9E-09	3.6	3.3	3.2	1.40	
21-Sep-01	1.6E-08	1.7E-08	3.3E-09	4.7	5.1	5.1	1.25	
22-Sep-01	3.9E-09	6.3E-09	3.3E-09	1.2	1.9	2.0	1.20	
23-Sep-01	1.7E-08	1.6E-08	3.3E-09	5.2	4.9	4.6	1.70	
24-Sep-01	1.6E-08	3.4E-08	3.3E-09	4.9	10.2	13.2	1.20	
2-Oct-01	2.0E-08	1.8E-08	3.3E-09	6.1	5.3	4.5	1.20	
3-Oct-01	1.8E-08	1.0E-08	3.3E-09	5.5	3.1	2.1	1.50	
4-Oct-01	1.3E-08	1.4E-08	4.3E-09	2.9	3.2	3.1	2.00	
5-Oct-01	2.3E-08	1.6E-08	4.3E-09	5.3	3.7	3.0	2.55	
10-Oct-01	2.6E-08	1.3E-08	3.3E-09	7.9	3.9	2.5	1.80	
11-Oct-01	5.6E-08	3.0E-08	3.8E-09	15.0	7.9	5.0	3.30	
12-Oct-01	7.5E-08	2.6E-08	8.0E-09	9.4	3.3	2.1	3.92	0.7
13-Oct-01	4.6E-08	1.7E-08	4.9E-09	9.4	3.4	2.1	3.84	
14-Oct-01	5.3E-08	1.6E-08	4.9E-09	10.8	3.2	1.8	4.46	
15-Oct-01	7.0E-08	2.2E-08	5.7E-09	12.2	3.8	2.3	5.08	
16-Oct-01	7.4E-08	1.7E-08	5.7E-09	12.9	2.9	1.4	5.70	1.1
17-Oct-01	5.6E-08	1.5E-08	8.0E-09	7.0	1.9	1.1	5.10	1.1
18-Oct-01	5.9E-08	1.7E-08	4.9E-09	12.0	3.4	1.9	4.60	
24-Oct-01	2.2E-08	9.7E-09	4.9E-09	4.5	2.0	1.4	5.20	
25-Oct-01	6.6E-08	1.5E-08	4.3E-09	15.4	3.5	1.6	6.00	
26-Oct-01	5.6E-08	9.4E-09	4.3E-09	13.2	2.2	0.8	6.90	1.1
27-Oct-01	7.1E-08	1.4E-08	5.7E-09	12.4	2.4	1.1	6.10	
28-Oct-01	5.7E-08	1.1E-08	4.9E-09	11.6	2.2	1.1	6.50	1.1
29-Oct-01	5.8E-08	1.2E-08	5.7E-09	10.2	2.1	0.8	6.00	
30-Oct-01	5.8E-08	1.2E-08	5.7E-09	10.2	2.0	0.8	6.40	1.1
31-Oct-01	5.7E-08	1.5E-08	6.7E-09	8.4	2.3	1.2	6.10	

Date	CRT		Harvested Product Data				Total Mass (g)
	Actual (days)	CRT Averaged In reactor SS Ratio	> 2 mm (g)	> 1 mm (g)	> 0.5 mm (g)	< 0.5 mm (g)	
2-Sep-01							
4-Sep-01							
5-Sep-01							
13-Sep-01							
14-Sep-01							
15-Sep-01							
16-Sep-01							
17-Sep-01							
18-Sep-01							
19-Sep-01							
20-Sep-01							
21-Sep-01							
22-Sep-01							
23-Sep-01							
24-Sep-01							
2-Oct-01							
3-Oct-01							
4-Oct-01							
5-Oct-01							
10-Oct-01							
11-Oct-01							
12-Oct-01	18	3.9	83.4	41.2	0.7	3.8	129.1
13-Oct-01							
14-Oct-01							
15-Oct-01							
16-Oct-01	23	3.9	7.4	26.9	25.7	122.6	182.5
17-Oct-01	24	3.8	0.2	17.8	35.4	98.2	151.5
18-Oct-01							
24-Oct-01							
25-Oct-01							
26-Oct-01	28	3.6	0.3	39.1	74.9	100.4	214.7
27-Oct-01							
28-Oct-01	30	3.6	0.4	43.6	68.7	82.7	195.3
29-Oct-01							
30-Oct-01	32	3.5	0.2	49.8	81.8	102.7	234.6
31-Oct-01							

Date	Harvested Product Data					Mass P	Theoretical
	% > 2mm	% 1-2 mm	% 0.5-1mm	% < 0.5mm	Mean Crystal Size (mm)	Removed (g)	Mass MAP Grown (g)
2-Sep-01						0.7	5.5
4-Sep-01						-5.4	-43.1
5-Sep-01						-0.6	-4.5
13-Sep-01						3.4	26.7
14-Sep-01						3.5	27.4
15-Sep-01						4.5	35.7
16-Sep-01						4.9	38.9
17-Sep-01						-2.2	-17.4
18-Sep-01						1.0	7.6
19-Sep-01						4.4	34.7
20-Sep-01						3.9	30.8
21-Sep-01						4.2	32.9
22-Sep-01						6.8	54.2
23-Sep-01						5.5	43.2
24-Sep-01						-10.8	-85.8
2-Oct-01						9.4	74.6
3-Oct-01						10.3	81.2
4-Oct-01						11.8	93.5
5-Oct-01						7.5	59.7
10-Oct-01						15.9	125.6
11-Oct-01						41.9	331.9
12-Oct-01	64.6	31.9	0.5	3.0	2.1	30.8	243.7
13-Oct-01						31.4	248.6
14-Oct-01						28.5	225.7
15-Oct-01						35.8	283.6
16-Oct-01	4.0	14.7	14.1	67.2	0.6	35.2	278.4
17-Oct-01	0.2	11.7	23.3	64.8	0.5	32.0	253.8
18-Oct-01						35.6	282.1
24-Oct-01						28.9	229.2
25-Oct-01						35.5	281.1
26-Oct-01	0.2	18.2	34.9	46.8	0.7	30.6	242.5
27-Oct-01						32.6	258.5
28-Oct-01	0.2	22.3	35.2	42.3	0.7	28.3	224.0
29-Oct-01						32.7	258.9
30-Oct-01	0.1	21.2	34.9	43.8	0.7	31.6	250.2
31-Oct-01						32.0	253.4

Date	Notes
<i>2-Sep-01</i>	
<i>4-Sep-01</i>	
<i>5-Sep-01</i>	
<i>13-Sep-01</i>	
<i>14-Sep-01</i>	
<i>15-Sep-01</i>	
<i>16-Sep-01</i>	
<i>17-Sep-01</i>	
<i>18-Sep-01</i>	
<i>19-Sep-01</i>	
<i>20-Sep-01</i>	
<i>21-Sep-01</i>	
<i>22-Sep-01</i>	<i>Mg Feed off</i>
<i>23-Sep-01</i>	
<i>24-Sep-01</i>	<i>Power Failure</i>
<i>2-Oct-01</i>	
<i>3-Oct-01</i>	
<i>4-Oct-01</i>	
<i>5-Oct-01</i>	
<i>10-Oct-01</i>	
<i>11-Oct-01</i>	
<i>12-Oct-01</i>	
<i>13-Oct-01</i>	
<i>14-Oct-01</i>	
<i>15-Oct-01</i>	
<i>16-Oct-01</i>	
<i>17-Oct-01</i>	
<i>18-Oct-01</i>	
<i>24-Oct-01</i>	
<i>25-Oct-01</i>	
<i>26-Oct-01</i>	
<i>27-Oct-01</i>	
<i>28-Oct-01</i>	
<i>29-Oct-01</i>	
<i>30-Oct-01</i>	
<i>31-Oct-01</i>	

Date	MgCl Feed	Supernatant Lab results			Effluent Lab results			pH
	Mg (mg/l)	PO ₄ -P (mg/L)	NH ₄ N (mg/L)	Mg (mg/L)	PO ₄ -P (mg/L)	NH ₄ N (mg/L)	Mg (mg/L)	
1-Nov-01	733	46.7	284	25.8	9.0	272	32.3	8.3
2-Nov-01	733	46.4	283	25.5	7.8	262	31.5	8.4
7-Nov-01	733	46.4	324	30.1	12.3	262	29.8	8.1
8-Nov-01	733	45.6	298	28.8	6.0	230	25.5	8.6
9-Nov-01	733	45.9	302	29.1	6.2	245	24.9	8.6
10-Nov-01	733	46.3	274	28.8	6.6	244	22.8	8.6
11-Nov-01	733	54.8	298	29.7	5.7	220	33.9	8.6
12-Nov-01	733	53.7	267	30.7	6.4	230	27.7	8.6
13-Nov-01	733	54.8	284	29.4	8.8	256	18.1	8.4
14-Nov-01	495	53.0	304	32.4	9.0	255	17.9	8.4
15-Nov-01	495	51.9	299	30.6	6.4	267	20.2	8.5
16-Nov-01	495	51.9	299	30.6	6.4	267	20.2	8.5
17-Nov-01	495	51.9	299	30.6	6.4	267	20.2	8.5
18-Nov-01	495	51.9	273	29.3	6.2	236	23.9	8.5
19-Nov-01	495	61.2	197	30.3	6.1	176	38.3	8.6
20-Nov-01	495	59.8	354	28.3	4.1	275	69.2	8.5
21-Nov-01	495	64.0	365	28.9	11.5	309	13.1	8.5
22-Nov-01	495	63.7	360	27.1	10.2	299	15.1	8.5
23-Nov-01	495	61.5	369	29.9	11.0	317	15.4	8.5
24-Nov-01	623	60.2	356	27.1	8.3	305	17.7	8.5
25-Nov-01	623	60.2	356	27.1	8.3	305	17.7	8.5
26-Nov-01	623	60.2	356	27.1	8.3	305	17.7	8.5
27-Nov-01	623	61.5	354	26.3	8.3	305	18.4	8.5
28-Nov-01	623	60.6	366	27.3	7.7	312	19.7	8.5
29-Nov-01	623	61.7	346	28.2	8.6	285	17.1	8.5
30-Nov-01	623	58.5	359	25.7	7.4	296	17.5	8.5
1-Dec-01	623	65.2	380	26.3	12.4	305	17.8	8.4
2-Dec-01	623	68.1	406	26.0	17.0	345	22.3	8.1
3-Dec-01	623	67.2	391	26.1	13.7	338	17.9	8.5
4-Dec-01	623	69.2	436	24.9	12.0	351	19.5	8.3
5-Dec-01	616	69.1	400	29.5	12.1	336	18.7	8.4
6-Dec-01	616	68.2	398	25.4	7.8	354	15.1	8.7
7-Dec-01	616	71.1	399	25.4	11.8	330	18.3	8.4
8-Dec-01	616	71.1	399	25.4	11.8	330	18.3	8.4
9-Dec-01	616	71.1	399	25.4	11.8	330	18.3	8.4
10-Dec-01	616	71.1	399	25.4	11.8	330	18.3	8.4
11-Dec-01	616	71.2	409	23.7	11.5	332	17.7	8.4
12-Dec-01	616	65.7	426	29.4	10.5	320	18.2	8.4
13-Dec-01	616	64.6	399	30.6	12.4	346	16.1	8.4
Oct 12-Dec 13								
Average	647	55.1	330	26.8	9.3	281	25.9	8.5
Minimum	495	37.2	197	11.1	4.1	176	13.1	8.1
Maximum	792	71.2	436	35.1	17.7	354	69.5	8.7
St.Dev.	96	10.3	53	4.5	2.9	41	11.9	0.1
Count	55	55	55	55	55	55	55	55

Date	MgCl Flow (mL/min)	Caustic Flow (l/day)	Total Influent Flow (mL/min)	Supernatant Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
1-Nov-01	41	65	720	634	2880	3600
2-Nov-01	42	70	710	619	2890	3600
7-Nov-01	40	30	690	629	2810	3500
8-Nov-01	28	40	460	404	2990	3450
9-Nov-01	28	47.5	500	439	3000	3500
10-Nov-01	28	25	510	465	3040	3550
11-Nov-01	29	25	280	234	3320	3600
12-Nov-01	27	30	380	332	2870	3250
13-Nov-01	28	30	560	511	2990	3550
14-Nov-01	26	37.5	590	538	3010	3600
15-Nov-01	27	30	530	482	3000	3530
16-Nov-01	27	30	470	422	2995	3465
17-Nov-01	27	30	415	367	2985	3400
18-Nov-01	27	15	390	353	3010	3400
19-Nov-01	28	30	250	201	3500	3750
20-Nov-01	26	17.5	160	122	3540	3700
21-Nov-01	27	42.5	590	533	2860	3450
22-Nov-01	28	45	540	481	3010	3550
23-Nov-01	27	25	520	476	3080	3600
24-Nov-01	26	40	540	486	2910	3450
25-Nov-01	26	40	540	486	2910	3450
26-Nov-01	26	40	540	486	2910	3450
27-Nov-01	27	30	520	472	2930	3450
28-Nov-01	31	25	550	502	2800	3350
29-Nov-01	21	30	400	358	3200	3600
30-Nov-01	21	27.5	380	340	3220	3600
1-Dec-01	22	30	390	347	3235	3625
2-Dec-01	21	32.5	360	316	3280	3640
3-Dec-01	22	40	450	400	3200	3650
4-Dec-01	22	70	390	319	3160	3550
5-Dec-01	22	20	400	364	3175	3575
6-Dec-01	23	20	360	323	3190	3550
7-Dec-01	21	1.25	390	368	3140	3530
8-Dec-01	21	1.25	390	368	3140	3530
9-Dec-01	21	1.25	390	368	3140	3530
10-Dec-01	21	1.25	390	368	3140	3530
11-Dec-01	21	30	360	318	3200	3560
12-Dec-01	21	15	360	329	3190	3550
13-Dec-01	22	30	410	367	3190	3600
Oct 12-Dec 13						
Average	29	30	533	483	3021	3554
Minimum	0	1.25	160	122	2800	3250
Maximum	54	95	810	766	3540	3750
St.Dev.	11	18	163	155	174	91
Count	55	55	55	55	55	55

Date	Conditions at the inlet			Removal efficiency (%)		
	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	PO ₄ -P	NH ₄ -N	Mg
1-Nov-01	41.1	250	64.4	78	-9	50
2-Nov-01	40.5	247	65.6	81	-6	52
7-Nov-01	42.3	295	69.9	71	11	57
8-Nov-01	40.1	262	69.9	85	12	64
9-Nov-01	40.3	265	66.6	85	8	63
10-Nov-01	42.2	250	66.5	84	2	66
11-Nov-01	45.7	249	100.7	88	12	66
12-Nov-01	46.9	233	78.9	86	1	65
13-Nov-01	50.0	259	63.5	82	1	71
14-Nov-01	48.3	277	51.3	81	8	65
15-Nov-01	47.2	272	53.0	86	2	62
16-Nov-01	46.6	269	55.9	86	1	64
17-Nov-01	45.9	265	59.3	86	-1	66
18-Nov-01	46.9	247	60.7	87	4	61
19-Nov-01	49.2	159	79.8	88	-11	52
20-Nov-01	45.5	270	101.9	91	-2	32
21-Nov-01	57.9	330	48.8	80	6	73
22-Nov-01	56.7	321	49.8	82	7	70
23-Nov-01	56.2	338	53.0	80	6	71
24-Nov-01	54.2	321	54.4	85	5	67
25-Nov-01	54.2	321	54.4	85	5	67
26-Nov-01	54.2	321	54.4	85	5	67
27-Nov-01	55.8	321	56.2	85	5	67
28-Nov-01	55.2	334	60.0	86	7	67
29-Nov-01	55.2	310	58.0	84	8	70
30-Nov-01	52.3	321	57.4	86	8	70
1-Dec-01	58.0	338	58.6	79	10	70
2-Dec-01	59.8	357	59.2	72	3	62
3-Dec-01	59.8	348	53.7	77	3	67
4-Dec-01	56.6	357	55.5	79	2	65
5-Dec-01	62.9	364	60.7	81	8	69
6-Dec-01	61.2	357	62.1	87	1	76
7-Dec-01	67.1	377	57.1	82	12	68
8-Dec-01	67.1	377	57.1	82	12	68
9-Dec-01	67.1	377	57.1	82	12	68
10-Dec-01	67.1	377	57.1	82	12	68
11-Dec-01	62.9	361	56.9	82	8	69
12-Dec-01	59.9	389	62.7	83	18	71
13-Dec-01	57.8	357	60.4	79	3	73
Oct 12-Dec 13						
Average	49.6	297	61.0	81	5	57
Minimum	33.5	159	18.6	60	-13	-2
Maximum	67.1	389	101.9	91	18	76
St.Dev.	9.3	49	12.3	6	6	17
Count	55	55	55	55	55	55

Date	Molar removal Inlet to outlet			Mg:P Removal Ratio	N:P Removal Ratio
	PO ₄ -P	NH ₄ -N	Mg		
1-Nov-01	1.0E-03	-1.6E-03	1.3E-03	1.3	-1.5
2-Nov-01	1.1E-03	-1.1E-03	1.4E-03	1.3	-1.0
7-Nov-01	9.7E-04	2.4E-03	1.7E-03	1.7	2.5
8-Nov-01	1.1E-03	2.3E-03	1.8E-03	1.7	2.1
9-Nov-01	1.1E-03	1.4E-03	1.7E-03	1.6	1.3
10-Nov-01	1.1E-03	4.0E-04	1.8E-03	1.6	0.3
11-Nov-01	1.3E-03	2.0E-03	2.7E-03	2.1	1.6
12-Nov-01	1.3E-03	2.4E-04	2.1E-03	1.6	0.2
13-Nov-01	1.3E-03	2.3E-04	1.9E-03	1.4	0.2
14-Nov-01	1.3E-03	1.6E-03	1.4E-03	1.1	1.2
15-Nov-01	1.3E-03	3.6E-04	1.4E-03	1.0	0.3
16-Nov-01	1.3E-03	1.1E-04	1.5E-03	1.1	0.1
17-Nov-01	1.3E-03	-1.8E-04	1.6E-03	1.3	-0.1
18-Nov-01	1.3E-03	7.7E-04	1.5E-03	1.2	0.6
19-Nov-01	1.4E-03	-1.2E-03	1.7E-03	1.2	-0.9
20-Nov-01	1.3E-03	-3.9E-04	1.3E-03	1.0	-0.3
21-Nov-01	1.5E-03	1.5E-03	1.5E-03	1.0	1.0
22-Nov-01	1.5E-03	1.5E-03	1.4E-03	1.0	1.0
23-Nov-01	1.5E-03	1.5E-03	1.5E-03	1.1	1.0
24-Nov-01	1.5E-03	1.1E-03	1.5E-03	1.0	0.7
25-Nov-01	1.5E-03	1.1E-03	1.5E-03	1.0	0.7
26-Nov-01	1.5E-03	1.1E-03	1.5E-03	1.0	0.7
27-Nov-01	1.5E-03	1.2E-03	1.6E-03	1.0	0.8
28-Nov-01	1.5E-03	1.6E-03	1.7E-03	1.1	1.0
29-Nov-01	1.5E-03	1.8E-03	1.7E-03	1.1	1.2
30-Nov-01	1.5E-03	1.8E-03	1.6E-03	1.1	1.2
1-Dec-01	1.5E-03	2.4E-03	1.7E-03	1.1	1.6
2-Dec-01	1.4E-03	8.5E-04	1.5E-03	1.1	0.6
3-Dec-01	1.5E-03	7.0E-04	1.5E-03	1.0	0.5
4-Dec-01	1.4E-03	4.3E-04	1.5E-03	1.0	0.3
5-Dec-01	1.6E-03	2.0E-03	1.7E-03	1.1	1.2
6-Dec-01	1.7E-03	2.3E-04	1.9E-03	1.1	0.1
7-Dec-01	1.8E-03	3.3E-03	1.6E-03	0.9	1.9
8-Dec-01	1.8E-03	3.3E-03	1.6E-03	0.9	1.9
9-Dec-01	1.8E-03	3.3E-03	1.6E-03	0.9	1.9
10-Dec-01	1.8E-03	3.3E-03	1.6E-03	0.9	1.9
11-Dec-01	1.7E-03	2.1E-03	1.6E-03	1.0	1.3
12-Dec-01	1.6E-03	4.9E-03	1.8E-03	1.1	3.1
13-Dec-01	1.5E-03	8.1E-04	1.8E-03	1.2	0.6
Oct 12-Dec 13					
Average	1.3E-03	1.2E-03	1.4E-03	1.1	0.9
Minimum	8.4E-04	-2.5E-03	-6.3E-05	-0.1	-2.2
Maximum	1.8E-03	4.9E-03	2.7E-03	2.1	3.5
St.Dev.	2.7E-04	1.3E-03	4.7E-04	0.4	1.0
Count	55	55	55	55	55

Date	PO ₄ -P In-Reactor			NH ₄ -N In-Reactor		
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)
1-Nov-01	8.2	7.2	15.4	50	218	268
2-Nov-01	8.0	6.3	14.2	49	210	259
7-Nov-01	8.3	9.9	18.2	58	210	269
8-Nov-01	5.3	5.2	10.5	35	199	234
9-Nov-01	5.8	5.3	11.1	38	210	248
10-Nov-01	6.1	5.7	11.7	36	209	245
11-Nov-01	3.6	5.3	8.8	19	203	222
12-Nov-01	5.5	5.7	11.1	27	203	230
13-Nov-01	7.9	7.4	15.3	41	216	257
14-Nov-01	7.9	7.5	15.4	45	213	259
15-Nov-01	7.1	5.4	12.5	41	227	268
16-Nov-01	6.3	5.5	11.9	36	231	267
17-Nov-01	5.6	5.6	11.2	32	234	267
18-Nov-01	5.4	5.5	10.9	28	209	237
19-Nov-01	3.3	5.7	9.0	11	164	175
20-Nov-01	2.0	3.9	5.9	12	263	275
21-Nov-01	9.9	9.5	19.4	56	256	313
22-Nov-01	8.6	8.6	17.3	49	254	302
23-Nov-01	8.1	9.4	17.5	49	271	320
24-Nov-01	8.5	7.0	15.4	50	257	307
25-Nov-01	8.5	7.0	15.4	50	257	307
26-Nov-01	8.5	7.0	15.4	50	257	307
27-Nov-01	8.4	7.0	15.5	48	259	307
28-Nov-01	9.1	6.4	15.5	55	261	316
29-Nov-01	6.1	7.6	13.8	34	253	288
30-Nov-01	5.5	6.6	12.1	34	265	299
1-Dec-01	6.2	11.0	17.3	36	272	309
2-Dec-01	5.9	15.3	21.2	35	311	346
3-Dec-01	7.4	12.0	19.4	43	296	339
4-Dec-01	6.2	10.7	16.9	39	312	352
5-Dec-01	7.0	10.7	17.8	41	298	339
6-Dec-01	6.2	7.0	13.2	36	318	354
7-Dec-01	7.4	10.5	17.9	42	294	335
8-Dec-01	7.4	10.5	17.9	42	294	335
9-Dec-01	7.4	10.5	17.9	42	294	335
10-Dec-01	7.4	10.5	17.9	42	294	335
11-Dec-01	6.4	10.3	16.7	37	298	335
12-Dec-01	6.1	9.4	15.5	39	288	327
13-Dec-01	6.6	11.0	17.6	41	307	347
Oct 12-Dec 13						
Average	7.2	7.9	15.1	44	239	283
Minimum	2.0	3.8	5.9	11	164	175
Maximum	9.9	15.3	23.2	60	318	354
St.Dev.	1.6	2.5	3.4	11	42	41
Count	55	55	55	55	55	55

Date	Mg In-Reactor			In-Reactor Concentrations			In-Reacor Mg:P (molar ratio)	In-Reactor N:P (molar ratio)
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	PO ₄ -P (mol/L)	NH ₄ -N (mol/L)	Mg (mol/L)		
1-Nov-01	12.9	25.8	38.7	5.0E-04	1.9E-02	1.6E-03	3.2	38.4
2-Nov-01	12.9	25.3	38.2	4.6E-04	1.9E-02	1.6E-03	3.4	40.2
7-Nov-01	13.8	23.9	37.7	5.9E-04	1.9E-02	1.6E-03	2.6	32.6
8-Nov-01	9.3	22.1	31.4	3.4E-04	1.7E-02	1.3E-03	3.8	49.2
9-Nov-01	9.5	21.3	30.9	3.6E-04	1.8E-02	1.3E-03	3.6	49.5
10-Nov-01	9.6	19.5	29.1	3.8E-04	1.7E-02	1.2E-03	3.2	46.2
11-Nov-01	7.8	31.3	39.1	2.8E-04	1.6E-02	1.6E-03	5.7	55.8
12-Nov-01	9.2	24.5	33.7	3.6E-04	1.6E-02	1.4E-03	3.9	45.8
13-Nov-01	10.0	15.2	25.3	4.9E-04	1.8E-02	1.0E-03	2.1	37.1
14-Nov-01	8.4	15.0	23.4	5.0E-04	1.8E-02	9.6E-04	1.9	37.0
15-Nov-01	8.0	17.2	25.1	4.0E-04	1.9E-02	1.0E-03	2.6	47.3
16-Nov-01	7.6	17.5	25.0	3.8E-04	1.9E-02	1.0E-03	2.7	49.9
17-Nov-01	7.2	17.7	25.0	3.6E-04	1.9E-02	1.0E-03	2.8	52.6
18-Nov-01	7.0	21.2	28.1	3.5E-04	1.7E-02	1.2E-03	3.3	48.3
19-Nov-01	5.3	35.7	41.1	2.9E-04	1.2E-02	1.7E-03	5.8	43.1
20-Nov-01	4.4	66.2	70.6	1.9E-04	2.0E-02	2.9E-03	15.3	103.2
21-Nov-01	8.3	10.9	19.2	6.3E-04	2.2E-02	7.9E-04	1.3	35.7
22-Nov-01	7.6	12.8	20.4	5.6E-04	2.2E-02	8.4E-04	1.5	38.7
23-Nov-01	7.7	13.2	20.8	5.7E-04	2.3E-02	8.6E-04	1.5	40.4
24-Nov-01	8.5	14.9	23.4	5.0E-04	2.2E-02	9.6E-04	1.9	44.1
25-Nov-01	8.5	14.9	23.4	5.0E-04	2.2E-02	9.6E-04	1.9	44.1
26-Nov-01	8.5	14.9	23.4	5.0E-04	2.2E-02	9.6E-04	1.9	44.1
27-Nov-01	8.5	15.6	24.1	5.0E-04	2.2E-02	9.9E-04	2.0	44.0
28-Nov-01	9.9	16.5	26.3	5.0E-04	2.3E-02	1.1E-03	2.2	45.2
29-Nov-01	6.4	15.2	21.6	4.5E-04	2.1E-02	8.9E-04	2.0	46.2
30-Nov-01	6.1	15.7	21.7	3.9E-04	2.1E-02	8.9E-04	2.3	54.4
1-Dec-01	6.3	15.9	22.2	5.6E-04	2.2E-02	9.1E-04	1.6	39.5
2-Dec-01	5.9	20.1	25.9	6.8E-04	2.5E-02	1.1E-03	1.6	36.1
3-Dec-01	6.6	15.7	22.3	6.3E-04	2.4E-02	9.2E-04	1.5	38.7
4-Dec-01	6.1	17.4	23.5	5.5E-04	2.5E-02	9.7E-04	1.8	46.0
5-Dec-01	6.8	16.6	23.4	5.7E-04	2.4E-02	9.6E-04	1.7	42.2
6-Dec-01	6.3	13.6	19.9	4.3E-04	2.5E-02	8.2E-04	1.9	59.5
7-Dec-01	6.3	16.3	22.6	5.8E-04	2.4E-02	9.3E-04	1.6	41.4
8-Dec-01	6.3	16.3	22.6	5.8E-04	2.4E-02	9.3E-04	1.6	41.4
9-Dec-01	6.3	16.3	22.6	5.8E-04	2.4E-02	9.3E-04	1.6	41.4
10-Dec-01	6.3	16.3	22.6	5.8E-04	2.4E-02	9.3E-04	1.6	41.4
11-Dec-01	5.7	15.9	21.7	5.4E-04	2.4E-02	8.9E-04	1.7	44.5
12-Dec-01	6.4	16.4	22.7	5.0E-04	2.3E-02	9.3E-04	1.9	46.8
13-Dec-01	6.9	14.3	21.1	5.7E-04	2.5E-02	8.7E-04	1.5	43.7
Oct 12-Dec 13								
Average	9.0	21.9	30.9	4.9E-04	2.0E-02	1.3E-03	2.9	43.2
Minimum	3.9	10.9	15.5	1.9E-04	1.2E-02	6.4E-04	0.9	27.0
Maximum	14.4	66.2	70.6	7.5E-04	2.5E-02	2.9E-03	15.3	103.2
St.Dev.	3.0	10.1	11.4	1.1E-04	3.0E-03	4.7E-04	2.1	10.6
Count	55	55	55	55	55	55	55	55

Date	Feed P _S	In-Reactor P _S	Equilibrium P _S	Feed S.S. ratio	In-Reactor S.S. Ratio	Effluent S.S. Ratio	Crystal Volume (l)	Harvest Volume (l)
1-Nov-01	6.3E-08	1.5E-08	6.7E-09	9.4	2.3	1.1	6.70	1.1
2-Nov-01	6.2E-08	1.3E-08	5.7E-09	10.9	2.3	1.1	6.35	
7-Nov-01	8.3E-08	1.8E-08	9.5E-09	8.7	1.8	1.0	6.80	1.1
8-Nov-01	7.0E-08	7.4E-09	4.3E-09	16.3	1.7	0.8	6.25	
9-Nov-01	6.8E-08	8.0E-09	4.3E-09	15.8	1.9	0.8	6.65	
10-Nov-01	6.6E-08	7.9E-09	4.3E-09	15.5	1.8	0.8	7.10	1.1
11-Nov-01	1.1E-07	7.3E-09	4.3E-09	25.4	1.7	0.9	6.00	
12-Nov-01	8.2E-08	8.2E-09	4.3E-09	19.2	1.9	0.9	6.50	
13-Nov-01	7.8E-08	9.4E-09	5.7E-09	13.6	1.6	0.7	6.90	1.1
14-Nov-01	6.5E-08	8.9E-09	5.7E-09	11.4	1.5	0.7	6.30	
15-Nov-01	6.5E-08	8.0E-09	4.9E-09	13.1	1.6	0.7	6.80	
16-Nov-01	6.6E-08	7.5E-09	4.9E-09	13.5	1.5	0.7	7.30	
17-Nov-01	6.8E-08	7.1E-09	4.9E-09	13.9	1.4	0.7	7.75	
18-Nov-01	6.7E-08	6.9E-09	4.9E-09	13.5	1.4	0.7	8.10	1.1
19-Nov-01	5.9E-08	6.1E-09	4.3E-09	13.8	1.4	0.9	7.40	
20-Nov-01	1.2E-07	1.1E-08	4.9E-09	24.1	2.2	1.5	7.30	1.1
21-Nov-01	8.8E-08	1.1E-08	4.9E-09	17.9	2.2	0.9	7.10	
22-Nov-01	8.6E-08	1.0E-08	4.9E-09	17.4	2.0	0.9	7.65	1.1
23-Nov-01	9.5E-08	1.1E-08	4.9E-09	19.4	2.3	1.0	7.05	
24-Nov-01	9.0E-08	1.1E-08	4.9E-09	18.2	2.1	0.9	7.65	
25-Nov-01	9.0E-08	1.1E-08	4.9E-09	18.2	2.1	0.9	8.25	
26-Nov-01	9.0E-08	1.1E-08	4.9E-09	18.2	2.1	0.9	8.55	1.1
27-Nov-01	9.6E-08	1.1E-08	4.9E-09	19.4	2.2	0.9	8.25	1.1
28-Nov-01	1.1E-07	1.2E-08	4.9E-09	21.3	2.5	0.9	7.95	1.1
29-Nov-01	9.4E-08	8.1E-09	4.9E-09	19.1	1.7	0.8	7.25	
30-Nov-01	9.2E-08	7.5E-09	4.9E-09	18.6	1.5	0.7	7.65	1.1
1-Dec-01	1.1E-07	1.1E-08	5.7E-09	19.1	2.0	1.1	7.00	
2-Dec-01	1.2E-07	1.8E-08	9.5E-09	12.6	1.9	1.3	7.30	
3-Dec-01	1.1E-07	1.4E-08	4.9E-09	21.5	2.8	1.6	7.85	1.1
4-Dec-01	1.1E-07	1.3E-08	6.7E-09	15.9	2.0	1.2	7.10	
5-Dec-01	1.3E-07	1.3E-08	5.7E-09	23.0	2.3	1.3	7.30	
6-Dec-01	1.3E-07	8.8E-09	3.8E-09	34.4	2.3	1.0	7.65	1.1
7-Dec-01	1.4E-07	1.3E-08	5.7E-09	23.9	2.2	1.2		
8-Dec-01	1.4E-07	1.3E-08	5.7E-09	23.9	2.2	1.2		
9-Dec-01	1.4E-07	1.3E-08	5.7E-09	23.9	2.2	1.2		
10-Dec-01	1.4E-07	1.3E-08	5.7E-09	23.9	2.2	1.2	8.10	1.1
11-Dec-01	1.2E-07	1.1E-08	5.7E-09	21.4	2.0	1.1	7.25	
12-Dec-01	1.4E-07	1.1E-08	5.7E-09	24.2	1.9	1.0	7.60	1.1
13-Dec-01	1.2E-07	1.2E-08	5.7E-09	20.7	2.1	1.1	6.90	1.1
Oct 12-Dec 13								
Average	8.6E-08	1.2E-08	5.4E-09	16.2	2.2	1.1	6.74	1.1
Minimum	2.2E-08	6.1E-09	3.8E-09	4.5	1.4	0.7	3.84	0.7
Maximum	1.4E-07	2.6E-08	9.5E-09	34.4	3.8	2.3	8.55	1.1
St.Dev.	2.8E-08	3.9E-09	1.2E-09	5.8	0.6	0.4	1.10	0.1
Count	55	55	55	55	55	55	52	22

Date	CRT		Harvested Product Data				Total Mass (g)
	Actual (days)	Averaged In reactor SS Ratio	> 2 mm (g)	> 1 mm (g)	> 0.5 mm (g)	< 0.5 mm (g)	
1-Nov-01	12	2.4	0.3	85.9	86.9	83.0	256.1
2-Nov-01							
7-Nov-01	14	2.4	0.2	103.8	82.4	92.7	279.1
8-Nov-01							
9-Nov-01							
10-Nov-01	14	2.2	0.1	85.6	140.4	156.8	382.8
11-Nov-01							
12-Nov-01							
13-Nov-01	13	2.0	5.9	216.1	66.9	59.1	348.0
14-Nov-01							
15-Nov-01							
16-Nov-01							
17-Nov-01							
18-Nov-01	19	1.9	0.6	153.5	108.1	105.3	367.5
19-Nov-01							
20-Nov-01	17	1.8	11.7	216.9	89.8	47.0	365.4
21-Nov-01							
22-Nov-01	18	1.8	24.5	228.3	74.1	52.3	379.2
23-Nov-01							
24-Nov-01							
25-Nov-01							
26-Nov-01	21	1.9	24.6	253.2	55.6	36.3	369.7
27-Nov-01	19	1.9	6.6	246.8	71.9	59.0	384.3
28-Nov-01	17	1.9	13.1	282.7	73.1	34.3	403.2
29-Nov-01							
30-Nov-01	13	2.0	25.7	295.0	79.3	26.6	426.6
1-Dec-01							
2-Dec-01							
3-Dec-01	14	2.1	7.4	304.8	165.2	22.4	499.8
4-Dec-01							
5-Dec-01							
6-Dec-01	15	2.1	11.4	368.3	139.7	11.3	530.6
7-Dec-01							
8-Dec-01							
9-Dec-01							
10-Dec-01	16	2.2	6.1	368.9	154.7	14.4	544.0
11-Dec-01							
12-Dec-01	16	2.1	7.4	457.4	94.8	5.6	565.1
13-Dec-01	15	2.1	9.9	475.5	126.1	1.1	612.6
Oct 12-Dec 13							
Average	19	2.5	11.2	198.2	86.2	59.9	355.5
Minimum	12	1.8	0.1	17.8	0.7	1.1	129.1
Maximum	32	3.9	83.4	475.5	165.2	156.8	612.6
St.Dev.	6	0.8	18.1	143.3	40.7	43.8	139.0
Count	22	22	22	22	22	22	22

Date	Harvested Product Data				Mean Crystal Size (mm)	Mass P Removed (g)	Theoretical Mass MAP Grown (g)
	% > 2mm	% 1-2 mm	% 0.5-1mm	% < 0.5mm			
1-Nov-01	0.1	33.5	33.9	32.4	0.8	33.3	263.7
2-Nov-01						33.4	264.6
7-Nov-01	0.1	37.2	29.5	33.2	0.9	29.8	236.1
8-Nov-01						22.6	178.7
9-Nov-01						24.6	194.5
10-Nov-01	0.0	22.3	36.7	40.9	0.7	26.1	206.9
11-Nov-01						16.1	127.8
12-Nov-01						22.2	175.7
13-Nov-01	1.7	62.1	19.2	17.0	1.2	33.2	263.3
14-Nov-01						33.4	264.6
15-Nov-01						31.2	246.7
16-Nov-01						27.2	215.6
17-Nov-01						23.6	187.0
18-Nov-01	0.2	41.8	29.4	28.7	0.9	22.9	181.1
19-Nov-01						15.5	123.0
20-Nov-01	3.2	59.4	24.6	12.9	1.2	9.5	75.6
21-Nov-01						39.4	312.3
22-Nov-01	6.5	60.2	19.5	13.8	1.2	36.2	286.4
23-Nov-01						33.9	268.1
24-Nov-01						35.7	282.7
25-Nov-01						35.7	282.7
26-Nov-01	6.7	68.5	15.0	9.8	1.3	35.7	282.7
27-Nov-01	1.7	64.2	18.7	15.3	1.2	35.6	281.9
28-Nov-01	3.3	70.1	18.1	8.5	1.3	37.7	298.4
29-Nov-01						26.9	212.8
30-Nov-01	6.0	69.1	18.6	6.2	1.3	24.6	194.7
1-Dec-01						25.7	203.2
2-Dec-01						22.2	176.0
3-Dec-01	1.5	61.0	33.0	4.5	1.2	29.9	236.4
4-Dec-01						25.1	198.5
5-Dec-01						29.2	231.5
6-Dec-01	2.1	69.4	26.3	2.1	1.3	27.7	219.3
7-Dec-01						31.0	245.8
8-Dec-01						31.0	245.8
9-Dec-01						31.0	245.8
10-Dec-01	1.1	67.8	28.4	2.6	1.3	31.0	245.8
11-Dec-01						26.7	211.2
12-Dec-01	1.3	80.9	16.8	1.0	1.4	25.6	203.1
13-Dec-01	1.6	77.6	20.6	0.2	1.4	26.8	212.3
Oct 12-Dec 13							
Average	4.8	48.4	24.2	22.6	1.1	29.5	233.3
Minimum	0.0	11.7	0.5	0.2	0.5	9.5	75.6
Maximum	64.6	80.9	36.7	67.2	2.1	39.4	312.3
St.Dev.	13.5	22.9	9.0	20.9	0.4	5.8	46.0
Count	22	22	22	22	22	55	55

Date	Notes
<hr/> <hr/>	
1-Nov-01	
2-Nov-01	
7-Nov-01	
8-Nov-01	
9-Nov-01	
10-Nov-01	
11-Nov-01	
12-Nov-01	
13-Nov-01	
14-Nov-01	
15-Nov-01	
16-Nov-01	
17-Nov-01	
18-Nov-01	
19-Nov-01	
20-Nov-01	
21-Nov-01	
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25-Nov-01	
26-Nov-01	
27-Nov-01	
28-Nov-01	
29-Nov-01	
30-Nov-01	
1-Dec-01	
2-Dec-01	
3-Dec-01	
4-Dec-01	
5-Dec-01	
6-Dec-01	
7-Dec-01	
8-Dec-01	
9-Dec-01	
10-Dec-01	
11-Dec-01	
12-Dec-01	
13-Dec-01	
Oct 12-Dec 13	
Average	
Minimum	
Maximum	
St.Dev.	
Count	

APPENDIX D: OPERATING DATA FOR REACTOR B

Date	MgCl Feed	Supernatant Lab results			Effluent Lab results			pH
	Mg (mg/l)	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	
2-Sep-01	1092	9.4	263	28.0	6.7	234	94.0	8.4
4-Sep-01	1092	8.3	284	27.3	8.1	263	91.0	8.5
5-Sep-01	1092	8.0	270	41.9	6.3	248	86.0	8.4
6-Sep-01	1092	7.8	263	27.8	6.0	220		8.4
7-Sep-01	1092	10.9	270	29.3	9.0	262	65.3	8.4
13-Sep-01	714	10.2	273	16.7	7.8	256	59.8	8.9
14-Sep-01	714	10.5	283	16.2	7.6	268	55.6	8.8
15-Sep-01	986	10.8	271	14.9	7.5	249	69.4	8.8
16-Sep-01	986	12.1	314	16.9	17.7	276	65.0	6.8
17-Sep-01	986	12.1	282	15.7	10.8	235	78.1	8.3
18-Sep-01	986	11.9	298	16.0	9.3	252	65.0	8.3
19-Sep-01	986	13.7	272	16.1	9.0	235	69.1	8.6
20-Sep-01	986	11.7	277	14.4	8.6	270	70.9	8.7
21-Sep-01	977	11.5	277	13.5	8.0	267	75.9	8.7
22-Sep-01	977	12.8	279	11.7	13.9	263	25.8	8.7
23-Sep-01	977	12.6	281	16.4	10.4	267	77.1	8.7
24-Sep-01	977	12.3	276	13.4	16.4	194	115.0	8.8
2-Oct-01	977	12.3	290	21.1	8.5	259	78.0	8.8
3-Oct-01	977	11.8	262	21.4	7.4	240	87.0	8.8
5-Oct-01	792	18.0	260	29.7	18.9	248	61.1	8.6
10-Oct-01	792	17.8	265	28.8	7.1	235	53.8	8.8
11-Oct-01	792	43.4	252	30.3	26.4	249	38.2	8.8
12-Oct-01	792	44.3	314	11.1	12.6	240	63.8	8.4
13-Oct-01	792	42.3	279	14.8	10.7	242	49.4	8.4
14-Oct-01	792	43.5	282	14.1	9.4	246	45.0	8.4
15-Oct-01	792	46.2	285	35.1	13.0	274	34.3	8.4
16-Oct-01	792	44.9	295	34.3	11.0	261	37.4	8.4
17-Oct-01	792	45.8	299	28.3	8.8	270	42.1	8.5
18-Oct-01	792	48.7	284	29.3	12.1	258	30.9	8.5
24-Oct-01	792	44.5	290	18.9	18.2	280	17.3	8.4
25-Oct-01	657	43.9	302	21.1	7.8	241	38.6	8.4
26-Oct-01	657	37.2	289	24.3	5.8	250	43.4	8.4
27-Oct-01	657	42.9	293	26.3	6.4	265	44.2	8.4
28-Oct-01	657	40.4	245	29.1	8.4	237	35.1	8.4
29-Oct-01	657	40.1	293	24.7	6.5	233	47.9	8.4
30-Oct-01	657	39.9	293	21.7	6.3	227	48.0	8.4
31-Oct-01	733	45.6	295	23.4	11.4	251	43.0	8.3

Date	MgCl Flow (mL/min)	Caustic Flow (l/day)	Total Influent Flow (mL/min)	Supernatant Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
2-Sep-01	48	103.5	833	713	2917	3750
4-Sep-01	50	100	850	731	2700	3550
5-Sep-01	48	75	950	850	2750	3700
6-Sep-01	49	0	925	876	2700	3625
7-Sep-01	49	0	1200	1151	2550	3750
13-Sep-01	50	10	925	868	2600	3525
14-Sep-01	50	7.5	850	795	2600	3450
15-Sep-01	50	5	950	897	2550	3500
16-Sep-01	58	7.5	1250	1187	2900	4150
17-Sep-01	65	80	1075	954	2775	3850
18-Sep-01	50	115	1000	870	2600	3600
19-Sep-01	52	150	925	769	2625	3550
20-Sep-01	54	5	900	843	2750	3650
21-Sep-01	53	7.5	1150	1092	2500	3650
22-Sep-01	0	2.5	1300	1298	2400	3700
23-Sep-01	53	15	1250	1187	2550	3800
24-Sep-01	54	5	1233	1176	2600	3833
2-Oct-01	54	15	1100	1036	2500	3600
3-Oct-01	53	20	1000	933	2500	3500
5-Oct-01	56	57.5	1300	1204	2550	3850
10-Oct-01	56	5	1200	1141	2450	3650
11-Oct-01	56	50	1225	1134	2475	3700
12-Oct-01	58	15	620	552	2880	3500
13-Oct-01	31	15	620	579	2880	3500
14-Oct-01	31	12.5	660	620	2865	3525
15-Oct-01	32	20	930	884	2870	3800
16-Oct-01	32	17.5	820	776	2855	3675
17-Oct-01	20	20	430	396	1970	2400
18-Oct-01	21	17.5	720	687	2930	3650
24-Oct-01	0	17.5	780	768	2890	3670
25-Oct-01	52	15	780	718	2770	3550
26-Oct-01	54	30	740	665	2860	3600
27-Oct-01	54	17.5	700	634	2850	3550
28-Oct-01	53	22.5	690	621	2885	3575
29-Oct-01	54	50	740	651	2860	3600
30-Oct-01	58	42.5	750	662	2825	3575
31-Oct-01	46	95	830	718	2820	3650

Date	Conditions at the inlet			Removal efficiency (%)		
	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	PO ₄ -P	NH ₄ -N	Mg
2-Sep-01	8.0	225	86.9	16	-4	-8
4-Sep-01	7.1	244	87.7	-14	-8	-4
5-Sep-01	7.1	242	92.7	12	-3	7
6-Sep-01	7.4	249	84.2	19	12	100
7-Sep-01	10.5	259	72.7	14	-1	10
13-Sep-01	9.6	256	54.3	19	0	-10
14-Sep-01	9.8	265	57.1	23	-1	3
15-Sep-01	10.2	256	65.9	26	3	-5
16-Sep-01	11.5	298	61.8	-54	7	-5
17-Sep-01	10.7	250	73.5	-1	6	-6
18-Sep-01	10.4	259	63.2	10	3	-3
19-Sep-01	11.4	226	68.8	21	-4	-1
20-Sep-01	11.0	259	72.6	21	-4	2
21-Sep-01	10.9	263	57.8	27	-2	-31
22-Sep-01	12.8	279	11.7	-9	6	-121
23-Sep-01	12.0	267	56.9	13	0	-35
24-Sep-01	11.7	263	55.5	-40	26	-107
2-Oct-01	11.6	273	67.8	27	5	-15
3-Oct-01	11.0	244	71.8	33	2	-21
5-Oct-01	16.7	241	61.6	-13	-3	1
10-Oct-01	16.9	252	64.3	58	7	16
11-Oct-01	40.2	233	64.3	34	-7	41
12-Oct-01	39.4	279	83.9	68	14	24
13-Oct-01	39.5	260	53.4	73	7	8
14-Oct-01	40.9	265	50.4	77	7	11
15-Oct-01	43.9	271	60.6	70	-1	43
16-Oct-01	42.5	279	63.3	74	6	41
17-Oct-01	42.2	275	62.9	79	2	33
18-Oct-01	46.5	271	51.0	74	5	40
24-Oct-01	43.8	285	18.6	58	2	7
25-Oct-01	40.4	278	63.2	81	13	39
26-Oct-01	33.4	260	69.8	83	4	38
27-Oct-01	38.8	265	74.5	84	0	41
28-Oct-01	36.4	221	76.7	77	-7	54
29-Oct-01	35.3	258	69.7	82	10	31
30-Oct-01	35.2	259	70.0	82	12	31
31-Oct-01	39.4	255	60.9	71	2	29

Date	Molar removal Inlet to outlet			Mg:P	N:P
	PO ₄ -P	NH ₄ -N	Mg	Removal Ratio	Removal Ratio
2-Sep-01	4.2E-05	-6.3E-04	-2.9E-04	-6.9	-14.9
4-Sep-01	-3.3E-05	-1.4E-03	-1.4E-04	4.1	41.0
5-Sep-01	2.7E-05	-4.6E-04	2.8E-04	10.2	-17.0
6-Sep-01	4.5E-05	2.1E-03	3.5E-03	76.4	45.8
7-Sep-01	4.9E-05	-2.2E-04	3.1E-04	6.2	-4.4
13-Sep-01	5.7E-05	1.4E-05	-2.3E-04	-4.0	0.2
14-Sep-01	7.2E-05	-2.4E-04	6.4E-05	0.9	-3.4
15-Sep-01	8.7E-05	4.8E-04	-1.4E-04	-1.7	5.5
16-Sep-01	-2.0E-04	1.6E-03	-1.3E-04	0.7	-7.9
17-Sep-01	-1.8E-06	1.1E-03	-1.9E-04	102.2	-597.2
18-Sep-01	3.4E-05	5.2E-04	-7.4E-05	-2.2	15.3
19-Sep-01	7.7E-05	-6.4E-04	-1.5E-05	-0.2	-8.3
20-Sep-01	7.6E-05	-7.6E-04	7.1E-05	0.9	-10.0
21-Sep-01	9.4E-05	-2.9E-04	-7.4E-04	-7.9	-3.0
22-Sep-01	-3.6E-05	1.1E-03	-5.8E-04	16.2	-30.9
23-Sep-01	5.0E-05	-1.8E-05	-8.3E-04	-16.5	-0.4
24-Sep-01	-1.5E-04	4.9E-03	-2.4E-03	16.2	-32.7
2-Oct-01	9.9E-05	1.0E-03	-4.2E-04	-4.2	10.1
3-Oct-01	1.2E-04	3.2E-04	-6.3E-04	-5.4	2.7
5-Oct-01	-7.2E-05	-5.1E-04	1.8E-05	-0.3	7.1
10-Oct-01	3.2E-04	1.2E-03	4.3E-04	1.4	3.8
11-Oct-01	4.5E-04	-1.1E-03	1.1E-03	2.4	-2.5
12-Oct-01	8.7E-04	2.8E-03	8.3E-04	1.0	3.2
13-Oct-01	9.3E-04	1.3E-03	1.6E-04	0.2	1.4
14-Oct-01	1.0E-03	1.4E-03	2.2E-04	0.2	1.3
15-Oct-01	1.0E-03	-2.2E-04	1.1E-03	1.1	-0.2
16-Oct-01	1.0E-03	1.3E-03	1.1E-03	1.0	1.3
17-Oct-01	1.1E-03	3.9E-04	8.5E-04	0.8	0.4
18-Oct-01	1.1E-03	9.2E-04	8.3E-04	0.7	0.8
24-Oct-01	8.3E-04	3.9E-04	5.4E-05	0.1	0.5
25-Oct-01	1.1E-03	2.6E-03	1.0E-03	1.0	2.5
26-Oct-01	8.9E-04	7.0E-04	1.1E-03	1.2	0.8
27-Oct-01	1.0E-03	2.2E-05	1.2E-03	1.2	0.0
28-Oct-01	9.0E-04	-1.2E-03	1.7E-03	1.9	-1.3
29-Oct-01	9.3E-04	1.8E-03	9.0E-04	1.0	1.9
30-Oct-01	9.3E-04	2.3E-03	9.1E-04	1.0	2.4
31-Oct-01	9.1E-04	3.0E-04	7.4E-04	0.8	0.3

Date	PO ₄ -P In-Reactor			NH ₄ -N In-Reactor		
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)
2-Sep-01	1.8	5.2	7.0	50	182	232
4-Sep-01	1.7	6.2	7.9	58	200	258
5-Sep-01	1.8	4.7	6.5	62	184	246
6-Sep-01	1.9	4.5	6.4	64	164	227
7-Sep-01	3.4	6.1	9.4	83	178	261
13-Sep-01	2.5	5.8	8.3	67	189	256
14-Sep-01	2.4	5.7	8.1	65	202	267
15-Sep-01	2.8	5.5	8.2	69	181	251
16-Sep-01	3.5	12.4	15.8	90	193	283
17-Sep-01	3.0	7.8	10.8	70	169	239
18-Sep-01	2.9	6.7	9.6	72	182	254
19-Sep-01	3.0	6.7	9.6	59	174	233
20-Sep-01	2.7	6.5	9.2	64	203	267
21-Sep-01	3.4	5.5	8.9	83	183	266
22-Sep-01	4.5	9.0	13.5	98	171	268
23-Sep-01	3.9	7.0	10.9	88	179	267
24-Sep-01	3.8	11.1	14.9	85	132	216
2-Oct-01	3.5	5.9	9.4	83	180	263
3-Oct-01	3.1	5.3	8.4	70	171	241
5-Oct-01	5.6	12.5	18.1	81	164	246
10-Oct-01	5.6	4.8	10.3	83	158	241
11-Oct-01	13.3	17.7	31.0	77	167	244
12-Oct-01	7.0	10.4	17.3	49	197	247
13-Oct-01	7.0	8.8	15.8	46	199	245
14-Oct-01	7.7	7.6	15.3	50	200	250
15-Oct-01	10.7	9.8	20.6	66	207	273
16-Oct-01	9.5	8.5	18.0	62	203	265
17-Oct-01	7.6	7.2	14.8	49	222	271
18-Oct-01	9.2	9.7	18.9	53	207	261
24-Oct-01	9.3	14.3	23.6	61	220	281
25-Oct-01	8.9	6.1	15.0	61	188	249
26-Oct-01	6.9	4.6	11.5	53	199	252
27-Oct-01	7.7	5.1	12.8	52	213	265
28-Oct-01	7.0	6.8	13.8	43	191	234
29-Oct-01	7.3	5.2	12.4	53	185	238
30-Oct-01	7.4	5.0	12.4	54	179	234
31-Oct-01	9.0	8.8	17.8	58	194	252

Date	Mg In-Reactor			In-Reactor Concentrations			In-Reacor Mg:P (molar ratio)	In-Reactor N:P (molar ratio)
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	PO ₄ -P (mol/L)	NH ₄ -N (mol/L)	Mg (mol/L)		
2-Sep-01	19.3	73.1	92.4	2.3E-04	1.7E-02	3.8E-03	16.8	73.2
4-Sep-01	21.0	69.2	90.2	2.5E-04	1.8E-02	3.7E-03	14.6	72.6
5-Sep-01	23.8	63.9	87.7	2.1E-04	1.8E-02	3.6E-03	17.2	83.6
6-Sep-01	21.5	0.0	21.5	2.1E-04	1.6E-02	8.8E-04	4.3	78.9
7-Sep-01	23.3	44.4	67.7	3.0E-04	1.9E-02	2.8E-03	9.1	61.1
13-Sep-01	14.2	44.1	58.3	2.7E-04	1.8E-02	2.4E-03	9.0	68.5
14-Sep-01	14.1	41.9	56.0	2.6E-04	1.9E-02	2.3E-03	8.8	72.5
15-Sep-01	17.9	50.5	68.4	2.7E-04	1.8E-02	2.8E-03	10.6	67.4
16-Sep-01	18.6	45.4	64.0	5.1E-04	2.0E-02	2.6E-03	5.2	39.5
17-Sep-01	20.5	56.3	76.8	3.5E-04	1.7E-02	3.2E-03	9.1	49.1
18-Sep-01	17.6	46.9	64.5	3.1E-04	1.8E-02	2.7E-03	8.6	58.6
19-Sep-01	17.9	51.1	69.0	3.1E-04	1.7E-02	2.8E-03	9.1	53.5
20-Sep-01	17.9	53.4	71.3	3.0E-04	1.9E-02	2.9E-03	9.9	64.4
21-Sep-01	18.2	52.0	70.2	2.9E-04	1.9E-02	2.9E-03	10.0	65.9
22-Sep-01	4.1	16.8	20.9	4.4E-04	1.9E-02	8.6E-04	2.0	44.0
23-Sep-01	18.7	51.8	70.5	3.5E-04	1.9E-02	2.9E-03	8.2	54.1
24-Sep-01	17.9	78.0	95.9	4.8E-04	1.5E-02	3.9E-03	8.2	32.1
2-Oct-01	20.7	54.2	74.9	3.0E-04	1.9E-02	3.1E-03	10.1	61.7
3-Oct-01	20.5	62.1	82.6	2.7E-04	1.7E-02	3.4E-03	12.5	63.3
5-Oct-01	20.8	40.5	61.3	5.9E-04	1.8E-02	2.5E-03	4.3	29.9
10-Oct-01	21.1	36.1	57.2	3.3E-04	1.7E-02	2.4E-03	7.1	51.5
11-Oct-01	21.3	25.5	46.8	1.0E-03	1.7E-02	1.9E-03	1.9	17.4
12-Oct-01	14.9	52.5	67.3	5.6E-04	1.8E-02	2.8E-03	4.9	31.5
13-Oct-01	9.5	40.6	50.1	5.1E-04	1.8E-02	2.1E-03	4.0	34.3
14-Oct-01	9.4	36.6	46.0	4.9E-04	1.8E-02	1.9E-03	3.8	36.1
15-Oct-01	14.8	25.9	40.7	6.6E-04	2.0E-02	1.7E-03	2.5	29.4
16-Oct-01	14.1	29.1	43.2	5.8E-04	1.9E-02	1.8E-03	3.1	32.5
17-Oct-01	11.3	34.6	45.8	4.8E-04	1.9E-02	1.9E-03	4.0	40.6
18-Oct-01	10.1	24.8	34.8	6.1E-04	1.9E-02	1.4E-03	2.4	30.5
24-Oct-01	4.0	13.6	17.6	7.6E-04	2.0E-02	7.2E-04	0.9	26.3
25-Oct-01	13.9	30.1	44.0	4.8E-04	1.8E-02	1.8E-03	3.7	36.8
26-Oct-01	14.3	34.5	48.8	3.7E-04	1.8E-02	2.0E-03	5.4	48.6
27-Oct-01	14.7	35.5	50.2	4.1E-04	1.9E-02	2.1E-03	5.0	45.8
28-Oct-01	14.8	28.3	43.1	4.5E-04	1.7E-02	1.8E-03	4.0	37.5
29-Oct-01	14.3	38.1	52.4	4.0E-04	1.7E-02	2.2E-03	5.4	42.4
30-Oct-01	14.7	37.9	52.6	4.0E-04	1.7E-02	2.2E-03	5.4	41.8
31-Oct-01	13.8	33.2	47.1	5.7E-04	1.8E-02	1.9E-03	3.4	31.4

Date	Feed P _S	In-Reactor P _S	Equilibrium P _S	Feed S.S. ratio	In-Reactor S.S. Ratio	Effluent S.S. Ratio	Crystal Volume (l)	Harvest Volume (l)
2-Sep-01	1.5E-08	1.4E-08	5.7E-09	2.6	2.5	2.5		
4-Sep-01	1.4E-08	1.7E-08	4.9E-09	2.9	3.5	3.7		
5-Sep-01	1.5E-08	1.3E-08	5.7E-09	2.6	2.3	2.2		
6-Sep-01	1.5E-08	3.0E-09	5.7E-09	2.6	0.5	0.0		
7-Sep-01	1.9E-08	1.6E-08	5.7E-09	3.3	2.8	2.5	1.00	
13-Sep-01	1.3E-08	1.2E-08	3.0E-09	4.3	4.0	3.8	1.20	
14-Sep-01	1.4E-08	1.2E-08	3.3E-09	4.2	3.5	3.2	1.40	
15-Sep-01	1.6E-08	1.3E-08	3.3E-09	4.9	4.0	3.7	1.50	
16-Sep-01	2.0E-08	2.7E-08	2.3E-07	0.1	0.1	0.1	1.00	
17-Sep-01	1.9E-08	1.9E-08	6.7E-09	2.8	2.8	2.8	1.20	
18-Sep-01	1.6E-08	1.5E-08	6.7E-09	2.4	2.2	2.2	1.30	
19-Sep-01	1.7E-08	1.5E-08	4.3E-09	3.9	3.4	3.2	1.40	0.3
20-Sep-01	2.0E-08	1.7E-08	3.8E-09	5.2	4.4	4.2	1.60	
21-Sep-01	1.6E-08	1.6E-08	3.8E-09	4.2	4.2	4.1	1.75	
22-Sep-01	3.9E-09	7.2E-09	3.8E-09	1.1	1.9	2.4	1.40	
23-Sep-01	1.7E-08	1.9E-08	3.8E-09	4.6	5.2	5.4	1.60	
24-Sep-01	1.6E-08	2.9E-08	3.3E-09	4.9	8.8	10.5	2.10	
2-Oct-01	2.0E-08	1.8E-08	3.3E-09	6.1	5.3	4.9	0.40	
3-Oct-01	1.8E-08	1.6E-08	3.3E-09	5.5	4.8	4.4	0.53	
5-Oct-01	2.3E-08	2.6E-08	4.3E-09	5.5	6.1	6.4	0.65	
10-Oct-01	2.6E-08	1.3E-08	3.3E-09	7.8	4.1	2.6	0.50	
11-Oct-01	5.7E-08	3.4E-08	3.3E-09	17.2	10.1	7.2	1.00	
12-Oct-01	8.8E-08	2.7E-08	5.7E-09	15.3	4.8	3.2	1.50	
13-Oct-01	5.2E-08	1.8E-08	5.7E-09	9.1	3.2	2.1	3.50	
14-Oct-01	5.2E-08	1.7E-08	5.7E-09	9.1	2.9	1.7	2.60	
15-Oct-01	6.8E-08	2.2E-08	5.7E-09	12.0	3.8	2.0	3.30	
16-Oct-01	7.1E-08	2.0E-08	5.7E-09	12.5	3.4	1.8	3.95	
17-Oct-01	6.9E-08	1.7E-08	4.9E-09	14.1	3.5	1.9	4.50	0.3
18-Oct-01	6.1E-08	1.6E-08	4.9E-09	12.4	3.3	1.9	4.00	
24-Oct-01	2.2E-08	1.1E-08	5.7E-09	3.9	1.9	1.5	3.80	
25-Oct-01	6.7E-08	1.6E-08	5.7E-09	11.8	2.7	1.2	4.45	
26-Oct-01	5.8E-08	1.3E-08	5.7E-09	10.1	2.3	1.0	5.10	
27-Oct-01	7.3E-08	1.6E-08	5.7E-09	12.7	2.8	1.2	5.75	0.3
28-Oct-01	5.8E-08	1.3E-08	5.7E-09	10.2	2.3	1.2	5.70	
29-Oct-01	6.0E-08	1.5E-08	5.7E-09	10.5	2.6	1.2	6.35	1.1
30-Oct-01	6.1E-08	1.4E-08	5.7E-09	10.6	2.5	1.1	5.60	
31-Oct-01	5.8E-08	2.0E-08	6.7E-09	8.7	3.0	1.7	6.25	1.1

Date	CRT Actual (days)	CRT Averaged In reactor SS Ratio	Harvested Product Data				Total Mass (g)
			> 2 mm (g)	> 1 mm (g)	> 0.5 mm (g)	< 0.5 mm (g)	
2-Sep-01							
4-Sep-01							
5-Sep-01							
6-Sep-01							
7-Sep-01							
13-Sep-01							
14-Sep-01							
15-Sep-01							
16-Sep-01							
17-Sep-01							
18-Sep-01							
19-Sep-01	12						
20-Sep-01							
21-Sep-01							
22-Sep-01							
23-Sep-01							
24-Sep-01							
2-Oct-01							
3-Oct-01							
5-Oct-01							
10-Oct-01							
11-Oct-01							
12-Oct-01							
13-Oct-01							
14-Oct-01							
15-Oct-01							
16-Oct-01							
17-Oct-01	28	3.9	1.5	5.3	6.1	7.4	20.2
18-Oct-01							
24-Oct-01							
25-Oct-01							
26-Oct-01							
27-Oct-01	33	3.7	0.2	7.6	24.5	23.1	55.3
28-Oct-01							
29-Oct-01	35	3.6	1.3	62.6	106.6	87.7	258.1
30-Oct-01							
31-Oct-01	37	3.6	41.8	170.1	77.5	66.0	355.4

Date	Harvested Product Data				Mean Crystal Size (mm)	Mass P	Theoretical
	% > 2mm	% 1-2 mm	% 0.5-1mm	% < 0.5mm		Removed	Mass MAP Grown
(g)							
2-Sep-01						1.6	12.4
4-Sep-01						-1.2	-9.9
5-Sep-01						1.1	9.1
6-Sep-01						1.9	14.8
7-Sep-01						2.6	20.7
13-Sep-01						2.4	18.7
14-Sep-01						2.7	21.5
15-Sep-01						3.7	29.2
16-Sep-01						-11.2	-88.6
17-Sep-01						-0.1	-0.7
18-Sep-01						1.5	12.0
19-Sep-01						3.2	25.2
20-Sep-01						3.0	24.1
21-Sep-01						4.8	38.3
22-Sep-01						-2.1	-16.6
23-Sep-01						2.8	22.2
24-Sep-01						-8.3	-65.7
2-Oct-01						4.9	38.6
3-Oct-01						5.2	41.2
5-Oct-01						-4.2	-33.0
10-Oct-01						17.0	134.4
11-Oct-01						24.3	192.6
12-Oct-01						23.9	189.6
13-Oct-01						25.7	203.5
14-Oct-01						29.9	237.0
15-Oct-01						41.4	327.9
16-Oct-01						37.2	294.4
17-Oct-01	7.3	26.1	30.2	36.5		20.7	163.7
18-Oct-01						35.6	282.1
24-Oct-01						28.8	227.8
25-Oct-01						36.6	289.9
26-Oct-01						29.5	233.2
27-Oct-01	0.4	13.7	44.2	41.7	0.7	32.7	259.0
28-Oct-01						27.8	220.2
29-Oct-01	0.5	24.3	41.3	34.0	0.8	30.7	243.0
30-Oct-01						31.3	247.6
31-Oct-01	11.8	47.9	21.8	18.6	1.2	33.5	265.5

Date	Notes
2-Sep-01	
4-Sep-01	
5-Sep-01	
6-Sep-01	
7-Sep-01	
13-Sep-01	No Plugging
14-Sep-01	pH controller malfunction, ph up to 11
15-Sep-01	pH probe out of calibration, caustic inlet plugged
16-Sep-01	pH controller set to acid
17-Sep-01	
18-Sep-01	
19-Sep-01	
20-Sep-01	
21-Sep-01	
22-Sep-01	Mg feed off
23-Sep-01	Effluent Plugged
24-Sep-01	Power Failure + Seed hopper fitting broke off
2-Oct-01	
3-Oct-01	
5-Oct-01	
10-Oct-01	
11-Oct-01	
12-Oct-01	
13-Oct-01	
14-Oct-01	
15-Oct-01	
16-Oct-01	
17-Oct-01	
18-Oct-01	
24-Oct-01	
25-Oct-01	
26-Oct-01	
27-Oct-01	
28-Oct-01	
29-Oct-01	
30-Oct-01	
31-Oct-01	

Date	MgCl Feed Supernatant Lab results			Effluent Lab results			pH	
	Mg	PO ₄ -P	NH ₄ -N	Mg	PO ₄ -P	NH ₄ -N		
	(mg/l)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		
1-Nov-01	733	46.7	284	25.8	8.2	240	46.0	8.4
2-Nov-01	733	46.4	283	25.5	8.9	231	47.0	8.3
7-Nov-01	733	46.4	324	30.1	14.0	239	34.7	8.0
8-Nov-01	733	45.6	298	28.8	13.9	238	31.1	8.0
9-Nov-01	733	45.9	302	29.1	14.1	242	30.8	8.0
10-Nov-01	733	46.3	274	28.8	15.7	232	30.5	8.0
11-Nov-01	733	54.8	298	29.7	16.2	252	22.9	8.0
12-Nov-01	733	53.7	267	30.7	14.2	220	22.6	8.0
13-Nov-01	733	54.8	284	29.4	16.9	257	27.4	8.0
14-Nov-01	495	53.0	304	32.4	27.0	282	37.9	7.7
15-Nov-01	495	51.9	299	30.6	23.5	270	37.8	7.8
16-Nov-01	495	51.9	299	30.6	23.5	270	37.8	7.8
17-Nov-01	495	51.9	299	30.6	23.5	270	37.8	7.8
18-Nov-01	495	51.9	273	29.3	24.8	255	37.4	7.7
19-Nov-01	495	61.2	197	30.3	43.6	194	18.0	7.8
20-Nov-01	495	59.8	354	28.3	29.4	313	29.8	7.8
21-Nov-01	495	64.0	365	28.9	33.2	330	29.3	7.8
22-Nov-01	495	63.7	360	27.1	29.8	320	28.9	7.8
23-Nov-01	495	61.5	369	29.9	31.3	321	32.6	7.8
24-Nov-01	623	60.2	356	27.1	28.0	321	35.4	7.7
25-Nov-01	623	60.2	356	27.1	28.0	321	35.4	7.7
26-Nov-01	623	60.2	356	27.1	28.0	321	35.4	7.7
27-Nov-01	623	61.5	354	26.3	26.4	317	36.3	7.7
28-Nov-01	623	60.6	366	27.3	27.2	334	36.2	7.7
29-Nov-01	623	61.7	346	28.2	25.6	311	33.5	7.8
30-Nov-01	623	58.5	359	25.7	24.2	326	32.2	7.8
1-Dec-01	623	65.2	380	26.3	34.1	335	36.6	7.7
2-Dec-01	623	68.1	406	26.0	35.1	360	36.1	7.6
3-Dec-01	623	67.2	391	26.1	32.6	339	34.1	7.6
4-Dec-01	623	69.2	436	24.9	26.3	359	32.7	7.7
5-Dec-01	616	69.1	400	29.5	34.2	378	35.2	7.6
6-Dec-01	616	68.2	398	25.4	34.1	358	33.9	7.7
7-Dec-01	616	71.1	399	25.4	30.4	351	33.6	7.6
8-Dec-01	616	71.1	399	25.4	30.4	351	33.6	7.6
9-Dec-01	616	71.1	399	25.4	30.4	351	33.6	7.6
10-Dec-01	616	71.1	399	25.4	30.4	351	33.6	7.6
11-Dec-01	616	71.2	409	23.7	30.3	395	32.2	7.6
12-Dec-01	616	65.7	426	29.4	28.9	442	31.8	7.6
13-Dec-01	616	64.6	399	30.6	33.3	362	32.6	7.6
Oct 12-Dec 13								
Average	647	55.1	330	26.8	21.4	291	35.6	8.0
Minimum	495	37.2	197	11.1	5.8	194	17.3	7.6
Maximum	792	71.2	436	35.1	43.6	442	63.8	8.5
St.Dev.	96	10.3	53	4.5	10.0	54	7.8	0.3
Count	55	55	55	55	55	55	55	55

Date	MgCl Flow (mL/min)	Caustic Flow (l/day)	Total Influent Flow (mL/min)	Supernatant Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
1-Nov-01	43	65	725	637	2925	3650
2-Nov-01	42	70	730	639	2920	3650
7-Nov-01	42	30	710	647	2890	3600
8-Nov-01	42	40	700	630	2850	3550
9-Nov-01	40	47.5	710	637	2840	3550
10-Nov-01	40	25	700	643	2875	3575
11-Nov-01	39	25	800	744	2875	3675
12-Nov-01	39	30	810	750	2890	3700
13-Nov-01	38	30	720	661	2880	3600
14-Nov-01	40	37.5	690	624	2910	3600
15-Nov-01	37	30	680	622	2890	3570
16-Nov-01	37	30	670	612	2870	3540
17-Nov-01	37	30	660	602	2850	3510
18-Nov-01	37	15	630	583	2870	3500
19-Nov-01	0	30	550	529	3100	3650
20-Nov-01	38	17.5	650	600	3100	3750
21-Nov-01	39	42.5	760	691	2890	3650
22-Nov-01	39	45	710	640	2840	3550
23-Nov-01	38	25	740	685	2810	3550
24-Nov-01	37	40	720	655	2780	3500
25-Nov-01	37	40	720	655	2780	3500
26-Nov-01	37	40	720	655	2780	3500
27-Nov-01	37	30	700	642	2800	3500
28-Nov-01	40	25	710	653	2790	3500
29-Nov-01	36	30	600	543	2950	3550
30-Nov-01	34	27.5	590	537	2960	3550
1-Dec-01	34	30	600	545	3000	3600
2-Dec-01	32	32.5	600	545	3000	3600
3-Dec-01	33	40	590	529	3010	3600
4-Dec-01	33	70	610	528	2990	3600
5-Dec-01	32	20	570	524	2980	3550
6-Dec-01	32	20	575	529	3000	3575
7-Dec-01	35	1.25	590	554	2910	3500
8-Dec-01	35	1.25	590	554	2910	3500
9-Dec-01	35	1.25	590	554	2910	3500
10-Dec-01	35	1.25	590	554	2910	3500
11-Dec-01	35	30	570	514	2990	3560
12-Dec-01	35	15	540	495	3060	3600
13-Dec-01	34	30	560	505	3015	3575
Oct 12-Dec 13						
Average	37	30	676	618	2882	3557
Minimum	0	1.25	430	396	1970	2400
Maximum	58	95	930	884	3100	3800
St.Dev.	11	18	90	84	148	174
Count	55	55	55	55	55	55

Date	Conditions at the inlet			Removal efficiency (%)		
	PO ₄ -P (mg/L)	NH ₄ -N (mg/L)	Mg (mg/L)	PO ₄ -P	NH ₄ -N	Mg
1-Nov-01	41.0	249	66.1	80	4	30
2-Nov-01	40.6	248	64.5	78	7	27
7-Nov-01	42.3	295	70.8	67	19	51
8-Nov-01	41.1	268	69.9	66	11	56
9-Nov-01	41.2	271	67.4	66	11	54
10-Nov-01	42.5	252	68.3	63	8	55
11-Nov-01	50.9	277	63.3	68	9	64
12-Nov-01	49.7	247	63.7	71	11	65
13-Nov-01	50.3	261	65.7	66	1	58
14-Nov-01	47.9	275	58.0	44	-3	35
15-Nov-01	47.5	274	54.9	51	1	31
16-Nov-01	47.4	273	55.3	50	1	32
17-Nov-01	47.4	273	55.6	50	1	32
18-Nov-01	48.0	252	56.1	48	-1	33
19-Nov-01	58.9	190	29.2	26	-2	38
20-Nov-01	55.2	327	55.0	47	4	46
21-Nov-01	58.2	332	51.7	43	1	43
22-Nov-01	57.4	324	51.6	48	1	44
23-Nov-01	56.9	341	53.1	45	6	39
24-Nov-01	54.7	324	56.7	49	1	38
25-Nov-01	54.7	324	56.7	49	1	38
26-Nov-01	54.7	324	56.7	49	1	38
27-Nov-01	56.4	325	57.1	53	2	36
28-Nov-01	55.7	336	60.2	51	1	40
29-Nov-01	55.9	313	62.9	54	1	47
30-Nov-01	53.2	327	59.3	55	0	46
1-Dec-01	59.2	345	59.2	42	3	38
2-Dec-01	61.9	369	56.9	43	2	37
3-Dec-01	60.3	351	58.3	46	3	41
4-Dec-01	59.9	378	55.3	56	5	41
5-Dec-01	63.5	368	61.7	46	-3	43
6-Dec-01	62.7	366	57.6	46	2	41
7-Dec-01	66.7	375	60.4	54	6	44
8-Dec-01	66.7	375	60.4	54	6	44
9-Dec-01	66.7	375	60.4	54	6	44
10-Dec-01	66.7	375	60.4	54	6	44
11-Dec-01	64.2	369	59.2	53	-7	46
12-Dec-01	60.1	390	66.8	52	-13	52
13-Dec-01	58.2	360	65.0	43	-1	50
Oct 12-Dec 13						
Average	50.5	301	60.0	60	4	40
Minimum	33.4	190	18.6	26	-13	7
Maximum	66.7	390	83.9	84	19	65
St.Dev.	9.6	48	9.9	14	6	12
Count	55	55	55	55	55	55

Date	Molar removal Inlet to outlet			Mg:P	N:P
	PO ₄ -P	NH ₄ -N	Mg	Removal Ratio	Removal Ratio
1-Nov-01	1.1E-03	6.8E-04	8.3E-04	0.8	0.6
2-Nov-01	1.0E-03	1.2E-03	7.2E-04	0.7	1.2
7-Nov-01	9.1E-04	4.0E-03	1.5E-03	1.6	4.4
8-Nov-01	8.8E-04	2.2E-03	1.6E-03	1.8	2.5
9-Nov-01	8.7E-04	2.1E-03	1.5E-03	1.7	2.4
10-Nov-01	8.7E-04	1.4E-03	1.6E-03	1.8	1.6
11-Nov-01	1.1E-03	1.8E-03	1.7E-03	1.5	1.6
12-Nov-01	1.1E-03	1.9E-03	1.7E-03	1.5	1.7
13-Nov-01	1.1E-03	2.7E-04	1.6E-03	1.5	0.3
14-Nov-01	6.8E-04	-5.1E-04	8.3E-04	1.2	-0.8
15-Nov-01	7.7E-04	2.6E-04	7.0E-04	0.9	0.3
16-Nov-01	7.7E-04	2.3E-04	7.2E-04	0.9	0.3
17-Nov-01	7.7E-04	2.0E-04	7.3E-04	1.0	0.3
18-Nov-01	7.5E-04	-1.8E-04	7.7E-04	1.0	-0.2
19-Nov-01	4.9E-04	-3.2E-04	4.6E-04	0.9	-0.6
20-Nov-01	8.3E-04	9.8E-04	1.0E-03	1.2	1.2
21-Nov-01	8.1E-04	1.5E-04	9.2E-04	1.1	0.2
22-Nov-01	8.9E-04	3.1E-04	9.3E-04	1.0	0.4
23-Nov-01	8.3E-04	1.5E-03	8.4E-04	1.0	1.8
24-Nov-01	8.6E-04	2.1E-04	8.8E-04	1.0	0.2
25-Nov-01	8.6E-04	2.1E-04	8.8E-04	1.0	0.2
26-Nov-01	8.6E-04	2.1E-04	8.8E-04	1.0	0.2
27-Nov-01	9.7E-04	5.5E-04	8.5E-04	0.9	0.6
28-Nov-01	9.2E-04	1.7E-04	9.9E-04	1.1	0.2
29-Nov-01	9.8E-04	1.6E-04	1.2E-03	1.2	0.2
30-Nov-01	9.4E-04	4.9E-05	1.1E-03	1.2	0.1
1-Dec-01	8.1E-04	7.3E-04	9.3E-04	1.1	0.9
2-Dec-01	8.6E-04	6.5E-04	8.5E-04	1.0	0.8
3-Dec-01	8.9E-04	8.4E-04	9.9E-04	1.1	0.9
4-Dec-01	1.1E-03	1.3E-03	9.3E-04	0.9	1.2
5-Dec-01	9.5E-04	-7.3E-04	1.1E-03	1.1	-0.8
6-Dec-01	9.3E-04	5.9E-04	9.8E-04	1.1	0.6
7-Dec-01	1.2E-03	1.7E-03	1.1E-03	0.9	1.4
8-Dec-01	1.2E-03	1.7E-03	1.1E-03	0.9	1.4
9-Dec-01	1.2E-03	1.7E-03	1.1E-03	0.9	1.4
10-Dec-01	1.2E-03	1.7E-03	1.1E-03	0.9	1.4
11-Dec-01	1.1E-03	-1.9E-03	1.1E-03	1.0	-1.7
12-Dec-01	1.0E-03	-3.7E-03	1.4E-03	1.4	-3.7
13-Dec-01	8.1E-04	-1.5E-04	1.3E-03	1.7	-0.2
Oct 12-Dec 13					
Average	9.4E-04	7.2E-04	1.0E-03	1.1	0.7
Minimum	4.9E-04	-3.7E-03	5.4E-05	0.1	-3.7
Maximum	1.2E-03	4.0E-03	1.7E-03	1.9	4.4
St.Dev.	1.4E-04	1.2E-03	3.5E-04	0.4	1.2
Count	55	55	55	55	55

Date	PO ₄ -P In-Reactor			NH ₄ -N In-Reactor		
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)
1-Nov-01	8.1	6.6	14.7	50	192	242
2-Nov-01	8.1	7.1	15.2	50	185	234
7-Nov-01	8.3	11.2	19.6	58	192	250
8-Nov-01	8.1	11.2	19.3	53	191	244
9-Nov-01	8.2	11.3	19.5	54	194	248
10-Nov-01	8.3	12.6	20.9	49	187	236
11-Nov-01	11.1	12.7	23.8	60	197	257
12-Nov-01	10.9	11.1	22.0	54	172	226
13-Nov-01	10.1	13.5	23.6	52	206	258
14-Nov-01	9.2	21.8	31.0	53	228	281
15-Nov-01	9.0	19.0	28.1	52	219	271
16-Nov-01	9.0	19.1	28.0	52	219	271
17-Nov-01	8.9	19.1	28.0	51	219	271
18-Nov-01	8.6	20.3	29.0	45	209	255
19-Nov-01	8.9	37.0	45.9	29	165	193
20-Nov-01	9.6	24.3	33.9	57	259	315
21-Nov-01	12.1	26.3	38.4	69	261	330
22-Nov-01	11.5	23.8	35.3	65	256	321
23-Nov-01	11.9	24.7	36.6	71	254	325
24-Nov-01	11.3	22.2	33.5	67	255	322
25-Nov-01	11.3	22.2	33.5	67	255	322
26-Nov-01	11.3	22.2	33.5	67	255	322
27-Nov-01	11.3	21.1	32.4	65	254	319
28-Nov-01	11.3	21.6	32.9	68	266	334
29-Nov-01	9.4	21.2	30.7	53	258	311
30-Nov-01	8.8	20.1	29.0	54	272	326
1-Dec-01	9.9	28.4	38.3	58	279	337
2-Dec-01	10.3	29.3	39.6	62	300	362
3-Dec-01	9.9	27.3	37.1	57	283	341
4-Dec-01	10.1	21.8	32.0	64	298	362
5-Dec-01	10.2	28.7	38.9	59	317	376
6-Dec-01	10.1	28.6	38.7	59	300	359
7-Dec-01	11.2	25.3	36.5	63	292	355
8-Dec-01	11.2	25.3	36.5	63	292	355
9-Dec-01	11.2	25.3	36.5	63	292	355
10-Dec-01	11.2	25.3	36.5	63	292	355
11-Dec-01	10.3	25.4	35.7	59	332	391
12-Dec-01	9.0	24.6	33.6	59	376	434
13-Dec-01	9.1	28.0	37.2	56	305	362
Oct 12-Dec 13						
Average	9.5	17.5	26.9	57	237	293
Minimum	6.9	4.6	11.5	29	165	193
Maximum	12.1	37.0	45.9	71	376	434
St.Dev.	1.5	8.4	9.4	8	48	52
Count	55	55	55	55	55	55

Date	Mg In-Reactor			In-Reactor Concentrations			In-Reacor Mg:P (molar ratio)	In-Reactor N:P (molar ratio)
	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	PO ₄ -P (mol/L)	NH ₄ -N (mol/L)	Mg (mol/L)		
1-Nov-01	13.1	36.9	50.0	4.8E-04	1.7E-02	2.1E-03	4.3	36.4
2-Nov-01	12.9	37.6	50.5	4.9E-04	1.7E-02	2.1E-03	4.2	34.0
7-Nov-01	14.0	27.9	41.8	6.3E-04	1.8E-02	1.7E-03	2.7	28.3
8-Nov-01	13.8	25.0	38.8	6.2E-04	1.7E-02	1.6E-03	2.6	28.0
9-Nov-01	13.5	24.6	38.1	6.3E-04	1.8E-02	1.6E-03	2.5	28.1
10-Nov-01	13.4	24.5	37.9	6.8E-04	1.7E-02	1.6E-03	2.3	24.9
11-Nov-01	13.8	17.9	31.7	7.7E-04	1.8E-02	1.3E-03	1.7	24.0
12-Nov-01	13.9	17.7	31.6	7.1E-04	1.6E-02	1.3E-03	1.8	22.7
13-Nov-01	13.1	21.9	35.1	7.6E-04	1.8E-02	1.4E-03	1.9	24.2
14-Nov-01	11.1	30.6	41.7	1.0E-03	2.0E-02	1.7E-03	1.7	20.0
15-Nov-01	10.5	30.6	41.1	9.1E-04	1.9E-02	1.7E-03	1.9	21.3
16-Nov-01	10.5	30.6	41.1	9.0E-04	1.9E-02	1.7E-03	1.9	21.4
17-Nov-01	10.5	30.7	41.2	9.0E-04	1.9E-02	1.7E-03	1.9	21.4
18-Nov-01	10.1	30.7	40.8	9.4E-04	1.8E-02	1.7E-03	1.8	19.4
19-Nov-01	4.4	15.3	19.7	1.5E-03	1.4E-02	8.1E-04	0.5	9.3
20-Nov-01	9.5	24.6	34.2	1.1E-03	2.3E-02	1.4E-03	1.3	20.6
21-Nov-01	10.8	23.2	34.0	1.2E-03	2.4E-02	1.4E-03	1.1	19.0
22-Nov-01	10.3	23.1	33.4	1.1E-03	2.3E-02	1.4E-03	1.2	20.1
23-Nov-01	11.1	25.8	36.9	1.2E-03	2.3E-02	1.5E-03	1.3	19.7
24-Nov-01	11.7	28.1	39.8	1.1E-03	2.3E-02	1.6E-03	1.5	21.3
25-Nov-01	11.7	28.1	39.8	1.1E-03	2.3E-02	1.6E-03	1.5	21.3
26-Nov-01	11.7	28.1	39.8	1.1E-03	2.3E-02	1.6E-03	1.5	21.3
27-Nov-01	11.4	29.0	40.5	1.0E-03	2.3E-02	1.7E-03	1.6	21.8
28-Nov-01	12.2	28.9	41.1	1.1E-03	2.4E-02	1.7E-03	1.6	22.5
29-Nov-01	10.6	27.8	38.5	9.9E-04	2.2E-02	1.6E-03	1.6	22.5
30-Nov-01	9.9	26.8	36.7	9.4E-04	2.3E-02	1.5E-03	1.6	24.9
1-Dec-01	9.9	30.5	40.4	1.2E-03	2.4E-02	1.7E-03	1.3	19.5
2-Dec-01	9.5	30.1	39.6	1.3E-03	2.6E-02	1.6E-03	1.3	20.2
3-Dec-01	9.5	28.5	38.1	1.2E-03	2.4E-02	1.6E-03	1.3	20.3
4-Dec-01	9.4	27.2	36.5	1.0E-03	2.6E-02	1.5E-03	1.5	25.1
5-Dec-01	9.9	29.6	39.5	1.3E-03	2.7E-02	1.6E-03	1.3	21.4
6-Dec-01	9.3	28.4	37.7	1.2E-03	2.6E-02	1.6E-03	1.2	20.6
7-Dec-01	10.2	27.9	38.1	1.2E-03	2.5E-02	1.6E-03	1.3	21.5
8-Dec-01	10.2	27.9	38.1	1.2E-03	2.5E-02	1.6E-03	1.3	21.5
9-Dec-01	10.2	27.9	38.1	1.2E-03	2.5E-02	1.6E-03	1.3	21.5
10-Dec-01	10.2	27.9	38.1	1.2E-03	2.5E-02	1.6E-03	1.3	21.5
11-Dec-01	9.5	27.0	36.5	1.2E-03	2.8E-02	1.5E-03	1.3	24.2
12-Dec-01	10.0	27.0	37.1	1.1E-03	3.1E-02	1.5E-03	1.4	28.6
13-Dec-01	10.2	27.5	37.7	1.2E-03	2.6E-02	1.6E-03	1.3	21.5
Oct 12-Dec 13								
Average	11.4	28.9	40.3	8.7E-04	2.1E-02	1.7E-03	2.3	26.5
Minimum	4.0	13.6	17.6	3.7E-04	1.4E-02	7.2E-04	0.5	9.3
Maximum	14.9	52.5	67.3	1.5E-03	3.1E-02	2.8E-03	5.4	48.6
St.Dev.	2.4	6.3	7.6	3.0E-04	3.7E-03	3.1E-04	1.3	7.9
Count	55	55	55	55	55	55	55	55

Date	Feed P _S	In-Reactor P _S	Equilibrium P _S	Feed S.S. ratio	In-Reactor S.S. Ratio	Effluent S.S. Ratio	Crystal Volume (l)	Harvest Volume (l)
1-Nov-01	6.4E-08	1.7E-08	5.7E-09	11.2	3.0	1.5	5.80	
2-Nov-01	6.2E-08	1.7E-08	6.7E-09	9.2	2.5	1.4	6.40	1.1
7-Nov-01	8.4E-08	1.9E-08	1.1E-08	7.3	1.7	1.0	5.80	
8-Nov-01	7.3E-08	1.7E-08	1.1E-08	6.4	1.5	0.9	6.25	
9-Nov-01	7.1E-08	1.7E-08	1.1E-08	6.2	1.5	0.9	6.80	1.1
10-Nov-01	6.9E-08	1.8E-08	1.1E-08	6.0	1.5	0.9	6.35	
11-Nov-01	8.5E-08	1.8E-08	1.1E-08	7.4	1.6	0.8	7.00	
12-Nov-01	7.4E-08	1.5E-08	1.1E-08	6.5	1.3	0.6	7.75	1.1
13-Nov-01	8.2E-08	2.0E-08	1.1E-08	7.1	1.8	1.0	7.30	
14-Nov-01	7.2E-08	3.4E-08	2.1E-08	3.4	1.6	1.3	7.80	1.1
15-Nov-01	6.8E-08	3.0E-08	1.7E-08	3.9	1.7	1.3	7.20	
16-Nov-01	6.8E-08	3.0E-08	1.7E-08	4.0	1.7	1.3	7.70	
17-Nov-01	6.8E-08	3.0E-08	1.7E-08	4.0	1.7	1.3	8.25	
18-Nov-01	6.5E-08	2.9E-08	2.1E-08	3.0	1.3	1.1	8.40	1.1
19-Nov-01	3.1E-08	1.7E-08	1.7E-08	1.8	1.0	0.8	7.65	
20-Nov-01	9.4E-08	3.5E-08	1.7E-08	5.5	2.0	1.5	8.20	1.1
21-Nov-01	9.5E-08	4.1E-08	1.7E-08	5.5	2.4	1.8	7.90	1.1
22-Nov-01	9.1E-08	3.6E-08	1.7E-08	5.3	2.1	1.5	7.10	
23-Nov-01	9.8E-08	4.2E-08	1.7E-08	5.7	2.4	1.8	7.30	1.1
24-Nov-01	9.5E-08	4.1E-08	2.1E-08	4.5	1.9	1.4	7.50	
25-Nov-01	9.5E-08	4.1E-08	2.1E-08	4.5	1.9	1.4	7.70	
26-Nov-01	9.5E-08	4.1E-08	2.1E-08	4.5	1.9	1.4	7.80	1.1
27-Nov-01	9.9E-08	4.0E-08	2.1E-08	4.7	1.9	1.3	6.90	
28-Nov-01	1.1E-07	4.3E-08	2.1E-08	5.0	2.0	1.5	7.55	1.1
29-Nov-01	1.0E-07	3.5E-08	1.7E-08	6.1	2.0	1.5	6.75	
30-Nov-01	9.8E-08	3.3E-08	1.7E-08	5.7	1.9	1.4	7.00	
1-Dec-01	1.1E-07	4.9E-08	2.1E-08	5.4	2.3	1.9	7.25	
2-Dec-01	1.2E-07	5.4E-08	2.7E-08	4.6	2.0	1.6	7.50	1.1
3-Dec-01	1.2E-07	4.6E-08	2.7E-08	4.4	1.7	1.3	6.65	
4-Dec-01	1.2E-07	4.0E-08	2.1E-08	5.6	1.9	1.4	7.00	
5-Dec-01	1.4E-07	5.5E-08	2.7E-08	5.1	2.1	1.6	7.25	
6-Dec-01	1.3E-07	5.0E-08	2.1E-08	5.9	2.3	1.8	7.45	1.1
7-Dec-01	1.4E-07	4.7E-08	2.7E-08	5.4	1.8	1.3		
8-Dec-01	1.4E-07	4.7E-08	2.7E-08	5.4	1.8	1.3		
9-Dec-01	1.4E-07	4.7E-08	2.7E-08	5.4	1.8	1.3		
10-Dec-01	1.4E-07	4.7E-08	2.7E-08	5.4	1.8	1.3	7.40	
11-Dec-01	1.3E-07	4.8E-08	2.7E-08	5.0	1.8	1.4	7.75	1.1
12-Dec-01	1.5E-07	5.1E-08	2.7E-08	5.6	1.9	1.4	6.80	
13-Dec-01	1.3E-07	4.8E-08	2.7E-08	4.8	1.8	1.4	7.00	1.1
Oct 12-Dec 13								
Average	8.8E-08	3.0E-08	1.5E-08	6.9	2.2	1.4	6.40	1.0
Minimum	2.2E-08	1.1E-08	4.9E-09	1.8	1.0	0.6	1.50	0.3
Maximum	1.5E-07	5.5E-08	2.7E-08	15.3	4.8	3.2	8.40	1.1
St.Dev.	3.1E-08	1.4E-08	8.0E-09	3.1	0.7	0.4	1.58	0.3
Count	55	55	55	55	55	55	52	18

Date	CRT Actual (days)	CRT Averaged In reactor SS Ratio	Harvested Product Data				Total Mass (g)
			> 2 mm (g)	> 1 mm (g)	> 0.5 mm (g)	< 0.5 mm (g)	
1-Nov-01							
2-Nov-01	39	3.5	62.5	212.3	62.0	30.5	367.4
7-Nov-01							
8-Nov-01							
9-Nov-01	42	3.4	27.6	193.0	55.4	48.4	324.5
10-Nov-01							
11-Nov-01							
12-Nov-01	45	3.3	17.6	202.8	54.4	58.7	333.5
13-Nov-01							
14-Nov-01	47	3.2	26.5	185.5	66.8	64.6	343.3
15-Nov-01							
16-Nov-01							
17-Nov-01							
18-Nov-01	24	2.1	31.3	206.2	62.4	37.1	336.9
19-Nov-01							
20-Nov-01	18	1.8	12.0	255.9	90.8	37.0	395.8
21-Nov-01	16	1.7	39.1	215.1	58.8	56.9	369.9
22-Nov-01							
23-Nov-01	13	1.7	55.5	219.5	50.4	63.7	389.1
24-Nov-01							
25-Nov-01							
26-Nov-01	15	1.8	80.6	251.0	43.7	31.1	406.3
27-Nov-01							
28-Nov-01	15	1.8	64.2	245.5	53.6	49.7	413.0
29-Nov-01							
30-Nov-01							
1-Dec-01							
2-Dec-01	15	1.9	69.6	280.0	49.1	46.4	445.1
3-Dec-01							
4-Dec-01							
5-Dec-01							
6-Dec-01	17	2.0	151.6	277.9	24.0	27.1	480.7
7-Dec-01							
8-Dec-01							
9-Dec-01							
10-Dec-01							
11-Dec-01	21	2.0	219.3	304.0	14.4	13.1	550.8
12-Dec-01							
13-Dec-01	19	1.9	113.7	482.6	46.7	14.5	657.4
Oct 12-Dec 13							
Average	27	2.6	56.4	209.8	52.6	42.4	361.3
Minimum	13	1.7	0.2	5.3	6.1	7.4	20.2
Maximum	47	3.9	219.3	482.6	106.6	87.7	657.4
St.Dev.	12	0.8	57.0	109.8	25.2	21.6	148.6
Count	18	18	18	18	18	18	18

Date	Harvested Product Data				Mean Crystal Size (mm)	Mass P Removed (g)	Theoretical Mass MAP Grown
	% > 2mm	% 1-2 mm	% 0.5-1mm	% < 0.5mm			
1-Nov-01						34.3	271.4
2-Nov-01	17.0	57.8	16.9	8.3	1.4	33.4	264.2
7-Nov-01						28.9	229.1
8-Nov-01						27.4	216.8
9-Nov-01	8.5	59.5	17.1	14.9	1.3	27.7	219.3
10-Nov-01						27.0	214.0
11-Nov-01						40.0	316.9
12-Nov-01	5.3	60.8	16.3	17.6	1.2	41.4	328.2
13-Nov-01						34.7	274.4
14-Nov-01	7.7	54.0	19.5	18.8	1.2	20.8	164.7
15-Nov-01						23.5	186.0
16-Nov-01						23.1	182.8
17-Nov-01						22.7	179.5
18-Nov-01	9.3	61.2	18.5	11.0	1.3	21.0	166.6
19-Nov-01						12.1	95.9
20-Nov-01	3.0	64.7	22.9	9.4	1.2	24.1	191.1
21-Nov-01	10.6	58.2	15.9	15.4	1.3	27.4	216.9
22-Nov-01						28.2	223.5
23-Nov-01	14.3	56.4	13.0	16.4	1.3	27.3	216.1
24-Nov-01						27.8	220.0
25-Nov-01						27.8	220.0
26-Nov-01	19.8	61.8	10.8	7.6	1.5	27.8	220.0
27-Nov-01						30.3	240.0
28-Nov-01	15.5	59.4	13.0	12.0	1.4	29.1	230.8
29-Nov-01						26.2	207.4
30-Nov-01						24.7	195.7
1-Dec-01						21.7	172.0
2-Dec-01	15.6	62.9	11.0	10.4	1.4	23.1	183.1
3-Dec-01						23.5	186.2
4-Dec-01						29.6	234.1
5-Dec-01						24.0	190.4
6-Dec-01	31.5	57.8	5.0	5.6	1.7	23.7	187.9
7-Dec-01						30.9	244.5
8-Dec-01						30.9	244.5
9-Dec-01						30.9	244.5
10-Dec-01						30.9	244.5
11-Dec-01	39.8	55.2	2.6	2.4	1.8	27.8	220.2
12-Dec-01						24.3	192.3
13-Dec-01	17.3	73.4	7.1	2.2	1.6	20.1	159.5
Oct 12-Dec 13							
Average	13.1	53.1	18.2	15.7	1.3	28.2	223.7
Minimum	0.4	13.7	2.6	2.2	0.7	12.1	95.9
Maximum	39.8	73.4	44.2	41.7	1.8	41.4	328.2
St.Dev.	10.1	15.6	11.1	11.2	0.3	5.6	44.5
Count	18	18	18	18	17	55	55

Date	Notes
1-Nov-01	
2-Nov-01	
7-Nov-01	
8-Nov-01	
9-Nov-01	
10-Nov-01	
11-Nov-01	
12-Nov-01	
13-Nov-01	
14-Nov-01	
15-Nov-01	
16-Nov-01	
17-Nov-01	
18-Nov-01	
19-Nov-01	
20-Nov-01	
21-Nov-01	
22-Nov-01	
23-Nov-01	
24-Nov-01	
25-Nov-01	
26-Nov-01	
27-Nov-01	
28-Nov-01	
29-Nov-01	
30-Nov-01	
1-Dec-01	
2-Dec-01	
3-Dec-01	
4-Dec-01	
5-Dec-01	
6-Dec-01	
7-Dec-01	
8-Dec-01	
9-Dec-01	
10-Dec-01	
11-Dec-01	
12-Dec-01	
13-Dec-01	
Oct 12-Dec 13	
Average	
Minimum	
Maximum	
St.Dev.	
Count	

APPENDIX E: MODEL RESULTS

Date	Influent				Actual Effluent			Predicted Effluent		
	Mg mg/L	NH4 mg/L	PO4 mg/L	pH	Mg mg/L	NH4 mg/L	PO4 mg/L	Mg mg/L	NH4 mg/L	PO4 mg/L
Reactor A										
12-Oct-01	67.9	286.5	40.42	8.2	69.5	239	10.4	42	272	7
13-Oct-01	46.5	263.6	39.96	8.5	41.7	257	10.1	22	250	9
14-Oct-01	52.2	264.1	40.74	8.5	44.8	255	8.3	26	249	8
15-Oct-01	62.5	269.6	43.70	8.4	39.8	263	13.0	34	253	7
16-Oct-01	66.3	277.3	42.21	8.4	38.8	259	8.3	38	261	6
17-Oct-01	47.1	285.6	43.74	8.2	27.1	270	12.4	23	272	13
18-Oct-01	49.5	271.4	46.53	8.5	28.2	306	11.2	21	255	10
24-Oct-01	18.6	285.4	43.80	8.5	14.7	283	17.7	7	278	28
25-Oct-01	61.6	278.6	40.50	8.6	32.3	254	8.9	34	263	5
26-Oct-01	68.1	260.6	33.54	8.6	31.7	230	4.8	45	247	4
27-Oct-01	72.1	266.5	39.02	8.4	36.6	249	7.1	46	251	5
28-Oct-01	74.2	221.7	36.55	8.5	31.4	207	8.5	50	207	5
29-Oct-01	66.3	260.0	35.58	8.4	33.4	251	6.1	43	246	6
30-Oct-01	66.6	260.4	35.46	8.4	35.1	235	6.2	43	247	6
31-Oct-01	59.6	254.2	39.29	8.3	31.5	258	10.8	35	240	8
1-Nov-01	64.4	250.0	41.11	8.3	32.3	272	9.0	38	235	8
2-Nov-01	65.6	246.9	40.48	8.4	31.5	262	7.8	39	232	7
7-Nov-01	69.9	295.4	42.31	8.1	29.8	262	12.3	43	280	8
8-Nov-01	69.9	261.9	40.07	8.6	25.5	230	6.0	42	246	4
9-Nov-01	66.6	265.2	40.30	8.6	24.9	245	6.2	39	249	5
10-Nov-01	66.5	249.6	42.18	8.6	22.8	244	6.6	37	233	5
11-Nov-01	100.7	248.7	45.73	8.6	33.9	220	5.7	67	229	3
12-Nov-01	78.9	233.4	46.94	8.6	27.7	230	6.4	46	214	5
13-Nov-01	63.5	259.2	50.02	8.4	18.1	256	8.8	31	240	8
14-Nov-01	51.3	277.2	48.33	8.4	17.9	255	9.0	22	260	11
15-Nov-01	53.0	272.0	47.22	8.5	20.2	267	6.4	23	255	9
16-Nov-01	55.9	268.6	46.62	8.5	20.2	267	6.4	26	251	8
17-Nov-01	59.3	264.5	45.92	8.5	20.2	267	6.4	29	247	7
18-Nov-01	60.7	246.8	46.92	8.5	23.9	236	6.2	30	229	8
19-Nov-01	79.8	158.5	49.25	8.6	38.3	176	6.1	47	139	7
20-Nov-01	101.9	269.6	45.54	8.5	69.2	275	4.1	69	250	3
21-Nov-01	48.8	330.0	57.87	8.5	13.1	309	11.5	13	310	13
22-Nov-01	49.8	320.5	56.71	8.5	15.1	299	10.2	15	300	12
23-Nov-01	53.0	337.5	56.21	8.5	15.4	317	11.0	17	317	10
24-Nov-01	54.4	320.5	54.16	8.5	17.7	305	8.3	19	300	9
25-Nov-01	54.4	320.5	54.16	8.5	17.7	305	8.3	19	300	9
26-Nov-01	54.4	320.5	54.16	8.5	17.7	305	8.3	19	300	9
27-Nov-01	56.2	321.4	55.84	8.5	18.4	305	8.3	19	300	9
28-Nov-01	60.0	333.8	55.23	8.5	19.7	312	7.7	22	312	7
29-Nov-01	58.0	309.8	55.25	8.5	17.1	285	8.6	21	289	8
30-Nov-01	57.4	321.1	52.33	8.5	17.5	296	7.4	22	301	8
1-Dec-01	58.6	338.3	58.04	8.4	17.8	305	12.4	20	316	9
2-Dec-01	59.2	356.9	59.81	8.1	22.3	345	17.0	23	336	13
3-Dec-01	53.7	347.7	59.77	8.5	17.9	338	13.7	15	326	11
4-Dec-01	55.5	357.1	56.63	8.3	19.5	351	12.0	20	336	11
5-Dec-01	60.7	364.1	62.85	8.4	18.7	336	12.1	19	340	9
6-Dec-01	62.1	357.2	61.17	8.7	15.1	354	7.8	19	332	6
7-Dec-01	57.1	376.6	67.07	8.4	18.3	330	11.8	14	352	12
8-Dec-01	57.1	376.6	67.07	8.4	18.3	330	11.8	14	352	12
9-Dec-01	57.1	376.6	67.07	8.4	18.3	330	11.8	14	352	12
10-Dec-01	57.1	376.6	67.07	8.4	18.3	330	11.8	14	352	12
11-Dec-01	56.9	361.5	62.88	8.4	17.7	332	11.5	16	338	11
12-Dec-01	62.7	388.8	59.92	8.4	18.2	320	10.5	22	365	8
13-Dec-01	60.4	357.3	57.81	8.4	16.1	346	12.4	22	335	8
Average										

Date	Mg mol/L	Influent		Predicted Effluent			P _{sin}	P _{seq}	P _{sout}
		NH4 mol/L	PO4 mol/L	Mg mol/L	NH4 mol/L	PO4 mol/L			
Reactor A									
12-Oct-01	0.0028	0.020	0.0013	0.00173	0.019	0.00024	7.5E-08	8.0E-09	8.0E-09
13-Oct-01	0.0019	0.019	0.0013	0.00092	0.018	0.00030	4.6E-08	4.9E-09	4.9E-09
14-Oct-01	0.0021	0.019	0.0013	0.00109	0.018	0.00026	5.3E-08	4.9E-09	4.9E-09
15-Oct-01	0.0026	0.019	0.0014	0.00139	0.018	0.00023	7.0E-08	5.7E-09	5.7E-09
16-Oct-01	0.0027	0.020	0.0014	0.00156	0.019	0.00020	7.4E-08	5.7E-09	5.7E-09
17-Oct-01	0.0019	0.020	0.0014	0.00095	0.019	0.00043	5.6E-08	8.0E-09	8.0E-09
18-Oct-01	0.0020	0.019	0.0015	0.00085	0.018	0.00032	5.9E-08	4.9E-09	4.9E-09
24-Oct-01	0.0008	0.020	0.0014	0.00027	0.020	0.00092	2.2E-08	4.9E-09	4.9E-09
25-Oct-01	0.0025	0.020	0.0013	0.00139	0.019	0.00016	6.6E-08	4.3E-09	4.3E-09
26-Oct-01	0.0028	0.019	0.0011	0.00185	0.018	0.00013	5.6E-08	4.3E-09	4.3E-09
27-Oct-01	0.0030	0.019	0.0013	0.00188	0.018	0.00017	7.1E-08	5.7E-09	5.7E-09
28-Oct-01	0.0031	0.016	0.0012	0.00204	0.015	0.00016	5.7E-08	4.9E-09	4.9E-09
29-Oct-01	0.0027	0.019	0.0011	0.00176	0.018	0.00018	5.8E-08	5.7E-09	5.7E-09
30-Oct-01	0.0027	0.019	0.0011	0.00178	0.018	0.00018	5.8E-08	5.7E-09	5.7E-09
31-Oct-01	0.0025	0.018	0.0013	0.00145	0.017	0.00027	5.6E-08	6.7E-09	6.7E-09
1-Nov-01	0.0027	0.018	0.0013	0.00158	0.017	0.00025	6.3E-08	6.7E-09	6.7E-09
2-Nov-01	0.0027	0.018	0.0013	0.00161	0.017	0.00022	6.2E-08	5.7E-09	5.7E-09
7-Nov-01	0.0029	0.021	0.0014	0.00178	0.020	0.00027	8.3E-08	9.5E-09	9.5E-09
8-Nov-01	0.0029	0.019	0.0013	0.00172	0.018	0.00014	7.0E-08	4.3E-09	4.3E-09
9-Nov-01	0.0027	0.019	0.0013	0.00159	0.018	0.00015	6.7E-08	4.3E-09	4.3E-09
10-Nov-01	0.0027	0.018	0.0014	0.00154	0.017	0.00017	6.6E-08	4.3E-09	4.3E-09
11-Nov-01	0.0041	0.018	0.0015	0.00276	0.016	0.00009	1.1E-07	4.3E-09	4.3E-09
12-Nov-01	0.0032	0.017	0.0015	0.00188	0.015	0.00015	8.2E-08	4.3E-09	4.3E-09
13-Nov-01	0.0026	0.019	0.0016	0.00126	0.017	0.00026	7.8E-08	5.7E-09	5.7E-09
14-Nov-01	0.0021	0.020	0.0016	0.00090	0.019	0.00034	6.5E-08	5.7E-09	5.7E-09
15-Nov-01	0.0022	0.019	0.0015	0.00094	0.018	0.00029	6.5E-08	4.9E-09	4.9E-09
16-Nov-01	0.0023	0.019	0.0015	0.00106	0.018	0.00026	6.6E-08	4.9E-09	4.9E-09
17-Nov-01	0.0024	0.019	0.0015	0.00119	0.018	0.00023	6.8E-08	4.9E-09	4.9E-09
18-Nov-01	0.0025	0.018	0.0015	0.00123	0.016	0.00025	6.7E-08	4.9E-09	4.9E-09
19-Nov-01	0.0033	0.011	0.0016	0.00192	0.010	0.00022	5.9E-08	4.3E-09	4.3E-09
20-Nov-01	0.0042	0.019	0.0015	0.00282	0.018	0.00010	1.2E-07	4.9E-09	4.9E-09
21-Nov-01	0.0020	0.024	0.0019	0.00055	0.022	0.00041	8.8E-08	4.9E-09	4.9E-09
22-Nov-01	0.0020	0.023	0.0018	0.00060	0.021	0.00038	8.6E-08	4.9E-09	4.9E-09
23-Nov-01	0.0022	0.024	0.0018	0.00069	0.023	0.00032	9.5E-08	4.9E-09	4.9E-09
24-Nov-01	0.0022	0.023	0.0017	0.00078	0.021	0.00029	9.0E-08	4.9E-09	4.9E-09
25-Nov-01	0.0022	0.023	0.0017	0.00078	0.021	0.00029	9.0E-08	4.9E-09	4.9E-09
26-Nov-01	0.0022	0.023	0.0017	0.00078	0.021	0.00029	9.0E-08	4.9E-09	4.9E-09
27-Nov-01	0.0023	0.023	0.0018	0.00080	0.021	0.00029	9.6E-08	4.9E-09	4.9E-09
28-Nov-01	0.0025	0.024	0.0018	0.00093	0.022	0.00024	1.0E-07	4.9E-09	4.9E-09
29-Nov-01	0.0024	0.022	0.0018	0.00087	0.021	0.00027	9.4E-08	4.9E-09	4.9E-09
30-Nov-01	0.0024	0.023	0.0017	0.00092	0.021	0.00025	9.1E-08	4.9E-09	4.9E-09
1-Dec-01	0.0024	0.024	0.0019	0.00084	0.023	0.00030	1.1E-07	5.7E-09	5.7E-09
2-Dec-01	0.0024	0.025	0.0019	0.00093	0.024	0.00043	1.2E-07	9.5E-09	9.5E-09
3-Dec-01	0.0022	0.025	0.0019	0.00062	0.023	0.00034	1.1E-07	4.9E-09	4.9E-09
4-Dec-01	0.0023	0.025	0.0018	0.00080	0.024	0.00035	1.1E-07	6.7E-09	6.7E-09
5-Dec-01	0.0025	0.026	0.0020	0.00077	0.024	0.00031	1.3E-07	5.7E-09	5.7E-09
6-Dec-01	0.0026	0.026	0.0020	0.00078	0.024	0.00020	1.3E-07	3.8E-09	3.8E-09
7-Dec-01	0.0024	0.027	0.0022	0.00058	0.025	0.00039	1.4E-07	5.7E-09	5.7E-09
8-Dec-01	0.0024	0.027	0.0022	0.00058	0.025	0.00039	1.4E-07	5.7E-09	5.7E-09
9-Dec-01	0.0024	0.027	0.0022	0.00058	0.025	0.00039	1.4E-07	5.7E-09	5.7E-09
10-Dec-01	0.0024	0.027	0.0022	0.00058	0.025	0.00039	1.4E-07	5.7E-09	5.7E-09
11-Dec-01	0.0023	0.026	0.0020	0.00067	0.024	0.00036	1.2E-07	5.7E-09	5.7E-09
12-Dec-01	0.0026	0.028	0.0019	0.00089	0.026	0.00025	1.4E-07	5.7E-09	5.7E-09
13-Dec-01	0.0025	0.026	0.0019	0.00089	0.024	0.00027	1.2E-07	5.7E-09	5.7E-09
Average									

Date	Mol Reduction	Absolute Concentration error			% Relative Absolute Error		
		Mg mg/L	NH4 mg/L	PO4 mg/L	Mg	NH4	PO4
Reactor A							
12-Oct-01	0.0011	27.5	32.5	3.0	39.5	13.6	29.2
13-Oct-01	0.0010	19.2	7.3	0.8	46.2	2.8	8.1
14-Oct-01	0.0011	18.4	5.7	0.4	41.1	2.2	4.8
15-Oct-01	0.0012	6.0	10.0	5.9	15.2	3.8	45.7
16-Oct-01	0.0012	0.8	2.0	2.2	2.0	0.8	26.6
17-Oct-01	0.0010	3.9	1.8	0.9	14.2	0.7	7.3
18-Oct-01	0.0012	7.5	51.2	1.3	26.5	16.7	12.1
24-Oct-01	0.0005	8.1	4.5	10.7	55.4	1.6	60.7
25-Oct-01	0.0011	1.5	8.6	3.8	4.7	3.4	42.9
26-Oct-01	0.0010	13.3	17.2	0.7	41.8	7.5	15.4
27-Oct-01	0.0011	9.0	2.3	1.8	24.5	0.9	25.7
28-Oct-01	0.0010	18.1	0.4	3.4	57.7	0.2	40.5
29-Oct-01	0.0010	9.5	4.5	0.4	28.4	1.8	6.3
30-Oct-01	0.0010	8.1	11.9	0.5	23.2	5.1	8.7
31-Oct-01	0.0010	3.8	17.8	2.5	12.2	6.9	22.7
1-Nov-01	0.0011	6.1	37.0	1.1	18.7	13.6	12.7
2-Nov-01	0.0011	7.6	30.4	1.1	24.0	11.6	14.5
7-Nov-01	0.0011	13.4	18.0	4.0	45.1	6.9	32.7
8-Nov-01	0.0012	16.4	15.7	1.6	64.4	6.8	27.0
9-Nov-01	0.0011	13.7	4.1	1.5	55.2	1.7	24.4
10-Nov-01	0.0012	14.6	11.1	1.4	64.2	4.6	21.6
11-Nov-01	0.0014	33.2	9.3	2.8	98.0	4.2	48.6
12-Nov-01	0.0014	18.0	15.8	1.8	65.0	6.8	28.0
13-Nov-01	0.0014	12.6	15.7	0.6	69.4	6.1	6.9
14-Nov-01	0.0012	3.9	5.2	1.7	21.7	2.0	18.4
15-Nov-01	0.0012	2.8	12.3	2.5	13.7	4.6	38.8
16-Nov-01	0.0012	5.5	15.9	1.7	27.0	5.9	26.0
17-Nov-01	0.0012	8.7	19.9	0.9	43.2	7.5	13.6
18-Nov-01	0.0013	6.0	7.0	1.4	25.0	3.0	22.5
19-Nov-01	0.0014	8.3	36.6	0.8	21.7	20.8	13.9
20-Nov-01	0.0014	0.6	24.6	1.1	0.9	9.0	26.2
21-Nov-01	0.0015	0.2	0.6	1.2	1.4	0.2	10.4
22-Nov-01	0.0014	0.5	1.2	1.7	3.4	0.4	16.3
23-Nov-01	0.0015	1.3	0.4	1.1	8.2	0.1	10.4
24-Nov-01	0.0015	1.3	4.8	0.8	7.5	1.6	10.2
25-Nov-01	0.0015	1.3	4.8	0.8	7.5	1.6	10.2
26-Nov-01	0.0015	1.3	4.8	0.8	7.5	1.6	10.2
27-Nov-01	0.0015	1.0	4.8	0.6	5.5	1.6	7.4
28-Nov-01	0.0015	2.8	0.2	0.2	14.1	0.1	3.3
29-Nov-01	0.0015	4.2	3.7	0.1	24.3	1.3	1.5
30-Nov-01	0.0014	4.9	4.9	0.3	28.0	1.7	4.1
1-Dec-01	0.0016	2.6	11.3	3.0	14.4	3.7	24.1
2-Dec-01	0.0015	0.3	9.2	3.7	1.4	2.7	22.1
3-Dec-01	0.0016	2.8	12.5	3.1	15.8	3.7	22.7
4-Dec-01	0.0015	0.1	14.7	1.2	0.3	4.2	10.2
5-Dec-01	0.0017	0.1	4.0	2.6	0.4	1.2	21.9
6-Dec-01	0.0018	3.9	21.6	1.5	26.1	6.1	19.4
7-Dec-01	0.0018	4.2	21.8	0.4	23.1	6.6	3.4
8-Dec-01	0.0018	4.2	21.8	0.4	23.1	6.6	3.4
9-Dec-01	0.0018	4.2	21.8	0.4	23.1	6.6	3.4
10-Dec-01	0.0018	4.2	21.8	0.4	23.1	6.6	3.4
11-Dec-01	0.0017	1.5	6.0	0.4	8.6	1.8	3.6
12-Dec-01	0.0017	3.5	45.2	2.8	19.3	14.1	27.1
13-Dec-01	0.0016	5.5	11.1	4.1	34.3	3.2	32.8
Average		7.1	13.1	1.8	26.1	4.8	18.8

Date	Actual Error			% Relative Actual Error		
	Mg mg/L	NH4 mg/L	PO4 mg/L	Mg	NH4	PO4
Reactor A						
12-Oct-01	-27.5	32.5	-3.0	-39.5	13.6	-29.2
13-Oct-01	-19.2	-7.3	-0.8	-46.2	-2.8	-8.1
14-Oct-01	-18.4	-5.7	-0.4	-41.1	-2.2	-4.8
15-Oct-01	-6.0	-10.0	-5.9	-15.2	-3.8	-45.7
16-Oct-01	-0.8	2.0	-2.2	-2.0	0.8	-26.6
17-Oct-01	-3.9	1.8	0.9	-14.2	0.7	7.3
18-Oct-01	-7.5	-51.2	-1.3	-26.5	-16.7	-12.1
24-Oct-01	-8.1	-4.5	10.7	-55.4	-1.6	60.7
25-Oct-01	1.5	8.6	-3.8	4.7	3.4	-42.9
26-Oct-01	13.3	17.2	-0.7	41.8	7.5	-15.4
27-Oct-01	9.0	2.3	-1.8	24.5	0.9	-25.7
28-Oct-01	18.1	0.4	-3.4	57.7	0.2	-40.5
29-Oct-01	9.5	-4.5	-0.4	28.4	-1.8	-6.3
30-Oct-01	8.1	11.9	-0.5	23.2	5.1	-8.7
31-Oct-01	3.8	-17.8	-2.5	12.2	-6.9	-22.7
1-Nov-01	6.1	-37.0	-1.1	18.7	-13.6	-12.7
2-Nov-01	7.6	-30.4	-1.1	24.0	-11.6	-14.5
7-Nov-01	13.4	18.0	-4.0	45.1	6.9	-32.7
8-Nov-01	16.4	15.7	-1.6	64.4	6.8	-27.0
9-Nov-01	13.7	4.1	-1.5	55.2	1.7	-24.4
10-Nov-01	14.6	-11.1	-1.4	64.2	-4.6	-21.6
11-Nov-01	33.2	9.3	-2.8	98.0	4.2	-48.6
12-Nov-01	18.0	-15.8	-1.8	65.0	-6.8	-28.0
13-Nov-01	12.6	-15.7	-0.6	69.4	-6.1	-6.9
14-Nov-01	3.9	5.2	1.7	21.7	2.0	18.4
15-Nov-01	2.8	-12.3	2.5	13.7	-4.6	38.8
16-Nov-01	5.5	-15.9	1.7	27.0	-5.9	26.0
17-Nov-01	8.7	-19.9	0.9	43.2	-7.5	13.6
18-Nov-01	6.0	-7.0	1.4	25.0	-3.0	22.5
19-Nov-01	8.3	-36.6	0.8	21.7	-20.8	13.9
20-Nov-01	-0.6	-24.6	-1.1	-0.9	-9.0	-26.2
21-Nov-01	0.2	0.6	1.2	1.4	0.2	10.4
22-Nov-01	-0.5	1.2	1.7	-3.4	0.4	16.3
23-Nov-01	1.3	-0.4	-1.1	8.2	-0.1	-10.4
24-Nov-01	1.3	-4.8	0.8	7.5	-1.6	10.2
25-Nov-01	1.3	-4.8	0.8	7.5	-1.6	10.2
26-Nov-01	1.3	-4.8	0.8	7.5	-1.6	10.2
27-Nov-01	1.0	-4.8	0.6	5.5	-1.6	7.4
28-Nov-01	2.8	0.2	-0.2	14.1	0.1	-3.3
29-Nov-01	4.2	3.7	-0.1	24.3	1.3	-1.5
30-Nov-01	4.9	4.9	0.3	28.0	1.7	4.1
1-Dec-01	2.6	11.3	-3.0	14.4	3.7	-24.1
2-Dec-01	0.3	-9.2	-3.7	1.4	-2.7	-22.1
3-Dec-01	-2.8	-12.5	-3.1	-15.8	-3.7	-22.7
4-Dec-01	0.1	-14.7	-1.2	0.3	-4.2	-10.2
5-Dec-01	0.1	4.0	-2.6	0.4	1.2	-21.9
6-Dec-01	3.9	-21.6	-1.5	26.1	-6.1	-19.4
7-Dec-01	-4.2	21.8	0.4	-23.1	6.6	3.4
8-Dec-01	-4.2	21.8	0.4	-23.1	6.6	3.4
9-Dec-01	-4.2	21.8	0.4	-23.1	6.6	3.4
10-Dec-01	-4.2	21.8	0.4	-23.1	6.6	3.4
11-Dec-01	-1.5	6.0	-0.4	-8.6	1.8	-3.6
12-Dec-01	3.5	45.2	-2.8	19.3	14.1	-27.1
13-Dec-01	5.5	-11.1	-4.1	34.3	-3.2	-32.8
Average	2.9	-2.3	-0.7	12.7	-0.9	-8.3

Date	Influent				Actual Effluent			Predicted Effluent		
	Mg mg/L	NH4 mg/L	PO4 mg/L	pH	Mg mg/L	NH4 mg/L	PO4 mg/L	Mg mg/L	NH4 mg/L	PO4 mg/L
Reactor B										
12-Oct-01	83.9	279.4	39.41	8.4	63.8	240	12.6	56	263	4
13-Oct-01	53.4	260.4	39.47	8.4	49.4	242	10.7	29	246	8
14-Oct-01	50.4	265.0	40.88	8.4	45.0	246	9.4	26	251	9
15-Oct-01	60.6	270.9	43.92	8.4	34.3	274	13.0	32	254	7
16-Oct-01	63.3	279.1	42.48	8.4	37.4	261	11.0	35	263	7
17-Oct-01	62.9	275.4	42.19	8.5	42.1	270	8.8	34	259	6
18-Oct-01	51.0	270.9	46.46	8.5	30.9	258	12.1	22	254	9
24-Oct-01	18.6	285.5	43.81	8.4	17.3	280	18.2	7	279	29
25-Oct-01	63.2	277.8	40.39	8.4	38.6	241	7.8	36	262	6
26-Oct-01	69.8	259.8	33.44	8.4	43.4	250	5.8	48	247	5
27-Oct-01	74.5	265.3	38.85	8.4	44.2	265	6.4	48	250	5
28-Oct-01	76.7	220.6	36.38	8.4	35.1	237	8.4	53	207	6
29-Oct-01	69.7	257.9	35.29	8.4	47.9	233	6.5	46	244	5
30-Oct-01	70.0	258.8	35.24	8.4	48.0	227	6.3	46	245	5
31-Oct-01	60.9	255.2	39.45	8.3	43.0	251	11.4	36	241	8
1-Nov-01	66.1	249.5	41.02	8.4	46.0	240	8.2	39	234	7
2-Nov-01	64.5	247.9	40.64	8.3	47.0	231	8.9	39	233	8
7-Nov-01	70.8	295.3	42.29	8	34.7	239	14.0	45	281	10
8-Nov-01	69.9	268.3	41.05	8	31.1	238	13.9	46	254	10
9-Nov-01	67.4	271.0	41.18	8	30.8	242	14.1	44	257	11
10-Nov-01	68.3	251.5	42.51	8	30.5	232	15.7	44	238	12
11-Nov-01	63.3	277.0	50.94	8	22.9	252	16.2	34	260	14
12-Nov-01	63.7	247.3	49.73	8	22.6	220	14.2	36	231	15
13-Nov-01	65.7	260.8	50.32	8	27.4	257	16.9	37	244	13
14-Nov-01	58.0	274.9	47.93	7.7	37.9	282	27.0	38	263	22
15-Nov-01	54.9	273.6	47.49	7.8	37.8	270	23.5	34	261	21
16-Nov-01	55.3	273.2	47.42	7.8	37.8	270	23.5	34	261	20
17-Nov-01	55.6	272.8	47.35	7.8	37.8	270	23.5	34	261	20
18-Nov-01	56.1	252.5	47.99	7.7	37.4	255	24.8	38	242	25
19-Nov-01	29.2	189.5	58.88	7.8	18.0	194	43.6	21	185	48
20-Nov-01	55.0	326.7	55.19	7.8	29.8	313	29.4	28	311	21
21-Nov-01	51.7	332.1	58.23	7.8	29.3	330	33.2	24	316	23
22-Nov-01	51.6	324.4	57.40	7.8	28.9	320	29.8	25	309	23
23-Nov-01	53.1	341.4	56.85	7.8	32.6	321	31.3	26	326	22
24-Nov-01	56.7	324.0	54.74	7.7	35.4	321	28.0	32	310	23
25-Nov-01	56.7	324.0	54.74	7.7	35.4	321	28.0	32	310	23
26-Nov-01	56.7	324.0	54.74	7.7	35.4	321	28.0	32	310	23
27-Nov-01	57.1	324.8	56.42	7.7	36.3	317	26.4	31	310	23
28-Nov-01	60.2	336.4	55.66	7.7	36.2	334	27.2	33	321	21
29-Nov-01	62.9	313.2	55.86	7.8	33.5	311	25.6	33	296	18
30-Nov-01	59.3	326.7	53.24	7.8	32.2	326	24.2	32	311	18
1-Dec-01	59.2	345.3	59.24	7.7	36.6	335	34.1	30	329	23
2-Dec-01	56.9	369.1	61.86	7.6	36.1	360	35.1	30	353	27
3-Dec-01	58.3	350.7	60.28	7.6	34.1	339	32.6	32	335	26
4-Dec-01	55.3	377.7	59.90	7.7	32.7	359	26.3	27	361	23
5-Dec-01	61.7	367.8	63.49	7.6	35.2	378	34.2	32	351	25
6-Dec-01	57.6	366.2	62.71	7.7	33.9	358	34.1	27	349	24
7-Dec-01	60.4	374.7	66.73	7.6	33.6	351	30.4	29	357	27
8-Dec-01	60.4	374.7	66.73	7.6	33.6	351	30.4	29	357	27
9-Dec-01	60.4	374.7	66.73	7.6	33.6	351	30.4	29	357	27
10-Dec-01	60.4	374.7	66.73	7.6	33.6	351	30.4	29	357	27
11-Dec-01	59.2	368.9	64.18	7.6	32.2	395	30.3	30	352	27
12-Dec-01	66.8	390.2	60.13	7.6	31.8	442	28.9	36	372	21
13-Dec-01	65.0	359.9	58.23	7.6	32.6	362	33.3	37	344	22
Average										

Date	Influent			Predicted Effluent			P _{sin}	P _{seq}	P _{sout}
	Mg mol/L	NH ₄ mol/L	PO ₄ mol/L	Mg mol/L	NH ₄ mol/L	PO ₄ mol/L			
Reactor B									
12-Oct-01	0.0035	0.020	0.0013	0.00231	0.019	0.00013	8.8E-08	5.7E-09	5.7E-09
13-Oct-01	0.0022	0.019	0.0013	0.00119	0.018	0.00027	5.2E-08	5.7E-09	5.7E-09
14-Oct-01	0.0021	0.019	0.0013	0.00106	0.018	0.00030	5.2E-08	5.7E-09	5.7E-09
15-Oct-01	0.0025	0.019	0.0014	0.00132	0.018	0.00024	6.8E-08	5.7E-09	5.7E-09
16-Oct-01	0.0026	0.020	0.0014	0.00145	0.019	0.00021	7.1E-08	5.7E-09	5.7E-09
17-Oct-01	0.0026	0.020	0.0014	0.00141	0.018	0.00019	6.9E-08	4.9E-09	4.9E-09
18-Oct-01	0.0021	0.019	0.0015	0.00090	0.018	0.00030	6.1E-08	4.9E-09	4.9E-09
24-Oct-01	0.0008	0.020	0.0014	0.00030	0.020	0.00095	2.2E-08	5.7E-09	5.7E-09
25-Oct-01	0.0026	0.020	0.0013	0.00150	0.019	0.00020	6.7E-08	5.7E-09	5.7E-09
26-Oct-01	0.0029	0.019	0.0011	0.00196	0.018	0.00017	5.8E-08	5.7E-09	5.7E-09
27-Oct-01	0.0031	0.019	0.0013	0.00197	0.018	0.00016	7.3E-08	5.7E-09	5.7E-09
28-Oct-01	0.0032	0.016	0.0012	0.00216	0.015	0.00018	5.8E-08	5.7E-09	5.7E-09
29-Oct-01	0.0029	0.018	0.0011	0.00190	0.017	0.00017	6.0E-08	5.7E-09	5.7E-09
30-Oct-01	0.0029	0.018	0.0011	0.00191	0.018	0.00017	6.1E-08	5.7E-09	5.7E-09
31-Oct-01	0.0025	0.018	0.0013	0.00149	0.017	0.00026	5.8E-08	6.7E-09	6.7E-09
1-Nov-01	0.0027	0.018	0.0013	0.00161	0.017	0.00021	6.4E-08	5.7E-09	5.7E-09
2-Nov-01	0.0027	0.018	0.0013	0.00159	0.017	0.00025	6.2E-08	6.7E-09	6.7E-09
7-Nov-01	0.0029	0.021	0.0014	0.00186	0.020	0.00031	8.4E-08	1.1E-08	1.1E-08
8-Nov-01	0.0029	0.019	0.0013	0.00189	0.018	0.00034	7.3E-08	1.1E-08	1.1E-08
9-Nov-01	0.0028	0.019	0.0013	0.00179	0.018	0.00035	7.1E-08	1.1E-08	1.1E-08
10-Nov-01	0.0028	0.018	0.0014	0.00181	0.017	0.00037	6.9E-08	1.1E-08	1.1E-08
11-Nov-01	0.0026	0.020	0.0016	0.00140	0.019	0.00044	8.5E-08	1.1E-08	1.1E-08
12-Nov-01	0.0026	0.018	0.0016	0.00148	0.017	0.00047	7.4E-08	1.1E-08	1.1E-08
13-Nov-01	0.0027	0.019	0.0016	0.00151	0.017	0.00044	8.2E-08	1.1E-08	1.1E-08
14-Nov-01	0.0024	0.020	0.0015	0.00156	0.019	0.00073	7.2E-08	2.1E-08	2.1E-08
15-Nov-01	0.0023	0.020	0.0015	0.00139	0.019	0.00066	6.8E-08	1.7E-08	1.7E-08
16-Nov-01	0.0023	0.020	0.0015	0.00140	0.019	0.00066	6.8E-08	1.7E-08	1.7E-08
17-Nov-01	0.0023	0.019	0.0015	0.00141	0.019	0.00065	6.8E-08	1.7E-08	1.7E-08
18-Nov-01	0.0023	0.018	0.0015	0.00155	0.017	0.00079	6.5E-08	2.1E-08	2.1E-08
19-Nov-01	0.0012	0.014	0.0019	0.00084	0.013	0.00155	3.1E-08	1.7E-08	1.7E-08
20-Nov-01	0.0023	0.023	0.0018	0.00115	0.022	0.00067	9.4E-08	1.7E-08	1.7E-08
21-Nov-01	0.0021	0.024	0.0019	0.00100	0.023	0.00076	9.5E-08	1.7E-08	1.7E-08
22-Nov-01	0.0021	0.023	0.0019	0.00103	0.022	0.00076	9.1E-08	1.7E-08	1.7E-08
23-Nov-01	0.0022	0.024	0.0018	0.00105	0.023	0.00070	9.8E-08	1.7E-08	1.7E-08
24-Nov-01	0.0023	0.023	0.0018	0.00130	0.022	0.00074	9.5E-08	2.1E-08	2.1E-08
25-Nov-01	0.0023	0.023	0.0018	0.00130	0.022	0.00074	9.5E-08	2.1E-08	2.1E-08
26-Nov-01	0.0023	0.023	0.0018	0.00130	0.022	0.00074	9.5E-08	2.1E-08	2.1E-08
27-Nov-01	0.0023	0.023	0.0018	0.00128	0.022	0.00075	9.9E-08	2.1E-08	2.1E-08
28-Nov-01	0.0025	0.024	0.0018	0.00136	0.023	0.00068	1.1E-07	2.1E-08	2.1E-08
29-Nov-01	0.0026	0.022	0.0018	0.00138	0.021	0.00059	1.0E-07	1.7E-08	1.7E-08
30-Nov-01	0.0024	0.023	0.0017	0.00131	0.022	0.00059	9.8E-08	1.7E-08	1.7E-08
1-Dec-01	0.0024	0.025	0.0019	0.00125	0.023	0.00073	1.1E-07	2.1E-08	2.1E-08
2-Dec-01	0.0023	0.026	0.0020	0.00121	0.025	0.00087	1.2E-07	2.7E-08	2.7E-08
3-Dec-01	0.0024	0.025	0.0019	0.00131	0.024	0.00085	1.2E-07	2.7E-08	2.7E-08
4-Dec-01	0.0023	0.027	0.0019	0.00110	0.026	0.00076	1.2E-07	2.1E-08	2.1E-08
5-Dec-01	0.0025	0.026	0.0020	0.00131	0.025	0.00082	1.4E-07	2.7E-08	2.7E-08
6-Dec-01	0.0024	0.026	0.0020	0.00112	0.025	0.00077	1.3E-07	2.1E-08	2.1E-08
7-Dec-01	0.0025	0.027	0.0022	0.00120	0.025	0.00087	1.4E-07	2.7E-08	2.7E-08
8-Dec-01	0.0025	0.027	0.0022	0.00120	0.025	0.00087	1.4E-07	2.7E-08	2.7E-08
9-Dec-01	0.0025	0.027	0.0022	0.00120	0.025	0.00087	1.4E-07	2.7E-08	2.7E-08
10-Dec-01	0.0025	0.027	0.0022	0.00120	0.025	0.00087	1.4E-07	2.7E-08	2.7E-08
11-Dec-01	0.0024	0.026	0.0021	0.00123	0.025	0.00087	1.3E-07	2.7E-08	2.7E-08
12-Dec-01	0.0027	0.028	0.0019	0.00149	0.027	0.00068	1.5E-07	2.7E-08	2.7E-08
13-Dec-01	0.0027	0.026	0.0019	0.00151	0.025	0.00072	1.3E-07	2.7E-08	2.7E-08

Average

Date	Mol Reduction	Absolute Concentration error			% Relative Absolute Error		
		Mg mg/L	NH4 mg/L	PO4 mg/L	Mg	NH4	PO4
Reactor B							
12-Oct-01	0.0011	7.6	23.4	8.5	11.9	9.7	67.6
13-Oct-01	0.0010	20.3	4.3	2.3	41.2	1.8	21.1
14-Oct-01	0.0010	19.3	4.8	0.0	42.9	1.9	0.4
15-Oct-01	0.0012	2.3	19.6	5.6	6.6	7.1	42.9
16-Oct-01	0.0012	2.3	1.9	4.5	6.1	0.7	40.6
17-Oct-01	0.0012	7.8	11.0	3.0	18.4	4.1	33.6
18-Oct-01	0.0012	9.0	3.9	2.8	29.0	1.5	22.9
24-Oct-01	0.0005	10.0	1.0	11.3	57.5	0.4	61.9
25-Oct-01	0.0011	2.1	21.4	1.5	5.5	8.9	19.2
26-Oct-01	0.0009	4.2	3.0	0.7	9.7	1.2	11.4
27-Oct-01	0.0011	3.8	15.0	1.4	8.6	5.7	21.4
28-Oct-01	0.0010	17.4	30.3	2.8	49.6	12.8	33.8
29-Oct-01	0.0010	1.7	11.3	1.2	3.5	4.9	17.7
30-Oct-01	0.0010	1.5	18.3	1.0	3.1	8.0	16.0
31-Oct-01	0.0010	6.7	10.0	3.3	15.7	4.0	28.9
1-Nov-01	0.0011	6.9	6.1	1.6	15.0	2.5	19.5
2-Nov-01	0.0011	8.2	2.0	1.1	17.5	0.9	11.9
7-Nov-01	0.0011	10.4	41.5	4.4	30.0	17.4	31.7
8-Nov-01	0.0010	14.7	16.4	3.5	47.4	6.9	25.3
9-Nov-01	0.0010	12.8	15.2	3.3	41.4	6.3	23.4
10-Nov-01	0.0010	13.5	5.6	4.1	44.4	2.4	26.3
11-Nov-01	0.0012	11.2	8.1	2.5	48.8	3.2	15.7
12-Nov-01	0.0011	13.5	11.3	0.3	59.6	5.2	2.1
13-Nov-01	0.0012	9.4	12.9	3.4	34.2	5.0	20.2
14-Nov-01	0.0008	0.1	18.6	4.5	0.3	6.6	16.8
15-Nov-01	0.0009	4.0	8.6	3.0	10.7	3.2	12.6
16-Nov-01	0.0009	3.7	9.0	3.1	9.9	3.3	13.2
17-Nov-01	0.0009	3.4	9.5	3.3	9.1	3.5	13.9
18-Nov-01	0.0008	0.4	13.1	0.2	1.1	5.1	0.8
19-Nov-01	0.0004	2.5	9.4	4.3	14.0	4.9	9.8
20-Nov-01	0.0011	1.8	1.9	8.6	5.9	0.6	29.3
21-Nov-01	0.0011	4.9	13.6	9.7	16.7	4.1	29.3
22-Nov-01	0.0011	3.9	11.0	6.3	13.6	3.4	21.2
23-Nov-01	0.0011	7.0	4.5	9.5	21.6	1.4	30.3
24-Nov-01	0.0010	3.7	11.4	5.0	10.4	3.6	18.0
25-Nov-01	0.0010	3.7	11.4	5.0	10.4	3.6	18.0
26-Nov-01	0.0010	3.7	11.4	5.0	10.4	3.6	18.0
27-Nov-01	0.0011	5.2	7.2	3.0	14.3	2.3	11.4
28-Nov-01	0.0011	3.1	13.2	6.0	8.5	3.9	22.1
29-Nov-01	0.0012	0.1	14.8	7.3	0.2	4.7	28.4
30-Nov-01	0.0011	0.3	15.1	5.9	1.0	4.6	24.3
1-Dec-01	0.0012	6.2	6.3	11.6	17.0	1.9	34.0
2-Dec-01	0.0011	6.6	6.7	8.1	18.2	1.9	23.0
3-Dec-01	0.0011	2.4	3.6	6.1	6.9	1.1	18.8
4-Dec-01	0.0012	6.1	2.2	2.9	18.6	0.6	10.9
5-Dec-01	0.0012	3.5	27.5	8.9	10.0	7.3	25.9
6-Dec-01	0.0013	6.8	9.4	10.2	20.0	2.6	30.1
7-Dec-01	0.0013	4.4	5.8	3.4	13.0	1.6	11.1
8-Dec-01	0.0013	4.4	5.8	3.4	13.0	1.6	11.1
9-Dec-01	0.0013	4.4	5.8	3.4	13.0	1.6	11.1
10-Dec-01	0.0013	4.4	5.8	3.4	13.0	1.6	11.1
11-Dec-01	0.0012	2.3	43.0	3.5	7.3	10.9	11.5
12-Dec-01	0.0013	4.3	69.5	7.9	13.5	15.7	27.5
13-Dec-01	0.0012	4.2	18.3	11.0	12.8	5.1	33.0
Average		6.1	12.8	4.6	18.2	4.4	22.1

Date	Actual Error			% Relative Actual Error		
	Mg mg/L	NH4 mg/L	PO4 mg/L	Mg	NH4	PO4
Reactor B						
12-Oct-01	-7.6	23.4	-8.5	-11.9	9.7	-67.6
13-Oct-01	-20.3	4.3	-2.3	-41.2	1.8	-21.1
14-Oct-01	-19.3	4.8	0.0	-42.9	1.9	-0.4
15-Oct-01	-2.3	-19.6	-5.6	-6.6	-7.1	-42.9
16-Oct-01	-2.3	1.9	-4.5	-6.1	0.7	-40.6
17-Oct-01	-7.8	-11.0	-3.0	-18.4	-4.1	-33.6
18-Oct-01	-9.0	-3.9	-2.8	-29.0	-1.5	-22.9
24-Oct-01	-10.0	-1.0	11.3	-57.5	-0.4	61.9
25-Oct-01	-2.1	21.4	-1.5	-5.5	8.9	-19.2
26-Oct-01	4.2	-3.0	-0.7	9.7	-1.2	-11.4
27-Oct-01	3.8	-15.0	-1.4	8.6	-5.7	-21.4
28-Oct-01	17.4	-30.3	-2.8	49.6	-12.8	-33.8
29-Oct-01	-1.7	11.3	-1.2	-3.5	4.9	-17.7
30-Oct-01	-1.5	18.3	-1.0	-3.1	8.0	-16.0
31-Oct-01	-6.7	-10.0	-3.3	-15.7	-4.0	-28.9
1-Nov-01	-6.9	-6.1	-1.6	-15.0	-2.5	-19.5
2-Nov-01	-8.2	2.0	-1.1	-17.5	0.9	-11.9
7-Nov-01	10.4	41.5	-4.4	30.0	17.4	-31.7
8-Nov-01	14.7	16.4	-3.5	47.4	6.9	-25.3
9-Nov-01	12.8	15.2	-3.3	41.4	6.3	-23.4
10-Nov-01	13.5	5.6	-4.1	44.4	2.4	-26.3
11-Nov-01	11.2	8.1	-2.5	48.8	3.2	-15.7
12-Nov-01	13.5	11.3	0.3	59.6	5.2	2.1
13-Nov-01	9.4	-12.9	-3.4	34.2	-5.0	-20.2
14-Nov-01	0.1	-18.6	-4.5	0.3	-6.6	-16.8
15-Nov-01	-4.0	-8.6	-3.0	-10.7	-3.2	-12.6
16-Nov-01	-3.7	-9.0	-3.1	-9.9	-3.3	-13.2
17-Nov-01	-3.4	-9.5	-3.3	-9.1	-3.5	-13.9
18-Nov-01	0.4	-13.1	-0.2	1.1	-5.1	-0.8
19-Nov-01	2.5	-9.4	4.3	14.0	-4.9	9.8
20-Nov-01	-1.8	-1.9	-8.6	-5.9	-0.6	-29.3
21-Nov-01	-4.9	-13.6	-9.7	-16.7	-4.1	-29.3
22-Nov-01	-3.9	-11.0	-6.3	-13.6	-3.4	-21.2
23-Nov-01	-7.0	4.5	-9.5	-21.6	1.4	-30.3
24-Nov-01	-3.7	-11.4	-5.0	-10.4	-3.6	-18.0
25-Nov-01	-3.7	-11.4	-5.0	-10.4	-3.6	-18.0
26-Nov-01	-3.7	-11.4	-5.0	-10.4	-3.6	-18.0
27-Nov-01	-5.2	-7.2	-3.0	-14.3	-2.3	-11.4
28-Nov-01	-3.1	-13.2	-6.0	-8.5	-3.9	-22.1
29-Nov-01	-0.1	-14.8	-7.3	-0.2	-4.7	-28.4
30-Nov-01	-0.3	-15.1	-5.9	-1.0	-4.6	-24.3
1-Dec-01	-6.2	-6.3	-11.6	-17.0	-1.9	-34.0
2-Dec-01	-6.6	-6.7	-8.1	-18.2	-1.9	-23.0
3-Dec-01	-2.4	-3.6	-6.1	-6.9	-1.1	-18.8
4-Dec-01	-6.1	2.2	-2.9	-18.6	0.6	-10.9
5-Dec-01	-3.5	-27.5	-8.9	-10.0	-7.3	-25.9
6-Dec-01	-6.8	-9.4	-10.2	-20.0	-2.6	-30.1
7-Dec-01	-4.4	5.8	-3.4	-13.0	1.6	-11.1
8-Dec-01	-4.4	5.8	-3.4	-13.0	1.6	-11.1
9-Dec-01	-4.4	5.8	-3.4	-13.0	1.6	-11.1
10-Dec-01	-4.4	5.8	-3.4	-13.0	1.6	-11.1
11-Dec-01	-2.3	-43.0	-3.5	-7.3	-10.9	-11.5
12-Dec-01	4.3	-69.5	-7.9	13.5	-15.7	-27.5
13-Dec-01	4.2	-18.3	-11.0	12.8	-5.1	-33.0
Average	-1.5	-4.8	-4.0	-2.8	-1.2	-19.3

APPENDIX F: CRYSTAL CHEMICAL ANALYSIS

Date	Reactor Sample	Crystal Mass mg	Solution Volume L	Mg mg/L	Ca mg/L	K mg/L	Al mg/L	Fe mg/L	NH3-N mg/L	PO4-P mg/L
13-Nov-01	A >2mm	31.0	0.050	60.1	5.3	0.2	0.3	0.2	33.5	77.8
13-Nov-01	A >1mm	32.1	0.050	60.0	5.9	0.3	0.1	0.1	34.0	77.6
13-Nov-01	A >0.5mm	30.4	0.050	58.9	4.6	0.3	1.1	0.3	32.8	75.5
13-Nov-01	A <0.5mm	30.4	0.050	60.6	2.5	0.2	0.4	0.1	31.9	76.1
30-Nov-01	A >2mm	30.3	0.050	61.8	7.3	0.3	0.2	0.2	33.4	79.4
30-Nov-01	A >1mm	30.1	0.050	60.5	2.6	0.2	0.4	0.1	32.9	76.7
30-Nov-01	A >0.5mm	30.6	0.050	61.3	3.4	0.2	-0.3	0.1	34.0	79.3
30-Nov-01	A <0.5mm	29.5	0.050	62.6	1.7	0.3	0.2	0.1	30.0	84.0
12-Dec-01	A >2mm	28.6	0.050	57.8	3.7	0.2	-0.1	0.1	32.8	73.5
12-Dec-01	A >1mm	30.8	0.050	63.1	3.6	0.2	0.0	0.2	34.7	80.4
12-Dec-01	A >0.5mm	29.6	0.050	59.4	1.4	0.2	-0.4	0.1	33.3	74.4
12-Dec-01	A <0.5mm	31.3	0.050	65.7	1.4	0.2	-1.1	0.1	36.0	80.6
20-Nov-01	B >2mm	30.3	0.050	55.4	1.6	0.2	-0.5	0.1	32.8	69.9
20-Nov-01	B >1mm	29.4	0.050	60.3	1.4	0.2	-0.1	0.1	33.7	76.1
20-Nov-01	B >0.5mm	29.3	0.050	58.5	4.5	0.2	-0.5	0.1	33.8	77.0
20-Nov-01	B <0.5mm	31.0	0.050	61.8	1.5	0.2	-0.5	0.2	36.1	79.6
2-Dec-01	B >2mm	30.7	0.050	60.7	1.1	0.2	-0.4	0.2	36.0	78.1
2-Dec-01	B >1mm	29.8	0.050	58.7	1.0	0.2	-0.8	0.2	34.6	76.3
2-Dec-01	B >0.5mm	29.9	0.050	61.4	5.9	0.2	-0.4	0.4	34.9	80.3
2-Dec-01	B <0.5mm	29.8	0.050	64.3	3.9	0.2	0.0	0.3	33.0	83.3
11-Dec-01	B >2mm	30.9	0.050	61.0	1.3	0.2	0.0	0.2	36.0	78.4
11-Dec-01	B >1mm	29.7	0.050	57.6	1.2	0.2	0.1	0.3	35.1	78.2
11-Dec-01	B >0.5mm	30.7	0.050	61.5	7.8	0.3	0.9	0.4	35.3	83.7
11-Dec-01	B <0.5mm	30.4	0.050	53.6	1.3	0.2	0.3	0.2	25.5	70.7
30-Nov-01	A >1mm	29.4	0.050	56.6	2.5	0.2	0.1	0.1	34.3	75.3
2-Dec-01	B >0.5mm	30.8	0.050	59.1	1.1	0.2	-0.2	0.9	35.3	78.9
11-Dec-01	B >2mm	31.0	0.050	60.1	1.5	0.2	-0.3	0.3	36.2	79.4
13-Nov-01	A <0.5mm	30.8	0.050	58.6	3.6	0.3	0.3	0.2	34.0	79.7
11-Dec-01	B Bulk	29.2	0.050	57.5	1.2	0.2	-0.3	0.2	32.4	75.0
Average		30.3	0.050	60.0	3.0	0.2	-0.1	0.2	33.7	77.8
min		28.6	0.050	53.6	1.0	0.2	-1.1	0.1	25.5	69.9
max		32.1	0.050	65.7	7.8	0.3	1.1	0.9	36.2	84.0
St.Dev.		0.8	0.000	2.5	2.0	0.0	0.5	0.2	2.1	3.3

Date	Reactor Sample	Theoretical Mg mg/L	Theoretical NH3-N mg/L	Theoretical PO4-P mg/L	% Struvite
13-Nov-01	A >2mm	61.4	35.4	78.3	97.3
13-Nov-01	A >1mm	63.6	36.6	81.1	94.3
13-Nov-01	A >0.5mm	60.2	34.7	76.8	96.9
13-Nov-01	A <0.5mm	60.2	34.7	76.8	97.2
30-Nov-01	A >2mm	60.0	34.6	76.5	101.1
30-Nov-01	A >1mm	59.6	34.4	76.0	99.3
30-Nov-01	A >0.5mm	60.6	34.9	77.3	100.4
30-Nov-01	A <0.5mm	58.5	33.7	74.5	102.9
12-Dec-01	A >2mm	56.7	32.6	72.2	101.4
12-Dec-01	A >1mm	61.0	35.2	77.8	101.8
12-Dec-01	A >0.5mm	58.7	33.8	74.8	99.8
12-Dec-01	A <0.5mm	62.0	35.7	79.0	102.9
20-Nov-01	B >2mm	60.0	34.6	76.5	92.8
20-Nov-01	B >1mm	58.3	33.6	74.2	102.2
20-Nov-01	B >0.5mm	58.1	33.4	74.0	101.9
20-Nov-01	B <0.5mm	61.4	35.4	78.3	101.4
2-Dec-01	B >2mm	60.8	35.0	77.5	101.1
2-Dec-01	B >1mm	59.0	34.0	75.3	100.9
2-Dec-01	B >0.5mm	59.2	34.1	75.5	104.1
2-Dec-01	B <0.5mm	59.0	34.0	75.3	105.5
11-Dec-01	B >2mm	61.2	35.3	78.0	100.8
11-Dec-01	B >1mm	58.9	33.9	75.0	101.9
11-Dec-01	B >0.5mm	60.8	35.0	77.5	103.3
11-Dec-01	B <0.5mm	60.2	34.7	76.8	84.9
30-Nov-01	A >1mm	58.3	33.6	74.2	100.3
2-Dec-01	B >0.5mm	61.0	35.2	77.8	99.6
11-Dec-01	B >2mm	61.4	35.4	78.3	100.5
13-Nov-01	A <0.5mm	61.0	35.2	77.8	98.4
11-Dec-01	B Bulk	57.9	33.3	73.7	99.4
Average		60.0	34.6	76.4	99.8
min		56.7	32.6	72.2	84.9
max		63.6	36.6	81.1	105.5
St.Dev.		1.5	0.9	1.9	4.0

Date	Reactor Sample	% of Theoretical Mg	% of Theoretical NH3-N	% of Theoretical PO4-P
13-Nov-01	A >2mm	97.8	94.8	99.4
13-Nov-01	A >1mm	94.4	92.8	95.7
13-Nov-01	A >0.5mm	97.8	94.4	98.4
13-Nov-01	A <0.5mm	100.5	91.9	99.1
30-Nov-01	A >2mm	103.0	96.7	103.7
30-Nov-01	A >1mm	101.5	95.6	101.0
30-Nov-01	A >0.5mm	101.1	97.4	102.6
30-Nov-01	A <0.5mm	107.1	89.1	112.7
12-Dec-01	A >2mm	101.9	100.6	101.7
12-Dec-01	A >1mm	103.4	98.7	103.3
12-Dec-01	A >0.5mm	101.3	98.7	99.5
12-Dec-01	A <0.5mm	105.9	100.7	101.9
20-Nov-01	B >2mm	92.3	94.8	91.3
20-Nov-01	B >1mm	103.6	100.5	102.5
20-Nov-01	B >0.5mm	100.7	101.0	104.0
20-Nov-01	B <0.5mm	100.7	101.9	101.7
2-Dec-01	B >2mm	99.8	102.6	100.7
2-Dec-01	B >1mm	99.4	101.8	101.4
2-Dec-01	B >0.5mm	103.6	102.3	106.3
2-Dec-01	B <0.5mm	109.0	97.0	110.6
11-Dec-01	B >2mm	99.7	102.1	100.5
11-Dec-01	B >1mm	97.9	103.4	104.3
11-Dec-01	B >0.5mm	101.2	100.7	108.0
11-Dec-01	B <0.5mm	89.0	73.6	92.1
30-Nov-01	A >1mm	97.2	102.1	101.4
2-Dec-01	B >0.5mm	96.9	100.4	101.4
11-Dec-01	B >2mm	97.8	102.2	101.4
13-Nov-01	A <0.5mm	96.0	96.6	102.4
11-Dec-01	B Bulk	99.3	97.2	101.7
Average		100.0	97.6	101.8
min		89.0	73.6	91.3
max		109.0	103.4	112.7
St.Dev.		4.2	5.9	4.4

Date	Reactor Sample	Mg mMol/L	Ca mMol/L	K mMol/L	Al mMol/L	Fe mMol/L	NH3-N mMol/L	PO4-P mMol/L
13-Nov-01	A >2mm	2.47	0.13	0.005	0.009	0.003	2.40	2.51
13-Nov-01	A >1mm	2.47	0.15	0.007	0.003	0.002	2.43	2.50
13-Nov-01	A >0.5mm	2.42	0.11	0.007	0.042	0.005	2.34	2.44
13-Nov-01	A <0.5mm	2.49	0.06	0.006	0.016	0.002	2.28	2.45
30-Nov-01	A >2mm	2.54	0.18	0.006	0.006	0.004	2.39	2.56
30-Nov-01	A >1mm	2.49	0.06	0.006	0.014	0.001	2.35	2.48
30-Nov-01	A >0.5mm	2.52	0.08	0.005	-0.011	0.002	2.43	2.56
30-Nov-01	A <0.5mm	2.58	0.04	0.006	0.009	0.001	2.14	2.71
12-Dec-01	A >2mm	2.38	0.09	0.005	-0.004	0.002	2.35	2.37
12-Dec-01	A >1mm	2.60	0.09	0.006	-0.001	0.004	2.48	2.59
12-Dec-01	A >0.5mm	2.45	0.04	0.005	-0.015	0.002	2.38	2.40
12-Dec-01	A <0.5mm	2.70	0.04	0.005	-0.039	0.002	2.57	2.60
20-Nov-01	B >2mm	2.28	0.04	0.006	-0.018	0.002	2.34	2.25
20-Nov-01	B >1mm	2.48	0.03	0.005	-0.003	0.002	2.41	2.45
20-Nov-01	B >0.5mm	2.41	0.11	0.005	-0.018	0.002	2.41	2.48
20-Nov-01	B <0.5mm	2.55	0.04	0.005	-0.020	0.003	2.58	2.57
2-Dec-01	B >2mm	2.50	0.03	0.004	-0.015	0.003	2.57	2.52
2-Dec-01	B >1mm	2.42	0.02	0.004	-0.029	0.003	2.47	2.46
2-Dec-01	B >0.5mm	2.53	0.15	0.006	-0.014	0.006	2.50	2.59
2-Dec-01	B <0.5mm	2.65	0.10	0.006	0.000	0.006	2.36	2.69
11-Dec-01	B >2mm	2.51	0.03	0.005	0.000	0.003	2.57	2.53
11-Dec-01	B >1mm	2.37	0.03	0.006	0.002	0.004	2.50	2.52
11-Dec-01	B >0.5mm	2.53	0.20	0.007	0.032	0.007	2.52	2.70
11-Dec-01	B <0.5mm	2.21	0.03	0.006	0.010	0.004	1.82	2.28
30-Nov-01	A >1mm	2.33	0.06	0.006	0.003	0.002	2.45	2.43
2-Dec-01	B >0.5mm	2.43	0.03	0.005	-0.008	0.015	2.52	2.54
11-Dec-01	B >2mm	2.47	0.04	0.005	-0.011	0.005	2.58	2.56
13-Nov-01	A <0.5mm	2.41	0.09	0.007	0.013	0.004	2.43	2.57
11-Dec-01	B Bulk	2.36	0.03	0.005	-0.012	0.004	2.31	2.42
Average		2.47	0.07	0.006	-0.002	0.004	2.41	2.51
min		2.21	0.02	0.004	-0.039	0.001	1.82	2.25
max		2.70	0.20	0.007	0.042	0.015	2.58	2.71
St.Dev.		0.10	0.05	0.001	0.017	0.003	0.15	0.11

Date	Reactor Sample	Mg:P Mole Ratio	N:P Mole Ratio	Mg:N Mole Ratio
13-Nov-01	A >2mm	0.98	0.95	1.03
13-Nov-01	A >1mm	0.99	0.97	1.02
13-Nov-01	A >0.5mm	0.99	0.96	1.04
13-Nov-01	A <0.5mm	1.02	0.93	1.09
30-Nov-01	A >2mm	0.99	0.93	1.07
30-Nov-01	A >1mm	1.01	0.95	1.06
30-Nov-01	A >0.5mm	0.99	0.95	1.04
30-Nov-01	A <0.5mm	0.95	0.79	1.20
12-Dec-01	A >2mm	1.00	0.99	1.01
12-Dec-01	A >1mm	1.00	0.96	1.05
12-Dec-01	A >0.5mm	1.02	0.99	1.03
12-Dec-01	A <0.5mm	1.04	0.99	1.05
20-Nov-01	B >2mm	1.01	1.04	0.97
20-Nov-01	B >1mm	1.01	0.98	1.03
20-Nov-01	B >0.5mm	0.97	0.97	1.00
20-Nov-01	B <0.5mm	0.99	1.00	0.99
2-Dec-01	B >2mm	0.99	1.02	0.97
2-Dec-01	B >1mm	0.98	1.00	0.98
2-Dec-01	B >0.5mm	0.98	0.96	1.01
2-Dec-01	B <0.5mm	0.99	0.88	1.12
11-Dec-01	B >2mm	0.99	1.02	0.98
11-Dec-01	B >1mm	0.94	0.99	0.95
11-Dec-01	B >0.5mm	0.94	0.93	1.00
11-Dec-01	B <0.5mm	0.97	0.80	1.21
30-Nov-01	A >1mm	0.96	1.01	0.95
2-Dec-01	B >0.5mm	0.96	0.99	0.96
11-Dec-01	B >2mm	0.97	1.01	0.96
13-Nov-01	A <0.5mm	0.94	0.94	0.99
11-Dec-01	B Bulk	0.98	0.96	1.02
Average		0.98	0.96	1.03
min		0.94	0.79	0.95
max		1.04	1.04	1.21
St.Dev.		0.03	0.06	0.06

Date	Reactor Sample	%Mg	%N	%P	%Ca	%K	%Al	%Fe
13-Nov-01	A >2mm	9.7	5.4	12.5	0.85	0.03	0.04	0.03
13-Nov-01	A >1mm	9.3	5.3	12.1	0.92	0.04	0.01	0.02
13-Nov-01	A >0.5mm	9.7	5.4	12.4	0.75	0.04	0.18	0.04
13-Nov-01	A <0.5mm	10.0	5.2	12.5	0.42	0.04	0.07	0.02
30-Nov-01	A >2mm	10.2	5.5	13.1	1.21	0.04	0.02	0.03
30-Nov-01	A >1mm	10.1	5.5	12.7	0.43	0.04	0.06	0.01
30-Nov-01	A >0.5mm	10.0	5.6	13.0	0.55	0.03	-0.05	0.02
30-Nov-01	A <0.5mm	10.6	5.1	14.2	0.28	0.04	0.04	0.01
12-Dec-01	A >2mm	10.1	5.7	12.8	0.65	0.04	-0.02	0.02
12-Dec-01	A >1mm	10.2	5.6	13.0	0.59	0.04	0.00	0.03
12-Dec-01	A >0.5mm	10.0	5.6	12.6	0.24	0.03	-0.07	0.02
12-Dec-01	A <0.5mm	10.5	5.8	12.9	0.23	0.03	-0.17	0.02
20-Nov-01	B >2mm	9.1	5.4	11.5	0.27	0.04	-0.08	0.01
20-Nov-01	B >1mm	10.3	5.7	12.9	0.23	0.03	-0.02	0.02
20-Nov-01	B >0.5mm	10.0	5.8	13.1	0.77	0.03	-0.08	0.02
20-Nov-01	B <0.5mm	10.0	5.8	12.8	0.25	0.03	-0.09	0.02
2-Dec-01	B >2mm	9.9	5.9	12.7	0.18	0.03	-0.07	0.02
2-Dec-01	B >1mm	9.9	5.8	12.8	0.17	0.03	-0.13	0.03
2-Dec-01	B >0.5mm	10.3	5.8	13.4	0.99	0.04	-0.06	0.06
2-Dec-01	B <0.5mm	10.8	5.5	14.0	0.66	0.04	0.00	0.05
11-Dec-01	B >2mm	9.9	5.8	12.7	0.22	0.03	0.00	0.03
11-Dec-01	B >1mm	9.7	5.9	13.2	0.20	0.04	0.01	0.04
11-Dec-01	B >0.5mm	10.0	5.8	13.6	1.27	0.04	0.14	0.07
11-Dec-01	B <0.5mm	8.8	4.2	11.6	0.21	0.04	0.04	0.04
30-Nov-01	A >1mm	9.6	5.8	12.8	0.42	0.04	0.01	0.02
2-Dec-01	B >0.5mm	9.6	5.7	12.8	0.18	0.03	-0.03	0.14
11-Dec-01	B >2mm	9.7	5.8	12.8	0.25	0.03	-0.05	0.04
13-Nov-01	A <0.5mm	9.5	5.5	12.9	0.58	0.05	0.06	0.04
11-Dec-01	B Bulk	9.8	5.5	12.8	0.20	0.04	-0.05	0.04
Average		9.9	5.6	12.8	0.49	0.04	-0.01	0.03
min		8.8	4.2	11.5	0.17	0.03	-0.17	0.01
max		10.8	5.9	14.2	1.27	0.05	0.18	0.14
St.Dev.		0.4	0.3	0.6	0.32	0.01	0.07	0.02

APPENDIX G: OPERATING COST ESTIMATES

Chemical Costs

Chemical cost analysis is based on calculated sodium hydroxide usage in both reactors during the period of November 9-27th 2001, and an estimate of the magnesium requirement based on equimolar dosing to supernatant phosphate content. Table G1 shows the cost calculations for sodium hydroxide and magnesium chloride.

Table G1: Chemical Cost Estimate

	Scenario A	Scenario B
Sodium Hydroxide Usage (kg/m ³ supernatant)	0.37	0.17
Magnesium Chloride Usage (kg/m ³ supernatant)	0.46	0.46
Supernatant Volume (m ³ /year)	32850	32850
Sodium Hydroxide Usage (kg/year)	12098	5428
Magnesium Chloride Usage (kg/year)	15080	15080
Supernatant Phosphate Concentration (mg/L)	70	70
% Phosphate Recovery	80	60
Mass of Struvite Produced (kg/year)	14533	10900
Sodium Hydroxide Cost (\$/year)	6049	2714
Magnesium Chloride Cost (\$/year)	3016	3016
Chemical Cost per kg Struvite (\$/kg Struvite)	0.62	0.53

Labour Costs

The labor costs developed in this study are based on the following estimates. These estimates were based on the labor required to operate the pilot scale reactors and approximation of the extra labor required to operate a full scale system. The cost of labor is assumed to be \$50 000 per year for 35 hours per week (\$27.50/hr). Table G2 shows the estimated labor allocation for each required task. This results in a labor requirement of 1600 hours per year or 0.63 persons per day (assuming 7 hour days), which translates to \$44 000 per year.

Table G2: Labor requirement Estimate

Task	Labor Estimate	Labor Estimate (hrs/year)
Process Monitoring	1 hr/day	365
Lab Analysis	0.5 hrs/day	182.5
Maintenance	4 hrs/week	208
Chemical Shipping/Receiving	2 hrs/week	104
Product Struvite Handling/Shipping	2 hrs/day	730
Reactor Cleanout/Overhaul	8hrs 2x per year	16
Total	-	1600

Process Savings

Three sources of savings and revenues were evaluated in this study. These are revenues associated with the sale of struvite estimated at \$730 / metric ton; reduction in sludge shipping cost at 62\$ per truckload (City of Penticton Data) and reduction in polymer usage at estimated at \$100 per day (Berne Udala, pers. comm.). During the course of the study it was estimated that the digestion of 40% of the WAS resulted in a reduction in polymer usage of approximately 50% and a reduction in sludge shipping by 9 truckloads per month according to operational records. This resulted in a cost reduction of approximately \$100 per day for polymer usage and \$18.34 per day for sludge shipping. The income due to struvite sale simply depends on the mass produced.