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October 9, 2002

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Re: MASc Thesis by Ali Adnan- Pilot-scale study of phosphorus recovery through struvite crystallization

At our request, the commencement of the period for which partial license shall operate shall by delayed from Oct 1, 2002 for a period of 6 months ; Such operation may be delayed for an additional period with good cause, as determined by the undersigned.

Signatures:

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Dean of Graduate Studies

PILOT-SCALE STUDY OF PHOSPHORUS RECOVERY THROUGH STRUVITE CRYSTALLIZATION

by

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ABSTRACT

The workability of a new pilot-scale reactor, based on the same process principle as that of the previously tested bench-scale reactor, was examined. This work extended the long-term research program, and bridged the gap between phosphorus removal and recovery. The problem of the fines encountered during the bench-scale study was overcome.

The pilot-scale UBC MAP Crystallizer, which was used to remove / recover phosphorus through struvite formation, achieved ortho-P removal rates of over 90%, for a tested range (47 mg/L ~ 220 m/L) of influent P concentrations. The desired degree of P-removal was achieved by controlling the reactor by varying operating pH and the supersaturation ratio at the inlet. The high P-removals rates (~90%) were achieved even at a pH 7.3, which is contrary to the information found in the literature, where generally higher pH values (8.2 ~ 9) are recommended. This indicates that alkaline pH is not the only factor which can cause the process fluid to be supersaturated. Limited results showed that process fluid can also be supersaturated by an excessive dosage of the magnesium ions, thereby indicating that magnesium can also be used as a controlling parameter.

About 80% of phosphate removed was recovered as harvestable struvite crystals. In general, there was no problem of fines production during the pilot-scale study. The average mean size of the harvested crystals remained over 2 mm, for all the experiments conducted. The in-reactor supersaturation ratio and the crystal retention time (CRT) were identified as the major factors affecting mean crystal size.

Using solubility criteria, the in-reactor supersaturation ratio was used to define the metastable zone boundaries. The system performance, both in terms of process efficiency and the quality of the harvested product, was at its best when the in-reactor supersaturation ratio was between 2 and 3. The results showed that there was a narrow working zone for optimized crystallization process and a deviation from the optimal metastable zone always resulted in the plugging of the reactor.

An equilibrium model (developed earlier) which predicts the effluent concentrations of struvite constituent ions, was validated using pilot-scale study results. The results predicted by an equilibrium model closely matched the actual pilot-scale results. With an expected knowledge of the effluent concentrations, a process engineer / operator can use an appropriate degree of recycle ratio, thereby ensuring the process conditions in the metastable zone of crystallization. Thus, the use of an equilibrium model is recommended in future related studies.

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My loving and caring parents, Ami and Jimmy Baba

CHAPTER 1 – INTRODUCTION

The limited extent of in situ phosphate reserves has long been known. Due to the danger of losing one of the most important nutrients, there is a high demand for sustainable phosphorus resources in the industrialized world. In many developed countries, research is currently underway in recovering phosphorus from wastewater, since domestic sewage offers a great potential for phosphorus to be recycled [1].

The release of phosphorus to surface waters, and its consequent contribution to eutrophication, has led to increasing concerns about water quality. Policies are therefore being implemented throughout the industrialized world, to reduce the levels of phosphorus entering the surface waters from domestic and industrial wastewater.

Phosphorus can be removed from wastewater by physical, chemical and biological methods. In physical and chemical methods, salts of aluminium, lime or iron are added to precipitate phosphorus. Chemical precipitation is a simple and reliable method and is used widely to remove phosphorus from wastewaters. High chemical cost and increase in sludge volumes are distinctive disadvantages associated with metal salt precipitation. Another disadvantage is that the precipitated metal salt species, such as iron and aluminium phosphate, tie up the available phosphorus and thus make it unavailable as a nutrient.

Biological nutrient removal (BNR) process is preferable in many instances. During BNR processes, greater phosphorus concentrations are removed, and stored within the biomass as poly-phosphates (as compared to the conventional processes). There are, however, certain problems associated with its successful operation e.g. the sludges wasted from BNR processes, if anaerobically digested, will re-hydrolyse the poly-phosphates, consequently releasing magnesium and phosphate ions into solution [2]. It is estimated that as much as 80% to 90% of phosphorus removed during treatment may be released, and re-introduced to the process from the digester supernatants. This can lead to potential process failure [3, 4].

Struvite (magnesium ammonium phosphate or MAP) is a crystalline mineral that accumulates on equipment surfaces of anaerobic digestion and post-digestion processes within the wastewater treatment industry; a result that plagues the industry commercially by major downtime, loss of hydraulic capacity and increasing pumping costs [5].

A novel solution to this problem is to recover phosphate as struvite before it accumulates on wastewater treatment equipment. When harvested properly, struvite can also be used as a slow release fertilizer; this solves a wastewater treatment problem and provides an environmentally sound, and renewable nutrient source to the agriculture industry.

To date, there have been a number of pilot and industrial scale crystallizers designed for phosphate recovery [6]. Although struvite crystallization is promising, phosphorus recycling from wastewaters has not been widely adopted. This is mainly due to a. number of design difficulties such as controlling precipitation, a poor understanding of growth, kinetics, pH control, formation of fines, and problems with the quality of the recovered phosphates [5].

1.1 Previous Research At UBC

In 1999, the Department of Civil Engineering at the University of British Columbia, started a phosphorus recovery project, in collaboration with BC Hydro. One of the driving forces behind this project was the important principle of sustainability. Japan is a leader in phosphate recovery, and several full-scale P-recovery plants have been operating there since the early 90's. Despite the experience of Japanese companies in full-scale P-recovery processes, very little literature has been published and little information exists outside of Japan about these processes. It was, therefore, deemed necessary to start this long-term research program from first principles.

Synthetic supernatant feed was used and the experiments were conducted at the bench-scale. After one year of work, the first results were obtained. The basic understanding of thermodynamics of struvite formation was developed. The bench-scale study revealed that there was a narrow working window for struvite crystallization. The removal rates were as high as 90%, but the crystals produced were of low quality, most of them being fines (Fred Koch, Environmental Engineering Group, Department of Civil Engineering, UBC, Vancouver, B.C., pers. Comm.). Another study conducted at the bench-scale showed that there was a limit to which the pH in the reactor could be elevated; this in turn, had drastic effects on the P-removals. The minimal P-removals, due to the imposed pH restrictions, nullified the impact of recycle ratio, which is otherwise used for diluting purposes. The problem of the fines existed, resulting in non-uniform operation of the crystallizer [7]. This initial research exposed the limitations of operating at the bench-scale.

Since one of the prime goals of this project was to ensure sustainable development, it was vital to have a better control over the harvested product. Supersaturation ratio appears to be the most reliable controlling parameter operating crystallization reactors, as it distinguishes between the process of crystallization and precipitation. Supersaturation ratio is a function of pH as well as the concentration of magnesium, ammonium and phosphate. For struvite crystallization, magnesium and ammonium ion concentrations are equally important, as that of phosphate ions. Supersaturation ratio takes into account all three struvite constituent ions concentrations at a given pH. It also controls the quality of the harvested product and the smooth operation of a crystallizer [8].

It is important to note here that no previous research has considered defining crystallization process control, in terms of the metastable zone boundaries for full-scale P-recovery applications from wastewater. This could possibly be due to the limited published literature in this area, as the P-recovery technology is relatively new or there is deliberate release of *filtered* information.

1.2 Objectives

For this study, a new pilot-scale reactor was developed to overcome the problems (reactor blockage, feed / recycle plugging), which were encountered at the bench-scale. The process principle used at the pilot-scale was the same as that of the bench-scale.

The specific research objectives of this study were:

1. To test the workability of the pilot-scale reactor.
2. To optimize phosphorus removal, and to bridge the gap between removal and recovery (i.e. to remove phosphorus in the form of harvestable product).
3. To identify the factors which affect struvite growth conditions.
4. To examine the feasibility of applying solubility criteria as a process control parameter.
5. To define operating protocols for running a smooth crystallization process.

CHAPTER 2 - BACKGROUND AND LITERATURE REVIEW

2.1 Why Recover Phosphorus?

Phosphorus (P) is an essential nutrient for all life forms. Phosphorus is the eleventh-most abundant mineral in the earth's crust and does not exist in a gaseous state. The commercial source of phosphate is "phosphate rock", the collective name given to natural calcium phosphates of various forms. Around 38 million tonnes of phosphate (expressed as P_2O_5) are extracted each year [9]. It is now well known, based on available estimates, that about 60 per cent of the world's known phosphate reserves will be depleted within 60 years or so [9]. With a slightly higher phosphate usage (e.g. 3% growth rate), the entire supply of commercially useable phosphate rock will be depleted even sooner. Figure 2.1 shows the scenario of the lifetime of phosphate rock reserves.

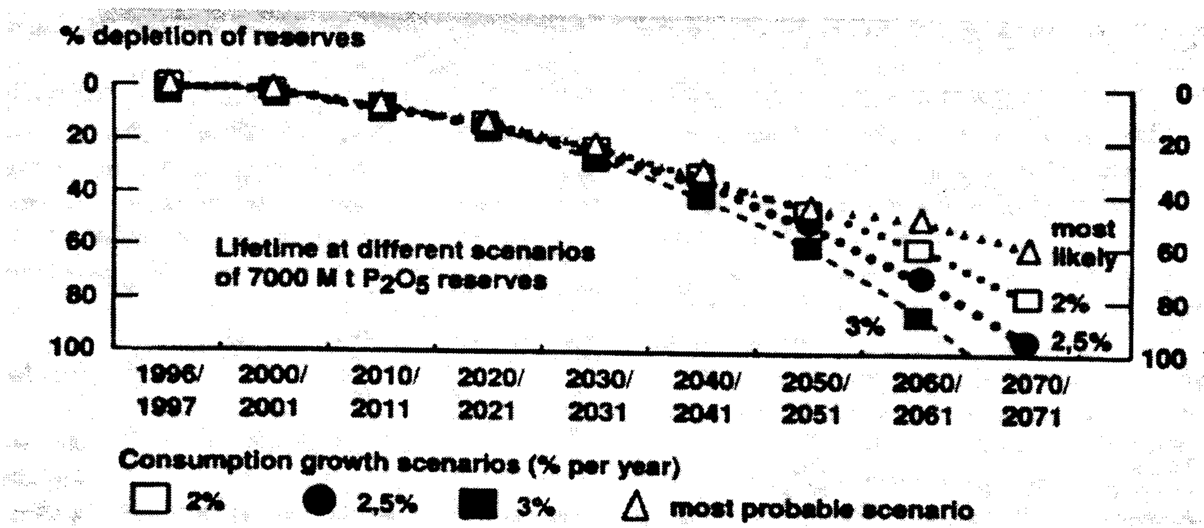

Figure 2.1: Scenario of lifetime of phosphate rock reserves [9].

Another concern for the phosphate industry is the increasing level of impurities in phosphate rock. As the quality of rock declines, the presence of problematic metallic contaminants increases [9]. Facing the possibility of running out of the most important raw ingredient, the phosphate industry is now seeking a sustainable source of high purity raw material [10].

2.2 Human And Animal Waste -- A Potential Source For Phosphate Recovery

Human and animal wastes offer a great potential for phosphorus recycling. It is estimated that, in Canada, total phosphorus in municipal sewage is about 23,000 tonnes/year [11]. In the province of British Columbia, the total phosphorus in the sewage is estimated to be about 3048 tonnes/year [11]. According to a recent study, 62 percent of total phosphorus in sewage, in B.C. can be recovered [12].

The nutrient contents of animal manures are higher than human sewage. However, lack of a proper collection system for the animal wastes poses a problem. The total phosphorus generated by all the livestock in B.C. is about 19,000 tonnes per year. Of the total phosphorus in manure, there are about 10,266 tonnes (54%) of P available for recovery [12].

2.3 Eutrophication And More Stringent Discharge Regulations For Phosphorus

Phosphorus is considered to be one of the limiting nutrients in most freshwater lakes, reservoirs and rivers. As a result, a low P concentration can cause algae blooms and eutrophication. Domestic wastewaters often contain 4 to 15 mg/L of P [13], whereas, in sensitive water bodies, the concentrations as low as 0.01 mg/L can be critical to initiate eutrophication [14]. Phosphorus inputs from point sources, such as municipal sewage effluents, are more amenable to control than from non-point sources. The European Commission's Urban Wastewater Treatment Directive has been imposing increasingly stringent regulations on nutrient discharge to water bodies in the region since 1991. In Canada, it was estimated that more than 12,000 tonnes of P entered fresh, ground, and coastal waters in 1996, as a result of human activity. The largest point source was municipal sewage, adding an estimated 5600 tonnes of P [15]. It was concluded that nutrients were causing problems in certain Canadian ecosystems and affecting quality of life for many Canadians [15].

2.4 Removal Of Phosphorus From Wastewaters

At present, there are two established methods of phosphorus removal, chemical precipitation and biological removal [16]. In chemical phosphorus precipitation, precipitation agents (typically ferric chloride, alum, or other metal salts) are added at various points in the conventional wastewater treatment process train to convert soluble phosphate to a particular form. Precipitated phosphate is removed with the waste sludge. Chemical precipitation of phosphorus is a simple and reliable method, and is, therefore, widely used in North America [17]. Despite these advantages, the present trend is more towards the BNR process, principally due to the following reasons [18, 19, 20, 21]:

- The cost of flocculants is increasing and with more stringent discharge regulations, the cost of chemical phosphorus removal could become very high,
- Addition of aluminium and ferric salts as coagulants has, in some cases, resulted in unacceptable concentrations of these cations in the final effluent, and
- Chemical precipitation generates huge amounts of a water-rich sludge which has to be disposed off at continuous increasing costs.

In a conventional activated sludge plant, bacteria only use enough phosphorus to satisfy their metabolic requirements, which results in typical removal rates of 20% to 40% [10]. In order to facilitate higher P-removals, BNR plants offer an environment, where certain bacteria accumulate phosphorus in excess of their normal metabolic requirements. In the anaerobic zone of a BNR process, PAO's (poly-phosphate accumulating organisms), take up short chain fatty acids, especially acetates and release the dissolved poly-phosphate into the solution. In the aerobic zone, the PAO's use the stored short chain fatty acids as the energy source and take up all the available poly-phosphates; this phenomenon seemingly comes with a simultaneous transfer of other soluble elements (K^+, Mg^{+2}) [18, 22, 23].

2.5 Problems Associated With BNR-Processes

2.5.1 Problems due to re-solubilization of phosphorus

Historically, BNR processes have been plagued by problems of dealing with the release of the biologically stored phosphorus. This problem becomes more pronounced when waste activated sludge from a BNR plant is digested, especially anaerobically. Most of the phosphate, which is removed from the wastewater in the main treatment train, is re-released under anaerobic conditions of the anaerobic digester. Various studies show that from 26% to 90% of the phosphorus entering the head of treatment works is due to the phosphorus feedback, i.e. phosphorus in the return liquors [3, 4, 24, 25]. Under this scenario, P is only circulated in a loop within the wastewater treatment system and is not potentially removed, thus increasing the P load to the treatment plant. The optimum operation of a BNR process depends heavily on the BOD:P ratio of the wastewater; below a critical BOD:P ratio, a potential system failure can occur [3, 4, 26].

2.5.2 Unintentional struvite formation

Struvite (magnesium ammonium phosphate) precipitation is a recognized problem in sludge handling at many wastewater treatment plants. It is likely to increase with the current trend towards biological nutrient removal. A number of treatment plants have reported the occurrence of unintentional struvite formation in plant piping, and other equipment (e.g. pumps, valves, filter belts etc) [27-32]. This is due to the fact that magnesium, ammonium and phosphate are released as the result of solids degradation in the subsequent digestion process. Struvite precipitation occurs when the combined concentrations of Mg^{+}, NH_4^{+} and PO_4^{-3} exceed the struvite solubility limit. Availability of the three components is controlled by system pH and the total dissolved concentrations of magnesium, ammonium and the phosphate species [30]. The problem of unintentional struvite formation is more severe in anaerobic digestion, since the pH of anaerobic digestion and post-digestion processes is generally higher than the pH of preceding treatment processes [30].

Struvite deposits are hard and once formed, are difficult to dislodge. These deposits have caused damage to pumping equipment and almost totally blocked sludge pipes, resulting in costly maintenance and repairs, and disruptions to the operations of the plant [28, 30, 32]. To date, several remedial measures have been suggested for alleviating the problem of unintentional struvite formation in wastewater treatment plants. Solutions so far have included: installation of water softening devices before and after sludge digestion, precipitating phosphorus by the addition of ferric chloride, diluting digester sludge with secondary effluent, adding meta-phosphates or other scale inhibitors, acidifying the waste stream and redesigning certain areas of the plants [27, 33, 34]. All of the above remedial measures are costly and, at times, only alleviate the problem, without eliminating it completely.

In summary, the industry is dealing with four problems associated with phosphorus. They are as follows:

- To recycle phosphorus, since it is a dwindling resource,
- To meet the stringent imposed standards of phosphorus discharge, to protect the sensitive water-bodies,
- To avoid huge chemical costs for the removal of phosphorus, and
- To provide stability to the BNR process.

Intentional struvite formation appears to be the most practical solution, which, in turn, may solve all the above mentioned problems.

2.6 Driving Forces For P-Recovery Through Struvite Formation

There are four major driving forces linked with P-recovery through struvite formation:

- Improvement of sewage sludge management

- Improvement of the biological nutrient removal operation in sewage treatment plants
- Development of the important principle of sustainability
- Production of the revenue due to the possible sale of recovered phosphates

P-recovery can reduce the quantities of sewage sludge generated by sewerage works, especially those operating BNR-type processes. P-recovery can significantly facilitate agriculture spreading (by improving P:N ratios). Decreasing the P-concentration in biosolids could either mean improving agriculture spreading, or reducing the area used for spreading and thus reducing the costs of transportation [35]. Another improvement in sludge management, due to the reduction of P-content, would be the reduced ash production, when sludges are incinerated. Between 12 and 48% reduction in incineration ash residues can are possible [35].

P-recovery can limit the P-flows that return to the head of the wastewater treatment plant; in this way P-load of the return liquors from sludge treatment can be reduced significantly, and a critical BOD:P ratio can be maintained for successful operation of a BNR process. The MAP process would enable enhanced biological phosphorus removal plants that use anaerobic digesters to achieve very low levels of effluent ortho-P concentrations. It can also contribute significantly in resolving the build-up of struvite deposits, in plant piping, and other equipment (e.g. pumps, valves, filter belts, etc.). The problems of unexpected struvite deposits are frequently related to high soluble concentrations of phosphate, ammonia and magnesium, and tend to occur particularly in sludge digestion or dewatering / supernatant return lines. If P is recovered in the form of struvite, the concentrations of soluble phosphate, ammonia and magnesium can be reduced significantly and hence the struvite build-up problem faced by the wastewater treatment industry can be reduced.

Phosphorus is a non-renewable, irreplaceable resource. Phosphates should be recovered from waste streams for recycling, instead of continued mining of depleted phosphate rock. This would provide a much needed, sustainable, phosphorus-related practice.

Availability of magnesium, phosphate, and nitrogen of MAP is similar to that of commercial fertilizer, and can be utilized as additive nutrients to compost, garden soil, or dried sewage sludge [36]. In fact, the quality of recovered product is better than some imported mined phosphate rock, particularly regarding the heavy metal content [36, 37, 38]. Unitika Ltd. in Japan currently obtains a price of about 360 CDN$/tonne for their sewage recovered 0.5 to 1 mm diameter struvite granules [39]. Overall, the market value of recovered phosphate (via struvite) will depend, on the quality of the recovered product and the local market conditions.

In the MAP formation, there is a simultaneous uptake P and N ions, therefore, aeration tank volume required for nitrification, as well as methanol dosage (if used) for denitrification, can be decreased significantly. It is an advantage in wastewater treatment practice, especially in cold climates, because nitrification efficiency diminishes significantly with decreasing temperature [40, 41].

2.7 Chemistry Of Struvite

Magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4.6H_2O$), or struvite, is a white crystalline substance consisting of magnesium, ammonium and phosphorus in equal molar concentrations ($MgNH_4PO_4.6H_2O$). It is formed according to the following chemical equation:

$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \longrightarrow MgNH_4PO_4.6H_2O$ ....(1)

It is actually sum of two related reactions that affect the pH:

$NH_3 + H^+ \longrightarrow NH4^+$ (increase in pH)

$HPO_4^{2-} \longrightarrow H^+ + PO_4^{3-}$ (decrease in pH)

The use of PO_4^{3-} in struvite formation will upset the equilibrium of the phosphate system, hence some HPO_4^{2-} will change to PO_4^{3-} and some $H_2PO_4^-$ will change to HPO_4^{2-} to keep the equilibrium constants satisfied. Therefore, the observed pH lowering during the precipitation of process can be related to the net decrease of strong basic ions, in the solution, particularly PO_4^{3-}, to form MAP crystals and / or the production of H^+.

2.7.1 Solubility product values for struvite

The equilibrium constant for a reaction involving a precipitate and its constituent ions is known as solubility product [42]. A poorly soluble salt will dissolve in water until there is a dynamic equilibrium between ions leaving the solid to go into the liquid and ions passing from the liquid to the solids. In some simple cases, the equilibrium conditions of a salt $X_n\ Y_m$ can be described in terms of an equation. Equation 2 shows such a case:

$$[X^{+\alpha}]^n\ [Y^{-\beta}]^m = K_{sp} \qquad \text{(2)}$$

This may be interpreted to mean that if, $X^n\ Y^m < K_{sp}$, all the salt will be in solution, but, if $X^n\ Y^m > K_{sp}$, solid salt will precipitate out until the concentrations of the ions remaining in solution obey the law, $X^n\ Y^m = K_{sp}$

Extensive studies have been conducted for calculating the solubility product (K_{sp}) value for struvite [28-32, 43-46]. Dissolution or formation of struvite precipitate in pure water and water solutions, are the two common approaches used in calculating K_{sp} value for struvite. The experiments are conducted under controlled conditions; such conditions include a constant temperature, careful adjusted ionic strength and a constant degree of mixing energy imparted to the solution. Dissolution may be carried out using precipitate created during a formation experiment or naturally formed precipitate obtained from the field. Every effort is made to eliminate sources of any chemical species not pertinent to the reaction in question.

Published values of pK_{sp}, i.e. $-\log K_{sp}$ for struvite range from 12.6 to 13.8, which differ by as many as up to five orders of magnitude [7]. Andrade [47] gives a good overview on the chemistry of struvite. He has mentioned four reasons which could result in dispersed K_{sp} values for struvite as described:

- The solubility products may be derived by using approximate solution equilibria.
- The effects of ionic strength are often neglected.
- Mass balance and electroneutrality equations are not always used.
- Different chemical species are selected for the calculations.

2.7.2 Problems associated with using K_{sp} value of struvite

The problems in using a reliable K_{sp} value of struvite stem from the very fact that there is no agreement over the exact chemical reaction responsible for the precipitation of struvite. Conventionally, struvite is considered to be formed due to the reaction between magnesium, ammonium and phosphate ions in the solution. However, it has been observed in the experiments that the precipitation of struvite produces a rapid decrease in the pH of the solution, which suggests that HPO_4^{2-} would participate in the reaction, rather than PO_4^{3-}[48]. The precipitation reaction for the formation of struvite should then be according to Equation 3 (involving PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^-$):

$$Mg^{2+} + NH_4^+ + HPO_4^{2-} + 6H_2O \longrightarrow MgNH_4PO_4.6H_2O + H^+ \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

It has also been claimed that the reaction would occur between NH_4^+ and the complex $MgHPO_4$, which is formed in solutions where Mg^{2+} and HPO_4^{2-} are present. In this case, the complex should be deprotonized before entering into crystal structure, leading to a pH decrease of the solution as well [49].

A fundamental requirement for an equilibrium characterization is the participation of the actual species present in the solution. The solubility of salts, such as struvite *cannot* be governed by its solubility product (K_{sp}) alone, because other equilibria, such as the formation of hydroxo-complexes (by the reactions of the cation with water, acid/base reactions of the anion and reactions of the anion and the cation with each other or with other species present in the solution) occur simultaneously. Slight variations in the solution pH produce a change in the speciation of the struvite constituents, leading to more or less favourable conditions for struvite precipitation. The proportion of ammonium ion present in a solution depends on its equilibrium with ammonia. It is known that the relative concentration of both species vary with the pH [47]. In the presence of phosphate, ammonium phosphate $NH_4PO_4^{2-}$, diammonium phosphate $(NH_4)_2PO_4^-$ and ammonium hydrogen phosphate $NH_4HPO_4^-$ ions can be formed, according to the pH and ion concentrations. Magnesium is in solution in the form of the hex-aquo complex with water [32]:

$Mg^{2+} + 6H_2O \leftrightarrow Mg\,(OH_2)_6$ ....(4)

Hydrolysis of magnesium ion, to the formation of $MgOH^+$ is only significant at higher pH's:

$Mg\,(OH_2)_6 + H_2O \leftrightarrow Mg\,(OH_2)_6(OH)^+ + H^+$ ....(5)

In the presence of phosphate, magnesium forms the complexes $MgPO_4$ and $MgHPO_4$ depending on the pH and concentrations of species in solution [30]. Orthophosphate acid is a triprotic acid and, therefore, several orthophosphate species exist in aqueous solution at any given pH value. The proportion of PO_4 varies with the pH of the solution in these complex ionic equilibria [47].

The net effect of these reactions is removal of the ions of the slightly soluble salt from the solution, thus increasing its solubility. Therefore, to calculate the theoretical solubility product of struvite, all these reactions must be considered, which is difficult due to the involvement of many species. Above all, a solubility product is only accurate for a single pH value. Since the speciation of the components of struvite is pH dependent, the solubility of struvite also varies with the pH. Therefore, by itself, the solubility product is of little use in analysing most systems, since it does not change with the pH [28].

2.8 Conditional Solubility Product

In order to overcome the complexities associated with the calculation of solubility product for struvite, a simple and well-defined concept of conditional solubility is used for practical purposes. The conditional solubility constants are equilibrium constants that are true for a given experimental condition and provide relationships between the quantities that are of direct interest. This reduces complicated solubility equilibrium to one where the cation and the anion do not undergo any side-reactions [31].

For struvite, conditional solubility product (Ps), would be defined by Equation 6:

$$P_s = [Mg^{+2}]_{total} \cdot [NH_4\text{-}N]_{total} \cdot [PO_4\text{-}P]_{total} = \frac{K_{sp}}{\alpha Mg^{+2}\,\alpha NH_4^{+}\,\alpha PO_4^{-3}\;\gamma Mg^{+2}\gamma NH_4^{+}\,\gamma PO_4^{-3}} \quad \ldots\ldots\ldots\ldots(6)$$

where

Ps = conditional solubility product (equals to the product of analytical molar concentrations of the struvite components, dissolved magnesium, ammonia nitrogen, and orthophosphate),

α = ionization fraction of the respective components, and

γ = activity coefficient for respective ion species.

Using standard physical chemistry, curves of conditional solubility product (Ps) against pH can be developed for various ionic strength and temperatures. Extensive research has been carried out to model struvite precipitation and to construct an acceptable struvite solubility curve. Ohlinger [30] determined that pK_{sp} for struvite was 13.26, by considering magnesium phosphate complexes in analysis of the struvite aqueous system, and from considering the ionic strength effects within the system. Ionic strength is important because electrostatic interaction of ions in solution reduces their activity, or effective concentration, thereby reducing struvite precipitation. Magnesium phosphate complex formation reduces the concentrations of Mg^{+2} and PO_4^{3-} ions available for struvite formation. Ohlinger [30] constructed a struvite solubility curve based on the method applied by Snoeyink and Jenkins [28], which considers the availability of Mg^{+2}, NH_4^+, and PO_4^{3-} ions using the bulk fluid pH and ionic strength, and struvite solubility constant.

2.9 Supersaturation Ratio

In order to quantify struvite precipitation potential, a term supersaturation ratio (SSR) is used [28, 31]. Precipitation potential for struvite can be determined by using a conditional solubility product analysis (Ps). Struvite Ps is calculated by using Equation 7.

$$Ps = [C_{TMg}]\,[CT_{NH3}]\,[CT_{PO4}] \qquad (7)$$

where

$[C_{TMg}]$, $[CT_{NH3}]$, $[CT_{PO4}]$ are the measured molar concentrations of total dissolved magnesium, ammonia and orthophosphate species respectively. Supersaturation ratio can be calculated by using Equation 8.

$$SSR = \frac{Ps}{Ps^{eq}} \qquad (8)$$

where

Ps^{eq} = conditional solubility product at equilibrium. Ps^{eq} is highly pH dependent, as shown by Figure 2.2. As the pH increases, the concentration of the phosphate ions increases, while the concentrations of Mg^{+2} and NH_4^+ decrease, thus establishing a range of solubility limits[30].

An increase in the concentrations of any of the constituent ions would increase the conditional solubility product, whereas at a higher pH the value of Ps^{eq} would decrease. It is clear from Equation 8, that the SSR of the process fluid can be increased either by increasing the concentration of struvite constituent ions or by increasing the pH of the process fluid.

Theoretically, values of SSR > 1 would mean that supersaturated conditions exist and precipitation is possible. The values of SSR = 1 would imply that the system is in equilibrium, and values of SSR < 1, mean that precipitation is not possible and the system is undersaturated.

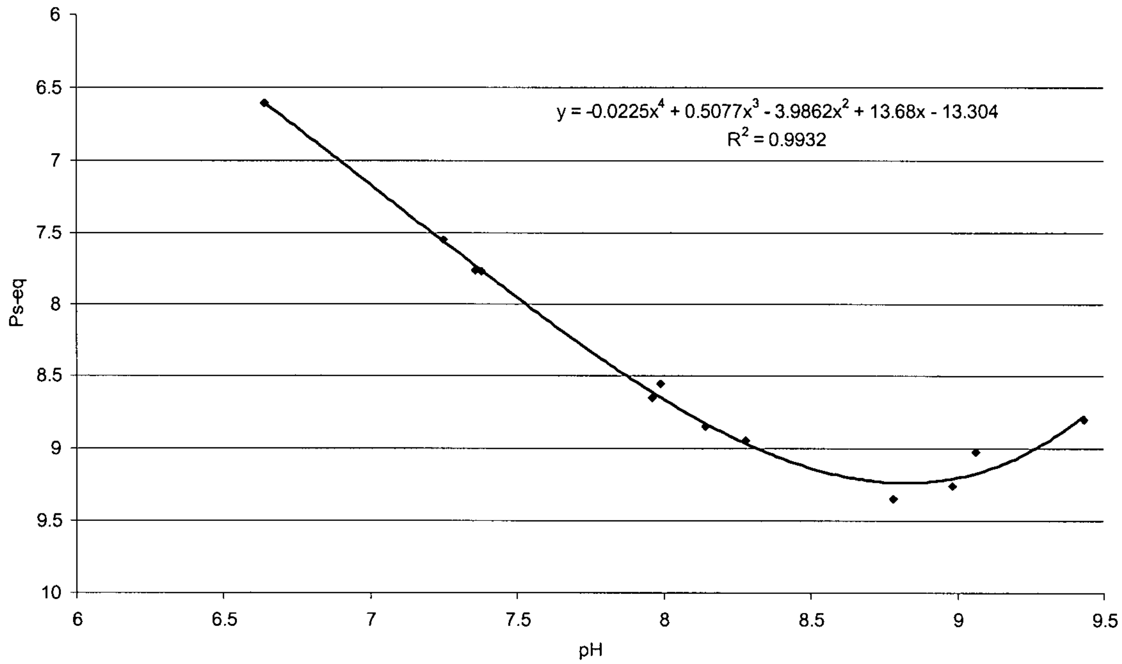

Figure 2.2: Equilibrium conditional solubility product curve for struvite experiment conducted at UBC (Tap water, 20°C)

The concept of the SSR can be used as an indicator for SPP (struvite precipitation potential). This quantification, along with the computer model is very helpful in determining the SPP, in the areas of treatment plant, which are more prone to the problem of unintentional struvite formation. The knowledge of SSP at a wastewater treatment plant will allow the operators to predict where and when struvite scaling could occur and the operation of the plant could be altered to avoid it. Furthermore, this technique is now used to assess the most economically viable place in the treatment plant for recovering phosphorus [24, 50].

Another very important application of SSR lies in defining the metastable zone of crystallization process. Knowledge of the width of the metastable zone is crucial in crystallization processes, as it aids in understanding the nucleation behaviour of a system.

Metastable zone

A supersaturated solution is required for crystallization to occur. A supersaturated solution is not in equilibrium. In order to relieve supersaturation and move towards equilibrium, the solution crystallizes. Once the crystallization starts, the supersaturation can be relieved by a combination of nucleation and crystal growth. It is the relation of the degree of nucleation to crystal growth, which controls the product size and size distribution, and is, therefore, a crucial aspect in industrial crystallization processes. Supersaturated solutions exhibit a metastable zone, where nucleation is not spontaneous. However, when the supersaturation is increased, eventually a point will be reached at which nucleation occurs spontaneously. This is called the metastable limit [51]. The desired process control of crystallization can only be achieved in the metastable region, since this is the region which differentiates between the process of crystallization and precipitation, and avoids the occurrence of undesirable spontaneous nucleation to a great extent [51].

2.10 Morphology And Size Of Struvite Crystals

Struvite is a white crystalline substance consisting of magnesium, ammonium and phosphorus in equal molar concentrations. Struvite has a distinctive orthorhombic crystal structure. The internal structure of the crystals consists of regular PO_4^{3-} tetrahedra distorted Mg $(H_2O)_6^{2+}$ octehedra and NH_4^+ groups which are bonded together by hydrogen bonding [49]. The developing crystal habit depends upon the supersaturation of the solution and the concentration of the impurities [49]. At a very high level of supersaturation, bidimensional and tridimensional twinned crystals can be shaped. At high supersaturation conditions tabular crystals are formed; however, at a low level of supersaturation, crystal habit changes from a tabular formation to an increasing elongation [49]. Crystals that develop more slowly tend to be more tabular or prismatic, resulting from more balanced growth along the entire crystal axis [49].

Crystallization from the solution can be thought of as a two-step process. The first step is phase separation or birth of new crystals. The second step is the growth of these newly formed crystals to larger crystals. The formation of nuclei is known as nucleation and an increase in the size of nuclei by layer-upon-layer addition of solute is known as growth. In case of struvite, nucleation is believed to be controlled by solubility chemistry, while mixing energy has a pronounced impact on growth rate. In the systems continuously replenished with struvite constituents, crystal growth continues indefinitely [52].

In reality, it is difficult to generalize about actual crystal sizes, since operating conditions exercise strong influence on the eventual dimensions of the crystals. Supersaturation has a major effect both on crystal morphology and size. The median size is predominantly influenced by the primary nucleation rate, especially in continuous crystallizer reactors. If supersaturation of the solution is high, the rate of primary nucleation is high, which would result in formation of tiny crystals i.e. $\sim 0.05\mu m$ within 5 seconds and would result in the depletion of ion concentration precluding crystal growth [53]. It has been shown that, as the pH increases, the crystal size extends over wider ranges, and similar trends were seen with the increase of Mg:P molar ratios [40].

2.11 Examples Of Phosphorus Recovery From Municipal Wastewater

2.11.1 Recovery methods

Phosphorus has been recovered from municipal wastewaters [24, 37-40, 52, 54-58] and animal wastes [48, 58], in the form of struvite, K-struvite (magnesium potassium phosphate), or calcium phosphate (hydroxyapatite).

2.11.2 Phosphorus crystallization processes

Considerable research has been undertaken on phosphate crystallization techniques. A number of different techniques are used to extract phosphorus from wastewater, prior to crystallization in a dedicated reactor. Following are some of the well-established, phosphate crystallization techniques.

DHV Crystalactor ™

The process is based on a fluidised reactor in which calcium phosphate crystallises on a seeding grain, typically sand. The phosphate containing wastewater is pumped in an upward direction, maintaining the pellet bed in a fluidised state. In order to crystallize the phosphate on the pellet bed, a driving force is created by a reagent dosage or sometimes the pH adjustment. Due to high rate of crystallization, a short retention time is required. In practice, a surface load of 40 m h^{-1} and a reactor height of 4 m is typical. During the operation, the pellets grow and move towards the reactor bottom. At regular intervals, a quantity of the largest fluidised pellets is discharged at full operation from the reactor and fresh seed material is added [59].

Examples of applications:

In Netherlands, three full-scale P-recovery plants had been installed at municipal wastewater treatment plants in the past. Now, only one plant is in operation. The other two plants have been decommissioned, since in Netherlands, the phosphate concentration in the total effluent flow of the municipal wastewater, after normal biological treatment unit, has decreased to 3-4 mg/L [59]. Due to this low P-concentration, it was not economically feasible to run the full-scale, P-recovery plants.

Unitika Phosnix Process

In this process, wastewater is fed into the base of the reactor where it is mixed with magnesium chloride to achieve a desired Mg:P molar ratio. A blower forces air into the base of the column, providing the agitation required for complete mixing and suspension of the growing particles. The crystals grow in size until they sink to the base of the tower where they are periodically removed [18].

Examples of Applications:

There are a number of full-scale and pilot-scale P-recovery operations documented based on Unitika Phosnix Process [6]. In fact, in Japan, three years experience of operating and selling recovered struvite from full-scale plant has been well documented [39].

Kurita Process

The Kurita Process uses phosphate rock as seed grains. Wastewater is introduced from the base of the column and travels upward through it. Unlike the Unitika process, this process does not employ air agitation in the reactor [18].

2.12 Parameters Of P-Recovery

2.12.1 The pH value and the addition of magnesium

Struvite is soluble at acidic pH and highly insoluble at alkaline pH. As has been discussed in Section 2.10, the key driving force behind the process of crystallization is the saturated condition of the solution. In case of struvite, the solution can be saturated, either by increasing the concentration of struvite constituent ions or by increasing the pH. Normally, for intentional struvite crystallization, pH of the process fluid is increased, since struvite is highly insoluble under alkaline conditions. In the application of struvite crystallization from municipal wastewater, pH is increased either by the addition of caustic [24, 39, 60, 61] or by CO_2 air stripping [52-55].

Suggested pH values for struvite crystallization are mostly between 8 and 9. However, one study suggested a pH value of ~7.7 [61]. A few examples, for the recommended pH values are given in Table 2.1.

For struvite crystallization, Mg is a limiting factor (except for very hard waters). In order to facilitate struvite crystallization, a magnesium source is usually added to achieve a desired Mg:P molar ratio. The two main types of magnesium sources used, in the MAP process, are magnesium hydroxide ($Mg(OH)_2$) and magnesium chloride ($MgCl_2$). Magnesium chloride has the advantage of dissociating faster, resulting in shorter reaction times. Magnesium hydroxide reacts more slowly, but is generally cheaper, and has the advantage of raising the pH as well. However, using magnesium hydroxide to serve both functions means that the magnesium dose or the pH cannot be optimised independent of each other [24, 54]. In one study, sea water was successfully used as a magnesium source, without affecting the overall performance of the process [61].

Table 2.1: Some recommended pH values and source of magnesium addition

Added base	Addition of Mg	Suggested pH value	Reference
NaOH, $Mg(OH)_2$	$MgCl_2$, $Mg(OH)_2$	pH $\geq$ 8.5	24
NaOH	MgO, $MgCl_2$	8.5 < pH value< 9	60
NaOH	Seawater	pH value ~ 7.7	61
Only CO_2 air stripping if alkalinity is low	Not required	8.2 < pH value< 8.8	55

2.12.2 Magnesium to phosphorus molar ratio

Struvite consist of magnesium, ammonium and phosphorus in equal molar concentrations ($MgNH_4PO_4.6H_2O$). In a municipal context or in the supernatant, the limiting element to the formation of struvite is magnesium. In order to optimize P-removal in the form of struvite, supplementation of magnesium source is usually necessary. To date, various studies have been conducted to assess the impact of Mg:P molar ratio on the P-removal ratio [24, 54, 62]. These studies showed that an increase in Mg:P molar ratio increased the P-removal ratio. The optimized Mg:P molar ratio was about 1.3:1.

2.12.3 Ammonium to phosphorus molar ratio

Not much research has been carried out in trying to optimize the N:P molar ratio, since the concentration of ammonium ions, in the supernatant, is typically higher than magnesium and phosphorus. One study showed that with the increase of ammonia concentration, the P-removal increased. Also the P-removal ratio was sharper, with a higher ammonia concentration [54].

2.12.4 Turbulence

Although not yet fully understood, turbulence is a very important parameter in struvite crystallization. Nucleation is controlled by solubility chemistry, while growth rate is believed to be limited by low turbulence or low mixing energy [5]. Energy input increases concentration gradients in boundary layers surrounding growing crystals and increases the struvite crystal growth rate [5]. In a crystallizer, a high-energy mixing environment is provided to optimize crystal growth. However, a problem lies in the fact that there is no universal quantification for turbulence, especially in the fluidized beds. One study at the UBC Pilot Plant used the concept of Reynolds number, as a measure of the degree of turbulence [7]. It is, however, noteworthy that, the concept of Reynolds number should only be used as a guideline and not a hard and fast rule. This is due to the fact that Reynolds number would change once the reactor would start to fill up with growing crystals.

2.12.5 Recycle ratio

The most important function of recycle ratio is to dilute the strong wastes so that the process of crystallization remains in the metastable zone. It also helps in achieving the desired up-flow velocities in a fluidised bed. A previous study at the UBC Pilot Plant showed that the feed concentration inside the reactor remained unchanged, regardless of the recycle ratio [7]. This was, in fact, due to under-optimized P-removals. It is important to note here, that recycle ratio can only deliver its objective i.e. dilution, if there is enough removal of struvite constituent ions. As a result, one of the proposed objectives of this research was to optimize P-removal / recovery, so that recycle ratio can be used effectively, especially for high strength feeds.

2.12.6 Seeding the reactor

The provision of a seed material, onto which depositions of struvite can occur, is of vital importance to the successful operation of crystallization systems. Nucleation is primarily a reaction-controlled process. It has an inherent lag period, which is a function of the struvite supersaturation level. However, using seed media in a high-energy mixing precipitation reactor, the inherited lag period can be avoided and growth can proceed right away [5].

Quartz, phosphate rock, bone charcoal and struvite have all been used successfully, as seed materials [5, 63]. Struvite removal efficiency is a function of media surface area. As the particles grow, the specific surface area decreases, which means reduced availability of reactive surface. Therefore, to maintain efficiency, there must be provision of replacing bigger crystals with the smaller ones [5]. It has also been suggested that seeding is only required at the start-up and the ongoing process eventually becomes self-seeding [54].

2.12.7 The effect of temperature in the struvite crystallization

In the literature, contrasting information regarding the effect of temperature on struvite crystallization has been presented. One study suggested that, as the temperature increases from 0 to 20°C, struvite solubility also increases to a maximum; however, above this temperature, struvite solubility declines with increasing temperature [27]. Another study showed contradictory results, when it was found that struvite was more soluble at 38°C than at 25°C [64]. Due to such contradictory information found in the literature, an effort was made to study the effect of temperature on struvite solubility, especially at a lower temperature. The results of this study are discussed in Chapter 4.

CHAPTER 3 - MATERIALS AND METHODS

3.1 Process Description

The reactor design shown in Figure 3.1, follows the concept of a fluidized bed. It has four different areas of cross section, increasing from the bottom to the top. For a given upflow rate, each section would have a different upflow velocity. Due to the increase of the diameter from the bottom to the top, the upflow velocities would also decrease from bottom to the top. Calculated upflow velocities in different sections, based on the flow rate of 3.6 L/min, are given in Table 3.1.

Wastewater is fed into the bottom of the reactor, along with the recycle stream. The injection port facilitates complete mixing, and spreads the supersaturation conditions of the processing fluid *more* evenly throughout the reactor. The bottom section has the highest degree of generated turbulence. Calculated Reynolds numbers in the different sections of the reactor are given in Table 3.2. Reynolds numbers have been used to quantify turbulence in this study. However, it is important to note that, with the reactor full of crystals, the actual Reynolds numbers would be quite different, in comparison to the calculated ones.

The supersaturation ratio in the bottom section would be higher when compared to the other sections of the reactor. Nucleation is believed to be reaction controlled and is a function of supersaturation ratio; therefore, it is believed that crystals nucleate out of the solution in the bottom section. Tiny crystals would either be trapped by the existing crystals (due to agglomeration), or would be carried to the upper sections, where velocities are low enough to keep them in the reactor. The rationale behind the varying cross-section and hence, the different upflow velocities in the UBC MAP Crystallizer,

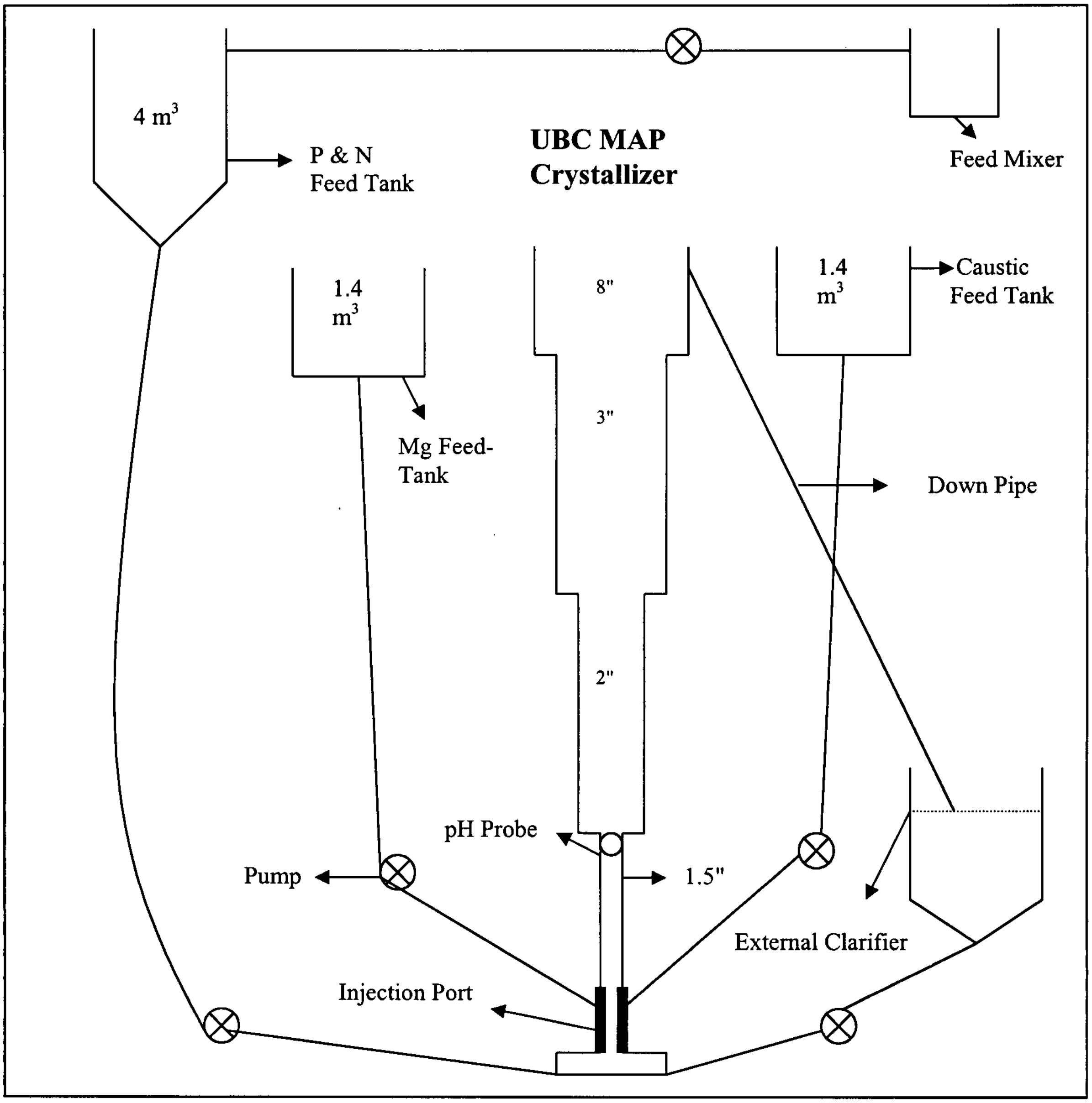

Figure 3.1: Pilot-scale UBC MAP Crystallizer flow sheet

Table 3.1: The dimensions of the reactors

		Reactor A	Reactor B
Length (cm)			
	Bottom section	101	106
	Middle section	108	275
	Top section	91[(a)]	93
	Top clarifier	45.7	45.7
Nominal Diameter (cm)			
	Bottom section	4	4
	Middle section	5.2	5.2
	Top section	7.7	7.7
	Top clarifier	20.2	20.2
Volume (L)			
	Bottom section	1.3	1.3
	Middle section	2.3	5.8
	Top section	4.2	4.3
	Top clarifier	13	13

[(a)] The length of the top section was changed to 250 cm after two months of operation

was to avoid the wash out of the tiny crystals in the effluent . As the crystals grow in size, they are able to overcome the higher upflow velocities and move towards the lower sections. The bottom section, due to the high turbulence would enhance crystal growth [5]. The larger crystals are then harvested from the bottom section after they are big / hard enough. This then gives the smaller crystals an opportunity to move towards the lower sections, repeating the process. The system is operated in a continuous feed mode and the reactor is shut-down only for the harvesting and monitoring the gross volume of the crystals in the reactor.

Table 3.2: Upflow velocities and Reynolds number in different sections of the reactor

Reactor sections	Upflow velocities (cm/min) [(a)]	Reynolds number[(b)]
Bottom section	286	2139
Middle section	170	1646
Top section	77	1111
Top clarifier	11	442

(a) Calculations are provided in Appendix A

(b) Calculations are provided in Appendix B

3.2 Materials And Equipment

3.2.1 The reactor

Two pilot-scale reactors, based on the same process principle as that of previously tested bench-scale reactors, were built and tested. As noted, the dimensions of the reactors are given in Table 3.1. The reactors were made of transparent polyvinyl chloride (PVC) plastic. Transparent piping facilitated in monitoring the behaviour and the settled bed height of the crystals. The inside diameters of the bottom, middle and the top sections were 4, 5.2 and 7.7 cm respectively. A clarifying section was located at the top of each reactor and was built of clear acrylic pipe. This section was provided to trap fine particles from washing out, since the velocity in this section was lowest among all sections. The total volume of water in Reactor A and B was 20.8 and 24.5 liters, respectively.

<u>Top clarifier</u>

The diameter and the height of the top clarifier were 20.3 and 45.7 cm, respectively. It was made of clear acrylic pipe. Two outlets were provided in the top clarifier. The lower outlet was positioned at approximately 40.6 cm water depth. The lower outlet carried the overflow to the external clarifier. It was connected to the external clarifier through a vertical 2.5 cm inside diameter clear PVC pipe. The upper outlet was placed 2.54 cm higher than the lower outlet. It was only used when the lower outlet was plugged. The upper outlet was connected to the external clarifier by 1.27 cm outside-diameter, LDPE (low density polyethylene) tubing.

External Clarifier

Both reactors were equipped with external clarifiers, which were mounted on the tables close to the reactors. The main function of the external clarifier was to recycle the effluent back into the reactor. It was also used to trap the washed out fine crystals from the reactor. The external clarifiers were square with surface dimensions of 36.5 cm by 40 cm and were made of clear acrylic pipe. The external clarifiers had a square pyramidal bottom with a 45° slope. The water level in the external clarifiers was approximately 30.5 cm. The approximate external clarifier volume was 54 liters. The recycle flow to the reactor was withdrawn from a port on the side of the external clarifier approximately 15 cm below the water surface. The clarifier normally had a clear effluent, when the removal efficiencies (i.e. the removal of struvite constituent ions) were high; in contrast, the effluent was cloudy / milky during low removal efficiencies. This observation helped in ascertaining the performance of the system visually and allowed changes to be made in the operating conditions, to optimize the system performance. When the system was under-optimized, in terms of the removal of struvite constituent ions, the effluent in the external clarifier had the potential to form struvite. A conscious effort was made to provide quiescent environment in the external clarifier, so that struvite would not form. However, over a period of time, there were signs of some struvite accumulation at the bottom of the external clarifiers; this accumulation was periodically removed. The treated effluent from the external clarifier overflowed by gravity from a port near the top of the external clarifier to a sewer drain. The effluent drain line was also equipped with a three way valve to allow flow measurements. The tubing used for drain line and flow measurements was 1.27 cm outside-diameter, LDPE tubing.

The injection port

The feed was being fed from three different tanks; the feed constituents required adequate mixing before entering into the reactor. To accomplish best possible mixing, an injection port was provided at the base of the bottom section. The injection port was built of stainless steel. Figure 3.2 shows a simplified cross section of the injection port. There were three entry inlets in the injection port. The N and P feed, blended with the recycle effluent, was introduced from the bottom of the injection port, while magnesium and caustic feeds were introduced from the sides of the injection port, through quick connectors. The diameter of the entry points for magnesium and caustic feed was 0.3 cm, while that of the entry point of other two feed constituents (N &P) and the recycle flow was 3.8 cm. Every time the reactor was stopped for harvesting or whenever there were low flows, the injection port was dissembled and cleaned with a thin, stainless steel rod.

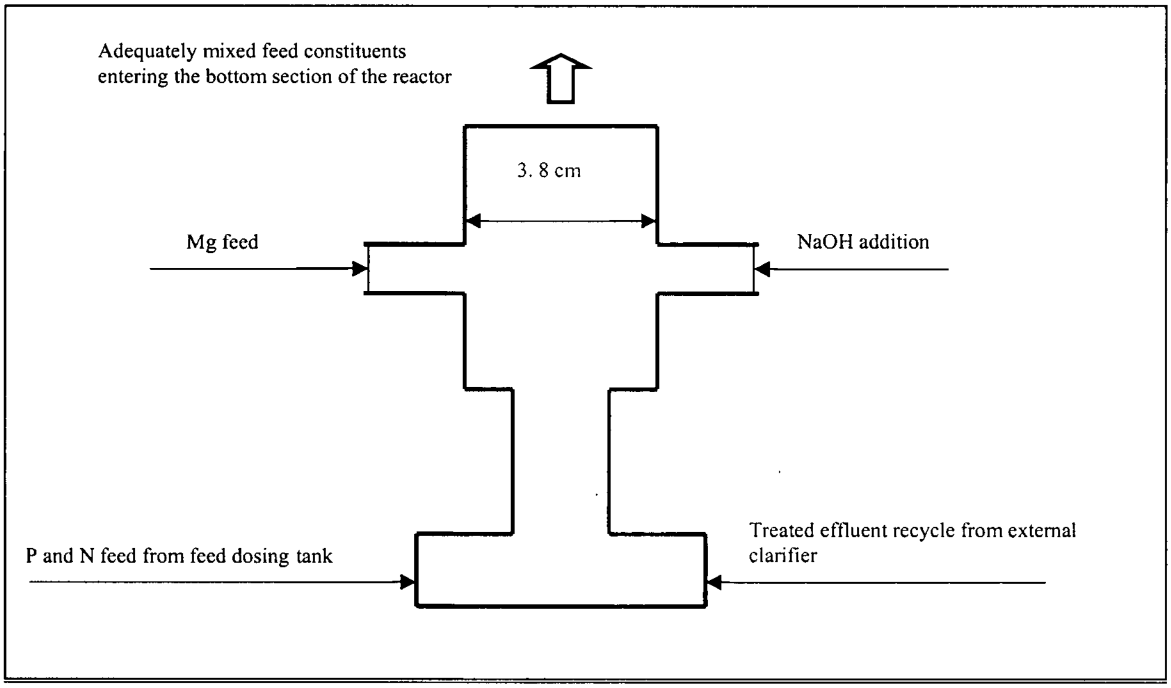

Figure 3.2: Pilot-scale UBC MAP Crystallizer injection port

The harvest section

The bottom section also served in harvesting the crystals. The nominal diameter of the harvesting section for both reactors was 4 cm. The lengths of the harvesting section for Reactor A and B were 101 and 106 cm, respectively. Two ball valves, one at the top and one at the bottom were used to disconnect the harvesting section. The harvesting procedure is described in Section 3.4.

3.2.2 Chemicals, storage tanks and pumps

Constituents of feedwater

Synthetic feedwater, containing the constituent ions of struvite, was used as influent for the experiments conducted at the pilot-scale. This was mainly due to the fact that large volumes of digester supernatant were not available. The salts used to make the synthetic feed were commercial grade magnesium chloride hexahydrate (Mg feed), diammonium hydrogen phosphate (P feed) and ammonium chloride (N feed). Commercial grade sodium hydroxide (caustic feed) was used for pH adjustment.

The same dosing tank was used for P and N feeds and separate dosing tanks were provided for Mg and caustic feeds. The water depth in the P and N feed dosing tank was 3888 liters, while it was about 1400 liters for Mg and caustic feed tanks. A separate mixing tank for P and N feed was used, prior to its metering into the dosing tank. The feed was delivered from the mixing tank to the dosing tank, using a submerged pump. Magnesium and caustic feeds were put directly in their respective dosing tanks. The feed was then mixed vigorously with water, using a pressure hose pipe.

P and N feed dosing in the reactor

P and N feed was introduced in the reactors using a Moyno Model 500 331 progressive cavity pump, with a ½ HP motor, with adjustable drive speed. The tubing used for this purpose was 1.27 cm outside-diameter LDPE, tubing.

Mg feed dosing in the reactor

The magnesium chloride solution was fed into the injection port using a MasterFlex L/S variable speed peristaltic pump, with Standard pump heads. All the tubing used for this purpose was 0.63 cm outside-diameter LPDE, tubing.

pH control and caustic soda dosing

The property of struvite (being less soluble under alkaline conditions), is normally exploited in optimizing struvite crystallization process. When struvite is formed, the pH is depressed, so pH control becomes critical. The pH in the system was monitored at the top of the harvesting zone. Control and continuous pH monitoring was accomplished using a Black-Stone BL 7916, with an Oakton gel-epoxy probe. The pH control unit allowed the pH to be controlled to within ± 0.1 pH units. The pH in the external clarifier was monitored using an Oakton continuous pH monitor, equipped with an Oakton gel filled, epoxy body pH probe. All tubing used for pH control units were 0.63 cm outside-diameter, LDPE tubing.

Recycle flow

In addition to trapping fine particles and preventing them from washing out in the effluent, the external clarifier was also used as an effluent storage tank. The effluent was pumped back into the reactor using a Moyno Model 500 332 progressive cavity pump, with a ½ HP motor, and adjustable drive speed. The tubing used for this purpose was 1.27 cm outside-diameter, LDPE tubing.

3.2.3 Flow measurements, sample collection and preservation

Influent flow rates were measured using a graduate cylinder and a stop watch. Total influent flow rate was measured by opening the three way valve of the effluent drain line from the external clarifier. Total flow (influent and recycle) was measured from the down pipe, from the crystallizer to the external clarifier.

Influent and effluent grab samples were collected at least once every 24 hours. Influent samples for Mg, N and P were collected from their respective dosing tanks, whereas the effluent samples were collected from the external clarifiers. Samples for $[PO_4\text{-}P]_{total}$ (influent and effluent) were preserved using phenyl mercuric acetate and 3% v/v sulphuric acid. All samples for $[NH_4\text{-}N]_{total}$ were preserved using 3% v/v sulphuric acid [65]. All samples for $[Mg^{+2}]_{total}$ were preserved using concentrated nitric acid [65].

Samples for $[PO_4\text{-}P]_{total}$ and $[NH_4\text{-}N]_{total}$ were stored at 4 °C until analysis. The analyses for $[NH_4\text{-}N]_{total}$ and $[Mg^{+2}]_{total}$ were completed within USEPA recommended holding times (65). It was not feasible to complete sample analysis for $[PO_4\text{-}P]_{total}$ within the USEPA recommended time [65]; however, results from a previous study showed that an extended holding time of one week had no affect on the integrity of the sample [7].

3.3 Analytical Methods

The constituents which were analyzed in this work included total magnesium or $[Mg^{+2}]_{total}$, total ammonia-nitrogen or $[NH_4\text{-}N]_{total}$ and total orthophosphate or $[PO_4\text{-}P]_{total}$. $[Mg^{+2}]_{total}$ was analyzed using flame atomic absorption spectrophotometry (model Varian Inc. SpectrAA220® Fast Sequential Atomic Absorption Spectrophotometer). $[NH_4\text{-}N]_{total}$ and $[PO_4\text{-}P]_{total}$ were analyzed using flow injection analysis (model LaChat QuikChem® 8000). Instrument operational parameters can be found in Appendix C.

3.4 Crystal Harvesting

Crystals were harvested from the harvesting section (bottom section), after every two or three days of operation. The frequency of the harvesting was depended on the desired CRT (crystals retention time), the concept of which is elaborated on in Section 3.7.4. Crystals were allowed to settle, once all the pumps were switched off. The height of the compressed bed was then measured. Using ball valves, the harvesting section was isolated from the remaining sections. In order to withdraw crystals, the injection port was removed using quick disconnects. Crystals were then collected in the bucket. Water was used to flush out crystals from the harvesting section. Once the harvesting was complete, the reactors were re-started.

Crystal drying and sieving

The crystals from the harvesting bucket were shifted to the drying racks. The crystals were dried for at least 24 hours, using a heater. The dried crystals were then sieved using W. S. Tyler® sieves. The sieve size openings used were 4.75 mm, 2.83 mm, 2.0 mm, 1.0 mm and 0.5 mm.

3.5 Monitoring And Maintenance

The influent flow rate, the total combined flow rate and the magnesium feed flow rate were monitored and recorded daily. Influent and effluent samples were also collected at least once every 24 hours and were later analyzed for magnesium, ortho-phosphate and ammonia nitrogen, as described in Section 3.3. Each day, before taking the effluent pH readings, the pH probes in the external clarifier were calibrated using standard pH 7 and pH 10 buffer solutions. The pH probes in the top of the harvesting sections were calibrated, whenever the reactors were shut down for harvesting. The temperature and the pH of the effluent was monitored and recorded daily. Each day, the reactors were shut down to monitor the compressed height of the crystals in the reactors. The amount of feed added to the chemical dosing storage tanks were recorded whenever new feed was made.

Normally, on the day of harvesting, the injection port was cleaned using a thin rod. Acid washing was carried out when the fouling in the injection port was severe. This situation was encountered when the supersaturation ratio at the inlet was very high. Once the cleaning and monitoring operations were completed, the reactors were restarted and flows were readjusted.

3.6 Struvite Solubility Determination

Previously, a conditional solubility curve was developed at the University of British Columbia, over a range of pH values. This curve was developed to be used as a controlling parameter for struvite crystallization at the bench-scale. To generate this conditional solubility curve, struvite crystals were dissolved in distilled water and the solution was stirred for one hour. The solution, at equilibrium, was then analyzed for pH, dissolved magnesium, ammonia and ortho-phosphate. The tests were conducted at a controlled temperature of 25°C. As has been discussed in Section 2.12.7, one finds contradictory information in literature, regarding the effect of temperature on struvite solubility. For this research work, the reactors were located outside the building, and the temperature was not controlled. Therefore, it became imperative to construct a conditional solubility curve at different temperatures. Tests were conducted at 10°C and 20°C, using tap water and synthetic supernatant.

Apparatus

The apparatus used for the determination of struvite solubility consisted of a six station paddle stirrer. The jars were immersed in a constant temperature bath, which maintained the desired temperature. The paddle stirrers were set to operate at 70 RPM. About 4 grams of struvite crystals were added in each jar, containing 1.5 liters of solution. Equilibrium was assumed to be reached in 24 hours, after which the conditions were changed in each jar. It was desired to have equilibrium points at various pH's (i.e. pH values between 6.5 to 10). The pH was adjusted using dilute hydrochloric acid and sodium hydroxide solutions. After 24 hours for a given set of conditions, the pH and conductivity in each jar were measured. Conductivity was measured using a Hanna Instruments HI9033 multi-range, conductivity meter. Samples were filtered and preserved as described in Section 3.2.3. The samples were later analyzed for total magnesium, total ammonia-nitrogen, and total ortho-phosphate, according to the analytical methods described in Section 3.3.

3.7 Terminology

3.7.1 Supersaturation ratio at the inlet

The Supersaturation Ratio at the inlet would quantify the degree of saturated condition of the feedwater, containing magnesium ions, phosphate ions and ammonium ions, at a given pH. The Supersaturation Ratio at the inlet doesn't take into account the effect of the recycle fluid. The Supersaturation Ratio would be calculated by using Equation 9:

$$SSR = P_{S\text{-feed}} / P_{S\ eq} \qquad (9)$$

where

$P_{s\text{-feed}}$ = conditional solubility product (equals to the product of analytical molar concentrations of the struvite components, dissolved magnesium, ammonia nitrogen, and orthophosphate, in proportions those fed to the reactor), and

Ps^{eq} = conditional solubility product at equilibrium for a given pH value. The conditional solubility product used in this study is the one developed using synthetic supernatant.

3.7.2 Supersaturation ratio in the reactor

The Supersaturation Ratio in the reactor can define the working window of the crystallization operation and the boundary limits of the metastable region, which differentiates between the process of crystallization and precipitation.

The Supersaturation Ratio in the reactor would be calculated by using Equation 10:

$$\text{In-reactor } SSR = \text{In-reactor } P_S / P_{S\ eq} \qquad (10)$$

where

The in-reactor P_S would be calculated by combining the concentrations of magnesium, ammonia and orthophosphate in the reactor feed and the recycle stream. Therefore, supersaturation in the reactor gives a true picture of the degree of saturated conditions existing inside the reactor; this would, in turn, govern the whole process of crystallization, at large.

3.7.3 Recycle ratio

The Recycle Ratio would be calculated using Equation 11. The main objective of the Recycle Ratio is to maintain a desirable supersaturation ratio in the reactor by diluting the feed with the processed effluent.

R.R. = Qr/Qt-inf.. (11)

where

Qr = the recycle flow
Qt-inf = the total influent flow

3.7.4 Crystal retention time

In addition to balanced chemistry (in terms of magnesium, ammonium and phosphate ion concentrations and the pH), crystals need to spend sufficient time in the reactor to ensure growth. In order to quantify crystal age (i.e. the number of days which the crystals spend in the reactor), the concept of Crystal Retention Time (CRT), has been developed. CRT in days is calculated by measuring the settled 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 settled bed volume was measured to be 7.8 liters, and 1.3 liters of crystals were harvested from the reactor every two days, then the CRT would be 12 days.

3.7.5 Mean crystal size

The mean crystal size was calculated from the sieve analysis. All the crystals that were greater than 4.75 mm were assumed to have a diameter of 5 mm. The 4.75-2.83 mm crystals were assumed to be 3.7 mm in diameter, the 2.83-2.0 mm crystals were assumed to be 2.4 mm in diameter, the 2-1 mm crystals were assumed to be 1.5 mm in diameter, the 1-0.5mm crystals were assumed to be 0.75 mm in diameter and the crystals which were less than 0.5 mm were assumed to be 0.2 mm in diameter. Based on these assumptions, the mean crystal diameter can be calculated by using Equation 12.

$$Cd_{mean} = (P1(5) + P2(3.7) + P3(2.4) + P4(1.5) + P5(0.75) + P6(0.2))/100 \quad (12)$$

where

Cd_{mean}= Mean crystal diameter in mm

P1 = Percentage of crystals of diameter greater than 4.75 mm in the harvest

P2 = Percentage of crystals of diameter from 4.75 to 2.83 mm in the harvest

P3 = Percentage of crystals of diameter from 2.83 to 2.0 mm in the harvest

P4 = Percentage of crystals of diameter from 2.0 to 1.0 mm in the harvest

P5 = Percentage of crystals of diameter from 1.0 to 0.5 mm in the harvest

P6 = Percentage of crystals of diameter less than 0.5 mm in the harvest

3.7.6 Phosphorus removal

The percentage P-removal was calculated by using Equation 13.

$$\text{P-removal}(\%) = (P_{influent} - P_{effluent})/P_{effluent} * 100 \quad (13)$$

where

$P_{influent}$ = Concentration of PO_4-P at the inlet (i.e. multiplying PO_4-P concentration with the feed flow rate and dividing by the total influent flow).

$P_{effluent}$ = Concentration of PO_4-P in the effluent collected from the external clarifier (mg/L).

CHAPTER 4 – RESULTS AND DISCUSSION

Overall, three different Runs with varying P concentrations were performed to investigate the performance of the pilot-scale reactors in terms of P- removal and the quality of harvested product. The study was completed in two phases. The operational period for the first phase, in which Run 1 and Run 2 were conducted, was from July 31st, 2001 to November 1st 2001. The operational period of the second phase, in which Run 3 was conducted, was from March 17th, 2002 to May 24th, 2002.

The main result of this study was that the pilot-scale UBC MAP Crystallizer achieved excellent P-removals from synthetic wastewater. MAP crystals produced were of good quality (hard and big enough, for easy separation and processing) throughout the course of study. The response of the system was also encouraging in terms of P-removal rates, even when the reactor was subjected to higher feed strengths (~ 250 mg/L of P), and there was no adverse impact on the quality of crystals. The summary of the results is shown in Table 4.1. Detailed operational data is given in Appendices D and E for the Reactors A and B, respectively.

4.1 Reactor Operation

In this section, the results obtained from the operation of crystallization reactors are discussed. Overall, the response of the reactor was quite encouraging in terms of P-removal. P-removal rates were as high as 97%, for the various feed strength tested. It was possible to achieve a very low effluent P concentration (~7.3 mg/L), even when the reactor was subjected to a high influent P concentration of about 242 mg/L. The focal point of this project was to increase the P-removal without compromising too much on the quality of the harvested product. In the following sections, the reactor operation and the parameters, which had a pronounced effect on the P-removal, are discussed.

Table 4.1: Range of the operational conditions and results summary of the pilot-scale MAP experiments

	Run 1		**Run 2**		**Run 3**	
	Reactor A	Reactor B	Reactor A	Reactor B	Reactor A	Reactor B
InfluentPO_4-P concentration at the inlet (mg/L)	47.5~68	50.6~69.6	69.7~93.1	67.9~92	127~220	133~221
Effluent PO_4-P concentration (mg/L)	1.5~46.8	1.5~43	5~44	2.6~45	9.3~60	3.9~144
Mg:P molar ratio	0.8~3.8	1~2.3	0.7~2	0.8~4.6	0.9~3.8	0.6~2.9
N:P molar ratio	5.3~10.5	5.9~10.5	4.2~6.6	4.5~6.5	2.6~4.6	2.6~4.9
pH	7.3~8.6	7.4~8.6	7.6~8.5	7.4~8.6	7.1~7.7	6.6~8
Recycle ratio	3.1~11	2.6~5.5	3.5~6.1	5.7~16.4	5.7~14	6~24.3
SS ratio at the inlet	1.6~38.5	1.7~41.4	7.2~31.7	3.6~59.3	10.2~59	3.7~87.5
In-reactor SS ratio	1~3.6	1~4.5	1.2~4	1.1~3.8	1.3~4.1	1~5.2
P-removal efficiency (%)	21~**97.5**	28.6~**97.8**	42.8~**93.6**	40~**96.2**	67~**93**	35~**97.2**
CRT (days)	6 ~ 13	7 ~ 17	8 ~ 12	10 ~ 12	N/A [a]	5 ~ 13
Total upflow rate (mL/min)	2700~4000	2750~3750	2950~4000	2150~4200	3100~3650	3300~5100
Mean MAP grain size (mm)	2.5~3.6	2.6~3.7	2.2~3.2	3.5~3.7	2.3~3.6	2.3~3.8

[a] CRT has been calculated after at least one full reactor volume had been harvested. This couldn't be accomplished in Run 3 (Reactor A), due to the short duration. This point is elaborated in Section 4.1.4.

4.1.1 P-removal efficiency

During this study, it was possible to achieve the phosphorus removal efficiency of over 95 % for all the feed strength tested. Figure 4.1 to 4.3 show the percentage phosphorus removal for the entire course of study. The desired degree of phosphate removal was achieved by controlling the reactor operating pH or by the inlet supersaturation ratio.

The effect of pH on P-removal

Struvite is soluble at acidic pH conditions and highly insoluble at alkaline pH [54]. In intentional struvite crystallization, this property is normally exploited. The desired degree of P-removal, through struvite crystallization, can be achieved by increasing the pH of the process fluid. Various researchers have investigated the effect of pH on P-removals [5, 7, 54, 55, 60, 62]. All these studies have shown that there is an increase in P-removal ratio, with an increase in pH.

Figures 4.4 to 4.6 show the effect of pH on P-removal. As can be seen, higher P-removals were achieved at higher pH values. It can also be seen that, at a given pH value, different P-removal rates were achieved. Theoretically, for consistent operating conditions (in terms of Mg:P molar ratio and N:P molar ratio), there should be a linear relationship between pH and the P-removal i.e. with an increase in the pH, P-removal should increase linearly. However, it was not possible to keep steady operating conditions consistently, at the pilot-scale, due to a large number of variables involved (flows, concentrations, etc). Therefore, the scatter of points at a given pH is probably due to the different operating conditions.

It is noteworthy that it was not always required to operate the system at higher pH values, in order to achieve higher P-removals rates. It was possible to achieve about 79 % P-removal rates even at a low pH of 7.1 (Figure 4.7). This is very interesting, since in the literature, higher pH values (8.2 ~ 9) are recommended to ensure higher (above 80%) P-removal rates [5, 24, 54, 55, 60, 62]. Achieving higher removal rates at a low pH, elucidates the fact that pH is not the only driving force for the process of struvite crystallization.

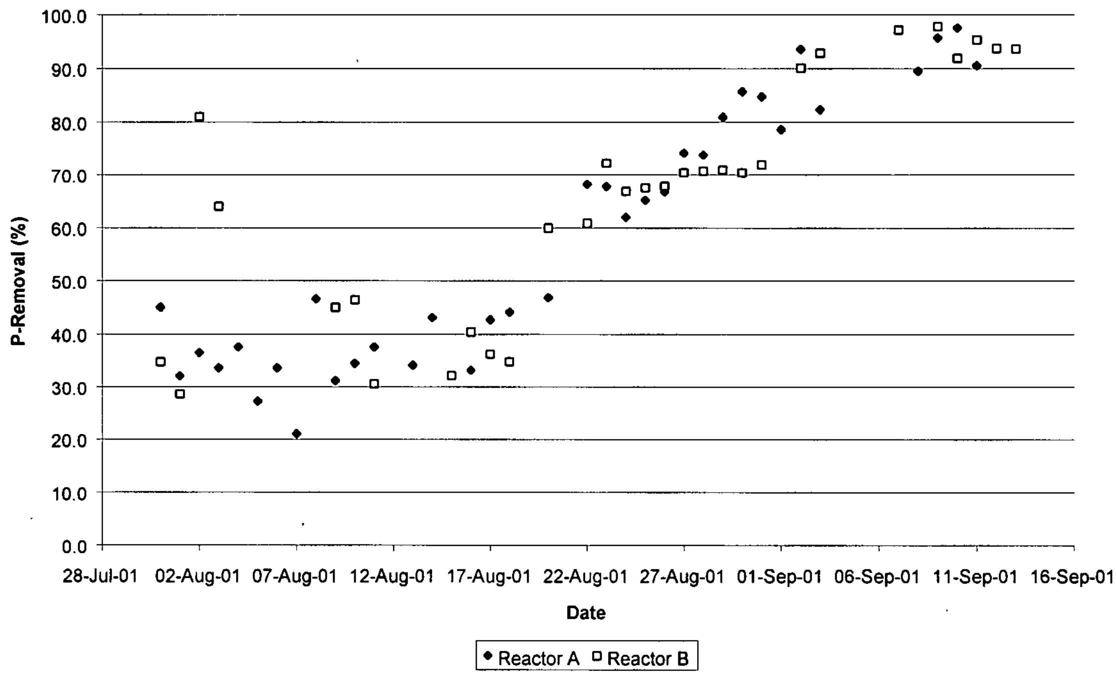

Figure 4.1: Percentage phosphate removal (Run 1)

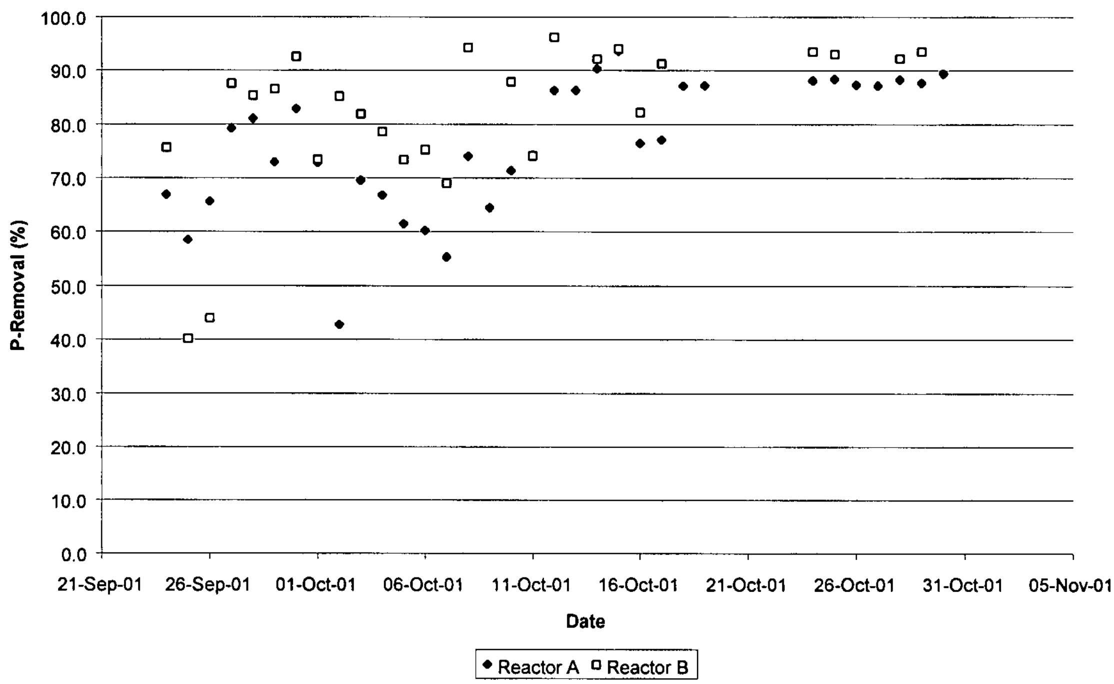

Figure 4.2: Percentage phosphate removal (Run 2)

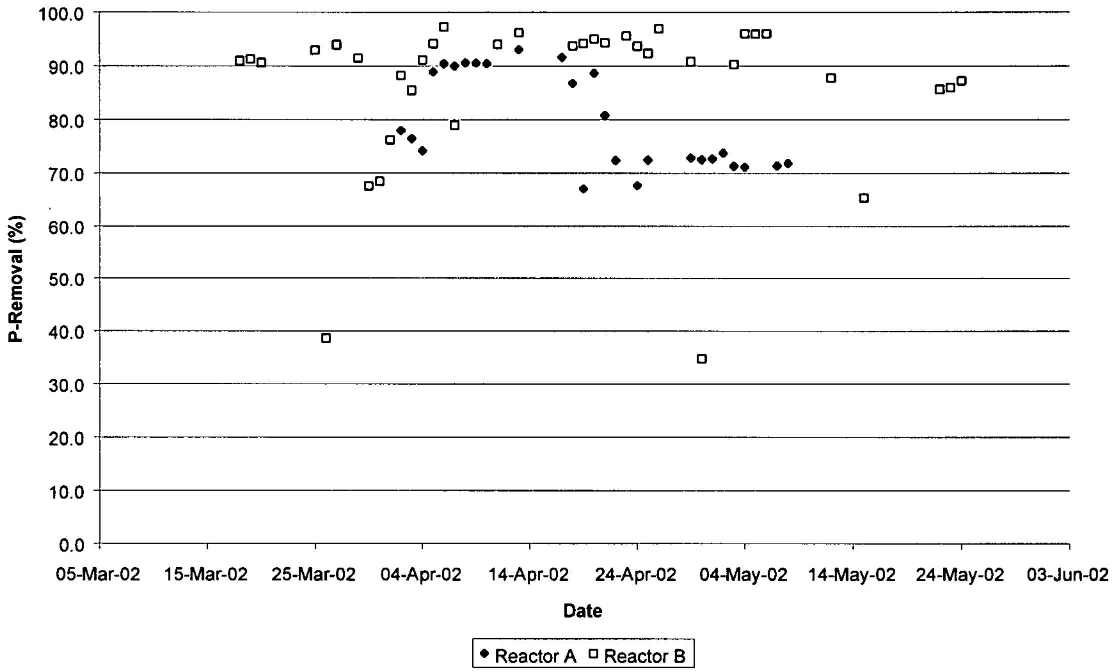

Figure 4.3: Percentage phosphate removal (Run 3)

As discussed in Section 2.9, the saturated conditions of the process fluid can be increased by either increasing the concentrations of struvite constituent ions or by increasing the operating pH. When 79 % of P-removal was achieved at a pH of 7.1 (Run 3, Figure 4.6), the process fluid was supersaturated with respect to struvite (P = 150 mg/L, N = 200 mg/L and Mg = 228 mg/L); hence a pH value of 7.1 was high enough to ensure higher P-removal rates.

For phosphate removal, there are two possible operating parameters, which can control the desired degree of percentage removal. These are the operating pH of the reactor, and the supersaturation ratio at the inlet. Evaluating the performance of a system, using pH as a controlling parameter is very useful and simple, since it takes into account only one of the factors involved, which can cause the process fluid to be supersaturated. However, the downside of having such a control indicates an incomplete understanding of the driving force for the process of crystallization, since pH control alone doesn't take into account the $Mg:NH_4:PO_4$ molar ratios.

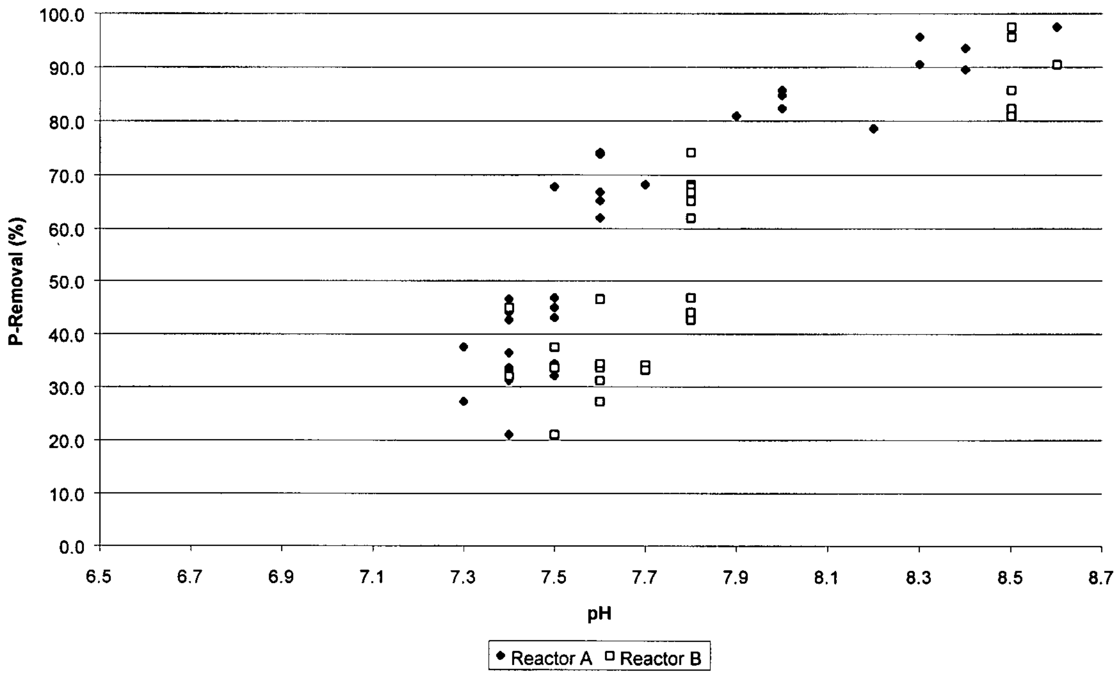

Figure 4.4: Effect of pH on P-removal (Run 1)

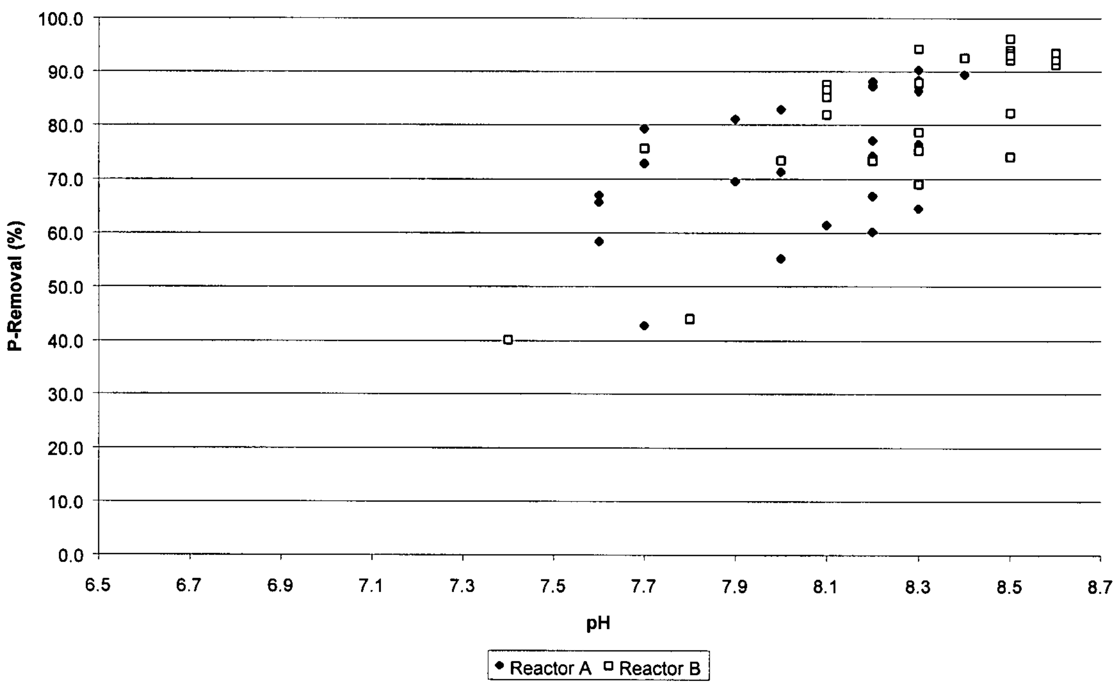

Figure 4.5: Effect of pH on P-removal (Run 2)

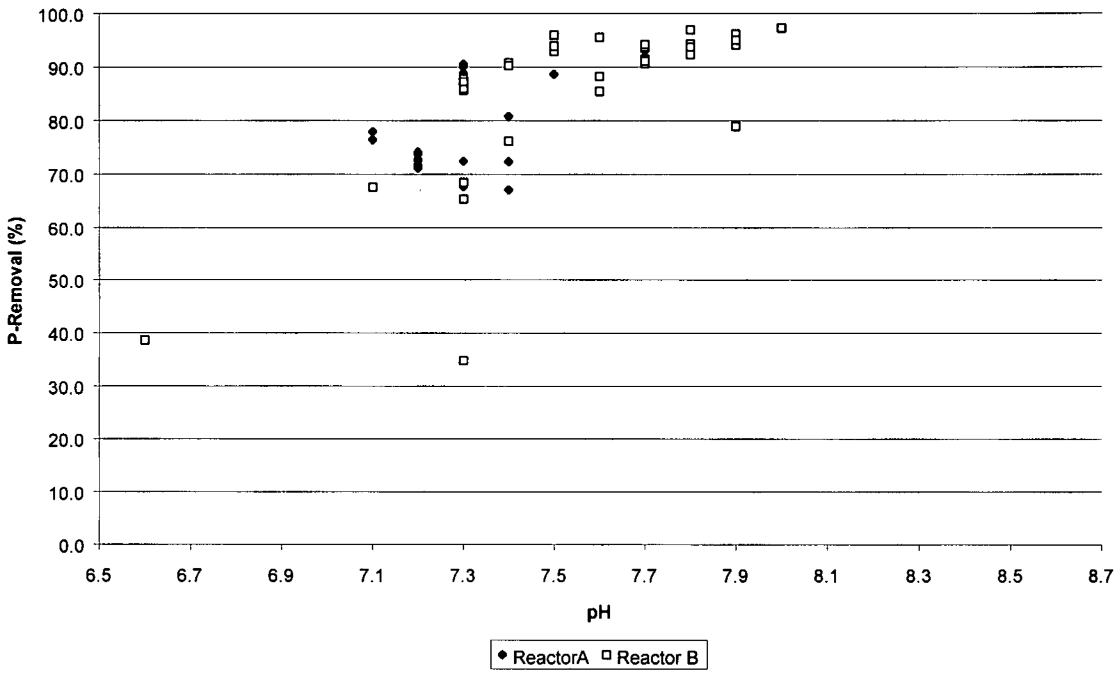

Figure 4.6: Effect of pH on P-removal (Run 3)

The effect of supersaturation ratio on P-removal

The supersaturation ratio at the inlet is an alternative operating parameter for controlling the process efficiency of struvite crystallization. When using this operating parameter, it is assumed that effluent supersaturation ratio would reach equilibrium i.e. it would be equal to unity. The supersaturation at the inlet takes into account the concentrations of all the three struvite constituent ions, at a given pH. This operating parameter, therefore, has a wider application, especially for the treatment of digester supernatant, where influent concentrations are likely to change over a period of time. Another advantage of controlling the system by the supersaturation ratio at the inlet is that the equilibrium model can be used, which predicts the effluent concentrations of struvite constituent ions.

Figures 4.7 to 4.9 show the percentage of phosphorus removal versus the inlet supersaturation ratio, for both the reactors during the entire course of study. It can be seen from these figures that the P-removal increases with an increase in the inlet supersaturation ratio. The supersaturation ratio at the inlet provides the driving force for the P-removal. The higher the driving force, the higher the potential of P-removal / recovery, provided that phosphate remains the limiting ion. Inaccuracies in the measurement of pH, struvite constituent ions concentrations and the flow measurements are the possible reasons for the scatter in the Figures 4.7 to 4.9. Even an error of 0.1 in the pH reading can cause a change of over 0.3 in the SS ratio. It is important to note here that there were some data points where Mg:P molar ratio was less than unity, which resulted in the suppression of P-removal (since magnesium became the limiting ingredient). For example, in Figure 4.8, for Reactor A, there are seven points, where Mg:P molar ratio was less than one; this could also have resulted in the scatter of points.

Figure 4.10 and 4.11 show the inlet and in-reactor supersaturation ratios, for the reactors A and B, respectively. At a given recycle ratio, and percentage P removal, an increase in the inlet supersaturation ratio would increase the in-reactor supersaturation ratio. However, it is clear from Figures 4.10 and 4.11 that the in-reactor SS ratio varies independently of the inlet SS ratio. This is attributable to the fact that the in-reactor SS ratios were kept in a narrow range, with variable recycle ratios. It was done on purpose and this point is further elaborated in Section 4.4.

The effect of Mg:P molar ratio on P-removal

For struvite crystallization, supplementation of magnesium with an external source is usually necessary. Struvite forms in a theoretical Mg:N:P molar ratio of 1:1:1. Therefore, magnesium ion supplementation of at least the stoichiometric requirement would be a must to ensure that magnesium ions don't become a limiting factor. However, this doesn't imply that the process of struvite crystallization can only proceed if Mg:N:P has a molar ratio of 1:1:1. Unintentional struvite crystallization at various treatment plants provides one such example, where Mg:N:P molar ratio is never unity, but hard scales of struvite can indeed, form over a period of time. However, in the case of intentional struvite crystallization, when Mg:P molar ratio falls below unity, the system becomes under-optimized, in terms of P-removal efficiencies.

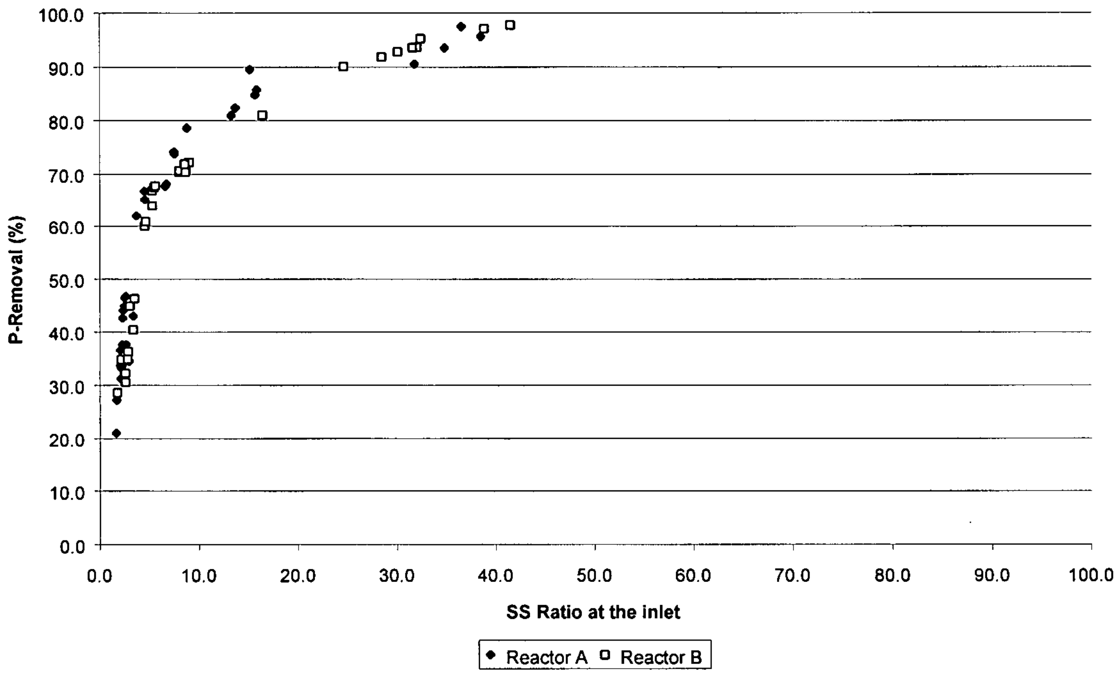

Figure 4.7: Supersaturation ratios vs. percentage P-removal (Run 1)

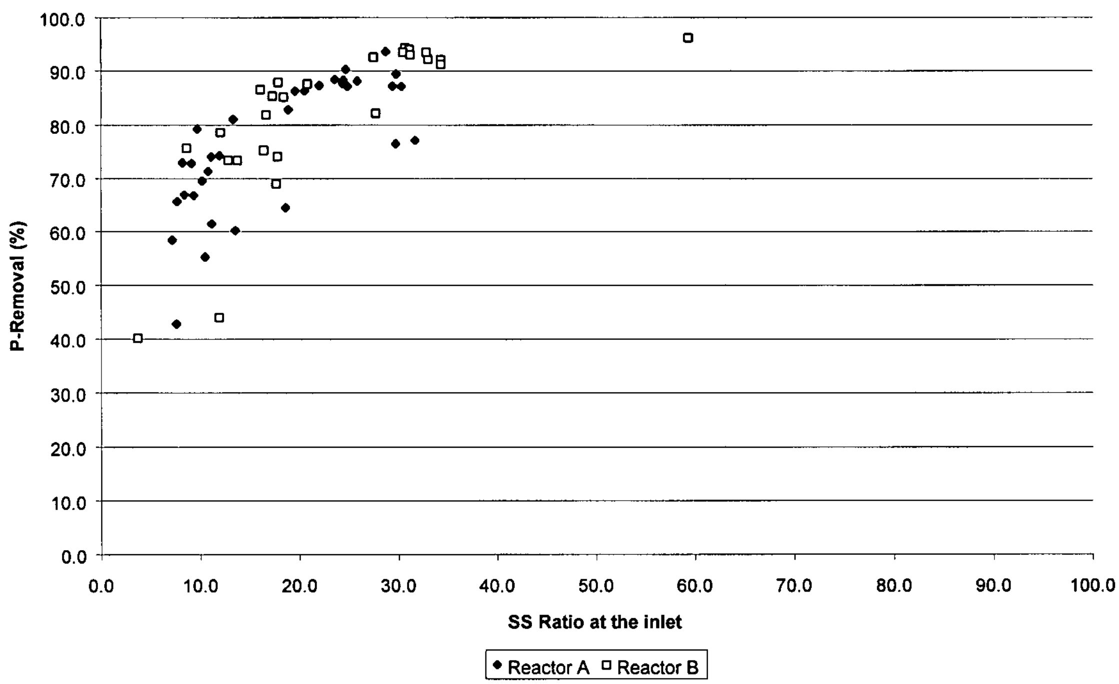

Figure 4.8: Supersaturation ratios vs. percentage P-removal (Run 2)

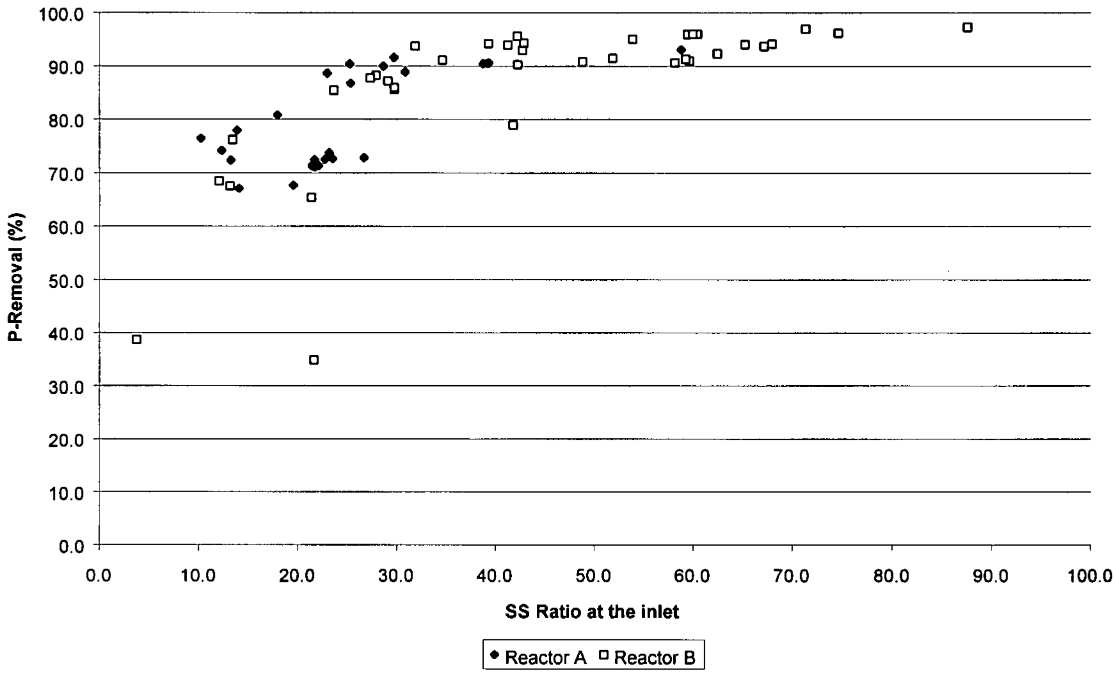

Figure 4.9: Supersaturation ratios vs. percentage P-removal (Run 3)

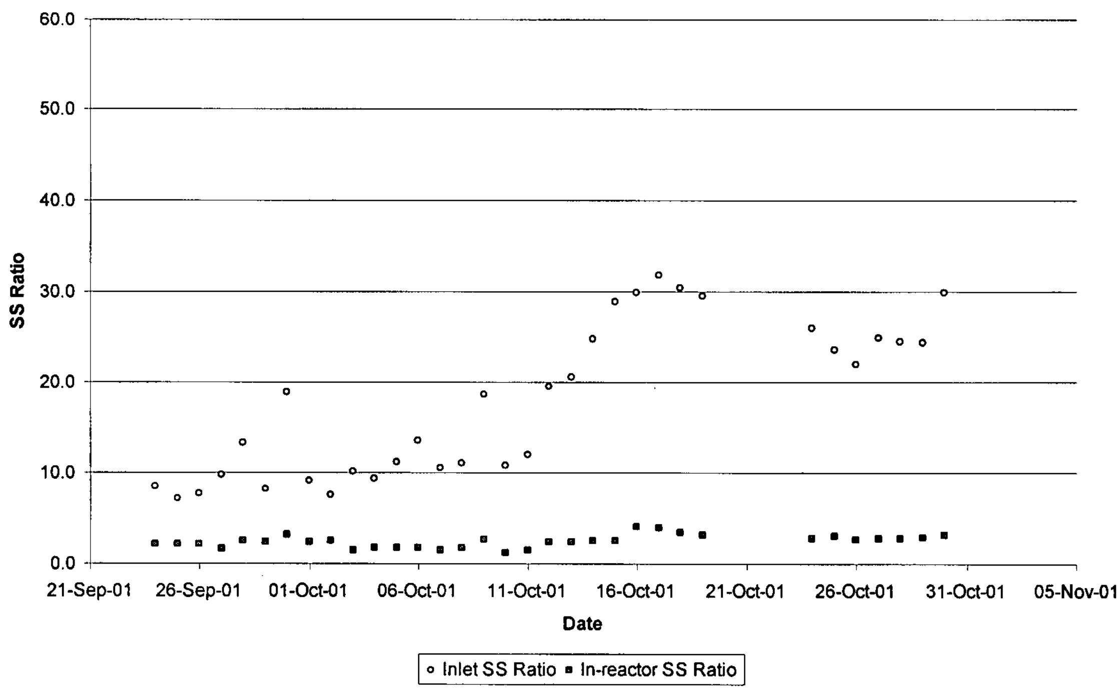

Figure 4.10: Supersaturation ratios during the study period (Run 2, Reactor A)

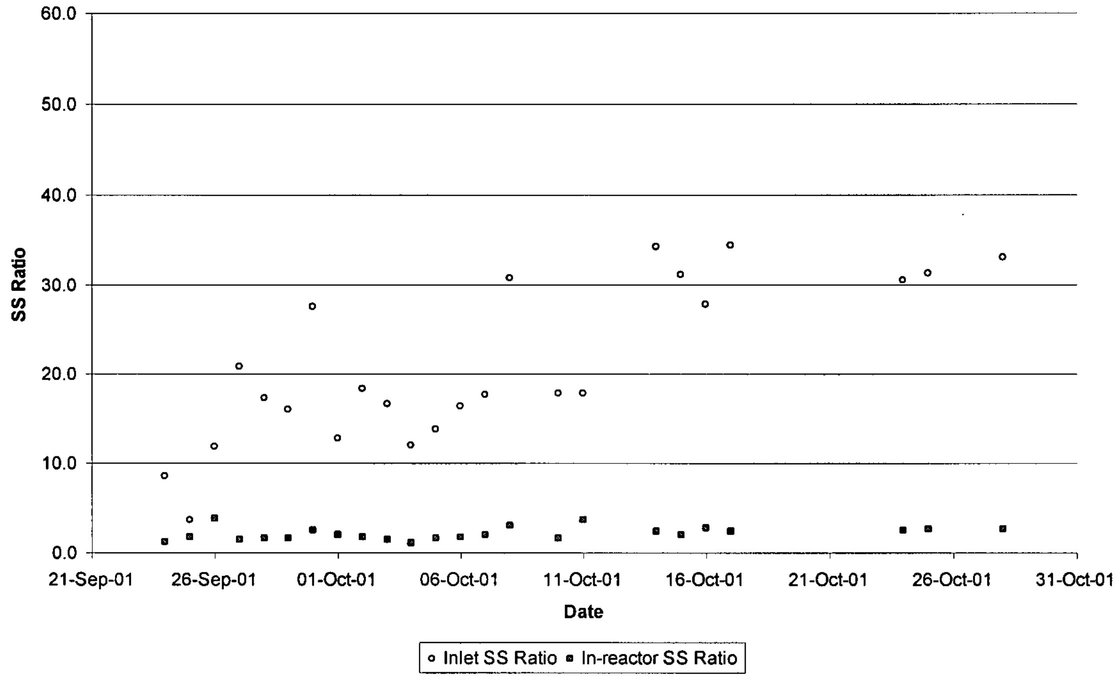

Figure 4.11: Supersaturation ratios during the study period (Run 2, Reactor B)

Table 4.2 shows limited data from Run 1 (Reactor A). It can been seen that at a given pH value, P-removal increased linearly with an increase in Mg:P molar ratio. This relationship is shown graphically in Figure 4.12. Similar results are reported in the literature, where increased Mg:P molar ratio resulted in the increase of P-removal ratio [54, 62]. This trend is attributable to the fact that at a given pH and N:P molar ratio, any increase in the Mg:P molar ratio would increase the degree of saturation with respect to struvite, which in turn, would enhance P-removal.

Table 4.2: The effect of Mg:P molar ratios on P-removal

pH	Mg:P molar ratio	N:P molar ratio	% P-removal
7.6	1.5	6.4	62.0
7.6	1.8	6.4	65.2
7.6	1.9	6.4	66.8
7.6	2.4	6.4	74.1
7.6	2.4	6.4	73.8

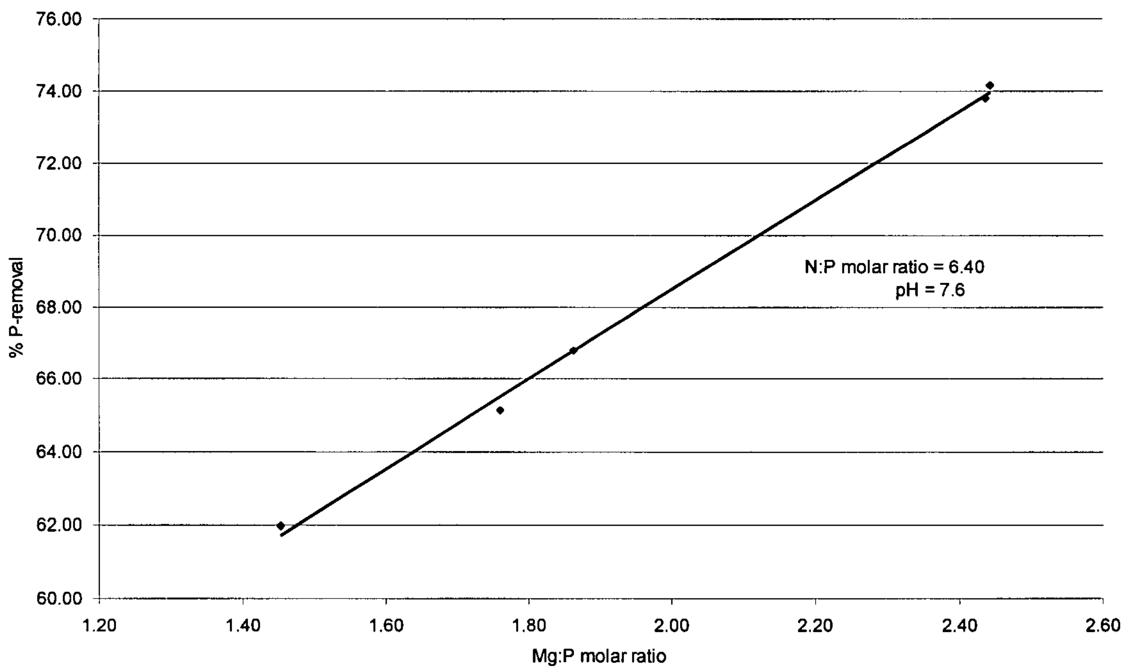

Figure 4.12: The effect of Mg:P ratio on P-removal

Magnesium as a controlling parameter

In intentional struvite crystallization, magnesium dosage can be manipulated to optimise the process operation. It has already been mentioned in the previous sections that saturated conditions of the process fluid would govern the P-removal efficiency (if phosphate is the limiting ion). It then follows that there are two possible ways to enhance P-removals; increasing the operating pH or applying higher Mg:P molar ratios. Table 4.3

shows limited data from Run 3 of the experiments, which indicates that magnesium can be used as a controlling parameter for achieving a desired degree of phosphate removal. It can be seen from Table 4.3, that instead of elevating the operating pH, higher Mg:P molar ratios were applied to achieve higher P-removal rates. This suggests that with the magnesium dosage manipulation, a desired degree of phosphate removal can be achieved. The results presented in this work should, therefore, be considered as preliminary only and future work with better control conditions is required to validate this point. An important point which might be of concern is the high effluent magnesium concentration, when operating the reactor with higher Mg:P molar ratios. This might have a detrimental effect on treatment plant operation, as effluent from the reactors would be pumped back to the inlet of the treatment plant. Increasing the magnesium concentration might then trigger the unintentional struvite formation.

Table 4.3: Option of using magnesium as a controlling parameter

Influent P (mg/L)	Mg:P molar ratio	pH	P-removal (%)
148	3.4	7.3	90.5
148	3.4	7.3	90.5
148	3.5	7.3	90.4
154	1.7	7.7	94.2
154	1.6	7.9	95.1
159	1.4	7.8	94.3

4.1.2 Ammonia removal

There are a number of physicochemical and biological techniques for the treatment of nitrogen-containing waste streams. The techniques such as biological nitrification / denitrification and breakpoint chlorination reduce nitrogen compounds to nitrogen gas. However, removing / recovering ammonia via struvite formation offers an alternative technology, which can convert ammonia in to a useful product.

Figures 4.13 to 4.15 show the percentage ammonia removal for the entire course of this study. It can be seen from these figures that there is a large variation in percentage ammonia removal. The removal of ammonia was not expected to be very high since ammonia, magnesium and phosphate should be removed in equimolar amounts during the formation of pure struvite. During this study, the P-removal optimization was targeted and phosphate ions were therefore, deliberately kept as the limiting ones. Nonetheless, it can be seen that upto 50% ammonia removal was achieved. Some researchers have used struvite formation to remove / recover ammonia with some success [60, 66]. If desired, consistent and better ammonia removal rates can be achieved, by engineering the process conditions in a way where ammonium ion is kept as the limiting one.

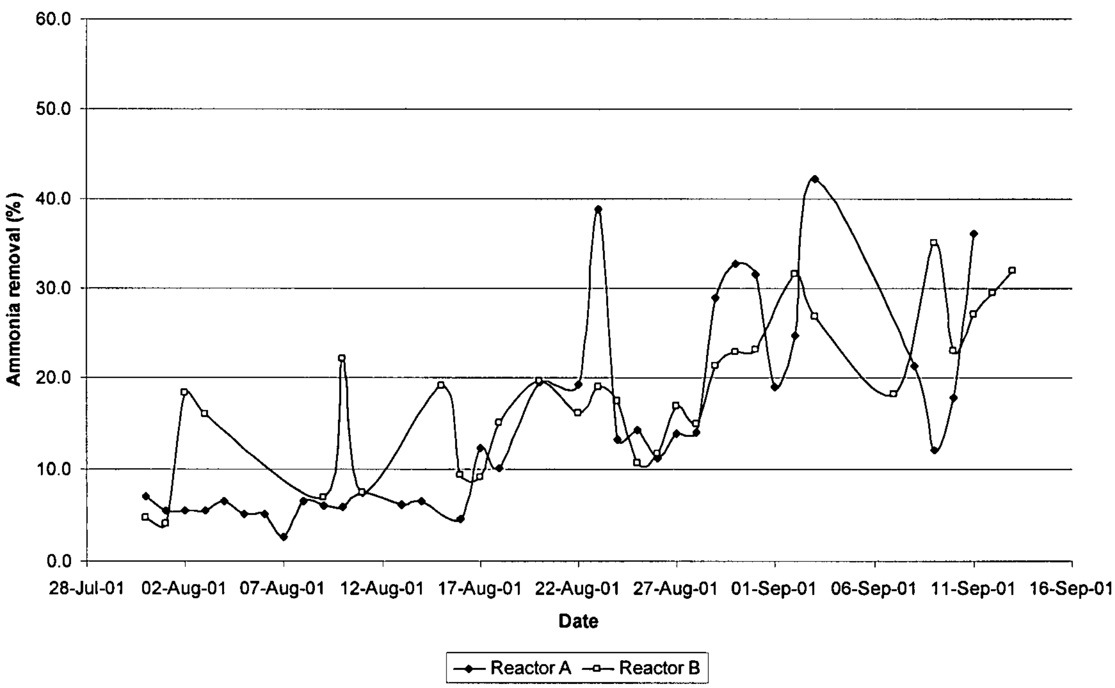

Figure 4.13: Percentage ammonia removal (Run 1)

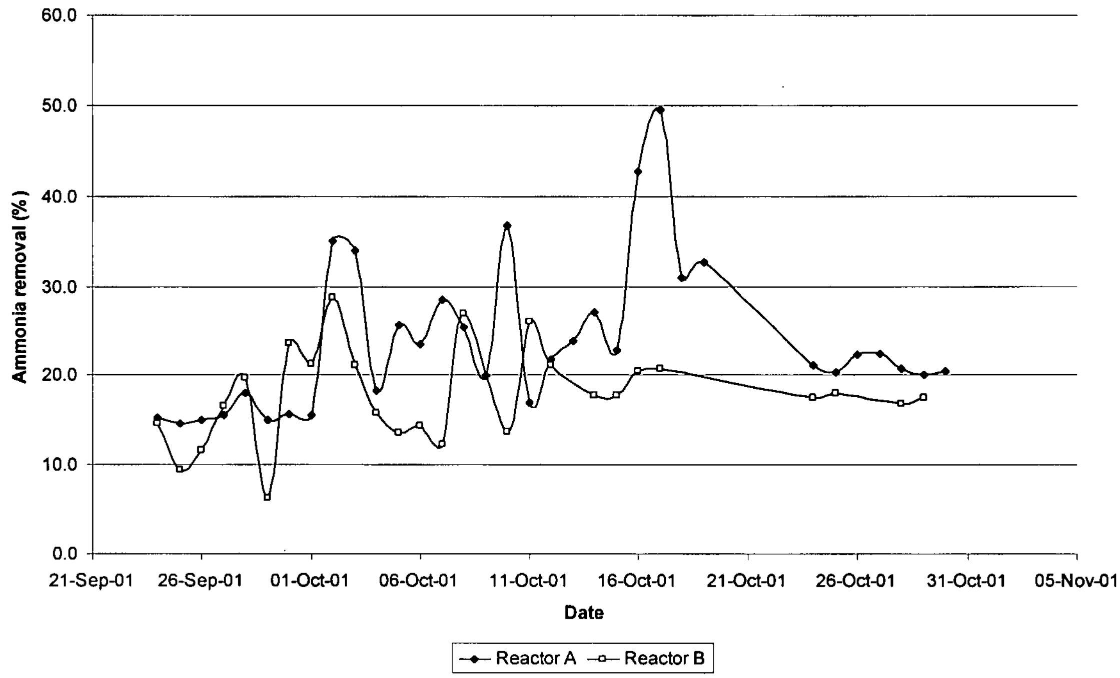

Figure 4.14: Percentage ammonia removal (Run 2)

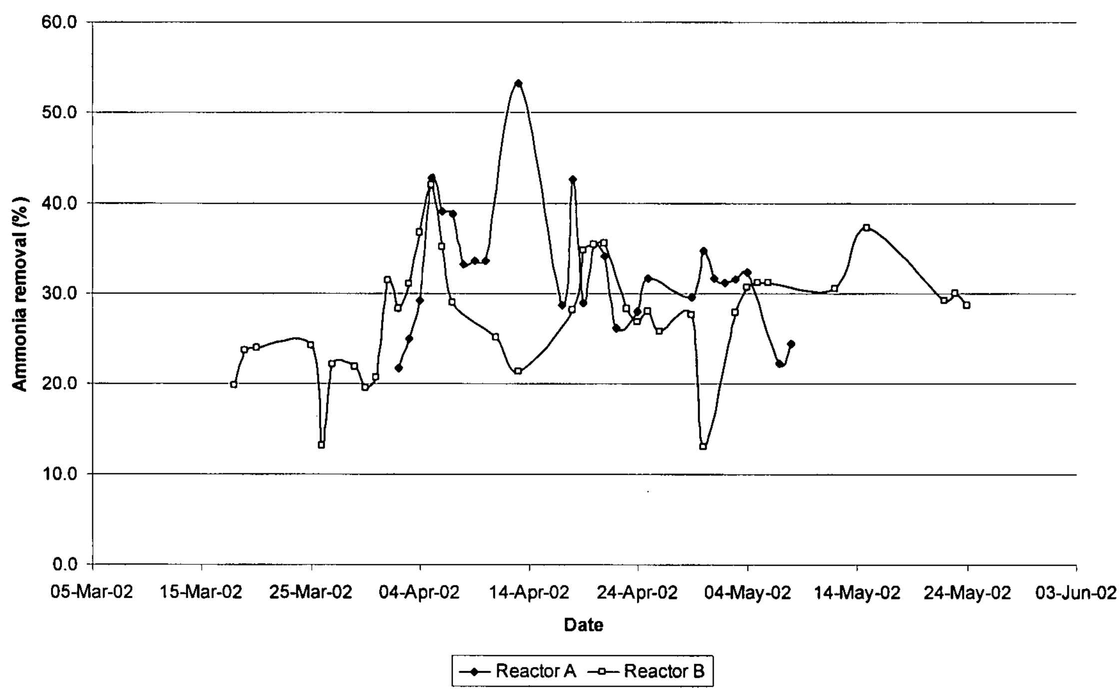

Figure 4.15: Percentage ammonia removal (Run 3)

4.1.3 Struvite loading rate

Figures 4.16 to 4.18 show the struvite loading rates for both reactors, during the entire study period. The struvite loading rate is defined as the theoretical mass of struvite grown daily, based on the daily mass of phosphate removed. The applied struvite loading rate was related to the desired degree of phosphate removal. Since the prime goal of this work was to optimize P-removal, it was possible to know the maximum struvite loading rate, which the reactor could handle, under a given set of conditions.

It can be seen from Figures 4.16 and 4.17 that the struvite loading rate was almost the highest at the end of the Runs. This was attributed to the reactors being subjected to a gradual increase in pH, resulting in a gradual increase in P-removal and subsequent struvite loading rates. As shown by Figure 4.19, the maximum loading rate was about 770 g/day for Reactor A and 700 g/day for Reactor B respectively, for given concentrations of struvite constituent ions at the inlet, and the total flow rate through the reactor. Any further attempt to increase the struvite loading rate always resulted in the plugging of the injection port or the recycle lines.

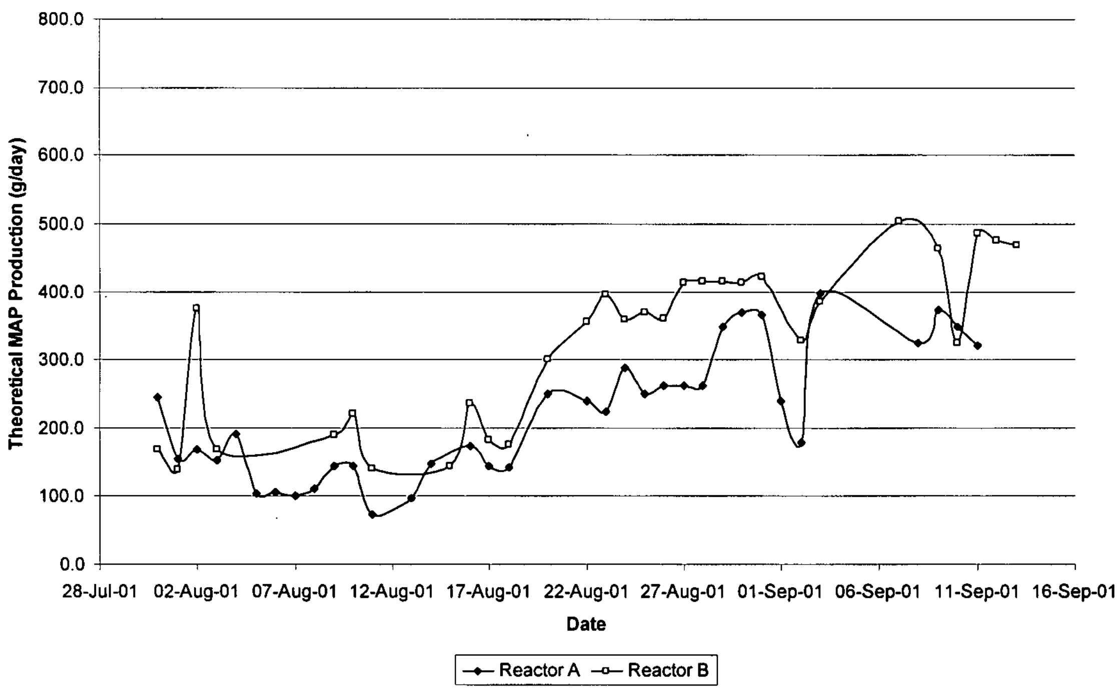

Figure 4.16: Struvite loading rate (Run 1)

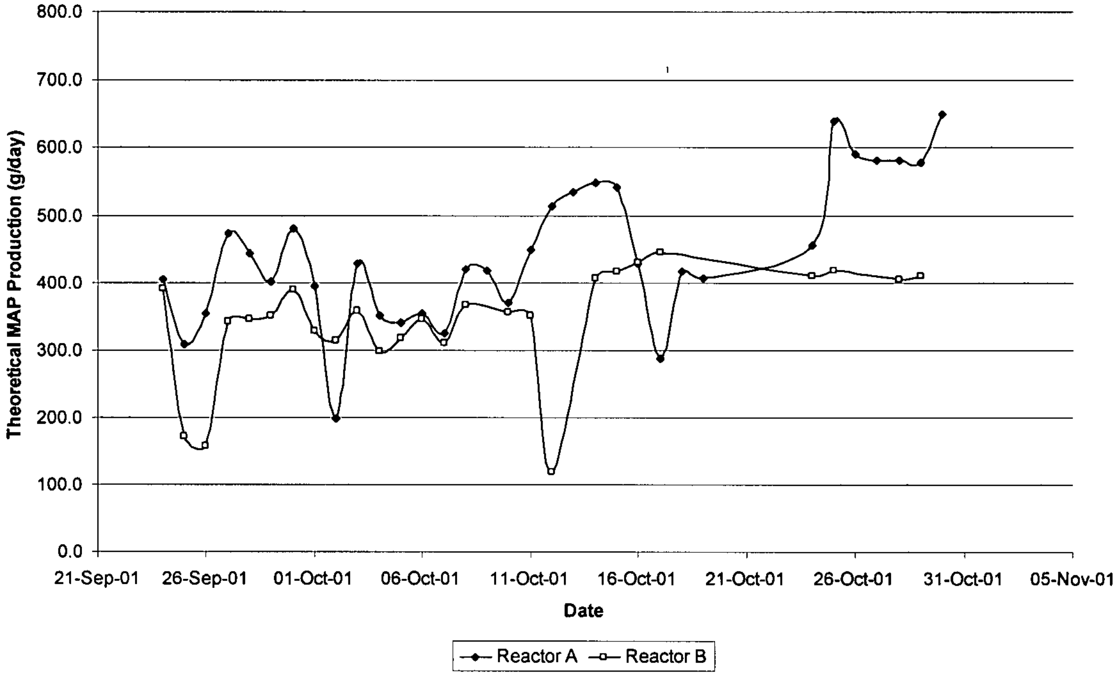

Figure 4.17: Struvite loading rate (Run 2)

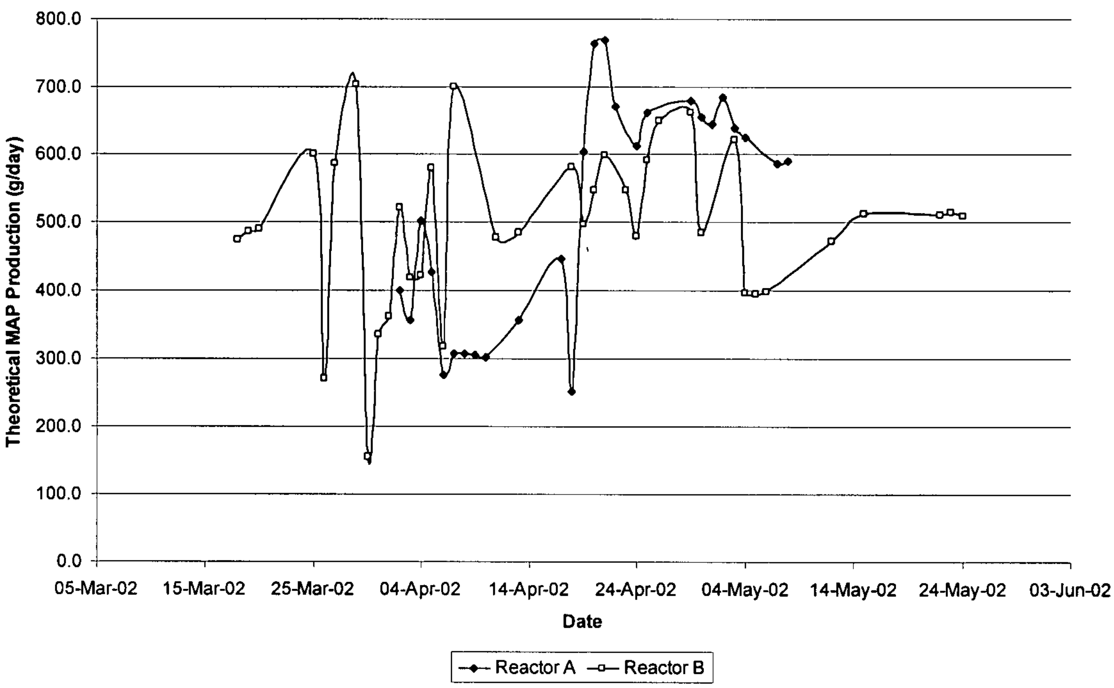

Figure 4.18: Struvite loading rate (Run 3)

An increase in the loading rate was attempted either by increasing the influent flow rate or by increasing the operating pH. However, for a given set of conditions, there seems to be a limit to which struvite loading can be applied to the reactor. During Run 3 of the experiments, plugging problems were encountered whenever the reactors were operated with increased struvite loading rates. The plugging can be attributed to the increase in the in-reactor supersaturation ratio. The reason for this is that, under a given set of conditions (for a given concentration of struvite constituent ions at the inlet and the total flow rate through the reactor), an increase in the influent flow rate would increase the conditional solubility product; which in turn, would increase the in-reactor supersaturation ratio. An increase in pH would decrease the conditional solubility product at equilibrium, consequently increasing the in-reactor supersaturation ratio. In order to avoid plugging problems, the reactors were operated below the maximum struvite loading rates during the concluding days of Run 3. This can be seen in Figure 4.18. Struvite loading rates were decreased by increasing the recycle ratios and reducing the operating pH of the reactors.

It is worth mentioning here that, during the last days of Run 3 of the experiments, the total flow through the reactors was increased to about 5000 mL/min instead of 3600 mL/min, which was the targeted flow rate during the entire course of study. Operating with 5000 mL/min meant a shorter HRT in the reactor; however, there wasn't a marked difference in the effluent supersaturation ratio, showing that HRT was *still* high enough to complete the reaction. Therefore, increasing the influent flow rate can increase the struvite loading rate, which would result in more struvite production. At the same time, however, the total flow rate through the reactor needs to be increased, so as to have a desired degree of recycle ratio. This would be *crucial* in keeping the in-reactor supersaturation ratio in the working range.

4.1.4 Crystal retention time

The time the crystals spend in the reactor can be crucial in attaining the required structural strength, to withstand the harvesting, drying and sieving procedure. It was expected that, with an increase in the time the crystals actually spend in the reactor, there would be a corresponding increase in the size and hardness of the crystals. However, there was no method available to quantify the time which the crystals spend in the reactor. Therefore, the concept of Crystal Retention Time (CRT) was developed to make estimates of struvite crystal age. The method of calculating CRT is described in Section 3.7.4. It is important to note here that the CRT is calculated once the seed materials were harvested, since the exact age of the seeding crystals was unknown.

Figures 4.19 to 4.21 show the calculated CRT of each harvest from both the reactors. The CRT in the reactors varied from 5 to 17 days. At the outset of experiments, the optimal range of CRT was not known; therefore, in Run 1, CRT was varied over a wide range of values. During Run 2 and 3, it was found that a CRT of 8 to 12 days was sufficient to yield the required structural strength in the crystals. However, CRT was not the only parameter which was controlling the eventual size of the crystals. The factor which had a dominant impact on the mean crystal size, are discussed in Section 4.3.1.

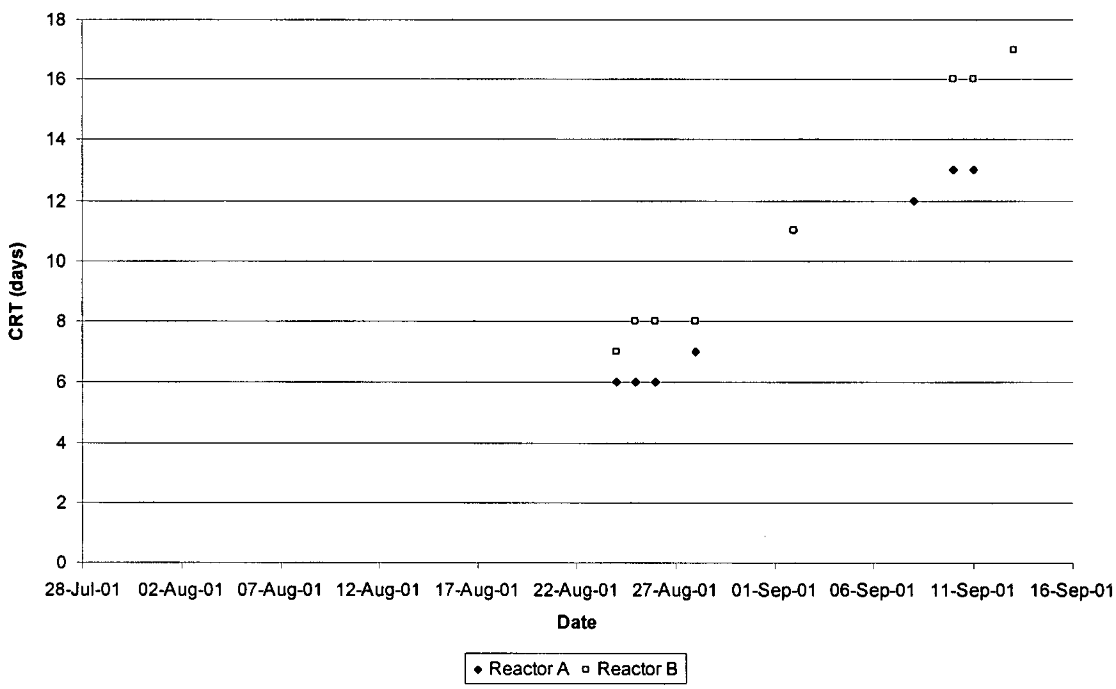

Figure 4.19: CRT for the harvests (Run 1)

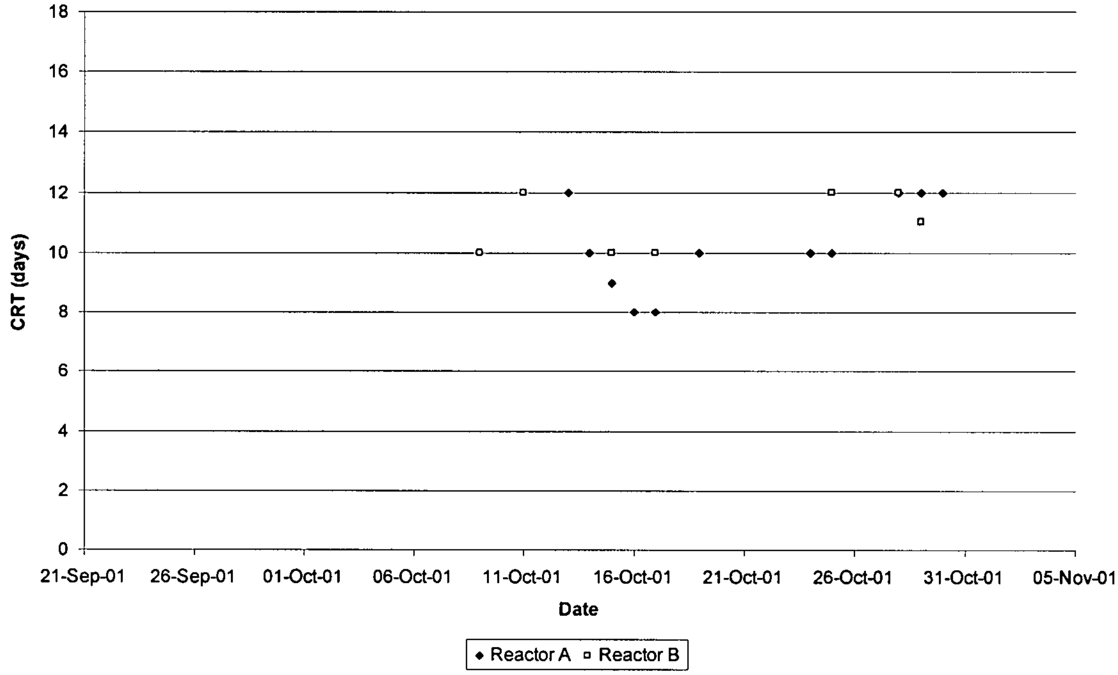

Figure 4.20: CRT for the harvests (Run 2)

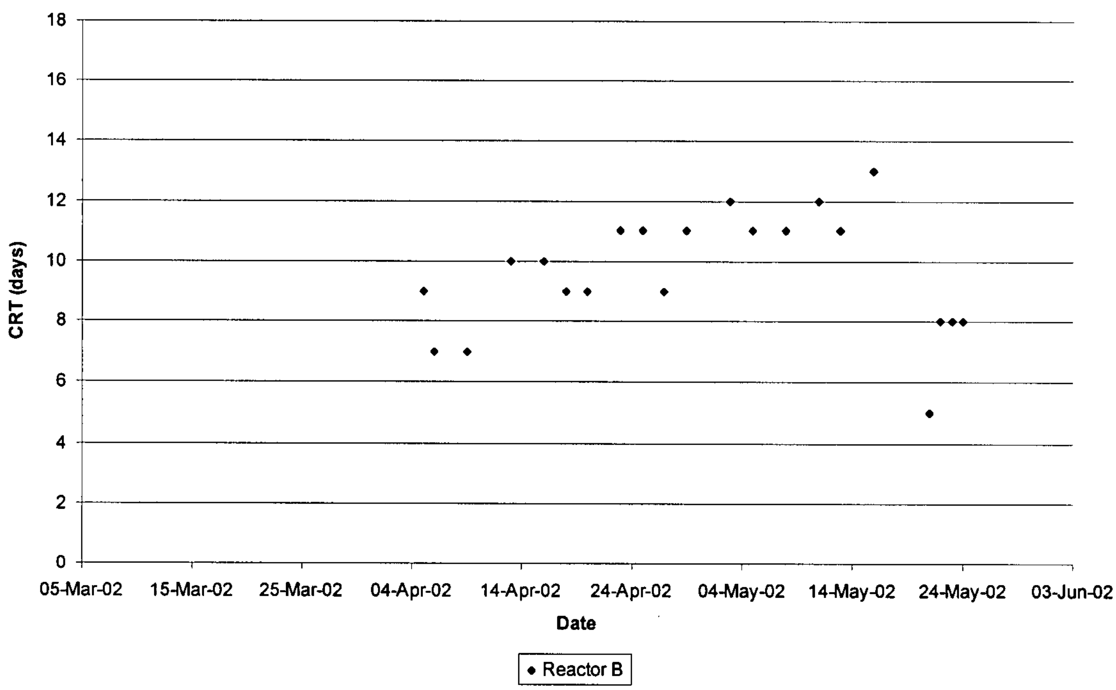

Figure 4.21: CRT for the harvests (Run 3)

4.1.5 Operational problems

The problems, which were experienced during operating the system, are discussed in this section. During the entire course of study, no major problem was encountered and the system responded in an expected manner.

Plugging of the Injection port

One of the major problems encountered during this study was the plugging of the reactor. This problem was pronounced during the Run 3 of the experiments, when the reactors were subjected to higher feed strengths. The injection port of the reactor was most prone to struvite encrustation. This was due to the fact that this section had the highest degree of supersaturation ratios, which might have resulted in the spontaneous nucleation, eventually plugging the injection port. Sometimes, the plugging was severe enough to stop the entire flow through the reactor. On those particular days, the injection port was dissembled and thoroughly cleaned with a thin rod, and sometimes acid wash was required to remove the hard scales formed. In order to avoid plugging of the injection port, the operating conditions of the reactors were changed either by reducing the operating pH or by increasing the recycle ratios. For future studies, it is recommended to separate the magnesium and caustic injection points; this might help in reducing the concentration gradient in the injection port.

Feed flow variation

The variation in the pump head between the full level and the empty level in N and P feed tank, caused variation in the feed flows. This problem was partially overcome by adjusting the pump speed daily. A better solution to this problem was to minimize the variation of water head in the feed tank. This was accomplished by preparing new feed each day, so that the water level in the feed tank remained more or less constant.

4.1.6 Protocols of running a smooth crystallization process

During the six months of running the reactors, some techniques were learned, which might prove useful in running a smooth struvite crystallization process. However, it is important to note that these protocols are based on the personal experience and should not be taken as the only protocols for running a smooth crystallization process.

Seeding the reactors at the startup proved very useful in avoiding the lag period, which is associated with the nucleation of the crystals. In one of the trial runs, startup of the reactor was tried without seeding. For homogenous nucleation to occur, the supersaturation ratio of the process fluid had to be elevated, which was achieved by increasing the operating pH to a very high value (~8.7). It resulted in the consistent reactor plugging during the initial days. It also proved to be time consuming, since the first harvest took place after about 20 days of operation. In all the remaining Runs, seeds were added at the startup. This resulted in the smooth operation of the reactors.

The struvite loading rate was increased gradually. Generally, the increase in struvite loading rate was achieved by increasing the operating pH. Gradually nudging the pH to a higher value, resulted in a smoother operation. In Run 3 of the experiments, when higher feed strengths were tested, a conservative approach was used. Initially, the system was started with a higher recycle ratio and a lower pH. After a couple of days, the recycle ratios were decreased. It was observed that it was easier to optimize P-removals, once the reactor was in operation for a couple of days. The plugging of the reactors, which is totally undesirable and contrary to the definition of a smooth process, indicated that the process control was out of the metastable region. Therefore, if the reactors were plugged, appropriate changes in the operating conditions were made, in order to retrieve the process conditions in the working window.

In summary, consistent, uninterrupted and prolonged runs were ideal for a smooth operation of crystallization process, which in turn, was directly related to the system performance, both in terms of process efficiency and the harvested product quality.

4.2 Struvite Conditional Solubility Product

Using the procedure presented in Section 3.6, experiments were conducted to determine the struvite equilibrium conditions in tap water and synthetic supernatant at 10°C and 20°C, respectively. Thermodynamically, there should be one value of solubility product, given that the activity of each chemical species is known accurately. Figure 4.22 shows the negative logarithm of struvite solubility product (pK_{SP}) calculated over a pH range, from approximately 6.5 to 9.4, for tap water at 10°C and 20°C, respectively. The solubility product value in tap water at 10°C varies from 8 X 10^{-15} to 1.7 X 10^{-13} and at 20°C it varies from 1.1 X 10^{-14} to 2.6 X 10^{-13}. The solubility product value, in synthetic supernatant at 10°C, varies from 5.9 X 10^{-15} to 1.4 X 10^{-13} and at 20°C, it varies from 7.2 X 10^{-15} to 3.7 X 10^{-13}. However, these variations are less pronounced between the pH values of 7.2 and 8.5. Some chemical reactions are probably occurring at lower and higher pH values, which are not accounted for in the analysis performed here.

The solubility of struvite has been investigated by a number of researchers and there is a wide range of reported solubility values [7]. In Section 2.7.2, the problems associated with using a solubility product value have been discussed in detail. One of the limitations of using a K_{sp} value for struvite is that it requires a complicated and accurate analysis for its determination, which might not be feasible in a full-scale application. Therefore, in this work, a conditional solubility curve was used to monitor the reactor operation. This curve is used to determine the saturated condition of a process fluid with respect to struvite, by calculating Ps from measured magnesium, ammonia and orthophosphate concentrations (as opposed to activities). A conditional solubility product is simpler to calculate and requires less analysis.

Figure 4.23 shows the experimentally determined Ps curves for tap water and synthetic supernatant, at 10°C and 20°C, respectively. As depicted by Figure 4.23, struvite was more soluble in synthetic supernatant than in the tap water, at both the testing temperatures. The increased solubility in the supernatant is probably due to the high ionic strength of the supernatant. Struvite solubility increases as ionic strength increases, due to the resultant decrease in the effective concentration of the component ions of struvite [30]. Other factors such as common ion effects that may compete with the crystallization or inhibit it, are not likely to play any role in the increased solubility of struvite, since in this work, synthetic supernatant (which only contained struvite constituent ions), was used.

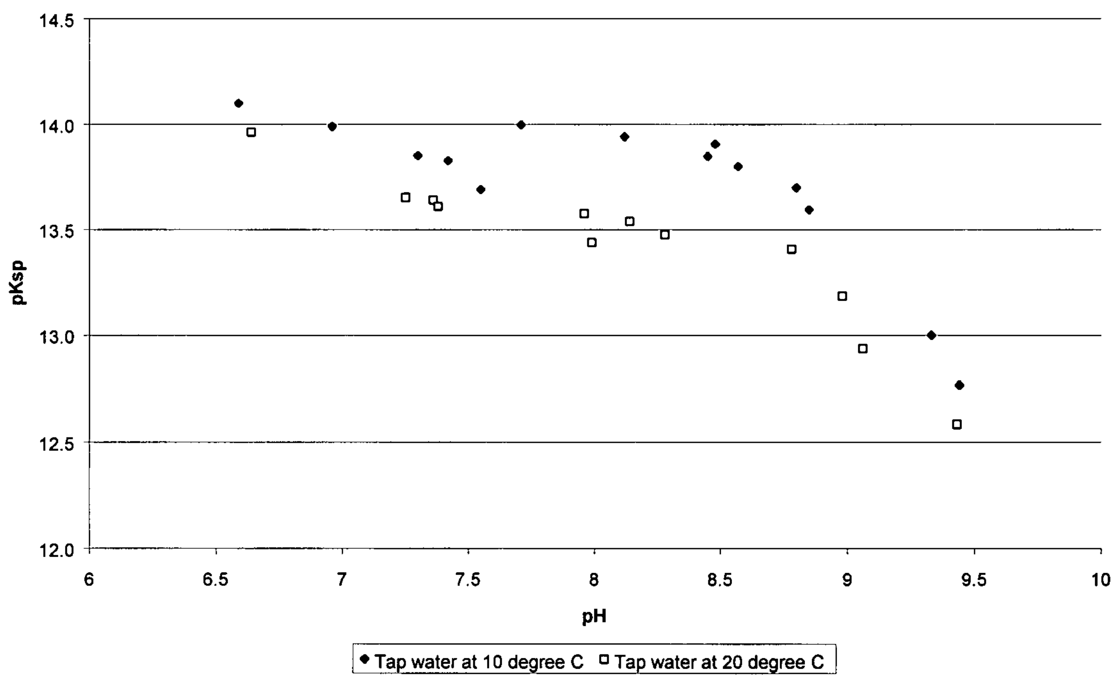

Figure 4.22: Struvite solubility product in tap water vs. sample pH

Figure 4.23 also shows the effect of temperature on struvite solubility. Struvite was found to be less soluble at 10°C than at 20°C, for both tap water and synthetic supernatant. These results are in agreement with the work done by Borgerding [27], who reported that struvite was less soluble at lower temperatures. For synthetic supernatant curve at 20°C, Equation 14 describes the polynomial curve. The curve fits the data with a R^2 value of 0.997, indicating it as an accurate representation of equilibrium conditions.

$$pPs = -0.0165\ pH^4 + 0.5142\ pH^3 - 6.3656\ pH^2 + 37.662\ pH - 81.447 \quad \ldots\ldots(14)$$

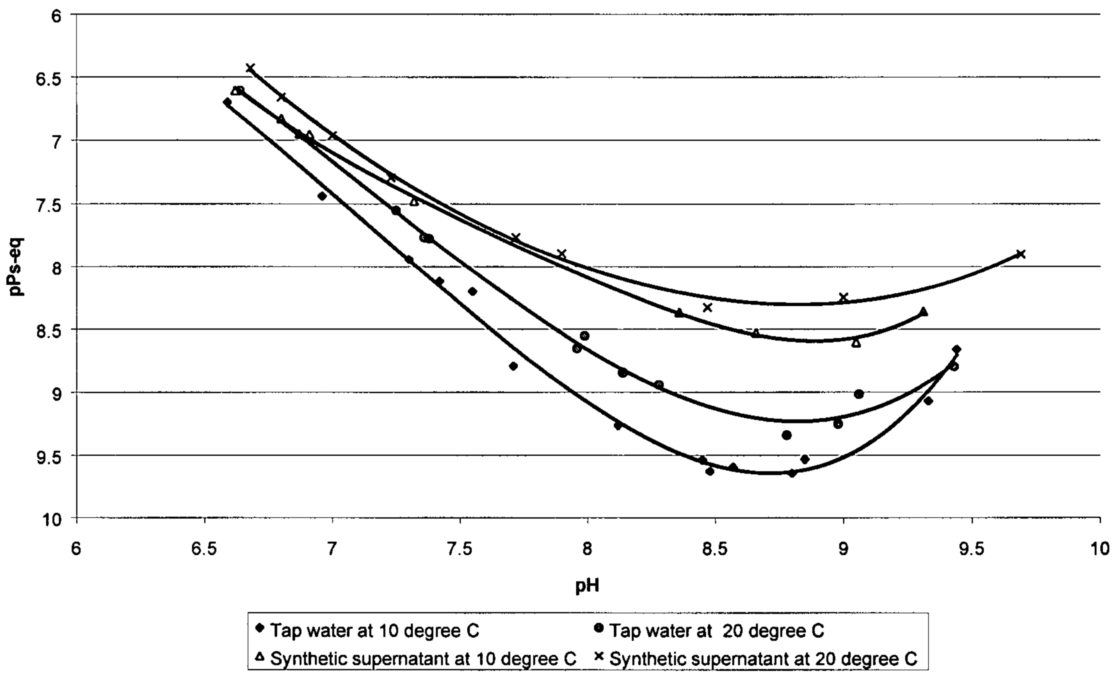

Figure 4.23: Struvite pPs curves for synthetic supernatant and tap water at 10°C and 20°C

Equation 15, describes the polynomial curve for synthetic supernatant at 10°C. The curve fits the data with a R^2 value of 0.999.

$$pPs = -0.1029\, pH^4 + 3.1552\, pH^3 - 36.363\, pH^2 + 187.61\, pH - 359.53 \qquad (15)$$

In this work, the curves developed using synthetic supernatant were used to evaluate the saturated conditions of the process fluid. For the experiments conducted between July 31st, 2001 and October 30th, 2001, the curve developed at a temperature of 20°C was used. For the experiments conducted between March 18th, 2002 and May 25th, 2002, the curve developed at a temperature of 10°C was used. The temperature of the feedwater in the reactor was monitored once daily. Since the reactor was not maintained at a constant temperature, the recorded temperature reflected the ambient temperature at the time of its recording only. However, curves developed at 10°C and 20°C closely represent the actual temperature of the process fluid. The problem of varying temperatures would probably attenuate, when using digester supernatant with an in-house P-recovery reactor. Detailed calculations and data for the calculation of solubility product values and conditional solubility curve can be found in Appendix F.

4.3 Characterization Of The Harvested Product

One of the main objectives of this work was to bridge the gap between removal and recovery. The size and the hardness of the harvested product are the key components towards bridging this gap. Very fine crystals are likely to be washed out in the effluent, and even if they stay in the reactor, they would cause more problems in harvesting than the larger diameter crystals. Therefore, the targeted crystal size for this study was greater than 2mm.

Figures 4.24 to 4.26 show the mean size of the harvested crystals during the entire course of study. It can be seen from these figures that the targeted crystal size of 2 mm was successfully achieved. In general, it was observed that the bigger crystals had more structural strength than the smaller ones. During Run 2 (Figure 4.25, Reactor B) and Run 3 of the experiments, there seem to be some sort of steady state in terms of the mean crystal size. However, during Run 3 (Figure 4.26), there was a decrease in the mean crystal size can be attributed to the variable operating conditions, which are discussed in the following sections. It has been shown that several complete reactor volumes of crystals must be harvested before a steady state crystal size will be reached [67]. Therefore, further studies of longer term, under consistent operating conditions, would be necessary to determine the final steady state size of struvite crystals.

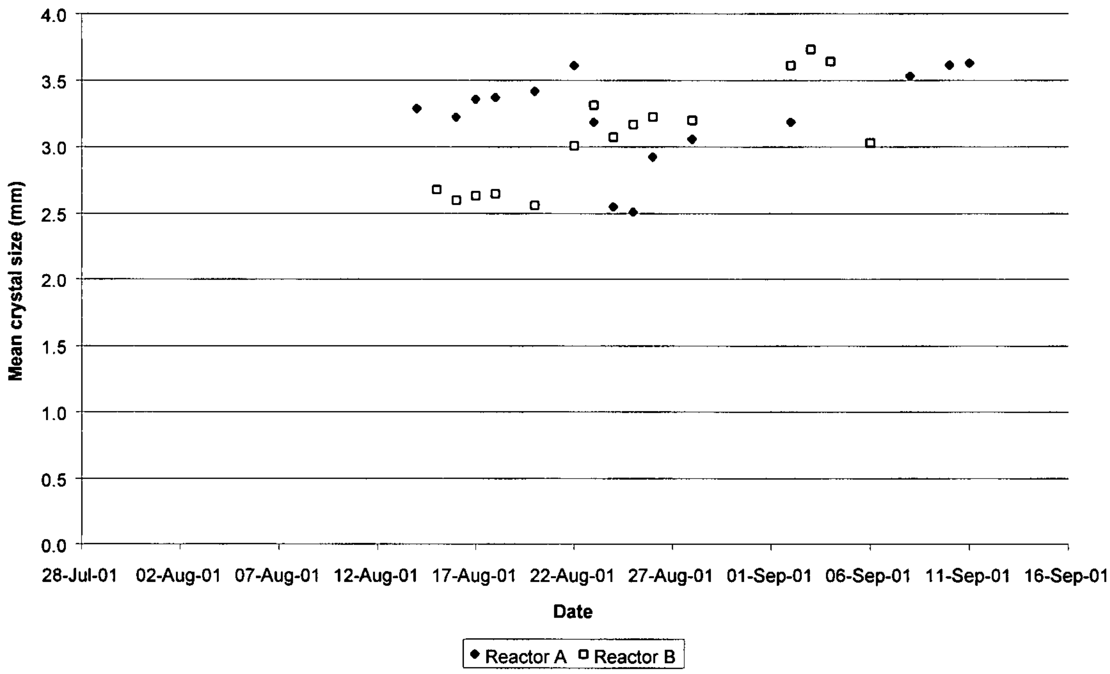

Figure 4.24: Mean crystal diameter harvested (Run 1)

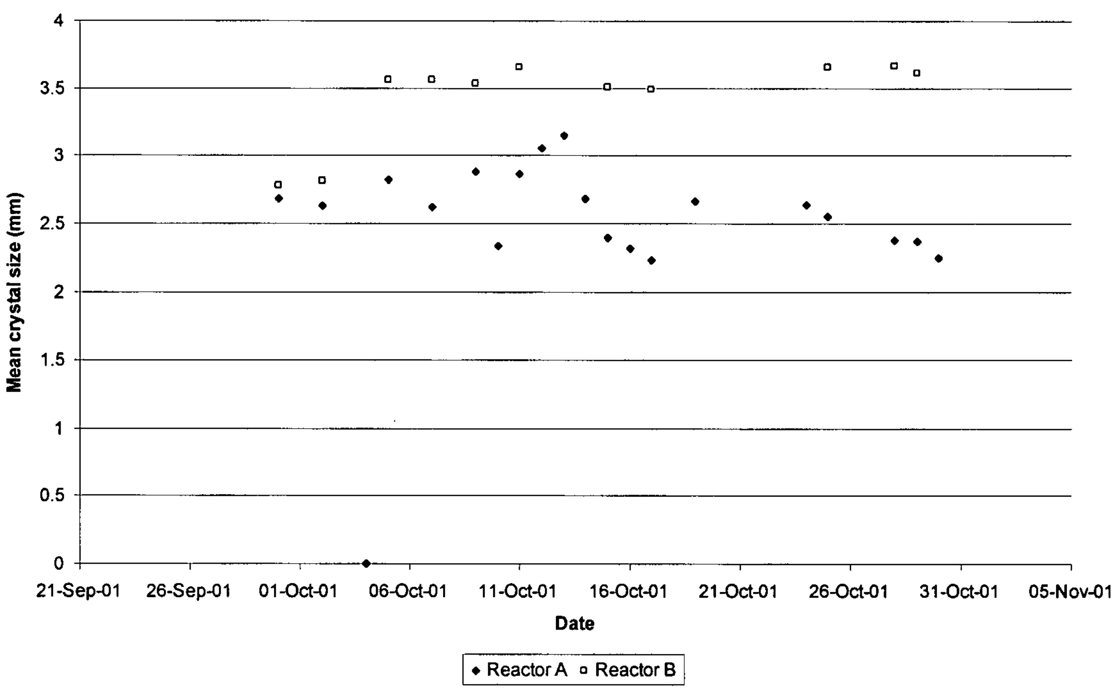

Figure 4.25: Mean crystal diameter harvested (Run 2)

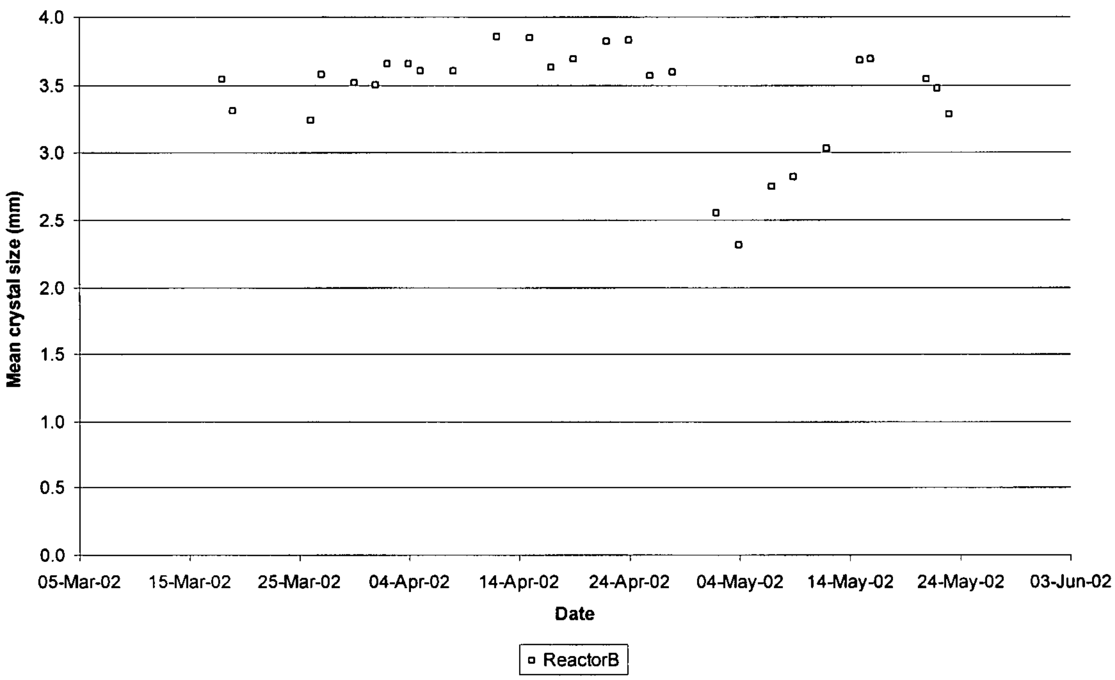

Figure 4.26: Mean crystal diameter harvested (Run 3)

4.3.1 Factors affecting mean crystal size

In-reactor supersaturation ratio

A balanced chemistry is a prerequisite for growing good, harvestable crystals. The saturated condition of the solution has a major effect on the mean crystal size. It is known that when the solution saturation levels are high, the rate of primary nucleation is corresponding high; this which would, in turn, result in the formation of many tiny crystals, within 5 seconds. This would also result in the rapid exhaustion of ion concentrations, leading to reduced crystal growth [5]. In this study, the in-reactor supersaturation ratio was used to define the boundaries of the metastable zone, where the undesirable occurrence of spontaneous nucleation is avoided to a large extent. There are two problems related with the formation of spontaneous nucleation. Firstly, the crystals cannot grow big and secondly, when the rate of spontaneous nucleation reaches a high level, the system gets plugged. In order to asses the impact of in-reactor supersaturation ratio on the mean crystal size, the average of the in-reactor supersaturation ratio of the CRT of the harvest is taken. In this study a trend in the decrease of the mean crystal size was observed, when the "CRT averaged" in-reactor supersaturation ratio was 2.5 or higher. This is shown graphically in Figure 4.27. This might also explain the decrease in mean crystal size from 3.6 mm to 2.6 mm in Figure 4.26. The decrease could be due to the increased "CRT averaged" in-reactor SS ratio, since CRT, which is the other main variable affecting the mean crystal size, was almost the same during that operational period. There is an outlier in Figure 4.27, which is attributable to human error because there was only one incident when the "CRT averaged" in-reactor SS ratio was over 2.6 and crystals of over 3.5 mm mean size were harvested.

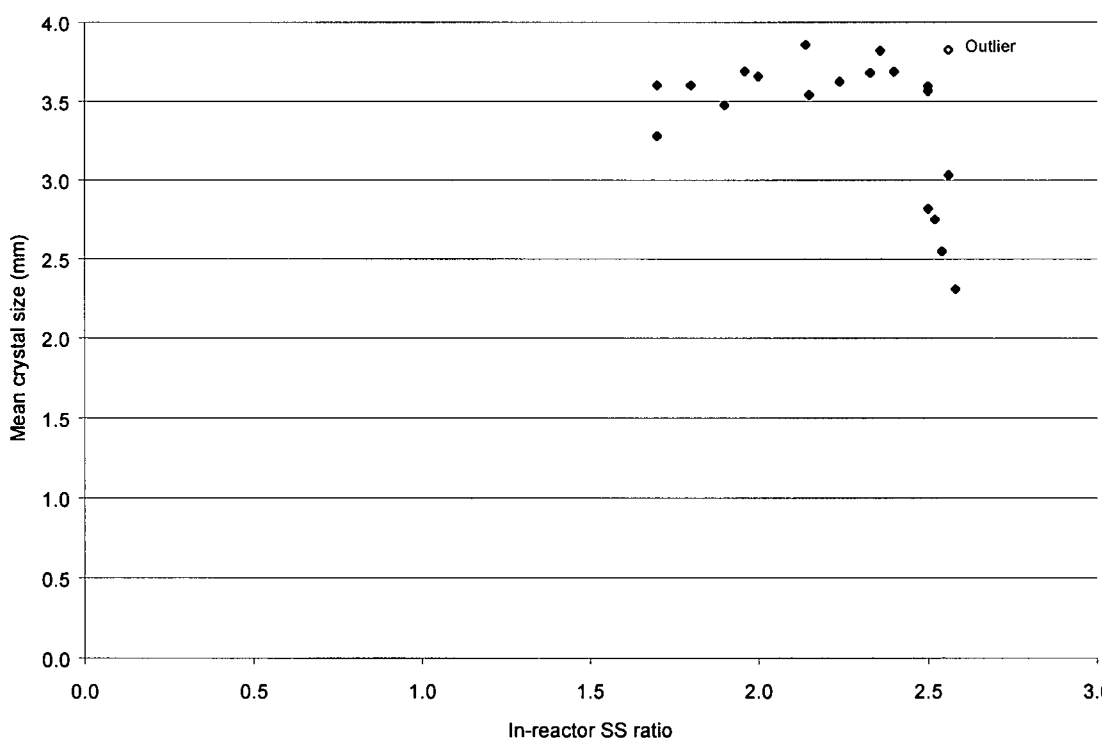

Figure 4.27: Mean crystal size vs. averaged CRT in-reactor SS ratio (Run 3, Reactor B)

Mean crystal size mainly depends on the in-reactor SS ratio as well as the CRT. In this study, it was possible to harvest crystals with mean sizes of over 3.5 mm, when the "CRT averaged" in-reactor SS ratio remained between 1 and 2.5. It is noteworthy that, working with "CRT averaged" in-reactor SS ratio of more than 2.5, did not result in the inferior quality crystals, in terms of harvestability. The only observation made was that if the "CRT averaged" in-reactor SS ratio was over 2.5, the crystals didn't grow over 3 mm of mean size, however their structural strength was almost the same. Results of this study showed that the reactor could handle the in-reactor SS ratio of about 5, without encountering serious plugging problems. However, the maximum "CRT averaged" in-reactor SS ratio of 3.1 was tested in this work. Even at this value, crystals were still harvestable. Working at a higher in-reactor SS ratio would result in higher struvite loading rates, which in turn, could have an economic impact at a full-scale application. In order to find the optimized "CRT averaged" in-reactor SS ratio, further studies are recommended. It would be worth exploring the maximum limits of "CRT averaged" in-reactor SS ratio, where crystals produced are good enough for harvesting.

Crystal retention time (CRT)

When ideal conditions are provided (in terms of balanced chemistry), good MAP crystal growth can be achieved, provided that crystals spend sufficient time in the reactor. It is now clear from the discussion in the preceding section, that CRT is not the *only* important factor in determining the final size of the harvested crystals. The combination of CRT and the in-reactor SS ratio are the two important parameters, which would govern the final size of the harvested crystals, to a large extent.

During Run 3 of the experiments, there were about 21 days, when the reactor was not working, either due to plugging, or equipment malfunctioning. However, it is assumed that, on those days, the reactor had run for at least half of the day, before plugging started. This is accounted for in the calculations of CRT. Figure 4.28 and 4.29 show the mean crystal size versus the CRT. There was a linear increase in the mean crystal size with an increase of CRT, as shown by Figure 4.28 (Reactor B). This trend is very much likely to occur once the favourable operating conditions, for crystal growth, are kept constant, since crystal growth would continue indefinitely in the systems (which are continuously reloaded with struvite constituents [5]). Figures 4.28 (Reactor A) and 4.29 show a decrease in mean crystal size, at a same or higher CRT. This could be due to the increased "CRT averaged" in-reactor SS ratio, as has been explained in the previous section. In Figure 4.28 (Reactor A) for example, at a CRT of 12 days, there are three different values for the mean crystal size. At these points, the progressive decrease in the mean crystal sizes (3.2 mm, 2.4 mm, 2.2 mm) corresponds to the increased "CRT averaged" in-reactor SS ratios (1.8, 2.9, 3). In addition to the in-reactor supersaturation ratio, there are some other factors including feed composition, operating pH, harvesting frequency and struvite loading rates, which could have resulted in the variation of mean crystal size at a same CRT. For example, higher struvite loading rates can result in higher crystal growth rates, and consequently less time would be required for the crystals to attain a given mean size.

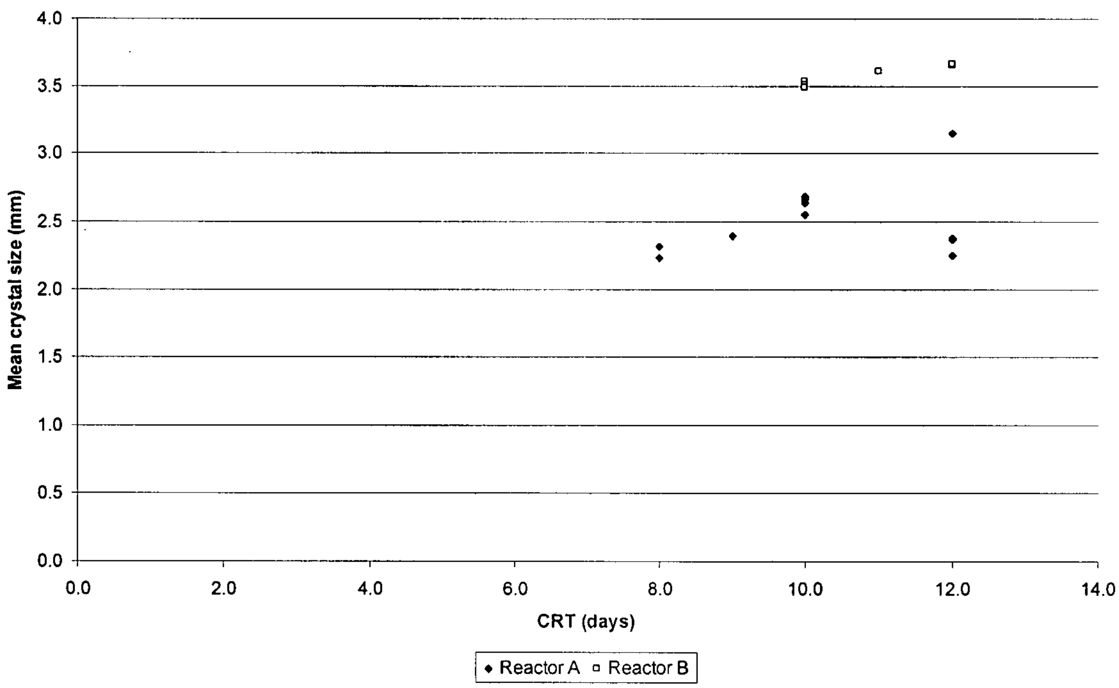

Figure 4.28: Mean crystal size vs. CRT (Run 2)

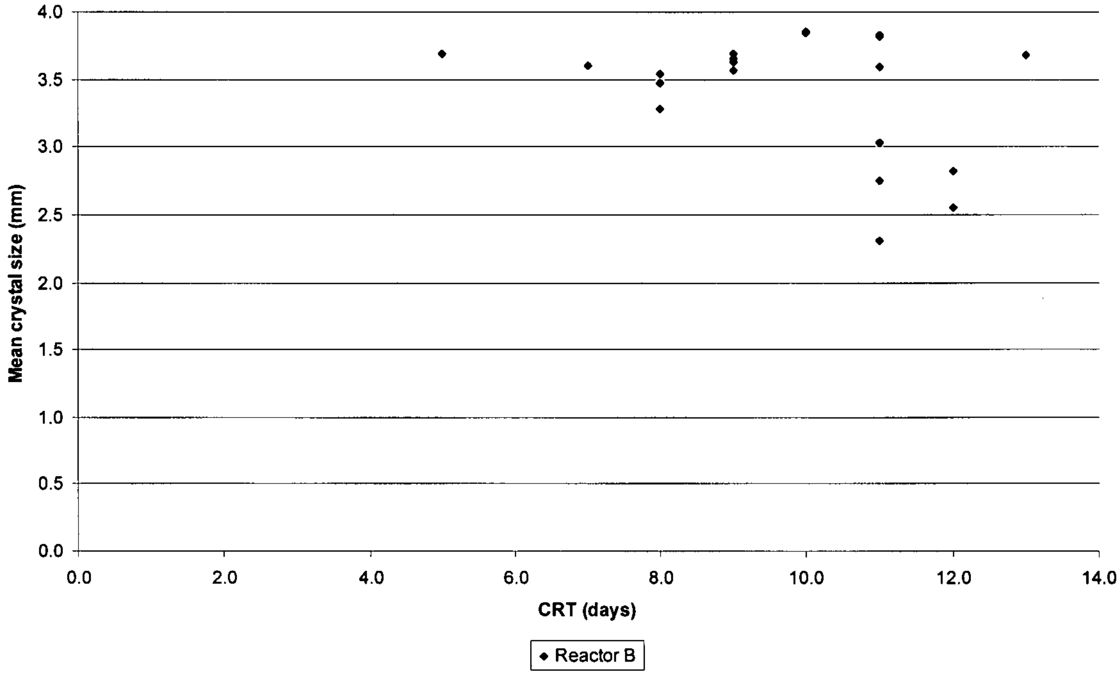

Figure 4.29: Mean crystal size vs. CRT (Run 3)

In summary, the results obtained during this study give an indication of the pair- impact of CRT and in-reactor SS ratio on the mean crystal size. However, two or three CRT's are required to be harvested in order to evaluate the exact impact of a given CRT on mean crystal size. This should be achieved by keeping the other operative parameters (operating pH, in-reactor SS ratio, the harvesting frequency and struvite loading rates) constant. The results presented in this work should, therefore, be considered as preliminary only.

4.4 Application Of Solubility Criteria As A Process Control Parameter

The importance of the metastable region in the process of crystallization has already been outlined in Section 2.9. Knowledge of the width of the metastable region is crucial in crystallization processes, as it aids in understanding the nucleation behaviour of a system. The desired process control of crystallization can only be achieved in the metastable region, since this is the region, wherein the occurrence of undesirable, spontaneous nucleation is reduced to a great extent. Applying solubility criteria as a process control parameter is even more important for the systems where seed materials are added only at the beginning of a run, while the process has to become self-seeding later on. This is due to the fact that if the supersaturation is too low, nucleation and subsequent growth cannot take place; this might result in subsequent failure of the on-going process, due to the lack of seed material. Another disadvantage of working at a very low SS ratio is the corresponding low struvite loading rates. On the other hand, if the supersaturation ratio is too high, the formation of numerous nuclei (due to spontaneous nucleation) in the solution *can* eventually plug the reactor. It was, therefore, desirable to operate the reactor in a way, that there was some sort of balance between nucleation and crystal growth; this resulted in no reseeding requirement for the reactor, for an already ongoing crystallization process. Therefore, it was imperative to establish a range of in-reactor SS ratio values, at which the system responded well in terms of both process efficiency and harvested product quality.

Figures 4.30 and 4.31 represent the conditional solubility curve. For Run 2 (Reactor A) and Run 3 (Reactor B), pP_s of the process fluid inside the reactor ($pP_{s\text{-}ins}$), which is calculated by combining the struvite constituent ions concentrations in the feed and the effluent stream, is plotted on the curve.

The data points representing $pP_{s\text{-}ins}$ lie above the solubility curve in Figures 4.30 and 4.31. This would mean that the conditions inside the reactor were supersaturated. The plot and observations during the experiments suggest that the working window for $pP_{s\text{-}ins}$ at the pilot-scale is very narrow. Figure 4.31 shows that in the experimentally found metastable region, the upper limits generally correspond to the in-reactor SS ratios of 5. Working beyond the metastable region always resulted in plugging of the reactor. With an appropriate degree of recycle ratio, the process conditions remained in the metastable region. Results and observations suggest that, when the in-reactor SS ratio was between 2 and 3, the system performance, in terms of both efficiency and crystal quality, was at its best. Operating within this range resulted in minimal reactor maintenance and intervention and the system never failed, due to the lack of seed materials.

Advantages of using solubility criteria as a process control parameter

There are several potential advantages of applying solubility criteria as a process control parameter. The main advantage is that the boundaries of metastable region, in terms of the in-reactor SS ratio, can be defined. Operating in the metastable region is the *single* most important factor, which can ensure smooth operation of a crystallization process. Using solubility criteria as a process control parameter helps in understanding the real driving force behind the process of crystallization, which is the saturated condition of the process fluid. This concept highlighted the fact that it was not always necessary to raise the operating pH to higher values, in order to optimize P-removal. The results of this study revealed that it was possible to achieve over 90% P-removals at a pH of 7.3 (Section 4.1.1). Another advantage of using solubility criteria, as a process control parameter, is that the equilibrium model can be used, which predicts the effluent concentrations of struvite constituent ions. This *can* facilitate in the optimization of the process conditions. The use of solubility criteria provides flexibility to operate the system, as a desired percentage of phosphate removal can also be achieved by the magnesium dosage manipulation.

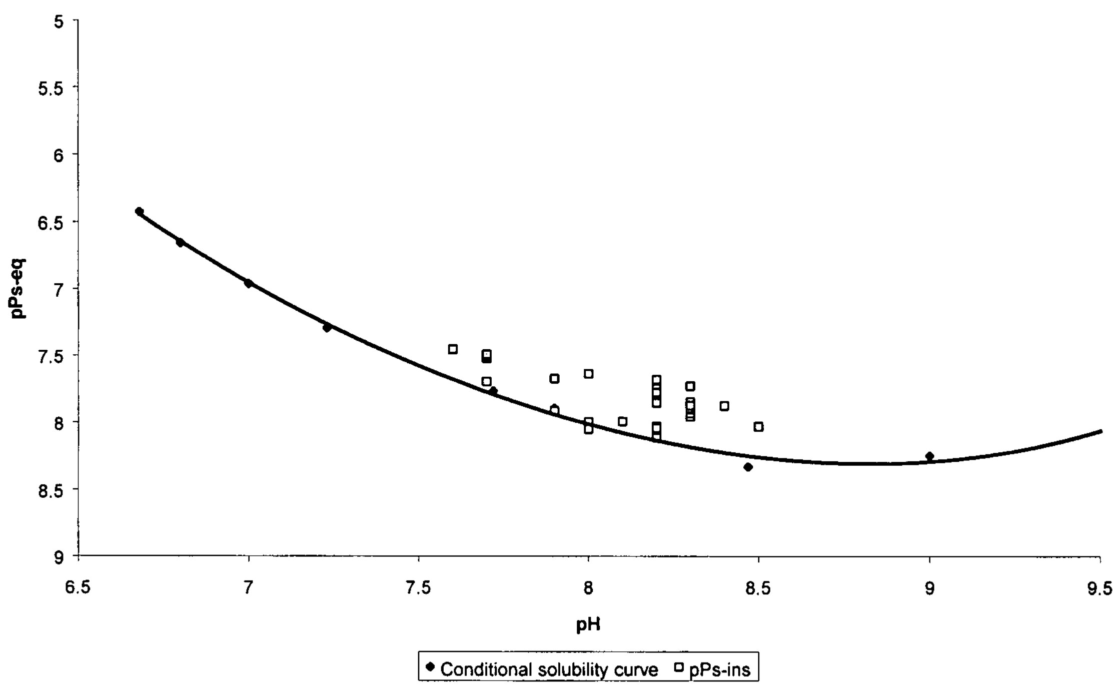

Figure 4.30: pPs versus pH plot (Run 2, Reactor A)

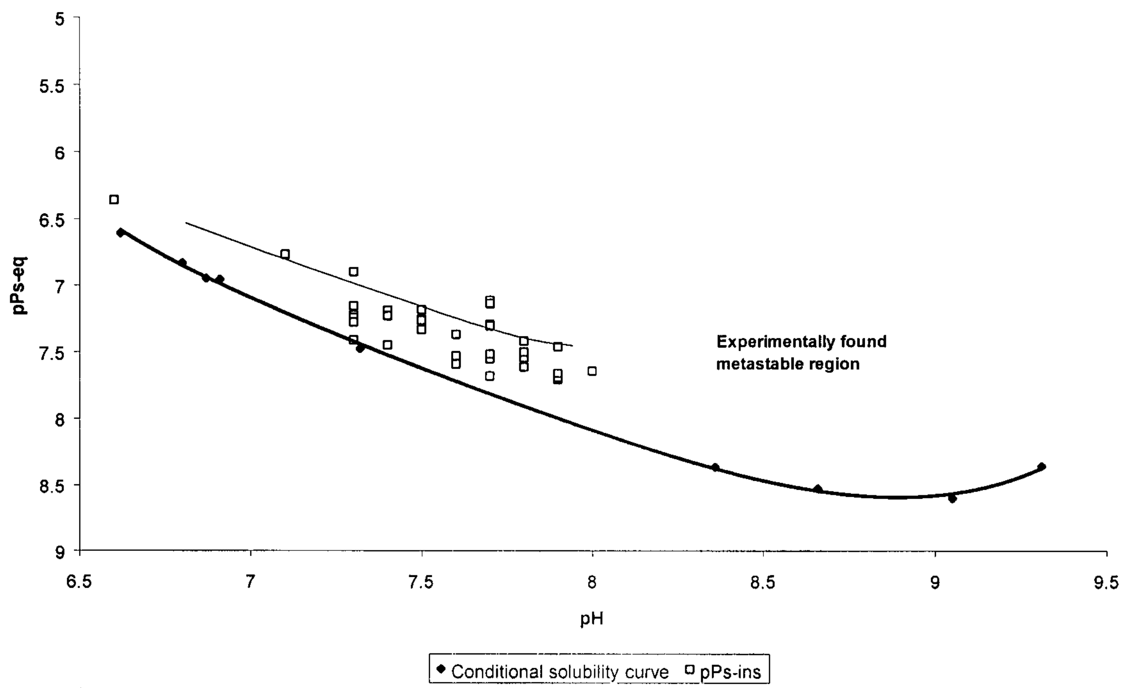

Figure 4.31: pPs versus pH plot (Run 3, Reactor B)

4.5 Scanning Electron Microscopy (SEM) Crystal Examination

During the entire course of study, crystals of various size and shape were harvested. In this section, SEM analyses of two types of crystals are presented. The first type represents softer crystals, which were harvested on 28th August, 2001 from Reactor A. The second type represents very hard crystals, which were harvested on 20th April, 2001 from Reactor B. Although for both the harvests there was not much difference in the mean crystal size, the hardness was significantly different. The crystals, which were harvested from Reactor A, were very soft and were easily broken, whereas the crystals from the other harvest were very hard and round. The two types of crystals were different in colour as well; the softer crystals were yellowish in colour, whereas the harder crystals were almost white. Figure 4.32 shows the comparison between these crystals, under 45X and 300X magnification, respectively.

It is clear from Figure 4.32 that the morphology of the two crystals is significantly different. Crystals harvested from the Reactor A, seem to be a loose aggregation of needle-like crystals. In the 300X magnification it shows some orthorhombic and rod like crystals as well. Figure 4.33 shows the SEM images of the broken crystals. For the crystals harvested from the Reactor A, the image of the soft broken crystal in Figure 4.33 (left), at 300X magnification shows some thin plates as well, but uniform needle like crystals are dominant. The cores of soft crystals appear to be weaker and less densely packed. On the contrary, the hard crystals from Reactor B consist of tightly aggregated crystals. The most striking feature is the roundness of these crystals. Close examination at 300X magnification in Figure 4.32 (bottom right) reveals that the crystals are fragmented aggregation of very fine and fused crystals. Figure 4.33 (right) shows that the inner core of harder crystals, in fact, consist of orthorhombic, wedge and bricked like crystals, which are solidly packed together. However, the edges of these crystals are bordered by the aggregation of very fine crystals. The edges of the hard crystals consist of slurry of aggregates. Figure 4.34 shows the SEM analysis of outer edge at 300X magnification, for the crystals harvested from the Reactor B. It is visible that the wall is an aggregation of extremely fine crystals, the shape of which is hard to identify even at this high magnification. The structural strength of the hard crystals seems to come from the tightly packed inner core, and outside thick coating of fine aggregates.

Struvite is a complex mineral which is known to have a number of natural morphological forms including coffin, short, prismatic, or short tabular forms [49]. Operating conditions have a strong influence over the morphology of struvite crystals. Since the operating conditions during the entire course of study were consistently changing, therefore, the morphology of the struvite crystals was expected to change as well. SEM analysis of these crystals shows that all the crystals are, in fact, aggregates of smaller crystals. Aggregation relates to the binding of particles as a consequence of collisions among them while in suspension. Inter-particle collision may result in permanent attachment if the particles are small enough for van der Waals' forces to exceed the gravitational forces, a condition that generally applies for sizes $< 1\mu m$ [51]. This implies that very fine particles were produced in the reactor, which eventually aggregated. The chances of forming very

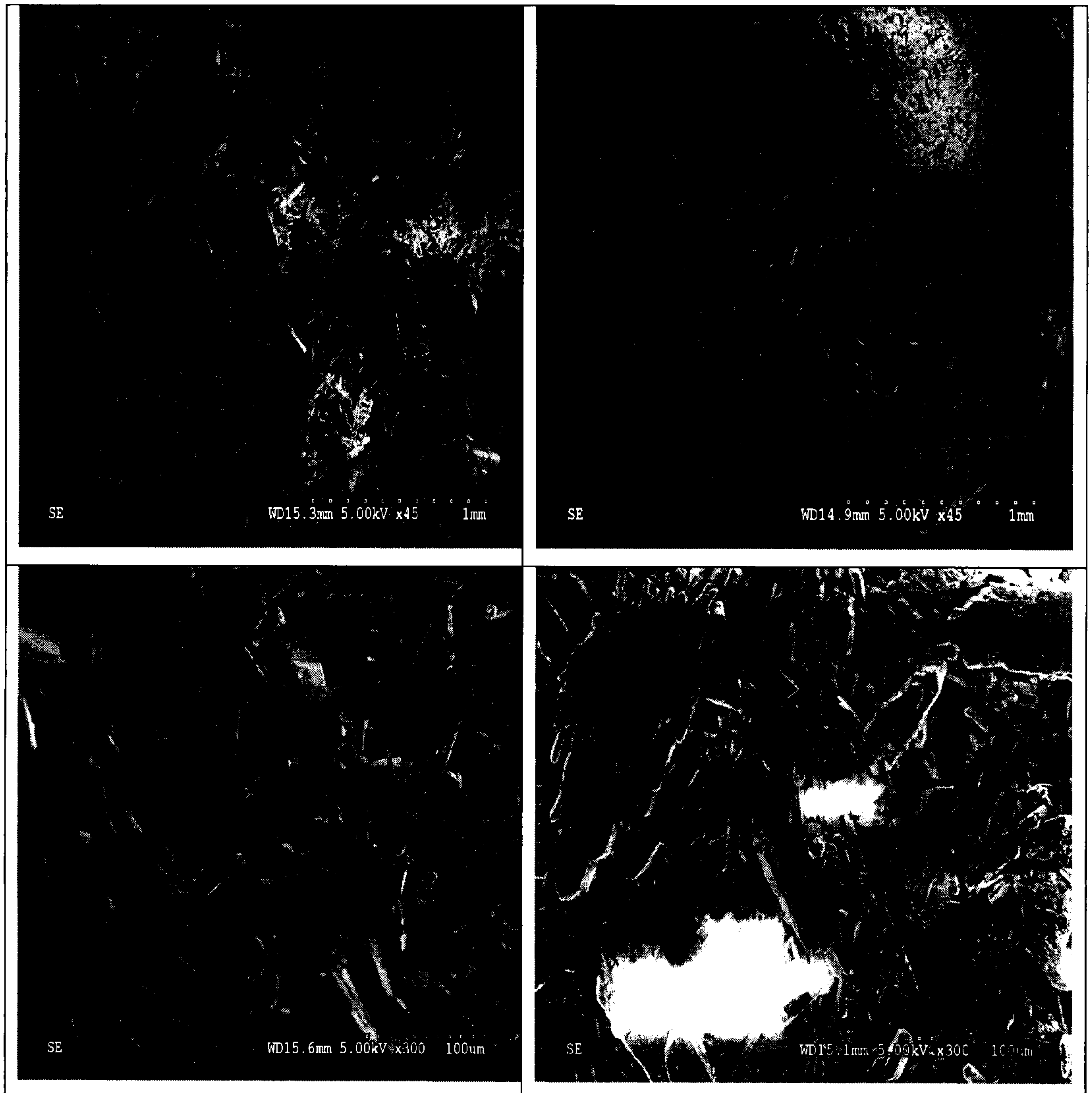

Figure 4.32: Comparison between soft and hard crystals (SEM images). Top left: harvested October 28, 2001 from Reactor A (45X magnification); Bottom left: harvested October 28, 2001 from Reactor A (300X magnification); Top right: harvested April 20, 2002 from Reactor B (45X magnification); Bottom right: harvested April 20, 2002 from Reactor B (300X magnification)

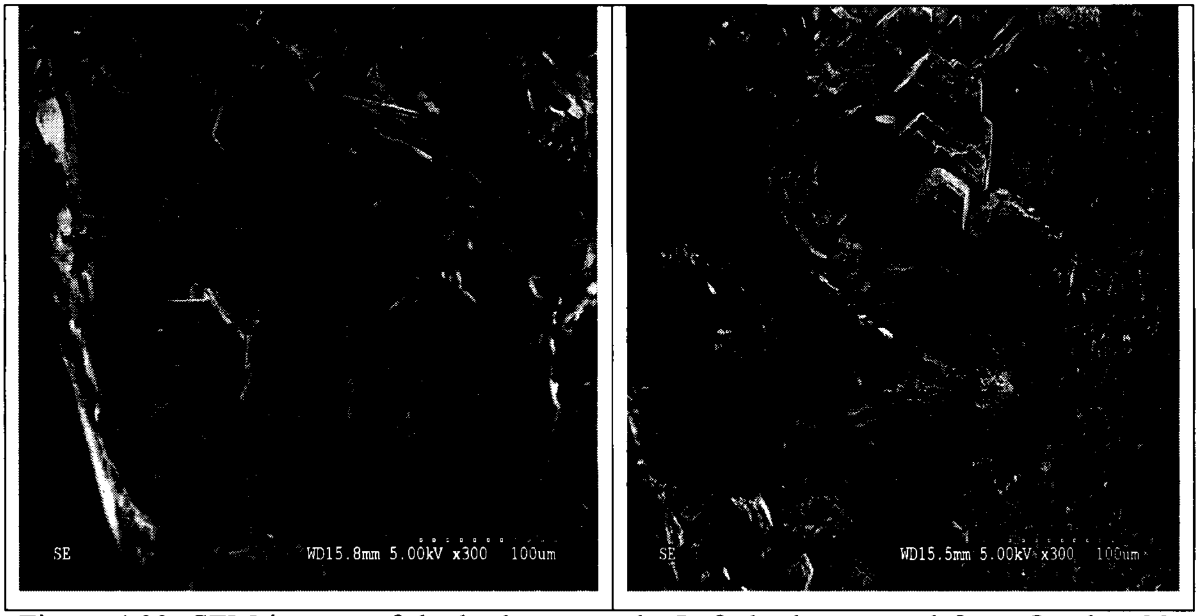

Figure 4.33: SEM images of the broken crystals. Left: broken crystal from October 28, 2001 harvest from Reactor A (300X magnification); Right: broken crystal from April 20, 2002 harvest from Reactor B (300X magnification).

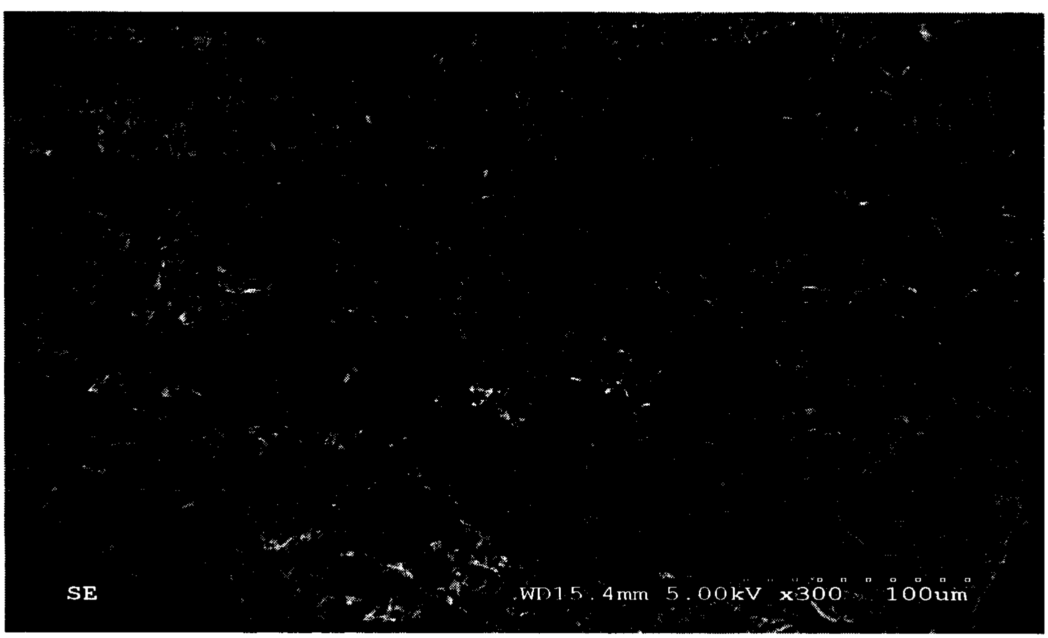

Figure 4.34: SEM image of outer edge (crystal from April 20, 2002 harvest, Reactor B, at 300X magnification)

fine particles exist, if the supersaturation of the solution is high. This shows that, in the reactor, there were pockets of high supersaturation ratios. This could occur at the injection point of magnesium and caustic dosing, since N and P feed was mixed with treated effluent, prior to the metering into the reactor. There could possibility be a surge in the supersaturation ratio, at the point where magnesium and caustic were introduced; which might had resulted in the formation of very fine crystals and those fine crystals eventually aggregated.

The soft crystals, which were harvested form Reactor A, were had a CRT of seven days. The time the crystals spend in the reactor under ideal growing conditions, can be a determining factor, in gaining the structural strength. Immature, high porosity aggregation of soft crystals, seem to be the result of insufficient stay in the reactor, since with similar operating conditions (pH, feed strength, etc), but with longer CRT, hard crystals were harvested in the month of August.

The most striking thing, which the SEM images revealed, was the outer coating of slurry, in the crystals harvested in the month of April. During the entire course of Run 3 of the experiments, very hard crystals were harvested. The exact reason for this unusual change in crystal morphology is not clearly understood. However, one of the reasons might be the higher magnesium concentration, which was applied during Run 3 of the experiments. One study suggested that aggregation may be favoured at higher magnesium concentration [68]. However, future studies are required in order to know the exact cause of this coating.

SEM images reveal that the increase in the crystal size was not due to molecular growth, which was hypothesized initially. During this study, fines-fines aggregation has most *likely* occurred. Therefore, an understanding of the aggregation process is warranted for a better control on the desired size and hardness of the harvested product.

4.6 Struvite Recovery

In order to confirm that the phosphate being removed was in fact being recovered, for Run 3 (Reactor B), the dry weight of each harvest was recorded, and the final dry weight of struvite in the reactor was recorded at the end of the run. The actual mass of struvite was then compared with theoretical mass of struvite that should have formed, based on the quantity of phosphate removed. There were some losses during the process of harvesting, drying, transferring and sieving. In addition, other losses were due to the accumulation of fine struvite, at the bottom of the external clarifiers; these losses are, however, not accounted for, in the calculations below. Table 4.4 shows the comparison of theoretical struvite production and actual struvite recovery, for Run 3 (Reactor B).

Table 4.4 shows that about 81 percent of the phosphate removed from the synthetic feed was being recovered. Unfortunately, there were 21 days in Run 3 of the experiments when the reactor was not working (either due to plugging or equipment malfunctioning). However, it was assumed that, during those particular days, the reactor had run for at least half of the day, before plugging started. To account for those days, the half of the average theoretical struvite production of the entire run is multiplied by 21. In reality, the percentage struvite recovered can be higher or lower than the above stated number. Nevertheless, it can be confidently concluded that most of the phosphate removed was being recovered in the form of harvestable product. Better and careful control in the harvesting, drying and sieving procedure can potentially increase the percentage struvite recovery.

Table 4.4: Comparison of theoretical struvite production and actual struvite recovery

	Reactor B
Total weight of seed added at the start up (kg)	2.5
Total weight of struvite harvested (kg)	14.3
Total struvite recovered (kg)	11.8
Theoretical struvite production (kg)	14.5
% Struvite recovered	81

4.7 Model Application

4.7.1 Model description

Britton [69] developed an equilibrium model, which can predict the effluent magnesium, ammonia and ortho-phosphate concentrations from a struvite crystallizer reactor such as the one used in this study. The model inputs are the operating pH of the reactor, as well as magnesium, ammonia and ortho-phosphate concentrations in the combined feed to the reactor. The model assumes that pure struvite is being formed, and that the reactor effluent is at equilibrium, with respect to struvite.

Equation 16 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 16. 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.

$$([Mg]_{in} - \Delta)([PO4]_{in} - \Delta)([NH_4]_{in} - \Delta) = P_{seq} \quad (16)$$

Care should be taken in using this model, since P_{seq} is case specific. Therefore, a P_{seq} curve, which was generated to evaluate various operating parameter for this study, was used in Equation 16. The model was not available before or during the study; however, the model was validated using pilot-scale, study results.

Figures 4.35 to 4.37 show the comparison of the model results to the measured effluent concentrations for Run 2 (Reactor B). The detailed model calculations and the analysis of the model results can be found in Appendix G. In general, the results predicted by the equilibrium model matched closely with the actual pilot-scale results, as shown by the following figures. However, Figure 4.36 shows that the model "over-predicts" the ammonia concentration. This was expected, since the effect of ammonia stripping, which

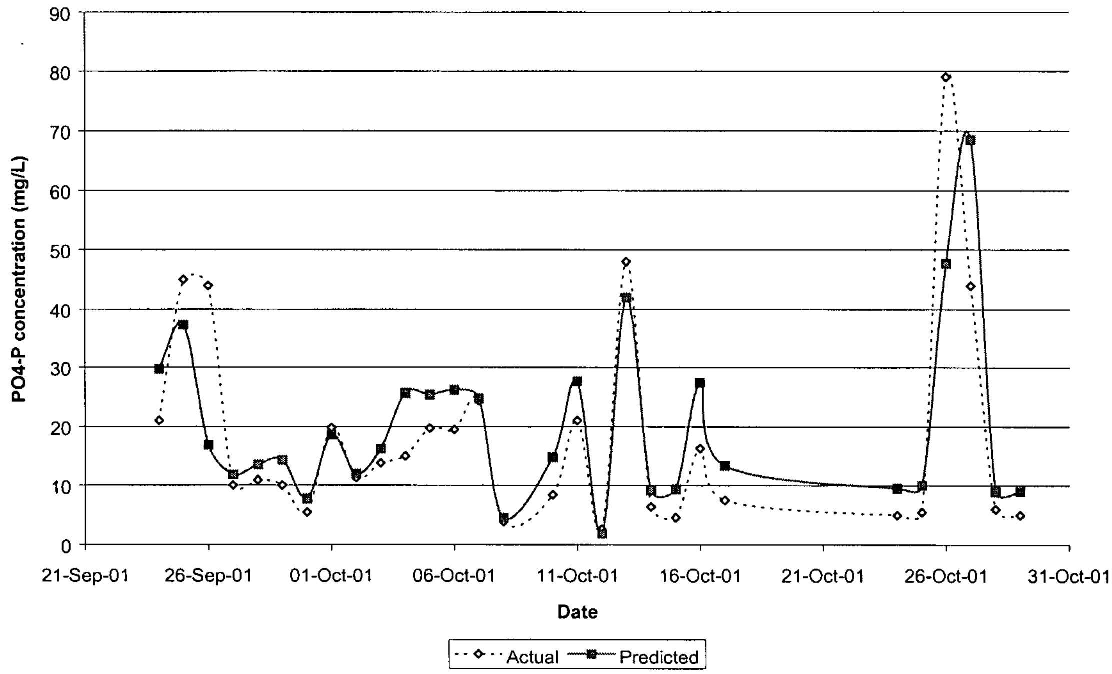

Figure 4.35: Modeled and actual effluent phosphate concentration

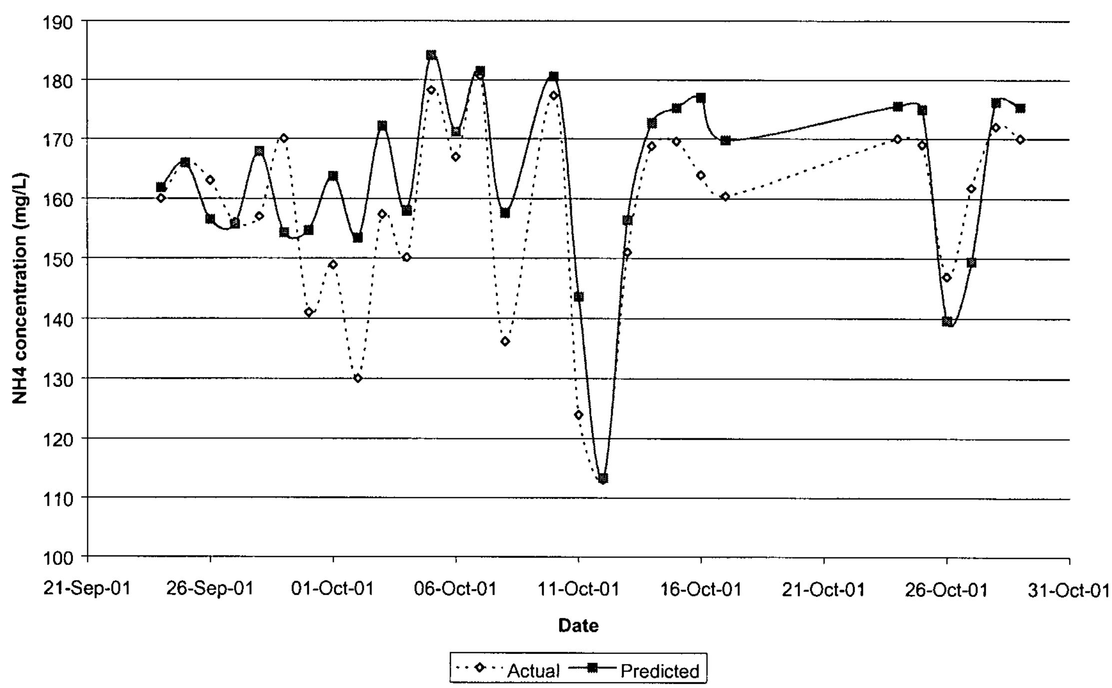

Figure 4.36: Modeled and actual effluent ammonia concentration

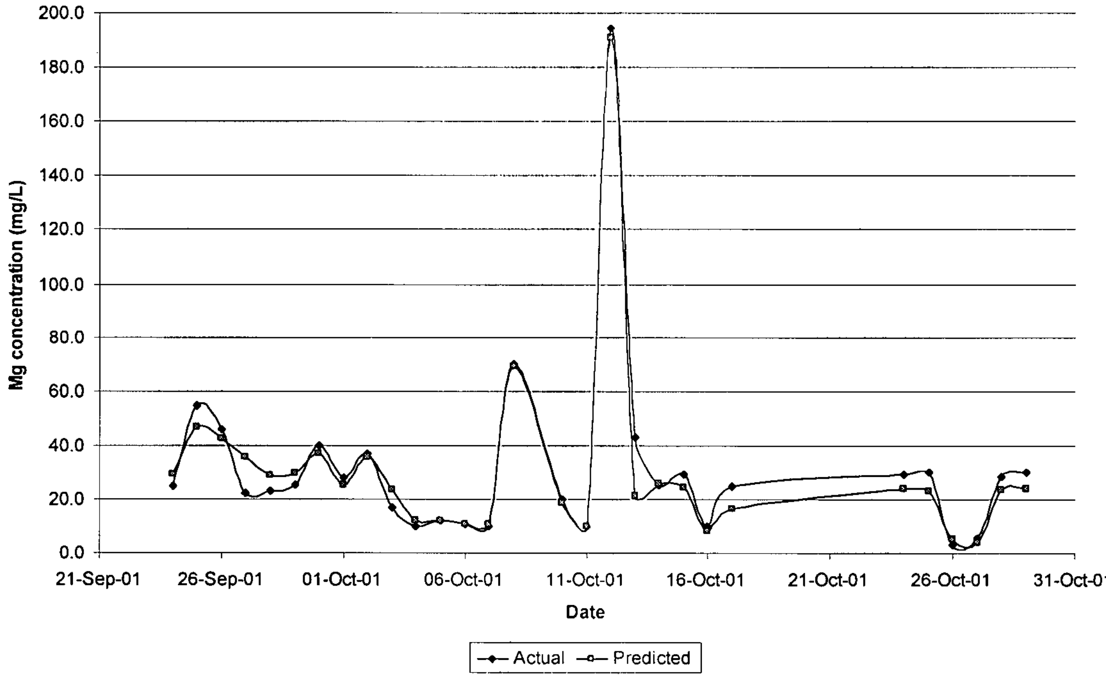

Figure 4.37: Modeled and actual effluent magnesium concentration

is most likely to occur especially at higher pH values, is not incorporated into this model. However, the model's application can still be quite useful and effective in struvite crystallization. For a given feed strength at a given pH, an expected knowledge of effluent concentrations would allow the operator to use an appropriate degree of recycle ratio to ensure that the process conditions remain in the metastable region of crystallization.

CHAPTER 5 - CONCLUSIONS

The following conclusions are drawn, based on the presented work at the pilot-scale from UBC MAP Crystallizer reactor operation.

- The pilot-scale UBC MAP Crystallizer was effective in recovering phosphate from synthetic feed.

- Over 90% of ortho-phosphate removal rates were achieved, for a range of influent P concentrations (47 mg/L ~ 220 m/L) tested.

- It is not always necessary to operate the system at a higher pH value. It was possible to achieve over 90% P-removal rates, at a low pH of 7.3. This is contrary to the higher recommended pH values (8.2 ~ 9), found in the literature. This indicates that alkaline pH is not the only factor which can cause the process fluid to be supersaturated.

- About 80% of the phosphate removed was recovered as harvestable struvite crystals. Mean crystal size of over 2 mm was consistently achieved during the entire course of study. Better handling on harvesting, drying and sieving procedures, can potentially increase the above stated percentage.

- Struvite was found to be less soluble at 10°C than at 20°C. Struvite was also found to be more soluble in the synthetic supernatant than in the tap water, most probably due to the different ionic strengths of the solutions.

- Operational control in the metastable zone is the single most important factor in the process of crystallization. For any set of given conditions, operating beyond the metastable region always resulted in the plugging of the reactors. The data collected at the pilot-scale related well to the conditional solubility curve, in the theoretically predicted manner. For the specific wastewater and the reactor, the boundary limits for metastable region in terms of in-let supersaturation ratio were experimentally found. The process efficiency and quality of the harvested product was, at its best, when the in-reactor supersaturation ratio was between 2 and 3, however, the reactor could handle the in-reactor SS ratio as high as 5.

- Limited data showed that magnesium can be also be used a controlling parameter. In order to achieve lower P effluent concentration and to confirm that ortho-phosphate was the limiting ion, a Mg:P molar ratio of 3:1 was used. It resulted in a 90% P-removal rate, at a pH of 7.3.

- Under a given set of conditions, the maximum struvite loading rate of about 770 g/day was applied to the reactors. A further increase in struvite loading rate was still possible, by increasing the total flow rate through the reactor.

- The main factors affecting the mean crystal size of the struvite crystals were found to be the crystal retention time (CRT) and the in-reactor SS ratio. It was observed that when the "CRT averaged" in-reactor SS ratio was over 2.6, the crystal size didn't exceed 3 mm. Under ideal crystal growing conditions, limited data appeared to show a linear increase in mean crystal size with CRT. CRT and the in-reactor SS ratio were not varied independently; therefore, it was impossible to distinguish the effects of these two parameters.

- Scanning Electron Microscopy (SEM) analysis shows that all the crystals were, in fact, aggregates of smaller crystals.

- Predicted results, from the equilibrium model, developed by Britton (69), matched very closely the experimentally found results.

CHAPTER 6 – RECOMMENDATIONS

The following recommendations are made, based on the knowledge gained from the pilot-scale study on struvite recovery from synthetic wastewater.

- In order to evaluate the exact impact of the in-reactor SS ratio on mean crystal size and morphology, longer term studies are required. This should be achieved by keeping the CRT constant.

- It would be useful to determine the optimum CRT, at which the desired target product quality can be achieved. Various CRT's should be evaluated on a longer term basis, by keeping the in-reactor SS ratio constant. To evaluate the impact of a given CRT on mean crystal size, it is also recommended to harvest at least two or three complete reactor volumes.

- The possibility of using magnesium ions as a controlling parameter should further be explored. It is also recommended that a comparison of the costs be made, using pH and magnesium as controlling parameters.

- Further studies with higher fluidization velocities would be useful to determine the minimum reactor volumes and maximum flow rates, which can be achieved without compromising the reactor performance. Higher flow rates can increase the struvite loading rates, which in turn, can have critical economic impact, at the full-scale level.

- With respect to the characteristics of feedwater, the process of P-recovery through struvite crystallization is very site-specific. It is, therefore, recommended that a conditional solubility curve be determined each and every time.

- Before any full implementation is undertaken, it would be desirable to have a better understanding of physical processes operating during the crystallization of struvite. A better understanding of the hydrodynamics within the reactor, with particular reference to flow patterns and shear forces, etc. around the crystals, could be very useful.

- A better understanding of the aggregation process is required, to exercise better control on the desired size and hardness of the harvested product.

- The use of an equilibrium model is recommended, since an expected knowledge of effluent concentration, can allow the use of a desired degree of recycle ratio, to ensure the process conditions in the metastable region.

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APPENDIX A : CALCULATIONS FOR UPFLOW VELOCITIES

Calculations For Upflow Velocities In The Different Sections Of The Reactor; Corresponding To A Flow Rate of 3600 ml/min.

Upflow velocity = Flow rate / cross-sectional area

Table A- 1

Reactor Sections	Nominal diameter (cm)	Cross-sectional area (cm^2)	Upflow velocity (cm/min)
Bottom	4	12.6	286
Middle	5.2	21.2	170
Top	7.7	46.6	77
Top Clarifier	20.2	320.5	11

APPENDIX B : CALCULATIONS FOR REYNOLDS NUMBERS

Calculations For Fluid Reynolds Numbers In Different Sections Of The Reactors; Corresponding To A Flow Rate Of 3600 ml/min At An Ambient Temperature of 25°C

The following equation[1] is used for calculating the Reynolds numbers:

Reynolds number = ρ * **V** * **D** / μ

Where

ρ = Mass density of the fluid

V = Average velocity of the fluid

D = Diameter

μ = Viscosity of the fluid

At a temperature of 25°C, the values[1] of ρ and μ are 997 kg/m^3 and 0.890 $N\text{-}s/m^2$ respectively.

The corresponding Reynolds numbers in different sections of the reactor would be presented as below.

Table B-1

Nominal diameter (m)	Upflow velocity (m/s)	Reynolds number at 25°C
400	286	2139
520	169	1646
770	77	1111
424	. 11	424

[1] From Metcalf and Eddy, Inc. (1991) *Wastewater Engineering Treatment Disposal and Reuse*. McGraw-Hill Series in Water Resources and Environmental Engineering, 1253.

APPENDIX C : INSTRUMENT OPREATIONAL PARAMETERS

Instrument operational parameters for the flame atomic absorption spectrophotometer

Table C-1

Element Analyzed	**Magnesium**
Concentration Units	mg/L
Instrument Mode	Absorbance
Sampling Mode	Autonormal
Calibration Mode	Concentration
Measurement Mode	Integrate
Lamp current	4.0 mA
Replicates Standard	3
Replicates Sample	3
Wavelength	202.6
Range	0-100 mg/L
Flame Type	N_2O/C_2H_2
Calibration Algorithm	New Rational

Instrument operational parameters for the LaChat QuikChem flow injection analysis instrument

Table C-2

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	Ammonium Molybdate	Phenate
Reference	1	2

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

2: APHA, AWWA and WPCF (1995) Part 4500-NH_3- F. Phenate method. *In Standard Methods for the examination of Water and Wastewater,* 19th edition. American Public Health Association, Washington, D.C.

APPENDIX D : DAILY RECORDS FOR ALL RUNS

On the following pages the operating data for the Runs 1, 2 and 3 for Reactors A and B is presented. The days when the Reactors were not in operation, either due to plugging, or equipment malfunctioning, are highlighted.

For the Run 1 and 2, in order to evaluate the equilibrium conditions, conditional solubility curve in synthetic supernatant at 20°C was used, Equation A describing the polynomial curve. For Run 3 conditional solubility curve in synthetic supernatant at 10°C was used, Equation B describing the polynomial curve.

$$pPs = -0.0165\ pH^4 + 0.5142\ pH^3 - 6.3656\ pH^2 + 37.662\ pH - 81.447 \ldots\ldots\ldots\ldots\text{(A)}$$

$$pPs = -0.1029\ pH^4 + 3.1552\ pH^3 - 36.363\ pH^2 + 187.61\ pH - 359.53 \ldots\ldots\ldots\ldots\text{(B)}$$

Sample Calculations

For the demonstration of calculations made in the spread sheet of the daily records, a sample point dated 31st July, 2001 from the Reactor A is taken.

PO_4-P: Calculations for conditions inside the reactor (mg/L)

If the contribution of PO_4-P from the feed tank = Y, then

$$Y = PO_4\text{-P from the feed tank X } \frac{\text{flow rate from the } PO_4\text{-P line}}{\text{total flow rate through the reactor}}$$

$$Y = 71 \text{ X } \frac{670}{3540}$$

Y = 13.4 mg/L

If the contribution of PO_4-P from the recycle line = Z, then

$$Z = \frac{PO_4\text{-P in the effluent sample from the clarifier X recycle flow rate}}{\text{total flow rate through the reactor}}$$

Z = 36.4 X 2820 / 3540

Z = 29 mg/L

Therefore, total PO_4-P inside the reactor = Y + Z, where

Y + Z = 42.4 mg/L

Similar logic applies for the calculations of Mg and NH_4-N conditions inside the reactor.

<u>Calculations for Feed P_s</u>

$$\text{Feed } P_s = \frac{P_{influent}}{MW_P} \text{ X } \frac{N_{influent}}{MW_N} \text{ X } \frac{Mg_{influent}}{MW_{Mg}}$$

where MW = Molecular weight

$$\text{Feed } P_s = \frac{66.1}{31000} \text{ X } \frac{185.2}{14000} \text{ X } \frac{45.1}{24300}$$

$$= 5.3 \text{ X } 10^{-8} \text{ (moles/L)}^3$$

<u>Calculations for In-reactor P_s</u>

$$\text{In-reactor Ps} = \frac{\text{Total } PO_4\text{-P}}{MW_P} \text{ X } \frac{\text{Total } NH_4\text{-N}}{MW_N} \text{ X } \frac{\text{Total Mg}}{MW_{Mg}}$$

$$= 42.4 / 31000 \text{ X } 174.8 / 14000 \text{ X } 29.7 / 24300$$

$$= 2.1 \text{ X } 10^{-8} \text{ (moles/L)}^3$$

Date *Reactor A* *Run 1*	Recyle flow	Temp $^{\circ}$C	Influent Lab results PO_4-P (mg/L)	 NH_4-N (mg/L)	 Mg (mg/L)	Effluent Lab results PO_4-P (mg/L)	 NH_4-N (mg/L)	 Mg (mg/L)	pH
31-Jul-01	3.9		71.0	199.0	650.0	36.4	172.2	25.7	7.5
1-Aug-01	3.9		63.2	177.0	812.0	40.0	155.6	41.8	7.5
2-Aug-01	4.0		61.8	190.0	900.0	36.7	168.0	42.0	7.4
3-Aug-01	4.1		61.8	190.0	900.0	38.3	167.8	44.1	7.4
4-Aug-01	3.8		65.4	177.0	800.0	38.3	155.1	32.9	7.5
5-Aug-01	5.0		70.0	180.9	719.3	46.6	157.0	49.5	7.3
6-Aug-01	5.8		63.7	182.7	717.5	38.3	157.0	53.2	7.4
7-Aug-01	3.8		63.4	181.0	734.3	46.8	164.9	41.1	7.4
8-Aug-01	5.8		58.6	191.7	728.0	27.8	159.0	60.0	7.4
9-Aug-01	3.2		66.6	193.0	800.0	42.6	169.0	45.0	7.4
10-Aug-01	4.9		66.0	193.0	800.0	40.0	168.0	45.0	7.5
11-Aug-01	11.2		66.7	200.0	700.0	35.4	157.4	90.4	7.3
13-Aug-01	5.8		54.7	186.0	650.0	32.8	159.0	41.0	7.5
14-Aug-01	6.0		71.0	199.0	650.0	36.4	167.5	39.7	7.5
16-Aug-01	3.9		67.7	190.0	880.0	42.4	170.0	40.4	7.4
17-Aug-01	6.3		58.3	195.0	850.0	30.7	157.0	52.5	7.4
18-Aug-01	6.6		58.6	190.0	850.0	30.0	156.0	55.9	7.4
20-Aug-01	3.6		58.2	210.0	1000.0	29.3	160.0	36.6	7.5
22-Aug-01	6.0		67.8	181.0	1010.0	19.6	133.0	55.4	7.7
23-Aug-01	6.0		63.7	235.0	1310.0	18.7	131.0	88.8	7.5
24-Aug-01	4.3		62.3	180.0	1020.0	22.2	146.0	42.3	7.6
25-Aug-01	5.3		63.5	183.7	1020.0	20.4	145.0	45.4	7.6
26-Aug-01	5.2		61.8	179.0	1100.0	19.0	147.0	43.6	7.6
27-Aug-01	6.2		68.0	196.5	1300.0	16.0	154.0	53.0	7.6
28-Aug-01	6.0		68.2	197.0	1300.0	16.3	154.0	52.0	7.6
29-Aug-01	5.0		68.0	213.0	1300.0	12.0	140.0	50.0	7.9
30-Aug-01	5.0		68.0	212.0	1300.0	9.0	132.0	42.0	8
31-Aug-01	5.0		68.0	210.0	1300.0	9.6	133.0	41.5	8
1-Sep-01	5.8		58.5	175.0	644.0	11.4	129.0	26.4	8.2
2-Sep-01	8.0		54.6	260.0	1100.0	3.1	170.6	105.0	8.4
3-Sep-01	3.9		60.0	250.0	1307.9	10.0	136.0	42.0	8
8-Sep-01	5.6		66.1	160.0	873.6	6.4	115.0	36.0	8.4
9-Sep-01	5.6		74.9	250.0	1350.0	3.0	200.0	47.0	8.3
10-Sep-01	5.4		68.0	220.0	1000.0	1.5	160.0	69.2	8.6
11-Sep-01	5.6		68.3	220.0	1389.5	5.9	128.0	78.9	8.3
Average	5.3		64.5	198.5	964.7	24.9	153.5	50.1	7.7
Minimum	3.2		54.6	160.0	644.0	1.5	115.0	25.7	7.3
Maximum	11.2		74.9	260.0	1389.5	46.8	200.0	105.0	8.6
St.Dev.	1.5		4.8	22.8	244.4	14.1	16.9	17.4	0.4
Count	35.0		35.0	35.0	35.0	35.0	35.0	35.0	35.0

Date	Removal efficiency (%)			MgCl	Total	N & P	Recycle	Total flow
	PO_4-P	NH_4.N	Mg	Flow	Influent Flow	Influent Flow	Flow	(influent+recycle)
Reactor A	(mg/L)	(mg/L)	(mg/L)	(mL/min)	(mL/min)	(mL/min)	(mL/min)	(mL/min)
Run 1								
31-Jul-01	44.9	7.0	43.1	50	720	670	2820	3540
1-Aug-01	32.1	5.5	25.9	50	720	670	2800	3520
2-Aug-01	36.5	5.5	27.3	45	700	655	2830	3530
3-Aug-01	33.6	5.5	24.9	45	690	645	2830	3520
4-Aug-01	37.6	6.6	33.8	45	725	680	2775	3500
5-Aug-01	27.2	5.1	19.7	45	525	480	2625	3150
6-Aug-01	33.6	5.1	21.8	45	475	430	2775	3250
7-Aug-01	21.0	2.6	13.0	45	700	655	2650	3350
8-Aug-01	46.5	6.5	26.7	45	400	355	2300	2700
9-Aug-01	31.2	5.9	18.8	45	650	605	2050	2700
10-Aug-01	34.5	5.9	25.0	45	600	555	2950	3550
11-Aug-01	37.6	7.4	13.9	45	300	255	3350	3650
13-Aug-01	34.2	6.1	29.9	45	500	455	2900	3400
14-Aug-01	43.0	6.5	38.9	47	470	423	2825	3295
16-Aug-01	33.2	4.6	26.5	45	720	675	2780	3500
17-Aug-01	42.7	12.3	24.5	45	550	505	3450	4000
18-Aug-01	44.1	10.2	23.3	45	525	480	3475	4000
20-Aug-01	46.8	19.6	30.9	45	850	805	3050	3900
22-Aug-01	68.2	19.3	39.1	45	500	455	3000	3500
23-Aug-01	67.7	38.7	24.7	45	500	455	3000	3500
24-Aug-01	62.0	13.3	35.5	45	700	655	3000	3700
25-Aug-01	65.2	14.3	43.1	45	575	530	3025	3600
26-Aug-01	66.8	11.2	47.1	45	600	555	3100	3700
27-Aug-01	74.1	13.9	54.7	45	500	455	3100	3600
28-Aug-01	73.8	14.1	55.6	45	500	455	3000	3500
29-Aug-01	80.9	28.9	48.7	45	600	555	3000	3600
30-Aug-01	85.7	32.7	56.9	45	600	555	2980	3580
31-Aug-01	84.8	31.5	57.4	45	600	555	3000	3600
1-Sep-01	78.6	19.0	54.5	45	500	455	2900	3400
2-Sep-01	93.5	24.7	25.8	45	350	305	2800	3150
3-Sep-01	82.3	42.1	46.5	45	750	705	2900	3650
8-Sep-01	89.5	21.4	51.9	45	525	480	2925	3450
9-Sep-01	95.6	12.1	61.3	45	500	455	2800	3300
10-Sep-01	97.5	17.8	40.0	60	520	460	2790	3310
11-Sep-01	90.5	36.1	36.9	45	500	455	2800	3300
Average	57.6	14.8	35.6	45.8	575.4	529.7	2895.9	3471.3
Minimum	21.0	2.6	13.0	45.0	300.0	255.0	2050.0	2700.0
Maximum	97.5	42.1	61.3	60.0	850.0	805.0	3475.0	4000.0
St.Dev.	23.7	11.0	13.7	2.8	120.6	120.6	263.6	276.5
Count	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0

Date	Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
	PO_4_P	NH_4-N	Mg	PO_4_P	NH_4-N	Mg	molar ratio	molar ratio		
Reactor A	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(at inlet)	(at inlet)		(at inlet)
Run 1										
31-Jul-01	66.1	185.2	45.1	9.6E-04	9.3E-04	8.0E-04	0.9	6.2	5.3E-08	2.5
1-Aug-01	58.8	164.7	56.4	6.1E-04	6.5E-04	6.0E-04	1.2	6.2	5.2E-08	2.5
2-Aug-01	57.8	177.8	57.9	6.8E-04	7.0E-04	6.5E-04	1.3	6.8	5.7E-08	2.1
3-Aug-01	57.8	177.6	58.7	6.3E-04	7.0E-04	6.0E-04	1.3	6.8	5.8E-08	2.1
4-Aug-01	61.3	166.0	49.7	7.4E-04	7.8E-04	6.9E-04	1.0	6.0	4.9E-08	2.3
5-Aug-01	64.0	165.4	61.7	5.6E-04	6.0E-04	5.0E-04	1.2	5.7	6.3E-08	1.7
6-Aug-01	57.7	165.4	68.0	6.3E-04	6.0E-04	6.1E-04	1.5	6.4	6.2E-08	2.3
7-Aug-01	59.3	169.4	47.2	4.0E-04	3.2E-04	2.5E-04	1.0	6.3	4.6E-08	1.7
8-Aug-01	52.0	170.1	81.9	7.8E-04	8.0E-04	9.0E-04	2.0	7.2	7.0E-08	2.5
9-Aug-01	62.0	179.6	55.4	6.2E-04	7.6E-04	4.3E-04	1.2	6.4	5.9E-08	2.1
10-Aug-01	61.1	178.5	60.0	6.8E-04	7.5E-04	6.2E-04	1.3	6.5	6.3E-08	3.0
11-Aug-01	56.7	170.0	105.0	6.9E-04	9.0E-04	6.0E-04	2.4	6.6	9.7E-08	2.7
13-Aug-01	49.8	169.3	58.5	5.5E-04	7.3E-04	7.2E-04	1.5	7.5	4.7E-08	2.2
14-Aug-01	63.9	179.1	65.0	8.9E-04	8.3E-04	1.0E-03	1.3	6.2	7.1E-08	3.4
16-Aug-01	63.5	178.1	55.0	6.8E-04	5.8E-04	6.0E-04	1.1	6.2	6.0E-08	2.2
17-Aug-01	53.5	179.0	69.5	7.4E-04	1.6E-03	7.0E-04	1.7	7.4	6.4E-08	2.3
18-Aug-01	53.6	173.7	72.9	7.6E-04	1.3E-03	7.0E-04	1.8	7.2	6.5E-08	2.4
20-Aug-01	55.1	198.9	52.9	8.3E-04	2.8E-03	6.7E-04	1.2	8.0	5.6E-08	2.6
22-Aug-01	61.7	164.7	90.9	1.4E-03	2.3E-03	1.5E-03	1.9	5.9	8.9E-08	6.7
23-Aug-01	57.9	213.9	117.9	1.3E-03	5.9E-03	1.2E-03	2.6	8.2	1.4E-07	6.6
24-Aug-01	58.3	168.4	65.6	1.2E-03	1.6E-03	9.6E-04	1.5	6.4	6.2E-08	3.7
25-Aug-01	58.6	169.3	79.8	1.2E-03	1.7E-03	1.4E-03	1.8	6.4	7.6E-08	4.6
26-Aug-01	57.2	165.5	82.5	1.2E-03	1.3E-03	1.6E-03	1.9	6.4	7.5E-08	4.5
27-Aug-01	61.9	178.9	117.0	1.5E-03	1.8E-03	2.6E-03	2.4	6.4	1.2E-07	7.5
28-Aug-01	62.0	179.3	117.0	1.5E-03	1.8E-03	2.7E-03	2.4	6.4	1.2E-07	7.5
29-Aug-01	62.9	197.0	97.5	1.6E-03	4.1E-03	2.0E-03	2.0	6.9	1.2E-07	13.3
30-Aug-01	62.9	196.1	97.5	1.7E-03	4.6E-03	2.3E-03	2.0	6.9	1.2E-07	15.8
31-Aug-01	62.9	194.3	97.5	1.7E-03	4.4E-03	2.3E-03	2.0	6.8	1.1E-07	15.7
1-Sep-01	53.2	159.3	58.0	1.3E-03	2.2E-03	1.3E-03	1.4	6.6	4.7E-08	8.8
2-Sep-01	47.6	226.6	141.4	1.4E-03	4.0E-03	1.5E-03	3.8	10.5	1.5E-07	34.8
3-Sep-01	56.4	235.0	78.5	1.5E-03	7.1E-03	1.5E-03	1.8	9.2	1.0E-07	13.7
8-Sep-01	60.5	146.3	74.9	1.7E-03	2.2E-03	1.6E-03	1.6	5.4	6.4E-08	15.1
9-Sep-01	68.2	227.5	121.5	2.1E-03	2.0E-03	3.1E-03	2.3	7.4	1.8E-07	38.5
10-Sep-01	60.1	194.6	115.4	1.9E-03	2.5E-03	1.9E-03	2.5	7.2	1.3E-07	36.5
11-Sep-01	62.2	200.2	125.1	1.8E-03	5.2E-03	1.9E-03	2.6	7.1	1.5E-07	31.8
Average	59.1	181.8	80.0	1.1E-03	2.0E-03	1.2E-03	1.8	6.9	8.4E-08	8.8
Minimum	47.6	146.3	45.1	4.0E-04	3.2E-04	2.5E-04	0.9	5.4	4.6E-08	1.7
Maximum	68.2	235.0	141.4	2.1E-03	7.1E-03	3.1E-03	3.8	10.5	1.8E-07	38.5
St.Dev.	4.5	20.2	26.4	4.7E-04	1.7E-03	7.3E-04	0.6	1.0	3.6E-08	10.7
Count	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0

Date	PO_4-P In-Reactor			NH_4-N In-Reactor			Mg In-Reactor		
	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total
Reactor A Run 1	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
31-Jul-01	13.4	29.0	42.4	37.7	137.2	174.8	9.2	20.5	29.7
1-Aug-01	12.0	31.8	43.8	33.7	123.8	157.5	11.5	33.2	44.8
2-Aug-01	11.5	29.4	40.9	35.3	134.7	169.9	11.5	33.7	45.2
3-Aug-01	11.3	30.8	42.1	34.8	134.9	169.7	11.5	35.4	47.0
4-Aug-01	12.7	30.3	43.0	34.4	123.0	157.4	10.3	26.1	36.3
5-Aug-01	10.7	38.8	49.5	27.6	130.8	158.4	10.3	41.3	51.5
6-Aug-01	8.4	32.7	41.1	24.2	134.0	158.2	9.9	45.4	55.3
7-Aug-01	12.4	37.0	49.4	35.4	130.4	165.8	9.9	32.5	42.3
8-Aug-01	7.7	23.7	31.4	25.2	135.4	160.6	12.1	51.1	63.2
9-Aug-01	14.9	32.4	47.3	43.2	128.3	171.6	13.3	34.2	47.5
10-Aug-01	10.3	33.2	43.6	30.2	139.6	169.8	10.1	37.4	47.5
11-Aug-01	4.7	32.5	37.1	14.0	144.5	158.4	8.6	83.0	91.6
13-Aug-01	7.3	28.0	35.3	24.9	135.6	160.5	8.6	35.0	43.6
14-Aug-01	9.1	31.2	40.3	25.5	143.6	169.2	9.3	34.0	43.3
16-Aug-01	13.1	33.7	46.7	36.6	135.0	171.7	11.3	32.1	43.4
17-Aug-01	7.4	26.5	33.8	24.6	135.4	160.0	9.6	45.3	54.9
18-Aug-01	7.0	26.0	33.1	22.8	135.5	158.3	9.6	48.5	58.1
20-Aug-01	12.0	22.9	35.0	43.3	125.1	168.5	11.5	28.6	40.2
22-Aug-01	8.8	16.8	25.6	23.5	114.0	137.5	13.0	47.5	60.4
23-Aug-01	8.3	16.0	24.3	30.6	112.3	142.8	16.8	76.1	92.9
24-Aug-01	11.0	18.0	29.0	31.9	118.4	150.2	12.4	34.3	46.7
25-Aug-01	9.4	17.2	26.5	27.0	121.8	148.9	12.8	38.1	50.9
26-Aug-01	9.3	15.9	25.2	26.8	123.2	150.0	13.4	36.6	49.9
27-Aug-01	8.6	13.8	22.4	24.8	132.6	157.5	16.3	45.6	61.9
28-Aug-01	8.9	13.9	22.8	25.6	132.0	157.6	16.7	44.6	61.3
29-Aug-01	10.5	10.0	20.5	32.8	116.7	149.5	16.3	41.7	57.9
30-Aug-01	10.5	7.5	18.0	32.9	109.9	142.7	16.3	35.0	51.3
31-Aug-01	10.5	8.0	18.5	32.4	110.8	143.2	16.3	34.6	50.8
1-Sep-01	7.8	9.7	17.5	23.4	110.0	133.4	8.5	22.5	31.0
2-Sep-01	5.3	2.7	8.0	25.2	151.6	176.8	15.7	93.3	109.0
3-Sep-01	11.6	7.9	19.5	48.3	108.1	156.3	16.1	33.4	49.5
8-Sep-01	9.2	5.4	14.6	22.3	97.5	119.8	11.4	30.5	41.9
9-Sep-01	10.3	2.5	12.8	34.5	169.7	204.2	18.4	39.9	58.3
10-Sep-01	9.4	1.3	10.7	30.6	134.9	165.4	18.1	58.4	76.5
11-Sep-01	9.4	5.0	14.4	30.3	108.6	138.9	18.9	67.0	85.9
Average	9.8	20.6	30.5	30.2	128.0	158.2	12.7	42.2	54.9
Minimum	4.7	1.3	8.0	14.0	97.5	119.8	8.5	20.5	29.7
Maximum	14.9	38.8	49.5	48.3	169.7	204.2	18.9	93.3	109.0
St.Dev.	2.2	11.5	12.3	6.9	14.3	15.1	3.2	16.1	17.5
Count	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0

Date	In-Reactor Concentrations			In-reactor	In-reactor	In-Reactor P_S	Ps (eg)	S.S.Ratio	Effluent SS
	PO_4-P	NH_4-N	Mg	Mg:P	N:P				
Reactor A	(mol/L)	(mol/L)	(mol/L)	(molar ratio)	(molar ratio)			(in-reactor)	
Run 1									
31-Jul-01	1.4E-03	1.2E-02	1.2E-03	0.9	9.1	2.1E-08	2.1E-08	1.0	0.7
1-Aug-01	1.4E-03	1.1E-02	1.9E-03	1.3	8.0	3.0E-08	2.1E-08	1.4	1.2
2-Aug-01	1.3E-03	1.2E-02	1.9E-03	1.4	9.2	3.0E-08	2.8E-08	1.1	0.9
3-Aug-01	1.4E-03	1.2E-02	2.0E-03	1.4	8.9	3.2E-08	2.8E-08	1.2	1.0
4-Aug-01	1.4E-03	1.1E-02	1.5E-03	1.1	8.1	2.4E-08	2.1E-08	1.1	0.9
5-Aug-01	1.6E-03	1.1E-02	2.1E-03	1.3	7.1	3.9E-08	3.6E-08	1.1	1.0
6-Aug-01	1.3E-03	1.1E-02	2.3E-03	1.7	8.5	3.5E-08	2.8E-08	1.3	1.1
7-Aug-01	1.6E-03	1.2E-02	1.8E-03	1.1	7.4	3.3E-08	2.8E-08	1.2	1.1
8-Aug-01	1.0E-03	1.1E-02	2.6E-03	2.6	11.3	3.1E-08	2.8E-08	1.1	0.9
9-Aug-01	1.5E-03	1.2E-02	2.0E-03	1.3	8.0	3.7E-08	2.8E-08	1.3	1.1
10-Aug-01	1.4E-03	1.2E-02	2.0E-03	1.4	8.6	3.4E-08	2.1E-08	1.6	1.4
11-Aug-01	1.2E-03	1.1E-02	3.8E-03	3.2	9.4	5.2E-08	3.6E-08	1.4	1.3
13-Aug-01	1.1E-03	1.1E-02	1.8E-03	1.6	10.1	2.4E-08	2.1E-08	1.1	1.0
14-Aug-01	1.3E-03	1.2E-02	1.8E-03	1.4	9.3	2.8E-08	2.1E-08	1.3	1.1
16-Aug-01	1.5E-03	1.2E-02	1.8E-03	1.2	8.1	3.3E-08	2.8E-08	1.2	1.0
17-Aug-01	1.1E-03	1.1E-02	2.3E-03	2.1	10.5	2.9E-08	2.8E-08	1.0	0.9
18-Aug-01	1.1E-03	1.1E-02	2.4E-03	2.3	10.6	2.9E-08	2.8E-08	1.1	0.9
20-Aug-01	1.1E-03	1.2E-02	1.7E-03	1.5	10.7	2.3E-08	2.1E-08	1.1	0.8
22-Aug-01	8.3E-04	9.8E-03	2.5E-03	3.0	11.9	2.0E-08	1.3E-08	1.6	1.1
23-Aug-01	7.8E-04	1.0E-02	3.9E-03	4.9	13.0	3.1E-08	2.1E-08	1.5	1.0
24-Aug-01	9.4E-04	1.1E-02	1.9E-03	2.1	11.5	2.0E-08	1.7E-08	1.2	0.8
25-Aug-01	8.5E-04	1.1E-02	2.1E-03	2.5	12.4	1.9E-08	1.7E-08	1.2	0.8
26-Aug-01	8.1E-04	1.1E-02	2.1E-03	2.6	13.2	1.8E-08	1.7E-08	1.1	0.7
27-Aug-01	7.2E-04	1.1E-02	2.6E-03	3.6	15.6	2.1E-08	1.7E-08	1.3	0.8
28-Aug-01	7.4E-04	1.1E-02	2.6E-03	3.5	15.3	2.1E-08	1.7E-08	1.3	0.8
29-Aug-01	6.6E-04	1.1E-02	2.4E-03	3.7	16.2	1.7E-08	8.7E-09	1.9	0.9
30-Aug-01	5.8E-04	1.0E-02	2.1E-03	3.7	17.5	1.3E-08	7.3E-09	1.7	0.7
31-Aug-01	6.0E-04	1.0E-02	2.1E-03	3.6	17.2	1.3E-08	7.3E-09	1.8	0.7
1-Sep-01	5.7E-04	9.5E-03	1.3E-03	2.3	16.9	7.0E-09	5.3E-09	1.3	0.7
2-Sep-01	2.6E-04	1.3E-02	4.5E-03	17.5	48.8	1.5E-08	4.2E-09	3.5	1.3
3-Sep-01	6.3E-04	1.1E-02	2.1E-03	3.3	17.8	1.4E-08	7.3E-09	2.0	0.7
8-Sep-01	4.7E-04	8.6E-03	1.7E-03	3.7	18.2	7.0E-09	4.2E-09	1.7	0.6
9-Sep-01	4.1E-04	1.5E-02	2.4E-03	5.9	35.2	1.5E-08	4.7E-09	3.1	0.6
10-Sep-01	3.5E-04	1.2E-02	3.2E-03	9.2	34.2	1.3E-08	3.5E-09	3.7	0.4
11-Sep-01	4.6E-04	9.9E-03	3.6E-03	7.7	21.3	1.7E-08	4.7E-09	3.5	1.2
Average	9.8E-04	1.1E-02	2.3E-03	3.2	14.3	2.4E-08	1.8E-08	1.6	0.9
Minimum	2.6E-04	8.6E-03	1.2E-03	0.9	7.1	7.0E-09	3.5E-09	1.0	0.4
Maximum	1.6E-03	1.5E-02	4.5E-03	17.5	48.8	5.2E-08	3.6E-08	3.7	1.4
St.Dev.	4.0E-04	1.1E-03	7.3E-04	3.1	8.9	9.8E-09	9.6E-09	0.7	0.2
Count	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0

Date	Crystal Volume	Harvest Volume	CRT Actual	CRT Averaged In reactor						Harvested Product Data
					>4.75mm	>2.83mm	>2mm	>1mm	>0.5mm	<0.5 mm
Reactor A Run 1	**(L)**	**(L)**	(days)	**SS Ratio**	(g)	(g)	(g)	(g)	(g)	(g)
31-Jul-01										
1-Aug-01										
2-Aug-01										
3-Aug-01										
4-Aug-01										
5-Aug-01										
6-Aug-01										
7-Aug-01										
8-Aug-01										
9-Aug-01										
10-Aug-01										
11-Aug-01										
13-Aug-01										
14-Aug-01	5	0.41			0.2	105.8	49	0.2	0	0
16-Aug-01	5	0.41			0.3	91	50	0.8	0.5	0
17-Aug-01	5.2	0.41			0.1	92.5	33	0.1	0	0
18-Aug-01	6	0.41			0.1	92.6	31	0.2	0	0
20-Aug-01	6	0.41			0.1	79.6	22	0.1	0	0
22-Aug-01	6.2	1.3			0.2	394.1	13.4	2.1	5	0
23-Aug-01	6.3	1.3			0	290	74.5	2.9	35.3	0
24-Aug-01	7	1.3	6.00	1.2	0	47	213	13.5	0.3	3.2
25-Aug-01	7	1.3	6.00	1.2	0	195	99	41.8	23	60
26-Aug-01	6.9	1.3	6.00	1.2	0	188	87.4	63.1	0.4	3.6
27-Aug-01										
28-Aug-01	7	1.3	7.00	1.3	0	190	58.2	14	6	17
29-Aug-01										
30-Aug-01										
31-Aug-01										
1-Sep-01										
2-Sep-01	7	1.3	11.00	1.5	0	288	74	2.8	35	0
3-Sep-01										
8-Sep-01	7	1.3	12.00	1.6	0	247	22	1.7	1.2	3
9-Sep-01										
10-Sep-01	7.2	1.3	13.00	1.9	0.2	393	13	2	4.9	0
11-Sep-01	7.2	1.3	13	2.1	0.5	390	12.6	1.9	3	0
Average	6.4	1.0	9.3	1.5	0.1	205.6	56.8	9.8	7.6	5.8
Minimum	5.0	0.4	6.0	1.2	0.0	47.0	12.6	0.1	0.0	0.0
Maximum	7.2	1.3	13.0	2.1	0.5	394.1	213.0	63.1	35.3	60.0
St.Dev.	0.8	0.4	3.3	0.3	0.1	122.7	51.6	18.3	12.6	15.6
Count	15.0	15.0	8.0	8.0	15.0	15.0	15.0	15.0	15.0	15.0

Date *Reactor A* *Run 1*	Total Mass (g)	Percentage Size Fractions >4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	<0.5mm	Mean Crystal Size (mm)	Mass P Removed (g)	Theoretical Mass MAP Grown
31-Jul-01									30.8	244.1
1-Aug-01									19.6	155.2
2-Aug-01									21.3	168.9
3-Aug-01									19.3	153.1
4-Aug-01									24.1	190.9
5-Aug-01									13.2	104.5
6-Aug-01									13.3	105.2
7-Aug-01									12.6	99.8
8-Aug-01									13.9	110.6
9-Aug-01									18.1	143.5
10-Aug-01									18.2	144.3
11-Aug-01									9.2	73.0
13-Aug-01									12.3	97.2
14-Aug-01	155.2	0.1	68.2	31.6	0.1	0.0	0	3.3	18.6	147.7
16-Aug-01	142.6	0.2	63.8	35.1	0.6	0.4	0	3.2	21.8	173.4
17-Aug-01	125.7	0.1	73.6	26.3	0.1	0.0	0	3.4	18.1	143.5
18-Aug-01	123.9	0.1	74.7	25.0	0.2	0.0	0	3.4	17.8	141.6
20-Aug-01	101.8	0.1	78.2	21.6	0.1	0.0	0	3.4	31.5	250.2
22-Aug-01	414.8	0.0	95.0	3.2	0.5	1.2	0	3.6	30.3	240.3
23-Aug-01	402.7	0.0	72.0	18.5	0.7	8.8	0	3.2	28.3	224.2
24-Aug-01	277	0.0	17.0	76.9	4.9	0.1	1.2	2.5	36.4	288.9
25-Aug-01	418.8	0.0	46.6	23.6	10.0	5.5	14.3	2.5	31.6	250.7
26-Aug-01	342.5	0.0	54.9	25.5	18.4	0.1	1.1	2.9	33.0	261.8
27-Aug-01									33.0	262.2
28-Aug-01	285.2	0.0	66.6	20.4	4.9	2.1	6.0	3.1	33.0	261.6
29-Aug-01									44.0	349.0
30-Aug-01									46.6	369.6
31-Aug-01									46.1	365.6
1-Sep-01									30.1	238.9
2-Sep-01	399.8	0.0	72.0	18.5	0.7	8.8	0.0	3.2	22.4	178.0
3-Sep-01									50.2	398.1
8-Sep-01	274.9	0.0	89.9	8.0	0.6	0.4	1.1	3.5	40.9	324.7
9-Sep-01									46.9	372.6
10-Sep-01	413.1	0.0	95.1	3.1	0.5	1.2	0.0	3.6	43.9	348.4
11-Sep-01	408	0.1	95.6	3.1	0.5	0.7	0.0	3.6	40.5	321.5
Average	285.7	0.1	70.9	22.7	2.8	2.0	1.6	3.2	27.7	220.1
Minimum	101.8	0.0	17.0	3.1	0.1	0.0	0.0	2.5	9.2	73.0
Maximum	418.8	0.2	95.6	76.9	18.4	8.8	14.3	3.6	50.2	398.1
St.Dev.	125.0	0.1	20.8	18.1	5.1	3.1	3.8	0.4	11.8	94.0
Count	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	35.0	35.0

Date	Recyle flow	Temp ° C	Influent Lab results			Effluent Lab results			pH
			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)	
Reactor A Run 2									
24-Sep-01	4.5	18.0	92.0	200.0	1165.0	28.0	156.0	51.9	7.6
25-Sep-01	4.5	16.0	80.5	196.0	1162.0	30.8	154.0	51.7	7.6
26-Sep-01	3.7	15.0	85.7	201.0	1101.0	27.0	156.7	50.4	7.6
27-Sep-01	4.4	14.0	87.3	202.5	1150.0	16.7	158.0	35.0	7.7
28-Sep-01	4.2	14.0	80.0	210.0	1102.0	14.0	159.0	44.7	7.9
29-Sep-01	4.2	16.0	80.0	195.0	1104.0	20.0	153.0	60.0	7.7
30-Sep-01	4.0	15.0	78.8	197.5	1342.4	12.4	153.0	50.0	8
1-Oct-01	4.2	14.0	79.5	201.7	1100.0	19.8	156.0	60.3	7.7
2-Oct-01	4.5	14.0	82.4	197.7	1102.4	44.0	120.0	46.0	7.7
3-Oct-01	3.9	14.0	81.5	213.0	1102.0	23.5	133.0	16.0	7.9
4-Oct-01	4.1	14.0	75.2	191.0	700.0	23.5	147.0	13.0	8.2
5-Oct-01	4.1	14.0	79.0	220.0	800.0	28.7	154.0	10.0	8.1
6-Oct-01	4.5	14.0	84.0	208.0	833.3	31.5	150.0	8.0	8.2
7-Oct-01	4.5	13.0	84.0	220.0	833.0	35.4	148.0	8.0	8
8-Oct-01	4.2	14.0	72.6	199.0	1853.5	18.4	145.0	16.0	8.2
9-Oct-01	4.5	14.0	90.0	219.0	1600.0	31.0	170.0	10.0	8.3
10-Oct-01	4.4	10.0	74.0	219.0	977.5	20.0	130.6	14.0	8
11-Oct-01	4.4	12.0	86.5	179.0	830.0	21.0	140.0	10.0	8.2
12-Oct-01	4.4	13.0	85.0	179.0	1213.8	11.0	132.0	27.0	8.3
13-Oct-01	4.4	13.0	88.5	184.0	1190.0	11.4	132.0	25.0	8.3
14-Oct-01	4.3	13.0	87.0	220.0	1218.0	8.0	151.2	26.0	8.3
15-Oct-01	4.4	14.0	82.7	220.0	1215.2	5.0	160.0	22.0	8.5
16-Oct-01	4.0	14.0	97.8	220.0	915.6	21.0	114.9	33.0	8.3
17-Oct-01	6.0	13.0	93.0	220.0	915.0	18.7	97.6	63.5	8.2
18-Oct-01	6.1	14.0	104.5	200.0	935.0	12.0	123.0	54.0	8.2
19-Oct-01	6.1	14.0	101.6	200.0	933.1	11.6	120.0	53.0	8.2
24-Oct-01	4.8	14.0	82.0	220.0	1200.0	9.0	160.0	33.3	8.2
25-Oct-01	3.5	13.0	84.0	220.0	1200.0	9.2	165.1	24.0	8.3
26-Oct-01	3.7	13.0	84.0	221.0	1200.0	10.0	161.0	24.0	8.2
27-Oct-01	4.0	13.0	83.0	220.0	1210.0	10.0	160.0	22.0	8.3
28-Oct-01	4.0	13.0	82.0	221.0	1200.0	9.0	164.2	24.0	8.3
29-Oct-01	4.0	14.0	82.0	220.0	1200.0	9.5	165.0	25.0	8.3
30-Oct-01	4.0	13.0	90.4	220.0	1190.0	9.0	164.0	23.0	8.4
Average	4.4	13.8	84.9	207.7	1115.0	18.5	147.1	31.3	8.1
Minimum	3.5	10.0	72.6	179.0	700.0	5.0	97.6	8.0	7.6
Maximum	6.1	18.0	104.5	221.0	1853.5	44.0	170.0	63.5	8.5
St.Dev.	0.6	1.3	7.1	13.3	223.7	9.5	17.4	17.4	0.3
Count	33	33	33	33	33	33	33	33	33

Date *Reactor A* *Run 2*	Removal efficiency (%) PO_4-P (mg/L)	 NH_4-N (mg/L)	 Mg (mg/L)	MgCl Flow (mL/min)	Total Influent Flow (mL/min)	N & P Influent Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
24-Sep-01	66.9	15.2	44.3	50	625	575	2825	3450
25-Sep-01	58.4	14.6	44.4	50	625	575	2825	3450
26-Sep-01	65.6	15.0	45.0	50	600	550	2200	2800
27-Sep-01	79.3	15.5	60.4	50	650	600	2850	3500
28-Sep-01	81.0	18.0	47.3	50	650	600	2750	3400
29-Sep-01	72.9	15.0	29.3	50	650	600	2700	3350
30-Sep-01	82.9	15.7	54.3	57	700	643	2800	3500
1-Oct-01	72.8	15.5	35.2	55	650	595	2750	3400
2-Oct-01	42.8	35.0	37.4	35	525	490	2350	2875
3-Oct-01	69.5	34.0	73.3	38	700	662	2700	3400
4-Oct-01	66.8	18.3	68.2	38	650	612	2650	3300
5-Oct-01	61.4	25.7	78.6	38	650	612	2675	3325
6-Oct-01	60.2	23.4	83.6	38	650	612	2950	3600
7-Oct-01	55.2	28.6	83.6	38	650	612	2950	3600
8-Oct-01	74.0	25.3	64.5	17	700	683	2950	3650
9-Oct-01	64.5	19.9	79.7	20	650	630	2950	3600
10-Oct-01	71.3	36.7	75.5	38	650	612	2850	3500
11-Oct-01	74.2	16.9	79.4	38	650	612	2850	3500
12-Oct-01	86.3	21.7	62.0	38	650	612	2850	3500
13-Oct-01	86.3	23.8	64.1	38	650	612	2850	3500
14-Oct-01	90.2	27.0	63.5	38	650	612	2800	3450
15-Oct-01	93.6	22.8	69.0	38	650	612	2850	3500
16-Oct-01	76.4	42.7	59.6	49	550	501	2200	2750
17-Oct-01	77.1	49.4	43.4	49	400	351	2380	2780
18-Oct-01	87.1	31.0	47.0	49	450	401	2750	3200
19-Oct-01	87.2	32.7	47.8	49	450	401	2750	3200
24-Oct-01	88.1	21.1	64.6	47	600	553	2900	3500
25-Oct-01	88.4	20.3	66.0	47	800	753	2800	3600
26-Oct-01	87.3	22.3	68.1	47	750	703	2800	3550
27-Oct-01	87.1	22.4	71.0	47	750	703	3000	3750
28-Oct-01	88.3	20.7	68.1	47	750	703	3000	3750
29-Oct-01	87.6	20.0	66.8	47	750	703	3000	3750
30-Oct-01	89.4	20.5	69.2	47	750	703	3000	3750
Average	76.4	23.8	61.0	43.2	643.2	599.9	2772.9	3416.1
Minimum	42.8	14.6	29.3	17.0	400.0	351.0	2200.0	2750.0
Maximum	93.6	49.4	83.6	57.0	800.0	753.0	3000.0	3750.0
St.Dev.	12.3	8.5	14.6	8.7	88.9	90.2	210.6	271.3
Count	33	33	33	33	33	33	33	33

Date	Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
	PO_4_P	NH_4-N	Mg	PO_4_P	NH_4-N	Mg	molar ratio	molar ratio		
Reactor A	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(at inlet)	(at inlet)		(at inlet)
Run 2										
24-Sep-01	84.6	184.0	93.2	1.8E-03	2.0E-03	1.7E-03	1.4	4.8	1.4E-07	8.4
25-Sep-01	74.1	180.3	93.0	1.4E-03	1.9E-03	1.7E-03	1.6	5.4	1.2E-07	7.2
26-Sep-01	78.6	184.3	91.8	1.7E-03	2.0E-03	1.7E-03	1.5	5.2	1.3E-07	7.7
27-Sep-01	80.6	186.9	88.5	2.1E-03	2.1E-03	2.2E-03	1.4	5.1	1.3E-07	9.7
28-Sep-01	73.8	193.8	84.8	1.9E-03	2.5E-03	1.6E-03	1.5	5.8	1.2E-07	13.3
29-Sep-01	73.8	180.0	84.9	1.7E-03	1.9E-03	1.0E-03	1.5	5.4	1.1E-07	8.2
30-Sep-01	72.4	181.4	109.3	1.9E-03	2.0E-03	2.4E-03	2.0	5.5	1.4E-07	18.9
1-Oct-01	72.8	184.6	93.1	1.7E-03	2.0E-03	1.3E-03	1.7	5.6	1.2E-07	9.1
2-Oct-01	76.9	184.5	73.5	1.1E-03	4.6E-03	1.1E-03	1.2	5.3	1.0E-07	7.6
3-Oct-01	77.1	201.4	59.8	1.7E-03	4.9E-03	1.8E-03	1.0	5.8	8.9E-08	10.2
4-Oct-01	70.8	179.8	40.9	1.5E-03	2.3E-03	1.1E-03	0.7	5.6	5.0E-08	9.4
5-Oct-01	74.4	207.1	46.8	1.5E-03	3.8E-03	1.5E-03	0.8	6.2	6.9E-08	11.2
6-Oct-01	79.1	195.8	48.7	1.5E-03	3.3E-03	1.7E-03	0.8	5.5	7.2E-08	13.5
7-Oct-01	79.1	207.1	48.7	1.4E-03	4.2E-03	1.7E-03	0.8	5.8	7.7E-08	10.5
8-Oct-01	70.8	194.2	45.0	1.7E-03	3.5E-03	1.2E-03	0.8	6.1	5.9E-08	11.1
9-Oct-01	87.2	212.3	49.2	1.8E-03	3.0E-03	1.6E-03	0.7	5.4	8.8E-08	18.6
10-Oct-01	69.7	206.2	57.1	1.6E-03	5.4E-03	1.8E-03	1.1	6.6	7.9E-08	10.8
11-Oct-01	81.4	168.5	48.5	1.9E-03	2.0E-03	1.6E-03	0.8	4.6	6.4E-08	12.0
12-Oct-01	80.0	168.5	71.0	2.2E-03	2.6E-03	1.8E-03	1.1	4.7	9.2E-08	19.6
13-Oct-01	83.3	173.2	69.6	2.3E-03	2.9E-03	1.8E-03	1.1	4.6	9.6E-08	20.5
14-Oct-01	81.9	207.1	71.2	2.4E-03	4.0E-03	1.9E-03	1.1	5.6	1.2E-07	24.7
15-Oct-01	77.9	207.1	71.0	2.4E-03	3.4E-03	2.0E-03	1.2	5.9	1.1E-07	28.8
16-Oct-01	89.1	200.4	81.6	2.2E-03	6.1E-03	2.0E-03	1.2	5.0	1.4E-07	29.8
17-Oct-01	81.6	193.1	112.1	2.0E-03	6.8E-03	2.0E-03	1.8	5.2	1.7E-07	31.7
18-Oct-01	93.1	178.2	101.8	2.6E-03	3.9E-03	2.0E-03	1.4	4.2	1.6E-07	30.3
19-Oct-01	90.5	178.2	101.6	2.5E-03	4.2E-03	2.0E-03	1.4	4.4	1.6E-07	29.4
24-Oct-01	75.6	202.8	94.0	2.1E-03	3.1E-03	2.5E-03	1.6	5.9	1.4E-07	25.9
25-Oct-01	79.1	207.1	70.5	2.3E-03	3.0E-03	1.9E-03	1.2	5.8	1.1E-07	23.6
26-Oct-01	78.7	207.2	75.2	2.2E-03	3.3E-03	2.1E-03	1.2	5.8	1.2E-07	22.0
27-Oct-01	77.8	206.2	75.8	2.2E-03	3.3E-03	2.2E-03	1.3	5.9	1.2E-07	24.9
28-Oct-01	76.9	207.2	75.2	2.2E-03	3.1E-03	2.1E-03	1.3	6.0	1.1E-07	24.5
29-Oct-01	76.9	206.2	75.2	2.2E-03	2.9E-03	2.1E-03	1.3	5.9	1.1E-07	24.4
30-Oct-01	84.7	206.2	74.6	2.4E-03	3.0E-03	2.1E-03	1.1	5.4	1.3E-07	29.8
Average	78.9	193.4	75.1	1.9E-03	3.3E-03	1.8E-03	1.2	5.5	0.0	17.8
Minimum	69.7	168.5	40.9	1.1E-03	1.9E-03	1.0E-03	0.7	4.2	0.0	7.2
Maximum	93.1	212.3	112.1	2.6E-03	6.8E-03	2.5E-03	2.0	6.6	0.0	31.7
St.Dev.	5.7	13.3	19.6	3.7E-04	1.2E-03	3.6E-04	0.3	0.5	0.0	8.4
Count	33	33	33	33	33	33	33	33	33	33

Date	PO$_4$-P In-Reactor			NH$_4$-N In-Reactor			Mg In-Reactor		
	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total
Reactor A *Run 2*	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
24-Sep-01	15.3	22.9	38.3	33.3	127.7	161.1	16.9	42.5	59.4
25-Sep-01	13.4	25.2	38.6	32.7	126.1	158.8	16.8	42.3	59.1
26-Sep-01	16.8	21.2	38.0	39.5	123.1	162.6	19.7	39.6	59.3
27-Sep-01	15.0	13.6	28.6	34.7	128.7	163.4	16.4	28.5	44.9
28-Sep-01	14.1	11.3	25.4	37.1	128.6	165.7	16.2	36.2	52.4
29-Sep-01	14.3	16.1	30.4	34.9	123.3	158.2	16.5	48.4	64.8
30-Sep-01	14.5	9.9	24.4	36.3	122.4	158.7	21.9	40.0	61.9
1-Oct-01	13.9	16.0	29.9	35.3	126.2	161.5	17.8	48.8	66.6
2-Oct-01	14.0	36.0	50.0	33.7	98.1	131.8	13.4	37.6	51.0
3-Oct-01	15.9	18.7	34.5	41.5	105.6	147.1	12.3	12.7	25.0
4-Oct-01	13.9	18.9	32.8	35.4	118.0	153.5	8.1	10.4	18.5
5-Oct-01	14.5	23.1	37.6	40.5	123.9	164.4	9.1	8.0	17.2
6-Oct-01	14.3	25.8	40.1	35.4	122.9	158.3	8.8	6.6	15.4
7-Oct-01	14.3	29.0	43.3	37.4	121.3	158.7	8.8	6.6	15.3
8-Oct-01	13.6	14.9	28.5	37.2	117.2	154.4	8.6	12.9	21.6
9-Oct-01	15.8	25.4	41.2	38.3	139.3	177.6	8.9	8.2	17.1
10-Oct-01	12.9	16.3	29.2	38.3	106.3	144.6	10.6	11.4	22.0
11-Oct-01	15.1	17.1	32.2	31.3	114.0	145.3	9.0	8.1	17.2
12-Oct-01	14.9	9.0	23.8	31.3	107.5	138.8	13.2	22.0	35.2
13-Oct-01	15.5	9.3	24.8	32.2	107.5	139.7	12.9	20.4	33.3
14-Oct-01	15.4	6.5	21.9	39.0	122.7	161.7	13.4	21.1	34.5
15-Oct-01	14.5	4.1	18.5	38.5	130.3	168.8	13.2	17.9	31.1
16-Oct-01	17.8	16.8	34.6	40.1	91.9	132.0	16.3	26.4	42.7
17-Oct-01	11.7	16.0	27.8	27.8	83.6	111.3	16.1	54.4	70.5
18-Oct-01	13.1	10.3	23.4	25.1	105.7	130.8	14.3	46.4	60.7
19-Oct-01	12.7	10.0	22.7	25.1	103.1	128.2	14.3	45.5	59.8
24-Oct-01	13.0	7.5	20.4	34.8	132.6	167.3	16.1	27.6	43.7
25-Oct-01	17.6	7.2	24.7	46.0	128.4	174.4	15.7	18.7	34.3
26-Oct-01	16.6	7.9	24.5	43.8	127.0	170.8	15.9	18.9	34.8
27-Oct-01	15.6	8.0	23.6	41.2	128.0	169.2	15.2	17.6	32.8
28-Oct-01	15.4	7.2	22.6	41.4	131.4	172.8	15.0	19.2	34.2
29-Oct-01	15.4	7.6	23.0	41.2	132.0	173.2	15.0	20.0	35.0
30-Oct-01	16.9	7.2	24.1	41.2	131.2	172.4	14.9	18.4	33.3
Average	14.8	15.0	29.8	36.4	119.3	155.7	14.0	25.6	39.5
Minimum	11.7	4.1	18.5	25.1	83.6	111.3	8.1	6.6	15.3
Maximum	17.8	36.0	50.0	46.0	139.3	177.6	21.9	54.4	70.5
St.Dev.	1.4	7.7	7.7	4.9	13.0	16.0	3.4	14.5	17.2
Count	33	33	33	33	33	33	33	33	33

Date	In-Reactor Concentrations			In-reactor	In-reactor	In-Reactor P_S	Ps (eg)	S.S.Ratio	Effluent SS
	PO_4-P	NH_4-N	Mg	Mg:P	N:P				
Reactor A	(mol/L)	(mol/L)	(mol/L)	(molar ratio)	(molar ratio)			(in-reactor)	
Run 2									
24-Sep-01	1.2E-03	1.2E-02	2.5E-03	2.0	9.3	3.5E-08	1.7E-08	2.1	1.3
25-Sep-01	1.2E-03	1.1E-02	2.5E-03	2.0	9.1	3.5E-08	1.7E-08	2.1	1.4
26-Sep-01	1.2E-03	1.2E-02	2.5E-03	2.0	9.5	3.5E-08	1.7E-08	2.1	1.2
27-Sep-01	9.2E-04	1.2E-02	1.9E-03	2.0	12.7	2.0E-08	1.3E-08	1.5	0.7
28-Sep-01	8.2E-04	1.2E-02	2.2E-03	2.7	14.4	2.1E-08	8.7E-09	2.4	1.1
29-Sep-01	9.8E-04	1.1E-02	2.7E-03	2.8	11.5	3.0E-08	1.3E-08	2.3	1.3
30-Sep-01	7.9E-04	1.1E-02	2.6E-03	3.3	14.4	2.3E-08	7.3E-09	3.2	1.2
1-Oct-01	9.7E-04	1.2E-02	2.8E-03	2.9	11.9	3.1E-08	1.3E-08	2.3	1.4
2-Oct-01	1.6E-03	9.4E-03	2.1E-03	1.3	5.8	3.2E-08	1.3E-08	2.5	1.8
3-Oct-01	1.1E-03	1.1E-02	1.0E-03	0.9	9.4	1.2E-08	8.7E-09	1.4	0.5
4-Oct-01	1.1E-03	1.1E-02	7.7E-04	0.7	10.4	8.9E-09	5.3E-09	1.7	0.8
5-Oct-01	1.2E-03	1.2E-02	7.2E-04	0.6	9.7	1.0E-08	6.2E-09	1.6	0.7
6-Oct-01	1.3E-03	1.1E-02	6.4E-04	0.5	8.7	9.4E-09	5.3E-09	1.7	0.7
7-Oct-01	1.4E-03	1.1E-02	6.4E-04	0.5	8.1	1.0E-08	7.3E-09	1.4	0.6
8-Oct-01	9.2E-04	1.1E-02	9.0E-04	1.0	12.0	9.1E-09	5.3E-09	1.7	0.8
9-Oct-01	1.3E-03	1.3E-02	7.1E-04	0.5	9.6	1.2E-08	4.7E-09	2.6	1.1
10-Oct-01	9.4E-04	1.0E-02	9.2E-04	1.0	11.0	8.9E-09	7.3E-09	1.2	0.5
11-Oct-01	1.0E-03	1.0E-02	7.1E-04	0.7	10.0	7.7E-09	5.3E-09	1.4	0.5
12-Oct-01	7.7E-04	9.9E-03	1.5E-03	1.9	12.9	1.1E-08	4.7E-09	2.4	0.8
13-Oct-01	8.0E-04	1.0E-02	1.4E-03	1.7	12.5	1.1E-08	4.7E-09	2.4	0.8
14-Oct-01	7.1E-04	1.2E-02	1.4E-03	2.0	16.3	1.2E-08	4.7E-09	2.5	0.6
15-Oct-01	6.0E-04	1.2E-02	1.3E-03	2.2	20.2	9.3E-09	3.8E-09	2.4	0.4
16-Oct-01	1.1E-03	9.4E-03	1.8E-03	1.6	8.4	1.9E-08	4.7E-09	4.0	1.6
17-Oct-01	9.0E-04	8.0E-03	2.9E-03	3.3	8.9	2.1E-08	5.3E-09	3.9	2.1
18-Oct-01	7.6E-04	9.3E-03	2.5E-03	3.4	12.4	1.8E-08	5.3E-09	3.3	1.4
19-Oct-01	7.3E-04	9.2E-03	2.5E-03	3.4	12.5	1.7E-08	5.3E-09	3.1	1.3
24-Oct-01	6.6E-04	1.2E-02	1.8E-03	2.8	18.2	1.4E-08	5.3E-09	2.7	0.9
25-Oct-01	8.0E-04	1.2E-02	1.4E-03	1.8	15.6	1.4E-08	4.7E-09	3.0	0.7
26-Oct-01	7.9E-04	1.2E-02	1.5E-03	1.8	15.4	1.4E-08	5.3E-09	2.6	0.7
27-Oct-01	7.6E-04	1.2E-02	1.4E-03	1.8	15.9	1.3E-08	4.7E-09	2.7	0.7
28-Oct-01	7.3E-04	1.2E-02	1.4E-03	2.0	17.0	1.3E-08	4.7E-09	2.7	0.7
29-Oct-01	7.4E-04	1.2E-02	1.5E-03	2.0	16.7	1.3E-08	4.7E-09	2.8	0.8
30-Oct-01	7.8E-04	1.2E-02	1.4E-03	1.8	15.8	1.3E-08	4.2E-09	3.2	0.8
Average	9.6E-04	1.1E-02	1.6E-03	1.8	12.3	1.7E-08	7.5E-09	2.4	1.0
Minimum	6.0E-04	8.0E-03	6.4E-04	0.5	5.8	7.7E-09	3.8E-09	1.2	0.4
Maximum	1.6E-03	1.3E-02	2.9E-03	3.4	20.2	3.5E-08	1.7E-08	4.0	2.1
St.Dev.	2.5E-04	1.1E-03	7.2E-04	0.9	3.4	8.6E-09	4.0E-09	0.7	0.4
Count	33	33	33	33	33	33	33	33	33

Date	Crystal Volume	Harvest	CRT	CRT Averaged					Harvested Product Data	
		Volume	Actual	In reactor	>4.75mm	>2.83mm	>2 mm	>1mm	>0.5mm	<0.5mm
Reactor A	(L)	(L)	(days)	SS Ratio	(g)	(g)	(g)	(g)	(g)	(g)
Run 2										
24-Sep-01	6.25									
25-Sep-01	6.5									
26-Sep-01	6.1									
27-Sep-01	7.1									
28-Sep-01	8.2									
29-Sep-01	9.2									
30-Sep-01	10.1	1.3			0	70	166	10.1	1	4.5
1-Oct-01	10.5	1.3								
2-Oct-01	10.4	1.3			0	90	100	59	0.6	2
3-Oct-01	8	1.3								
4-Oct-01	8.4	1.3								
5-Oct-01	8.4	1.3			0	92.1	120	10.1	1.9	5.1
6-Oct-01	10.5	1.3								
7-Oct-01	10.5	1.3			0	86	103	44	2.9	6
8-Oct-01										
9-Oct-01	12	1.3			0	130	65	10.4	7.2	17.3
10-Oct-01	11.8	1.3			0	125	55.1	18.4	65.1	25.7
11-Oct-01	11.6	1.3			0	139	90	18	8.5	11.7
12-Oct-01	11.2	1.3			0	146	46.2	11.6	14.3	4.3
13-Oct-01	10.2	1.3	9.0	1.8	0	150	59	7	6	4
14-Oct-01	10.2	1.3	10.0	1.9	0	120	108.7	25	21.4	8.8
15-Oct-01	10.6	1.3	9.0	1.8	0	47	176	39.2	11.3	3.6
16-Oct-01	10.6	1.3	8.0	2.3	0	6	139.2	22	0.9	0
17-Oct-01	10.4	1.3	8.0	2.5	0	3	251	60.6	2.1	0
18-Oct-01										
19-Oct-01	11.5	1.3	10.0	2.6	0	70	58.2	14	6	12
24-Oct-01	11.5	1.3	10.0	2.8	0	88	101	43	2.8	5.9
25-Oct-01	11.4	1.3	10.0	2.9	0	47	213	13.5	0.3	3.2
26-Oct-01										
27-Oct-01										
28-Oct-01	11.8	1.3	12.0	2.9	0	42	176	38.5	11.8	3.1
29-Oct-01	11.4	1.3	12.0	2.9	0	45	178	38	13	5
30-Oct-01	11.2	1.3	12.0	3.0	0	5	254	59	1.6	0.3
Average	9.9	1.3	10.0	2.5	0.0	79.0	129.4	28.5	9.4	6.4
Minimum	6.1	1.3	8.0	1.8	0.0	3.0	46.2	7.0	0.3	0.0
Maximum	12.0	1.3	12.0	3.0	0.0	150.0	254.0	60.6	65.1	25.7
St.Dev.	1.8	0.0	1.5	0.5	0.0	47.9	65.2	18.4	14.7	6.4
Count	29	23	11	11	19	19	19	19	19	19

Date	Total Mass	Percentage Size Fractions						Mean Crystal	Mass P	Theoretical
		>4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	<0.5mm	Size (mm)	Removed	Mass MAP
Reactor A Run 2	(g)								(g)	Grown
24-Sep-01									51.0	404.6
25-Sep-01									38.9	309.0
26-Sep-01									44.5	353.5
27-Sep-01									59.8	474.6
28-Sep-01									56.0	444.6
29-Sep-01									50.4	400.0
30-Sep-01	251.6	0	27.8	66.0	4.0	0.4	1.8	2.7	60.5	479.9
1-Oct-01									49.6	393.5
2-Oct-01	251.6	0	35.8	39.7	23.4	0.2	0.8	2.6	24.9	197.4
3-Oct-01									54.0	428.6
4-Oct-01									44.3	351.4
5-Oct-01	229.2	0	40.2	52.4	4.4	0.8	2.2	2.8	42.8	339.3
6-Oct-01									44.5	353.5
7-Oct-01	241.9	0	35.6	42.6	18.2	1.2	2.5	2.6	40.9	324.5
8-Oct-01									52.9	419.5
9-Oct-01	229.9	0	56.5	28.3	4.5	3.1	7.5	2.9	52.6	417.7
10-Oct-01	289.3	0	43.2	19.0	6.4	22.5	8.9	2.3	46.5	369.0
11-Oct-01	267.2	0	52.0	33.7	6.7	3.2	4.4	2.9	56.6	449.0
12-Oct-01	222.4	0	65.6	20.77	5.2	6.4	1.9	3.1	64.6	512.8
13-Oct-01	226	0	66.4	26.1	3.1	2.7	1.8	3.2	67.3	534.3
14-Oct-01	283.9	0	42.3	38.3	8.8	7.5	3.1	2.7	69.2	549.1
15-Oct-01	277.1	0	17.0	63.5	14.1	4.1	1.3	2.4	68.2	541.3
16-Oct-01	168.1	0	3.6	82.8	13.1	0.5	0.0	2.3	53.9	428.0
17-Oct-01	316.7	0	0.9	79.3	19.1	0.7	0.0	2.2	36.2	287.6
18-Oct-01									52.6	417.2
19-Oct-01	160.2	0	43.7	36.3	8.7	3.7	7.5	2.7	51.1	405.9
24-Oct-01	240.7	0	36.6	42.0	17.9	1.2	2.5	2.6	57.5	456.5
25-Oct-01	277	0	17.0	76.9	4.9	0.1	1.2	2.5	80.5	638.8
26-Oct-01									74.2	589.2
27-Oct-01									73.2	581.1
28-Oct-01	271.4	0	15.5	64.8	14.2	4.3	1.1	2.4	73.3	581.7
29-Oct-01	279	0	16.1	63.8	13.6	4.7	1.8	2.4	72.8	577.4
30-Oct-01	319.9	0	1.6	79.4	18.4	0.5	0.1	2.2	81.8	649.2
Average	252.8	0.0	32.5	50.3	11.0	3.6	2.6	2.6	56.0	444.2
Minimum	160.2	0.0	0.9	19.0	3.1	0.1	0.0	2.2	24.9	197.4
Maximum	319.9	0.0	66.4	82.8	23.4	22.5	8.9	3.2	81.8	649.2
St.Dev.	42.2	0.0	20.4	21.1	6.3	5.1	2.6	0.3	13.4	106.3
Count	19	19	19	19	19	19	19	19	33	33

Date	Recyle flow	Temp ° C	Influent Lab results			Effluent Lab results			pH
			PO_4-P	NH_4-N	Mg	PO_4-P	NH_4-N	Mg	
Reactor A			(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	
Run 3									
2-Apr-02	9.8	8	171.2	240.0	2110.4	33.0	164.0	194.4	7.1
3-Apr-02	9.8	10	155.4	229.0	1800.0	32.0	150.0	155.1	7.1
4-Apr-02	7.5	11	170.2	228.8	1800.0	39.5	145.3	91.3	7.2
5-Apr-02	9.9	12	179.0	260.0	2322.7	17.0	127.2	240.7	7.3
6-Apr-02	14.0	10	162.5	217.1	2200.0	12.8	108.5	298.8	7.3
7-Apr-02	14.0	10	182.0	220.0	2200.0	15.0	110.4	311.0	7.3
8-Apr-02	14.0	10	181.0	305.0	2190.0	14.0	167.0	309.0	7.3
9-Apr-02	14.0	13	180.0	305.0	2190.0	14.0	166.0	307.0	7.3
10-Apr-02	14.0	13	178.0	305.5	2190.0	14.0	166.5	300.0	7.3
11-Apr-02									
12-Apr-02									
13-Apr-02	12.8	13	144.5	300.0	3200.0	9.3	129.8	146.0	7.7
14-Apr-02									
15-Apr-02									
16-Apr-02									
17-Apr-02	11.8	10.0	172.0	211.4	1820.0	13.3	138.6	51.1	7.7
18-Apr-02	13.8	8.0	142.7	220.0	3444.0	16.8	112.4	290.0	7.3
19-Apr-02	6.2	10.0	164.8	202.7	3100.0	51.9	137.8	41.2	7.4
20-Apr-02	6.3	13.0	164.0	198.0	3101.0	17.5	120.1	102.3	7.5
21-Apr-02	6.3	13.0	168.3	200.3	3101.0	30.5	124.4	80.0	7.4
22-Apr-02	5.7	11.0	163.7	236.5	1996.0	42.7	164.6	28.3	7.4
23-Apr-02									
24-Apr-02	5.7	11.0	159.9	280.0	3200.0	48.8	190.0	110.0	7.3
25-Apr-02	6.2	11.0	170.0	280.0	3200.0	44.1	180.0	94.8	7.3
26-Apr-02									
27-Apr-02									
28-Apr-02									
29-Apr-02	9.7	12.0	255.0	377.5	1294.9	60.0	230.0	40.0	7.2
30-Apr-02	9.7	12.0	243.0	371.2	1187.0	58.0	210.0	38.0	7.2
1-May-02	10.1	12.0	250.0	365.0	1180.0	59.0	215.0	35.0	7.2
2-May-02	9.6	11.0	250.0	370.0	1180.0	57.0	221.0	40.0	7.2
3-May-02	9.7	12.0	241.0	362.2	1157.0	60.0	215.0	38.0	7.2
4-May-02	9.8	13.0	240.0	365.7	1157.0	60.0	214.0	40.0	7.2
5-May-02									
6-May-02									
7-May-02	10.3	12.0	240.0	360.0	1150.0	59.0	240.0	38.0	7.2
8-May-02	10.3	12.0	240.0	355.0	1150.0	58.0	230.0	38.0	7.2
Average	10.0	11.3	191.1	283.3	2100.8	36.0	168.4	133.0	7.3
Minimum	5.7	8.0	142.7	198.0	1150.0	9.3	108.5	28.3	7.1
Maximum	14.0	13.0	255.0	377.5	3444.0	60.0	240.0	311.0	7.7
St.Dev.	2.9	1.5	37.9	64.9	789.0	19.5	42.2	108.5	0.1
Count	26	26	26	26	26	26	26	26	26

Date	Removal efficiency (%)			MgCl	Total	N & P	Recycle	Total flow
	PO_4-P	NH_4-N	Mg	Flow	Influent Flow	Influent Flow	Flow	(influent+recycle)
Reactor A	(mg/L)	(mg/L)	(mg/L)	(mL/min)	(mL/min)	(mL/min)	(mL/min)	(mL/min)
Run 3								
2-Apr-02	77.9	21.8	27.3	38	300	262	2950	3250
3-Apr-02	76.4	25.0	32.0	38	300	262	2950	3250
4-Apr-02	74.1	29.2	50.8	40	388	348	2912	3300
5-Apr-02	88.9	42.7	28.8	40	275	235	2725	3000
6-Apr-02	90.4	39.1	24.5	36	200	164	2800	3000
7-Apr-02	89.9	38.8	21.5	36	200	164	2800	3000
8-Apr-02	90.6	33.2	21.6	36	200	164	2800	3000
9-Apr-02	90.5	33.6	22.1	36	200	164	2800	3000
10-Apr-02	90.4	33.5	23.9	36	200	164	2800	3000
11-Apr-02								
12-Apr-02								
13-Apr-02	93.0	53.2	40.0	19	250	231	3200	3450
14-Apr-02								
15-Apr-02								
16-Apr-02								
17-Apr-02	91.6	28.6	65.5	22	270	248	3175	3445
18-Apr-02	86.8	42.6	23.5	22	200	178	2750	2950
19-Apr-02	67.1	28.9	69.8	22	500	478	3100	3600
20-Apr-02	88.6	35.4	46.1	30	490	460	3100	3590
21-Apr-02	80.8	34.1	54.9	30	525	495	3300	3825
22-Apr-02	72.3	26.2	75.2	30	525	495	3000	3525
23-Apr-02								
24-Apr-02	67.6	28.0	39.9	30	525	495	3000	3525
25-Apr-02	72.4	31.6	50.6	30	500	470	3100	3600
26-Apr-02								
27-Apr-02								
28-Apr-02								
29-Apr-02	72.8	29.6	77.1	50	370	320	3600	3970
30-Apr-02	72.5	34.7	76.0	50	375	325	3620	3995
1-May-02	72.6	31.6	78.6	50	360	310	3620	3980
2-May-02	73.7	31.1	74.6	50	375	325	3600	3975
3-May-02	71.3	31.5	75.4	50	375	325	3625	4000
4-May-02	71.1	32.3	74.4	50	370	320	3620	3990
5-May-02								
6-May-02								
7-May-02	71.3	22.2	76.9	50	350	300	3600	3950
8-May-02	71.8	24.4	76.9	50	350	300	3590	3940
Average	79.5	32.4	51.1	37.3	345.1	307.8	3159.1	3504.2
Minimum	67.1	21.8	21.5	19.0	200.0	164.0	2725.0	2950.0
Maximum	93.0	53.2	78.6	50.0	525.0	495.0	3625.0	4000.0
St.Dev.	9.0	6.9	22.6	10.2	113.5	114.1	337.9	395.8
Count	26	26	26	26	26	26	26	26

Date	Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
	PO_4-P	NH_4-N	Mg	PO_4-P	NH_4-N	Mg	molar ratio	molar ratio		
Reactor A	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(at inlet)	(at inlet)		(at inlet)
Run 3										
2-Apr-02	149.5	209.6	267.3	3.8E-03	3.3E-03	3.0E-03	2.3	3.1	8.0E-07	13.9
3-Apr-02	135.7	200.0	228.0	3.3E-03	3.6E-03	3.0E-03	2.2	3.3	5.9E-07	10.2
4-Apr-02	152.7	205.2	185.6	3.7E-03	4.3E-03	3.9E-03	1.6	3.0	5.6E-07	12.3
5-Apr-02	153.0	222.2	337.9	4.4E-03	6.8E-03	4.0E-03	2.9	3.2	1.1E-06	30.9
6-Apr-02	133.3	178.0	396.0	3.9E-03	5.0E-03	4.0E-03	3.8	3.0	9.0E-07	25.3
7-Apr-02	149.2	180.4	396.0	4.3E-03	5.0E-03	3.5E-03	3.4	2.7	1.0E-06	28.7
8-Apr-02	148.4	250.1	394.2	4.3E-03	5.9E-03	3.5E-03	3.4	3.7	1.4E-06	39.3
9-Apr-02	147.6	250.1	394.2	4.3E-03	6.0E-03	3.6E-03	3.4	3.8	1.4E-06	39.1
10-Apr-02	146.0	250.5	394.2	4.3E-03	6.0E-03	3.9E-03	3.5	3.8	1.4E-06	38.8
11-Apr-02										
12-Apr-02										
13-Apr-02	133.5	277.2	243.2	4.0E-03	1.1E-02	4.0E-03	2.4	4.6	8.6E-07	58.8
14-Apr-02										
15-Apr-02										
16-Apr-02										
17-Apr-02	158.0	194.2	148.3	4.7E-03	4.0E-03	4.0E-03	1.2	2.7	4.4E-07	29.7
18-Apr-02	127.0	195.8	378.8	3.6E-03	6.0E-03	3.7E-03	3.9	3.4	9.0E-07	25.3
19-Apr-02	157.5	193.8	136.4	3.4E-03	4.0E-03	3.9E-03	1.1	2.7	4.0E-07	14.1
20-Apr-02	154.0	185.9	189.9	4.4E-03	4.7E-03	3.6E-03	1.6	2.7	5.2E-07	23.0
21-Apr-02	158.7	188.9	177.2	4.1E-03	4.6E-03	4.0E-03	1.4	2.6	5.1E-07	18.0
22-Apr-02	154.3	223.0	114.1	3.6E-03	4.2E-03	3.5E-03	1.0	3.2	3.8E-07	13.3
23-Apr-02										
24-Apr-02	150.8	264.0	182.9	3.3E-03	5.3E-03	3.0E-03	1.6	3.9	7.0E-07	19.6
25-Apr-02	159.8	263.2	192.0	3.7E-03	5.9E-03	4.0E-03	1.6	3.6	7.8E-07	21.7
26-Apr-02										
27-Apr-02										
28-Apr-02										
29-Apr-02	220.5	326.5	175.0	5.2E-03	6.9E-03	5.6E-03	1.0	3.3	1.2E-06	26.7
30-Apr-02	210.6	321.7	158.3	4.9E-03	8.0E-03	4.9E-03	1.0	3.4	1.0E-06	22.7
1-May-02	215.3	314.3	163.9	5.0E-03	7.1E-03	5.3E-03	1.0	3.2	1.1E-06	23.5
2-May-02	216.7	320.7	157.3	5.2E-03	7.1E-03	4.8E-03	0.9	3.3	1.0E-06	23.2
3-May-02	208.9	313.9	154.3	4.8E-03	7.1E-03	4.8E-03	1.0	3.3	9.7E-07	21.5
4-May-02	207.6	316.3	156.4	4.8E-03	7.3E-03	4.8E-03	1.0	3.4	9.9E-07	21.8
5-May-02										
6-May-02										
7-May-02	205.7	308.6	164.3	4.7E-03	4.9E-03	5.2E-03	1.0	3.3	1.0E-06	22.1
8-May-02	205.7	304.3	164.3	4.8E-03	5.3E-03	5.2E-03	1.0	3.3	9.9E-07	21.8
Average	167.7	248.4	232.7	4.2E-03	5.7E-03	4.1E-03	1.9	3.3	8.8E-07	24.8
Minimum	127.0	178.0	114.1	3.3E-03	3.3E-03	3.0E-03	0.9	2.6	3.8E-07	10.2
Maximum	220.5	326.5	396.0	5.2E-03	1.1E-02	5.6E-03	3.9	4.6	1.4E-06	58.8
St.Dev.	30.9	53.2	99.5	5.8E-04	1.6E-03	7.4E-04	1.1	0.4	3.0E-07	10.4
Count	26	26	26	26	26	26	26	26	26	26

Date	PO_4-P In-Reactor			NH_4-N In-Reactor			Mg In-Reactor		
	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total
Reactor A	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Run 3									
2-Apr-02	13.8	30.0	43.8	19.3	148.9	168.2	24.7	176.5	201.1
3-Apr-02	12.5	29.0	41.6	18.5	136.2	154.6	21.0	140.8	161.8
4-Apr-02	17.9	34.9	52.8	24.1	128.2	152.3	21.8	80.6	102.4
5-Apr-02	14.0	15.4	29.5	20.4	115.5	135.9	31.0	218.6	249.6
6-Apr-02	8.9	11.9	20.8	11.9	101.3	113.1	26.4	278.9	305.3
7-Apr-02	9.9	14.0	23.9	12.0	103.0	115.1	26.4	290.2	316.6
8-Apr-02	9.9	13.1	23.0	16.7	155.9	172.5	26.3	288.4	314.7
9-Apr-02	9.8	13.1	22.9	16.7	154.9	171.6	26.3	286.5	312.8
10-Apr-02	9.7	13.1	22.8	16.7	155.4	172.1	26.3	280.0	306.3
11-Apr-02									
12-Apr-02									
13-Apr-02	9.7	8.6	18.3	20.1	120.4	140.5	17.6	135.4	153.0
14-Apr-02									
15-Apr-02									
16-Apr-02									
17-Apr-02	12.4	12.3	24.6	15.2	127.7	143.0	11.6	47.1	58.7
18-Apr-02	8.6	15.7	24.3	13.3	104.8	118.1	25.7	270.3	296.0
19-Apr-02	21.9	44.7	66.6	26.9	118.6	145.6	18.9	35.5	54.4
20-Apr-02	21.0	15.1	36.1	25.4	103.7	129.1	25.9	88.3	114.3
21-Apr-02	21.8	26.3	48.1	25.9	107.4	133.3	24.3	69.0	93.3
22-Apr-02	23.0	36.3	59.3	33.2	140.1	173.3	17.0	24.1	41.1
23-Apr-02									
24-Apr-02	22.5	41.5	64.0	39.3	161.7	201.0	27.2	93.6	120.8
25-Apr-02	22.2	38.0	60.2	36.6	155.0	191.6	26.7	81.6	108.3
26-Apr-02									
27-Apr-02									
28-Apr-02									
29-Apr-02	20.6	54.4	75.0	30.4	208.6	239.0	16.3	36.3	52.6
30-Apr-02	19.8	52.6	72.3	30.2	190.3	220.5	14.9	34.4	49.3
1-May-02	19.5	53.7	73.1	28.4	195.6	224.0	14.8	31.8	46.7
2-May-02	20.4	51.6	72.1	30.3	200.2	230.4	14.8	36.2	51.1
3-May-02	19.6	54.4	74.0	29.4	194.8	224.3	14.5	34.4	48.9
4-May-02	19.2	54.4	73.7	29.3	194.2	223.5	14.5	36.3	50.8
5-May-02									
6-May-02									
7-May-02	18.2	53.8	72.0	27.3	218.7	246.1	14.6	34.6	49.2
8-May-02	18.3	52.8	71.1	27.0	209.6	236.6	14.6	34.6	49.2
Average	16.4	32.3	48.7	24.0	151.9	176.0	20.9	121.7	142.6
Minimum	8.6	8.6	18.3	11.9	101.3	113.1	11.6	24.1	41.1
Maximum	23.0	54.4	75.0	39.3	218.7	246.1	31.0	290.2	316.6
St.Dev.	5.1	17.5	21.5	7.6	38.4	43.0	5.7	101.8	106.1
Count	26	26	26	26	26	26	26	26	26

Date *Reactor A* *Run 3*	In-Reactor Concentrations PO_4-P (mol/L)	 NH_4-N (mol/L)	 Mg (mol/L)	In-reactor Mg:P (molar ratio)	In-reactor N:P (molar ratio)	In-Reactor Ps	Ps (eq)	S.S.Ratio (in-reactor)	Effluent SS
2-Apr-02	1.4E-03	1.2E-02	8.4E-03	5.9	8.5	1.4E-07	5.8E-08	2.5	1.7
3-Apr-02	1.3E-03	1.1E-02	6.7E-03	5.0	8.2	1.0E-07	5.8E-08	1.7	1.2
4-Apr-02	1.7E-03	1.1E-02	4.3E-03	2.5	6.4	7.9E-08	4.5E-08	1.7	1.1
5-Apr-02	9.5E-04	9.7E-03	1.0E-02	10.9	10.2	9.6E-08	3.6E-08	2.7	1.4
6-Apr-02	6.7E-04	8.1E-03	1.3E-02	18.9	12.0	6.9E-08	3.6E-08	1.9	1.1
7-Apr-02	7.7E-04	8.2E-03	1.3E-02	17.1	10.6	8.4E-08	3.6E-08	2.3	1.4
8-Apr-02	7.4E-04	1.2E-02	1.3E-02	17.7	16.6	1.2E-07	3.6E-08	3.4	1.9
9-Apr-02	7.4E-04	1.2E-02	1.3E-02	17.6	16.6	1.2E-07	3.6E-08	3.3	1.9
10-Apr-02	7.4E-04	1.2E-02	1.3E-02	17.4	16.7	1.2E-07	3.6E-08	3.2	1.9
11-Apr-02									
12-Apr-02									
13-Apr-02	5.9E-04	1.0E-02	6.4E-03	10.8	17.0	3.8E-08	1.5E-08	2.6	1.2
14-Apr-02									
15-Apr-02									
16-Apr-02									
17-Apr-02	7.9E-04	1.0E-02	2.4E-03	3.1	12.8	2.0E-08	1.5E-08	1.4	0.6
18-Apr-02	7.8E-04	8.4E-03	1.2E-02	15.8	10.8	8.1E-08	3.6E-08	2.3	1.5
19-Apr-02	2.1E-03	1.0E-02	2.3E-03	1.1	4.8	5.1E-08	2.8E-08	1.8	1.0
20-Apr-02	1.2E-03	9.2E-03	4.8E-03	4.1	7.9	5.1E-08	2.3E-08	2.3	0.9
21-Apr-02	1.6E-03	9.5E-03	3.9E-03	2.5	6.1	5.7E-08	2.8E-08	2.0	1.0
22-Apr-02	1.9E-03	1.2E-02	1.7E-03	0.9	6.5	4.1E-08	2.8E-08	1.4	0.7
23-Apr-02									
24-Apr-02	2.1E-03	1.4E-02	5.0E-03	2.4	7.0	1.5E-07	3.6E-08	4.2	2.7
25-Apr-02	1.9E-03	1.4E-02	4.5E-03	2.3	7.0	1.2E-07	3.6E-08	3.4	2.0
26-Apr-02									
27-Apr-02									
28-Apr-02									
29-Apr-02	2.4E-03	1.7E-02	2.2E-03	0.9	7.1	9.0E-08	4.5E-08	2.0	1.2
30-Apr-02	2.3E-03	1.6E-02	2.1E-03	0.9	6.8	7.5E-08	4.5E-08	1.7	1.0
1-May-02	2.4E-03	1.6E-02	1.9E-03	0.8	6.8	7.3E-08	4.5E-08	1.6	0.9
2-May-02	2.3E-03	1.6E-02	2.1E-03	0.9	7.1	8.1E-08	4.5E-08	1.8	1.1
3-May-02	2.4E-03	1.6E-02	2.0E-03	0.9	6.7	7.8E-08	4.5E-08	1.7	1.0
4-May-02	2.4E-03	1.6E-02	2.1E-03	0.9	6.7	8.0E-08	4.5E-08	1.8	1.1
5-May-02									
6-May-02									
7-May-02	2.3E-03	1.8E-02	2.0E-03	0.9	7.6	8.4E-08	4.5E-08	1.8	1.1
8-May-02	2.3E-03	1.7E-02	2.1E-03	0.9	7.4	8.0E-08	4.5E-08	1.8	1.1
Average	1.6E-03	1.3E-02	5.9E-03	6.3	9.3	8.4E-08	3.8E-08	2.2	1.3
Minimum	5.9E-04	8.1E-03	1.7E-03	0.8	4.8	2.0E-08	1.5E-08	1.4	0.6
Maximum	2.4E-03	1.8E-02	1.3E-02	18.9	17.0	1.5E-07	5.8E-08	4.2	2.7
St.Dev.	6.9E-04	3.1E-03	4.4E-03	6.8	3.7	3.1E-08	1.1E-08	0.7	0.5
Count	26	26	26	26	26	26	26	26	26

Date *Reactor A* *Run 3*	Crystal Volume (L)	Harvest Volume (L)	CRT Actual (days)	CRT Averaged In reactor SS Ratio	Harvested Product Data >4.75mm (g)	>2.83mm (g)	>2 mm (g)	>1mm (g)	>0.5mm (g)	<0.5mm (g)
2-Apr-02	5.7									
3-Apr-02		1.3			3.9	294.3	38.4	0.7	0.4	4
4-Apr-02	6.9									
5-Apr-02	6.5	1.3			0	228.4	79.1	2.8	0.7	7.2
6-Apr-02	6.6	1.3			0	213.7	67.8	0.8	0.4	6
7-Apr-02	5.5									
8-Apr-02	7									
9-Apr-02	7.2									
10-Apr-02										
11-Apr-02										
12-Apr-02										
13-Apr-02	7.2									
14-Apr-02										
15-Apr-02	8									
16-Apr-02	7.2	1.3			0	276	18.5	0.8	0.2	0.5
17-Apr-02	7.5	1.3								
18-Apr-02	8.4	1.3			0.2	211.1	3.9	0.6	2.5	5.1
19-Apr-02	8.4	1.3								
20-Apr-02	9.1	1.3			0	122	54.7	2.3	4	24
21-Apr-02	9.5	1.3								
22-Apr-02	10.5	1.3			0	190	10.1	0.4	0.1	4.1
23-Apr-02		1.3								
24-Apr-02	9.5	1.3								
25-Apr-02	10.3	1.3			0.4	230.5	3.5	0.4	0.3	11.7
26-Apr-02										
27-Apr-02	9.7									
28-Apr-02										
29-Apr-02										
30-Apr-02	10									
1-May-02										
2-May-02										
3-May-02	10.8									
4-May-02		1.3			0	4.4	133.3	13.7	0	4
5-May-02										
6-May-02	11	1.3			0	244	10.2	1.5	0	4.1
7-May-02	11.7									
8-May-02	12	1.3			0	92.4	199.5	1.3	0.3	6.2
Average	8.6	1.3			0.4	191.5	56.3	2.3	0.8	7.0
Minimum	5.5	1.3			0.0	4.4	3.5	0.4	0.0	0.5
Maximum	12.0	1.3			3.9	294.3	199.5	13.7	4.0	24.0
St.Dev.	1.9	0.0			1.2	86.0	62.2	3.9	1.3	6.3
Count	24	16			11	11	11	11	11	11

Date	Total Mass	Percentage Size Fractions						Mean Crystal	Mass P	Theoretical
		>4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	< 0.5mm	Size (mm)	Removed	Mass MAP
Reactor A	(g)								(g)	Grown
Run 3										
2-Apr-02									50.3	399.5
3-Apr-02	341.7	1.1	86.1	11.2	0.2	0.1	1.2	3.5	44.8	355.6
4-Apr-02									63.2	501.8
5-Apr-02	318.2	0	71.8	24.9	0.9	0.2	2.3	3.3	53.8	427.3
6-Apr-02	288.7	0	74.0	23.5	0.3	0.1	2.1	3.3	34.7	275.3
7-Apr-02									38.7	306.8
8-Apr-02									38.7	307.2
9-Apr-02									38.5	305.4
10-Apr-02									38.0	301.6
11-Apr-02										
12-Apr-02										
13-Apr-02									44.7	354.9
14-Apr-02										
15-Apr-02										
16-Apr-02	296	0	93.2	6.3	0.3	0.1	0.2	3.6		
17-Apr-02									56.3	446.5
18-Apr-02	223.4	0.1	94.5	1.7	0.3	1.1	2.3	3.6	31.7	251.9
19-Apr-02									76.1	603.7
20-Apr-02	207	0	58.9	26.4	1.1	1.9	11.6	2.9	96.3	764.2
21-Apr-02									96.9	769.1
22-Apr-02	204.7	0	92.8	4.9	0.2	0.0	2.0	3.6	84.4	669.9
23-Apr-02										
24-Apr-02									77.1	611.8
25-Apr-02	246.8	0.1621	93.4	1.4	0.2	0.1	4.7	3.5	83.3	661.1
26-Apr-02										
27-Apr-02										
28-Apr-02										
29-Apr-02									85.5	678.9
30-Apr-02									82.4	654.0
1-May-02									81.0	643.0
2-May-02									86.2	684.3
3-May-02									80.4	638.0
4-May-02	155.4	0	2.8	85.8	8.8	0.0	2.6	2.3	78.6	624.0
5-May-02										
6-May-02	259.8	0	93.9	3.9	0.6	0.0	1.6	3.6		
7-May-02									73.9	586.9
8-May-02	299.7	0	30.8	66.6	0.4	0.1	2.1	2.7	74.4	590.9
Average	258.3	0.1	72.0	23.3	1.2	0.4	3.0	3.3	65.0	515.9
Minimum	155.4	0.0	2.8	1.4	0.2	0.0	0.2	2.3	31.7	251.9
Maximum	341.7	1.1	94.5	85.8	8.8	1.9	11.6	3.6	96.9	769.1
St.Dev.	56.6	0.3	30.3	28.1	2.5	0.6	3.1	0.4	21.1	167.1
Count	11	11	11	11	11	11	11	11	26	26

Date	Recyle flow	Temp °C	Influent Lab results			Effluent Lab results			pH
			PO_4-P	NH_4-N	Mg	PO_4-P	NH_4-N	Mg	
Reactor B			(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	
Run 1									
31-Jul-01	4.1		65.7	194.0	840.0	40.0	172.7	41.0	7.4
1-Aug-01	3.9		63.2	177.0	812.0	42.2	159.0	46.0	7.4
2-Aug-01	4.0		61.8	190.0	900.0	11.0	145.0	29.0	8.6
3-Aug-01	5.5		61.8	190.0	900.0	19.8	142.0	52.4	7.6
9-Aug-01	2.6		66.6	193.0	800.0	33.9	166.0	45.0	7.5
10-Aug-01	4.4		66.0	193.0	800.0	33.0	140.0	44.0	7.6
11-Aug-01	4.5		66.7	200.0	700.0	43.0	172.0	28.0	7.5
15-Aug-01	5.0		60.0	225.0	740.0	38.0	170.0	27.0	7.5
16-Aug-01	3.6		67.7	190.0	880.0	38.0	162.3	28.8	7.6
17-Aug-01	3.6		58.3	195.0	850.0	35.0	167.0	34.3	7.6
18-Aug-01	3.7		58.6	190.0	850.0	36.0	152.0	34.0	7.6
19-Aug-01									
20-Aug-01	3.5		58.2	210.0	1000.0	21.9	159.0	33.8	7.7
21-Aug-01									
22-Aug-01	3.4		67.8	181.0	1010.0	25.0	143.0	33.8	7.7
23-Aug-01	3.4		63.7	235.0	1310.0	16.7	179.5	34.0	7.8
24-Aug-01	3.5		62.3	180.0	1020.0	19.5	140.0	32.0	7.8
25-Aug-01	3.5		63.5	183.7	1020.0	19.5	154.7	31.9	7.8
26-Aug-01	3.5		61.8	179.0	1100.0	18.8	149.0	38.9	7.8
27-Aug-01	3.5		68.0	196.5	1300.0	19.0	154.0	35.9	7.8
28-Aug-01	3.5		68.2	197.0	1300.0	18.9	158.0	35.9	7.8
29-Aug-01	3.5		68.0	213.0	1300.0	18.7	158.0	35.0	7.8
30-Aug-01	3.5		68.0	212.0	1300.0	19.0	154.0	34.8	7.8
31-Aug-01	3.5		68.0	210.0	1300.0	18.0	152.0	35.0	7.8
1-Sep-01									
2-Sep-01	4.4		54.6	260.0	1100.0	5.0	165.0	50.0	8.5
3-Sep-01	4.3		60.0	250.0	1307.9	4.0	170.0	48.8	8.5
4-Sep-01									
5-Sep-01									
6-Sep-01									
7-Sep-01	4.4		75.0	250.0	1350.0	2.0	190.0	55.0	8.5
8-Sep-01									
9-Sep-01	4.4		74.9	250.0	1350.0	1.5	150.0	55.0	8.5
10-Sep-01	5.4		68.0	220.0	1000.0	5.0	153.6	60.0	8.5
11-Sep-01	4.9		68.3	220.0	1389.5	3.0	150.0	50.0	8.6
12-Sep-01	4.8		68.0	220.0	1380.0	4.0	145.0	55.0	8.6
13-Sep-01	4.9		67.0	220.0	1380.0	4.0	140.0	52.0	8.6
Average	4.0		65.0	207.5	1076.3	20.4	157.1	40.5	7.9
Minimum	2.6		54.6	177.0	700.0	1.5	140.0	27.0	7.4
Maximum	5.5		75.0	260.0	1389.5	43.0	190.0	60.0	8.6
St.Dev.	0.7		4.7	23.5	231.2	13.4	12.5	9.7	0.4
Count	30		30	30	30	30	30	30	30

Date *Reactor B* *Run 1*	Removal efficiency (%) PO_4-P (mg/L)	 NH_4-N (mg/L)	 Mg (mg/L)	MgCl Flow (mL/min)	Total Influent Flow (mL/min)	N & P Influent Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
31-Jul-01	34.7	4.6	26.8	46	690	644	2820	3510
1-Aug-01	28.6	4.0	11.4	46	720	674	2800	3520
2-Aug-01	81.0	18.3	51.0	46	700	654	2830	3530
3-Aug-01	64.0	16.1	46.8	46	420	374	2300	2720
9-Aug-01	44.9	6.8	26.6	46	600	554	1550	2150
10-Aug-01	46.3	22.2	19.3	46	675	629	2975	3650
11-Aug-01	30.6	7.5	43.5	46	650	604	2950	3600
15-Aug-01	32.2	19.1	44.5	46	700	654	3500	4200
16-Aug-01	40.4	9.4	43.2	46	800	754	2900	3700
17-Aug-01	36.3	9.1	29.8	46	800	754	2880	3680
18-Aug-01	34.8	15.1	30.4	46	800	754	2920	3720
19-Aug-01								
20-Aug-01	60.0	19.7	41.3	46	800	754	2800	3600
21-Aug-01								
22-Aug-01	60.8	16.2	41.9	46	800	754	2700	3500
23-Aug-01	72.2	19.0	54.9	46	800	754	2700	3500
24-Aug-01	66.8	17.5	45.4	46	800	754	2800	3600
25-Aug-01	67.5	10.6	45.6	46	800	754	2800	3600
26-Aug-01	67.8	11.7	38.5	46	800	754	2825	3625
27-Aug-01	70.4	16.9	52.0	46	800	754	2800	3600
28-Aug-01	70.7	14.9	52.0	46	800	754	2800	3600
29-Aug-01	70.9	21.3	53.2	46	800	754	2800	3600
30-Aug-01	70.4	22.9	53.4	46	800	754	2800	3600
31-Aug-01	71.9	23.2	53.2	46	800	754	2800	3600
1-Sep-01								
2-Sep-01	90.1	31.5	37.7	46	630	584	2800	3430
3-Sep-01	92.8	26.8	47.2	46	650	604	2800	3450
4-Sep-01								
5-Sep-01								
6-Sep-01								
7-Sep-01	97.1	18.2	42.4	46	650	604	2850	3500
8-Sep-01								
9-Sep-01	97.8	35.0	46.9	46	600	554	2650	3250
10-Sep-01	91.9	23.1	34.8	46	500	454	2700	3200
11-Sep-01	95.3	27.0	45.2	46	700	654	3400	4100
12-Sep-01	93.7	29.5	39.4	46	700	654	3390	4090
13-Sep-01	93.6	31.9	42.7	46	700	654	3400	4100
Average	65.9	18.3	41.4	46.0	716.2	670.2	2834.7	3550.8
Minimum	28.6	4.0	11.4	46.0	420.0	374.0	1550.0	2150.0
Maximum	97.8	35.0	54.9	46.0	800.0	754.0	3500.0	4200.0
St.Dev.	22.7	8.2	10.5	0.0	99.0	99.0	346.2	386.0
Count	30	30	30	30	30	30	30	30

Date	Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
	PO_4_P	NH_4-N	Mg	PO_4_P	NH_4-N	Mg	molar ratio	molar ratio		
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(at inlet)	(at inlet)		(at inlet)
Run 1										
31-Jul-01	61.29	181.1	56.0	6.9E-04	6.0E-04	6.2E-04	1.2	6.5	6.0E-08	2.2
1-Aug-01	59.16	165.7	51.9	5.5E-04	4.8E-04	2.4E-04	1.1	6.2	4.9E-08	1.8
2-Aug-01	57.74	177.5	59.1	1.5E-03	2.3E-03	1.2E-03	1.3	6.8	5.8E-08	16.4
3-Aug-01	55.01	169.2	98.6	1.1E-03	1.9E-03	1.9E-03	2.3	6.8	8.8E-08	5.3
9-Aug-01	61.46	178.2	61.3	8.9E-04	8.7E-04	6.7E-04	1.3	6.4	6.4E-08	3.0
10-Aug-01	61.50	179.8	54.5	9.2E-04	2.8E-03	4.3E-04	1.1	6.5	5.8E-08	3.5
11-Aug-01	61.96	185.8	49.5	6.1E-04	9.9E-04	8.9E-04	1.0	6.6	5.5E-08	2.6
15-Aug-01	56.06	210.2	48.6	5.8E-04	2.9E-03	8.9E-04	1.1	8.3	5.5E-08	2.6
16-Aug-01	63.80	179.1	50.6	8.3E-04	1.2E-03	9.0E-04	1.0	6.2	5.5E-08	3.4
17-Aug-01	54.92	183.8	48.9	6.4E-04	1.2E-03	6.0E-04	1.1	7.4	4.7E-08	2.9
18-Aug-01	55.24	179.1	48.9	6.2E-04	1.9E-03	6.1E-04	1.1	7.2	4.6E-08	2.8
19-Aug-01										
20-Aug-01	54.83	197.9	57.5	1.1E-03	2.8E-03	9.8E-04	1.4	8.0	6.0E-08	4.6
21-Aug-01										
22-Aug-01	63.89	170.6	58.1	1.3E-03	2.0E-03	1.0E-03	1.2	5.9	6.1E-08	4.6
23-Aug-01	59.99	221.5	75.3	1.4E-03	3.0E-03	1.7E-03	1.6	8.2	9.6E-08	9.0
24-Aug-01	58.70	169.7	58.7	1.3E-03	2.1E-03	1.1E-03	1.3	6.4	5.6E-08	5.3
25-Aug-01	59.89	173.1	58.7	1.3E-03	1.3E-03	1.1E-03	1.3	6.4	5.8E-08	5.5
26-Aug-01	58.27	168.7	63.3	1.3E-03	1.4E-03	1.0E-03	1.4	6.4	6.0E-08	5.6
27-Aug-01	64.09	185.2	74.8	1.5E-03	2.2E-03	1.6E-03	1.5	6.4	8.5E-08	8.0
28-Aug-01	64.24	185.7	74.8	1.5E-03	2.0E-03	1.6E-03	1.5	6.4	8.6E-08	8.0
29-Aug-01	64.09	200.8	74.8	1.5E-03	3.1E-03	1.6E-03	1.5	6.9	9.2E-08	8.7
30-Aug-01	64.09	199.8	74.8	1.5E-03	3.3E-03	1.6E-03	1.5	6.9	9.2E-08	8.6
31-Aug-01	64.09	197.9	74.8	1.5E-03	3.3E-03	1.6E-03	1.5	6.8	9.1E-08	8.6
1-Sep-01										
2-Sep-01	50.61	241.0	80.3	1.5E-03	5.4E-03	1.2E-03	2.0	10.5	9.4E-08	24.6
3-Sep-01	55.75	232.3	92.6	1.7E-03	4.5E-03	1.8E-03	2.1	9.2	1.2E-07	30.1
4-Sep-01										
5-Sep-01										
6-Sep-01										
7-Sep-01	69.69	232.3	95.5	2.2E-03	3.0E-03	1.7E-03	1.8	7.4	1.5E-07	38.8
8-Sep-01										
9-Sep-01	69.18	230.8	103.5	2.2E-03	5.8E-03	2.0E-03	1.9	7.4	1.6E-07	41.5
10-Sep-01	61.72	199.8	92.0	1.8E-03	3.3E-03	1.3E-03	1.9	7.2	1.1E-07	28.5
11-Sep-01	63.81	205.5	91.3	2.0E-03	4.0E-03	1.7E-03	1.8	7.1	1.1E-07	32.4
12-Sep-01	63.53	205.5	90.7	1.9E-03	4.3E-03	1.5E-03	1.8	7.2	1.1E-07	32.0
13-Sep-01	62.60	205.54	90.7	1.9E-03	4.7E-03	1.6E-03	1.9	7.3	1.1E-07	31.6
Average	60.7	193.8	70.3	1.3E-03	2.6E-03	1.2E-03	1.5	7.1	8.1E-08	12.7
Minimum	50.6	165.7	48.6	5.5E-04	4.8E-04	2.4E-04	1.0	5.9	4.6E-08	1.8
Maximum	69.7	241.0	103.5	2.2E-03	5.8E-03	2.0E-03	2.3	10.5	1.6E-07	41.5
St.Dev.	4.4	21.5	17.5	4.8E-04	1.4E-03	4.8E-04	0.4	1.0	3.0E-08	12.7
Count	30	30	30	30	30	30	30	30	30	30

Date	PO$_4$-P In-Reactor			NH$_4$-N In-Reactor			Mg In-Reactor		
	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Run 1									
31-Jul-01	12.0	32.1	44.2	35.6	138.7	174.3	11.0	32.9	43.9
1-Aug-01	12.1	33.6	45.7	33.9	126.5	160.4	10.6	36.6	47.2
2-Aug-01	11.4	8.8	20.2	35.2	116.2	151.4	11.7	23.2	35.0
3-Aug-01	8.5	16.8	25.3	26.1	120.1	146.2	15.2	44.3	59.5
9-Aug-01	17.2	24.4	41.6	49.7	119.7	169.4	17.1	32.4	49.6
10-Aug-01	11.4	26.9	38.3	33.3	114.1	147.4	10.1	35.9	45.9
11-Aug-01	11.2	35.2	46.4	33.6	140.9	174.5	8.9	22.9	31.9
15-Aug-01	9.3	31.7	41.0	35.0	141.7	176.7	8.1	22.5	30.6
16-Aug-01	13.8	29.8	43.6	38.7	127.2	165.9	10.9	22.5	33.5
17-Aug-01	11.9	27.4	39.3	40.0	130.7	170.6	10.6	26.8	37.5
18-Aug-01	11.9	28.3	40.1	38.5	119.3	157.8	10.5	26.7	37.2
19-Aug-01									
20-Aug-01	12.2	17.1	29.2	44.0	123.7	167.7	12.8	26.3	39.0
21-Aug-01									
22-Aug-01	14.6	19.3	33.9	39.0	110.3	149.3	13.3	26.0	39.3
23-Aug-01	13.7	12.9	26.6	50.6	138.5	189.1	17.2	26.2	43.4
24-Aug-01	13.0	15.2	28.2	37.7	108.9	146.6	13.0	24.9	37.9
25-Aug-01	13.3	15.1	28.5	38.5	120.3	158.8	13.0	24.8	37.8
26-Aug-01	12.9	14.6	27.5	37.2	116.1	153.3	14.0	30.3	44.3
27-Aug-01	14.2	14.8	29.0	41.2	119.8	160.9	16.6	27.9	44.5
28-Aug-01	14.3	14.7	28.9	41.3	122.9	164.2	16.6	27.9	44.5
29-Aug-01	14.2	14.5	28.7	44.6	122.9	167.5	16.6	27.2	43.8
30-Aug-01	14.2	14.8	29.0	44.4	119.8	164.2	16.6	27.1	43.7
31-Aug-01	14.2	14.0	28.2	44.0	118.2	162.2	16.6	27.2	43.8
1-Sep-01									
2-Sep-01	9.3	4.1	13.4	44.3	134.7	179.0	14.8	40.8	55.6
3-Sep-01	10.5	3.2	13.8	43.8	138.0	181.7	17.4	39.6	57.1
4-Sep-01									
5-Sep-01									
6-Sep-01									
7-Sep-01	12.9	1.6	14.6	43.1	154.7	197.9	17.7	44.8	62.5
8-Sep-01									
9-Sep-01	12.8	1.2	14.0	42.6	122.3	164.9	19.1	44.8	64.0
10-Sep-01	9.6	4.2	13.9	31.2	129.6	160.8	14.4	50.6	65.0
11-Sep-01	10.9	2.5	13.4	35.1	124.4	159.5	15.6	41.5	57.1
12-Sep-01	10.9	3.3	14.2	35.2	120.2	155.4	15.5	45.6	61.1
13-Sep-01	10.7	3.3	14.0	35.1	116.1	151.2	15.5	43.1	58.6
Average	12.3	16.2	28.5	39.1	125.2	164.3	14.0	32.5	46.5
Minimum	8.5	1.2	13.4	26.1	108.9	146.2	8.1	22.5	30.6
Maximum	17.2	35.2	46.4	50.6	154.7	197.9	19.1	50.6	65.0
St.Dev.	1.9	10.7	11.1	5.4	10.5	12.5	3.0	8.5	10.2
Count	30	30	30	30	30	30	30	30	30

Date	In-Reactor Concentrations			In-reactor	In-reactor	In-Reactor P_S	Ps (eg)	S.S.Ratio	Effluent SS
	PO_4_P	NH_4-N	Mg	Mg:P	N:P				
Reactor B	(mol/L)	(mol/L)	(mol/L)	(molar ratio)	(molar ratio)			(in-reactor)	
Run 1									
31-Jul-01	1.4E-03	1.2E-02	1.8E-03	1.3	8.7	3.2E-08	2.8E-08	1.2	1.0
1-Aug-01	1.5E-03	1.1E-02	2.0E-03	1.3	7.8	3.3E-08	2.8E-08	1.2	1.1
2-Aug-01	6.5E-04	1.1E-02	1.5E-03	2.2	16.6	1.0E-08	3.5E-09	2.9	1.2
3-Aug-01	8.1E-04	1.0E-02	2.5E-03	3.0	12.8	2.1E-08	1.7E-08	1.3	0.9
9-Aug-01	1.3E-03	1.2E-02	2.1E-03	1.5	9.0	3.3E-08	2.1E-08	1.6	1.1
10-Aug-01	1.2E-03	1.1E-02	1.9E-03	1.6	8.5	2.5E-08	1.7E-08	1.5	1.2
11-Aug-01	1.5E-03	1.2E-02	1.3E-03	0.9	8.3	2.5E-08	2.1E-08	1.2	0.9
15-Aug-01	1.3E-03	1.3E-02	1.3E-03	1.0	9.5	2.1E-08	2.1E-08	1.0	0.8
16-Aug-01	1.4E-03	1.2E-02	1.4E-03	1.0	8.4	2.3E-08	1.7E-08	1.4	1.0
17-Aug-01	1.3E-03	1.2E-02	1.6E-03	1.2	9.6	2.4E-08	1.7E-08	1.5	1.2
18-Aug-01	1.3E-03	1.1E-02	1.5E-03	1.2	8.7	2.3E-08	1.7E-08	1.4	1.1
19-Aug-01									
20-Aug-01	9.4E-04	1.2E-02	1.6E-03	1.7	12.7	1.8E-08	1.3E-08	1.4	0.9
21-Aug-01									
22-Aug-01	1.1E-03	1.1E-02	1.6E-03	1.5	9.8	1.9E-08	1.3E-08	1.5	0.9
23-Aug-01	8.6E-04	1.4E-02	1.8E-03	2.1	15.8	2.1E-08	1.1E-08	2.0	0.9
24-Aug-01	9.1E-04	1.0E-02	1.6E-03	1.7	11.5	1.5E-08	1.1E-08	1.4	0.8
25-Aug-01	9.2E-04	1.1E-02	1.6E-03	1.7	12.4	1.6E-08	1.1E-08	1.5	0.9
26-Aug-01	8.9E-04	1.1E-02	1.8E-03	2.1	12.4	1.8E-08	1.1E-08	1.7	1.0
27-Aug-01	9.4E-04	1.1E-02	1.9E-03	2.0	12.3	2.0E-08	1.1E-08	1.9	0.9
28-Aug-01	9.3E-04	1.2E-02	1.9E-03	2.0	12.6	2.0E-08	1.1E-08	1.9	1.0
29-Aug-01	9.3E-04	1.2E-02	1.8E-03	2.0	12.9	2.0E-08	1.1E-08	1.9	0.9
30-Aug-01	9.4E-04	1.2E-02	1.8E-03	1.9	12.5	2.0E-08	1.1E-08	1.9	0.9
31-Aug-01	9.1E-04	1.2E-02	1.8E-03	2.0	12.7	1.9E-08	1.1E-08	1.8	0.9
1-Sep-01									
2-Sep-01	4.3E-04	1.3E-02	2.3E-03	5.4	29.6	1.3E-08	3.8E-09	3.3	1.0
3-Sep-01	4.4E-04	1.3E-02	2.4E-03	5.4	29.3	1.4E-08	3.8E-09	3.6	0.8
4-Sep-01									
5-Sep-01									
6-Sep-01									
7-Sep-01	4.7E-04	1.4E-02	2.6E-03	5.5	30.1	1.7E-08	3.8E-09	4.5	0.5
8-Sep-01									
9-Sep-01	4.5E-04	1.2E-02	2.7E-03	5.9	26.1	1.4E-08	3.8E-09	3.7	0.3
10-Sep-01	4.5E-04	1.1E-02	2.7E-03	6.1	25.7	1.4E-08	3.8E-09	3.6	1.2
11-Sep-01	4.3E-04	1.1E-02	2.4E-03	5.5	26.4	1.2E-08	3.5E-09	3.3	0.6
12-Sep-01	4.6E-04	1.1E-02	2.5E-03	5.56	24.2	1.3E-08	3.5E-09	3.6	0.9
13-Sep-01	4.5E-04	1.1E-02	2.4E-03	5.41	23.9	1.2E-08	3.5E-09	3.4	0.8
Average	9.2E-04	1.2E-02	1.9E-03	2.7	15.4	2.0E-08	1.2E-08	2.1	0.9
Minimum	4.3E-04	1.0E-02	1.3E-03	0.9	7.8	1.0E-08	3.5E-09	1.0	0.3
Maximum	1.5E-03	1.4E-02	2.7E-03	6.1	30.1	3.3E-08	2.8E-08	4.5	1.2
St.Dev.	3.6E-04	8.9E-04	4.2E-04	1.8	7.5	6.1E-09	7.1E-09	1.0	0.2
Count	30	30	30	30	30	30	30	30	30

Date	Crystal Volume	Harvest Volume	CRT Actual	CRT Averaged In reactor				Harvested Product Data		
					>4.75mm	>2.83mm	>2 mm	>1mm	>0.5mm	<0.5mm
Reactor B Run 1	(L)	(L)	(days)	SS Ratio	(g)	(g)	(g)	(g)	(g)	(g)
31-Jul-01										
1-Aug-01										
2-Aug-01										
3-Aug-01										
9-Aug-01										
10-Aug-01										
11-Aug-01										
15-Aug-01	5.5	0.41			0	33.5	110	2	0.6	0
16-Aug-01	5.5	0.41			0	31.8	115	7	2.3	0
17-Aug-01	5.8	0.41			0	38	170	0.3	0.3	0
18-Aug-01	5.8	0.41			0	30	120	0.7	0.7	0
19-Aug-01										
20-Aug-01	7	0.41			0	21.2	140	0.4	0.6	0
21-Aug-01										
22-Aug-01	8	1.3			0	289	52.5	0.3	5.5	55.2
23-Aug-01	8	1.3			0	295	54	0	24.9	0
24-Aug-01	8.1	1.3	7.0	1.5	0	170	50	1.5	3.1	22
25-Aug-01	8.6	1.3	8.0	1.5	0	225	58	20	1	13.1
26-Aug-01	8.6	1.3	8.0	1.5	0	300	56.5	5	11.7	19
27-Aug-01										
28-Aug-01	8.5	1.3	8.0	1.6	0	280	110.1	3.6	4	12
29-Aug-01										
30-Aug-01										
31-Aug-01										
1-Sep-01										
2-Sep-01	8.2	1.3	11.0	1.6	0	278	1.7	0.3	0.4	6
3-Sep-01										
4-Sep-01										
5-Sep-01										
6-Sep-01										
7-Sep-01										
8-Sep-01										
9-Sep-01										
10-Sep-01	8	1.3	16.0	2.3	8.9	267.8	0.1	0.1	0.1	0.4
11-Sep-01	8	1.3	16	2.4	4	279	2	0.5	0.3	5
12-Sep-01										
13-Sep-01	8.3	1.3	17	2.6	0	154	72	33	0.4	2.2
Average	7.5	1.0	11.4	1.9	0.9	179.5	74.1	5.0	3.7	9.0
Minimum	5.5	0.4	7.0	1.5	0.0	21.2	0.1	0.0	0.1	0.0
Maximum	8.6	1.3	17.0	2.6	8.9	300.0	170.0	33.0	24.9	55.2
St.Dev.	1.2	0.4	4.3	0.5	2.5	116.7	52.0	9.3	6.6	14.8
Count	15	15	8	8	15	15	15	15	15	15

Date	Total Mass	Percentage Size Fractions						Mean Crystal	Mass P	Theoretical
		>4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	< 0.5mm	Size (mm)	Removed	Mass MAP
Reactor B	(g)								(g)	Grown
Run 1										
31-Jul-01									21.2	167.9
1-Aug-01									17.6	139.3
2-Aug-01									47.1	374.2
3-Aug-01									21.3	168.9
9-Aug-01									23.9	189.3
10-Aug-01									27.7	219.9
11-Aug-01									17.7	140.9
15-Aug-01	146.1	0	22.9	75.3	1.4	0.4	0.0	2.7	18.2	144.5
16-Aug-01	156.1	0	20.4	73.7	4.5	1.5	0.0	2.6	29.7	235.9
17-Aug-01	208.6	0	18.2	81.5	0.1	0.1	0.0	2.6	22.9	182.1
18-Aug-01	151.4	0	19.8	79.3	0.5	0.5	0.0	2.6	22.2	175.9
19-Aug-01										
20-Aug-01	162.2	0	13.1	86.3	0.2	0.4	0.0	2.6	37.9	300.8
21-Aug-01										
22-Aug-01	402.5	0	71.8	13.0	0.1	1.4	13.7	3.0	44.8	355.4
23-Aug-01	373.9	0	78.9	14.4	0.0	6.7	0.0	3.3	49.9	396.2
24-Aug-01	246.6	0	68.9	20.3	0.6	1.3	8.9	3.1	45.2	358.6
25-Aug-01	317.1	0	71.0	18.3	6.3	0.3	4.1	3.2	46.6	369.5
26-Aug-01	392.2	0	76.5	14.4	1.3	3.0	4.8	3.2	45.5	361.2
27-Aug-01									51.9	412.3
28-Aug-01	409.7	0	68.3	26.9	0.9	1.0	2.9	3.2	52.3	415.0
29-Aug-01									52.3	415.5
30-Aug-01									51.9	412.3
31-Aug-01									53.1	421.4
1-Sep-01										
2-Sep-01	286.4	0	97.1	0.6	0.1	0.1	2.1	3.6	41.4	328.4
3-Sep-01									48.4	384.5
4-Sep-01										
5-Sep-01										
6-Sep-01										
7-Sep-01									63.4	502.9
8-Sep-01										
9-Sep-01									58.5	464.1
10-Sep-01	277.4	3.2	96.5	0.0	0.0	0.0	0.1	3.7	40.8	324.1
11-Sep-01	290.8	1.4	95.9	0.7	0.2	0.1	1.7	3.6	61.3	486.5
12-Sep-01									60.0	476.3
13-Sep-01	261.6	0	58.9	27.5	12.6	0.2	0.8	3.0	59.1	468.8
Average	272.2	0.3	58.5	35.5	1.9	1.1	2.6	3.1	41.1	326.4
Minimum	146.1	0.0	13.1	0.0	0.0	0.0	0.0	2.6	17.6	139.3
Maximum	409.7	3.2	97.1	86.3	12.6	6.7	13.7	3.7	63.4	502.9
St.Dev.	94.2	0.9	31.1	33.2	3.5	1.7	4.0	0.4	15.0	118.7
Count	15	15	15	15	15	15	15	15	30	30

Date	Recyle flow	Temp °C	Influent Lab results			Effluent Lab results			pH
			PO_4-P	NH_4-N	Mg	PO_4-P	NH_4-N	Mg	
Reactor B			(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	
Run 2									
24-Sep-01	5.8	18.0	92.0	200.0	1165.0	21.0	160.0	24.6	7.7
25-Sep-01	6.0	16.0	80.5	196.0	1162.0	45.0	166.0	54.8	7.4
26-Sep-01	6.8	15.0	85.7	201.0	1101.0	44.0	163.0	46.0	7.8
27-Sep-01	7.1	14.0	87.3	202.5	1150.0	10.0	156.0	22.0	8.1
28-Sep-01	6.2	14.0	80.0	210.0	1102.0	10.9	157.0	23.0	8.1
29-Sep-01	6.2	16.0	80.0	195.0	1104.0	10.0	170.0	25.0	8.1
30-Sep-01	5.6	15.0	78.8	197.5	1342.4	5.5	141.0	40.0	8.4
1-Oct-01	5.9	14.0	79.5	201.7	1100.0	19.8	148.9	27.8	8.0
2-Oct-01	7.6	14.0	82.4	197.7	1102.4	11.2	130.0	37.0	8.1
3-Oct-01	6.0	14.0	81.5	213.0	1102.0	13.8	157.4	17.0	8.1
4-Oct-01	6.3	14.0	75.2	191.0	700.0	15.0	150.1	9.8	8.3
5-Oct-01	6.0	14.0	79.0	220.0	800.0	19.7	178.2	12.0	8.2
6-Oct-01	6.1	14.0	84.0	208.0	833.3	19.5	166.9	11.0	8.3
7-Oct-01	6.0	13.0	84.0	220.0	833.0	24.4	180.7	10.0	8.3
8-Oct-01	6.0	14.0	72.6	199.0	1853.5	3.9	136.2	70.0	8.3
9-Oct-01									
10-Oct-01	5.9	10.0	74.0	219.0	977.5	8.4	177.3	20.0	8.3
11-Oct-01	5.7	12.0	86.5	179.0	830.0	21.0	124.0	10.0	8.5
12-Oct-01	16.4	13.0	85.0	179.0	1213.8	2.6	113.0	194.2	8.5
14-Oct-01	6.3	13.0	87.0	220.0	1218.0	6.4	168.8	25.0	8.5
15-Oct-01	6.3	14.0	82.7	220.0	1215.2	4.6	169.5	29.0	8.5
16-Oct-01	6.1	14.0	97.8	220.0	915.6	16.3	163.9	10.0	8.5
17-Oct-01	5.9	13.0	93.0	220.0	915.0	7.5	160.4	24.6	8.6
24-Oct-01	6.3	14.0	82.0	220.0	1200.0	5.0	170.0	29.0	8.5
25-Oct-01	6.3	14.0	84.0	220.0	1200.0	5.5	169.0	30.0	8.5
26-Oct-01									
27-Oct-01									
28-Oct-01	6.3	13.0	82.0	221.0	1200.0	6.0	172.0	28.0	8.6
29-Oct-01	6.3	14.0	82.0	220.0	1200.0	5.0	170.0	30.0	8.6
Average	6.6	14.0	83.0	207.3	1097.5	13.9	158.4	33.1	8.3
Minimum	5.6	10.0	72.6	179.0	700.0	2.6	113.0	9.8	7.4
Maximum	16.4	18.0	97.8	221.0	1853.5	45.0	180.7	194.2	8.6
St.Dev.	2.1	1.4	5.6	13.2	225.0	11.0	17.2	35.8	0.3
Count	26	26	26	26	26	26	26	26	26

Removal efficiency (%) PO$_4$-P (mg/L)	NH$_4$N (mg/L)	Mg (mg/L)	MgCl Flow (mL/min)	Total Influent Flow (mL/min)	N & P Influent Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
75.6	14.6	66.4	33	525	492	3025	3550
40.1	9.3	28.5	33	500	467	3000	3500
44.0	11.6	49.4	33	400	367	2700	3100
87.6	16.5	75.4	33	425	392	3000	3425
85.4	19.7	70.0	33	475	442	2950	3425
86.6	6.3	67.4	33	475	442	2950	3425
92.6	23.6	54.9	33	500	467	2800	3300
73.4	21.2	59.7	33	525	492	3075	3600
85.2	28.7	56.8	33	425	392	3225	3650
81.9	21.1	75.9	32	500	468	3000	3500
78.6	15.7	79.2	32	475	443	2975	3450
73.4	13.6	76.1	32	510	478	3040	3550
75.2	14.4	79.0	32	510	478	3090	3600
69.0	12.2	81.2	32	500	468	3000	3500
94.3	26.9	41.0	32	500	468	3000	3500
87.9	13.6	67.4	32	510	478	2990	3500
74.1	26.1	80.8	32	510	478	2890	3400
96.2	21.1	20.0	32	160	128	2630	2790
92.1	17.7	69.5	32	475	443	2975	3450
94.1	17.7	62.7	32	500	468	3150	3650
82.2	20.4	82.9	32	500	468	3050	3550
91.2	20.7	66.4	40	500	460	2950	3450
93.5	17.4	62.2	32	500	468	3150	3650
93.0	17.9	60.9	32	500	468	3150	3650
92.2	16.9	63.5	32	500	468	3150	3650
93.5	17.4	60.9	32	500	468	3150	3650
82.0	17.8	63.8	32.7	476.9	444.3	3002.5	3479.4
40.1	6.3	20.0	32.0	160.0	128.0	2630.0	2790.0
96.2	28.7	82.9	40.0	525.0	492.0	3225.0	3650.0
14.2	5.3	15.5	1.6	71.3	71.3	137.0	188.7
26	26	26	26	26	26	26	26

Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
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)	molar ratio (at inlet)	molar ratio (at inlet)		(at inlet)
86.22	187.4	73.2	2.1E-03	2.0E-03	2.0E-03	1.1	4.8	1.1E-07	8.6
75.19	183.1	76.7	9.7E-04	1.2E-03	9.0E-04	1.3	5.4	1.0E-07	3.7
78.63	184.4	90.8	1.1E-03	1.5E-03	1.8E-03	1.5	5.2	1.3E-07	11.9
80.52	186.8	89.3	2.3E-03	2.2E-03	2.8E-03	1.4	5.1	1.3E-07	20.8
74.44	195.4	76.6	2.0E-03	2.7E-03	2.2E-03	1.3	5.8	1.1E-07	17.3
74.44	181.5	76.7	2.1E-03	8.2E-04	2.1E-03	1.3	5.4	9.9E-08	16.1
73.60	184.5	88.6	2.2E-03	3.1E-03	2.0E-03	1.6	5.5	1.2E-07	27.5
74.50	189.0	69.1	1.8E-03	2.9E-03	1.7E-03	1.2	5.6	9.3E-08	12.8
76.00	182.3	85.6	2.1E-03	3.7E-03	2.0E-03	1.5	5.3	1.1E-07	18.4
76.28	199.4	70.5	2.0E-03	3.0E-03	2.2E-03	1.2	5.8	1.0E-07	16.6
70.13	178.1	47.2	1.8E-03	2.0E-03	1.5E-03	0.9	5.6	5.7E-08	12.0
74.04	206.2	50.2	1.8E-03	2.0E-03	1.6E-03	0.9	6.2	7.4E-08	13.8
78.73	194.9	52.3	1.9E-03	2.0E-03	1.7E-03	0.9	5.5	7.7E-08	16.4
78.62	205.9	53.3	1.7E-03	1.8E-03	1.8E-03	0.9	5.8	8.3E-08	17.6
67.95	186.3	118.6	2.1E-03	3.6E-03	2.0E-03	2.3	6.1	1.4E-07	30.7
69.36	205.3	61.3	2.0E-03	2.0E-03	1.7E-03	1.1	6.6	8.4E-08	17.8
81.07	167.8	52.1	1.9E-03	3.1E-03	1.7E-03	0.8	4.6	6.8E-08	17.8
68.00	143.2	242.8	2.1E-03	2.2E-03	2.0E-03	4.6	4.7	2.3E-07	59.3
81.14	205.2	82.1	2.4E-03	2.6E-03	2.3E-03	1.3	5.6	1.3E-07	34.3
77.41	205.9	77.8	2.3E-03	2.6E-03	2.0E-03	1.3	5.9	1.2E-07	31.1
91.54	205.9	58.6	2.4E-03	3.0E-03	2.0E-03	0.8	5.0	1.1E-07	27.7
85.56	202.4	73.2	2.5E-03	3.0E-03	2.0E-03	1.1	5.2	1.2E-07	34.3
76.75	205.9	76.8	2.3E-03	2.6E-03	2.0E-03	1.3	5.9	1.2E-07	30.5
78.62	205.9	76.8	2.4E-03	2.6E-03	1.9E-03	1.3	5.8	1.2E-07	31.2
76.75	206.9	76.8	2.3E-03	2.5E-03	2.0E-03	1.3	6.0	1.2E-07	33.0
76.75	205.9	76.8	2.3E-03	2.6E-03	1.9E-03	1.3	5.9	1.2E-07	32.8
77.0	192.5	79.8	2.0E-03	2.4E-03	1.9E-03	1.4	5.6	1.1E-07	22.9
68.0	143.2	47.2	9.7E-04	8.2E-04	9.0E-04	0.8	4.6	5.7E-08	3.7
91.5	206.9	242.8	2.5E-03	3.7E-03	2.8E-03	4.6	6.6	2.3E-07	59.3
5.4	15.2	36.7	3.7E-04	6.8E-04	3.3E-04	0.7	0.5	3.2E-08	11.6
26	26	26	26	26	26	26	26	26	26

PO$_4$-P In-Reactor			NH$_4$-N In-Reactor			Mg In-Reactor		
Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)	Feed gives (mg/L)	Recycle gives (mg/L)	Total (mg/L)
12.8	17.9	30.6	27.7	136.3	164.1	10.8	21.0	31.8
10.7	38.6	49.3	26.2	142.3	168.4	11.0	47.0	58.0
10.1	38.3	48.5	23.8	142.0	165.8	11.7	40.1	51.8
10.0	8.8	18.8	23.2	136.6	159.8	11.1	19.3	30.4
10.3	9.4	19.7	27.1	135.2	162.3	10.6	19.8	30.4
10.3	8.6	18.9	25.2	146.4	171.6	10.6	21.5	32.2
11.2	4.6	15.8	27.9	119.6	147.6	13.4	33.9	47.4
10.9	16.9	27.8	27.6	127.2	154.8	10.1	23.8	33.9
8.8	9.9	18.8	21.2	114.9	136.1	10.0	32.7	42.7
10.9	11.8	22.7	28.5	134.9	163.4	10.1	14.6	24.6
9.7	12.9	22.6	24.5	129.5	154.0	6.5	8.5	14.9
10.6	16.9	27.5	29.6	152.6	182.2	7.2	10.3	17.5
11.2	16.7	27.9	27.6	143.3	170.9	7.4	9.4	16.8
11.2	20.9	32.1	29.4	154.9	184.3	7.6	8.6	16.2
9.7	3.3	13.1	26.6	116.7	143.4	16.9	60.0	76.9
10.1	7.2	17.3	29.9	151.4	181.3	8.9	17.1	26.0
12.2	17.9	30.0	25.2	105.4	130.6	7.8	8.5	16.3
3.9	2.5	6.4	8.2	106.5	114.7	13.9	183.0	196.9
11.2	5.5	16.7	28.2	145.5	173.8	11.3	21.6	32.9
10.6	4.0	14.6	28.2	146.3	174.5	10.7	25.0	35.7
12.9	14.0	26.9	29.0	140.8	169.8	8.3	8.6	16.8
12.4	6.4	18.8	29.3	137.2	166.5	10.6	21.0	31.6
10.5	4.3	14.8	28.2	146.7	174.9	10.5	25.0	35.5
10.8	4.7	15.5	28.2	145.8	174.1	10.5	25.9	36.4
10.5	5.2	15.7	28.3	148.4	176.8	10.5	24.2	34.7
10.5	4.3	14.8	28.2	146.7	174.9	10.5	25.9	36.4
10.5	12.0	22.5	26.4	136.7	163.1	10.3	29.1	39.4
3.9	2.5	6.4	8.2	105.4	114.7	6.5	8.5	14.9
12.9	38.6	49.3	29.9	154.9	184.3	16.9	183.0	196.9
1.6	9.5	10.0	4.3	13.9	16.9	2.2	33.7	35.1
26	26	26	26	26	26	26	26	26

In-Reactor Concentrations PO$_4$-P (mol/L)	NH$_4$-N (mol/L)	Mg (mol/L)	In-reactor Mg:P (molar ratio)	In-reactor N:P (molar ratio)	In-Reactor P_S	Ps (eg)	S.S.Ratio (in-reactor)	Effluent SS
9.9E-04	1.2E-02	1.3E-03	1.3	11.9	1.5E-08	1.3E-08	1.2	0.6
1.6E-03	1.2E-02	2.4E-03	1.5	7.6	4.6E-08	2.8E-08	1.7	1.4
1.6E-03	1.2E-02	2.2E-03	1.4	7.6	4.0E-08	1.1E-08	3.8	3.0
6.0E-04	1.1E-02	1.3E-03	2.1	18.9	8.7E-09	6.2E-09	1.4	0.5
6.4E-04	1.2E-02	1.3E-03	2.0	18.2	9.3E-09	6.2E-09	1.5	0.6
6.1E-04	1.2E-02	1.3E-03	2.2	20.1	1.0E-08	6.2E-09	1.6	0.7
5.1E-04	1.1E-02	2.0E-03	3.9	20.7	1.1E-08	4.2E-09	2.5	0.7
9.0E-04	1.1E-02	1.4E-03	1.6	12.3	1.4E-08	7.3E-09	1.9	1.1
6.1E-04	9.7E-03	1.8E-03	2.9	16.0	1.0E-08	6.2E-09	1.7	0.8
7.3E-04	1.2E-02	1.0E-03	1.4	15.9	8.8E-09	6.2E-09	1.4	0.6
7.3E-04	1.1E-02	6.2E-04	0.9	15.1	5.0E-09	4.7E-09	1.1	0.5
8.9E-04	1.3E-02	7.3E-04	0.8	14.7	8.4E-09	5.3E-09	1.6	0.8
9.0E-04	1.2E-02	7.0E-04	0.8	13.6	7.7E-09	4.7E-09	1.6	0.7
1.0E-03	1.3E-02	6.7E-04	0.7	12.7	9.2E-09	4.7E-09	2.0	0.9
4.2E-04	1.0E-02	3.2E-03	7.6	24.3	1.4E-08	4.7E-09	2.9	0.8
5.6E-04	1.3E-02	1.1E-03	1.9	23.2	7.8E-09	4.7E-09	1.7	0.6
9.7E-04	9.3E-03	6.8E-04	0.7	9.6	6.1E-09	3.8E-09	1.6	0.7
2.0E-04	8.2E-03	8.2E-03	40.1	40.0	1.4E-08	3.8E-09	3.6	1.4
5.4E-04	1.2E-02	1.4E-03	2.5	23.1	9.1E-09	3.8E-09	2.4	0.7
4.7E-04	1.2E-02	1.5E-03	3.2	26.5	8.7E-09	3.8E-09	2.3	0.6
8.7E-04	1.2E-02	7.0E-04	0.8	14.0	7.4E-09	3.8E-09	1.9	0.7
6.1E-04	1.2E-02	1.3E-03	2.2	19.6	9.5E-09	3.5E-09	2.7	0.8
4.8E-04	1.2E-02	1.5E-03	3.1	26.1	8.9E-09	3.8E-09	2.3	0.6
5.0E-04	1.2E-02	1.5E-03	3.0	24.8	9.4E-09	3.8E-09	2.5	0.7
5.1E-04	1.3E-02	1.4E-03	2.9	24.9	9.2E-09	3.5E-09	2.6	0.8
4.8E-04	1.2E-02	1.5E-03	3.2	26.1	9.1E-09	3.5E-09	2.6	0.7
7.3E-04	1.2E-02	0.0	3.6	18.8	1.2E-08	6.2E-09	2.1	0.8
2.0E-04	8.2E-03	0.0	0.7	7.6	5.0E-09	3.5E-09	1.1	0.5
1.6E-03	1.3E-02	0.0	40.1	40.0	4.6E-08	2.8E-08	3.8	3.0
3.2E-04	1.2E-03	0.0	7.6	7.3	9.4E-09	4.9E-09	0.7	0.5
26	26	26	26	26	26	26	26	26

Crystal Volume (L)	Harvest Volume (L)	CRT Actual (days)	CRT Averaged In reactor SS Ratio	Harvested Product Data >4.75mm (g)	>2.83mm (g)	>2 mm (g)	>1mm (g)	>0.5mm (g)	<0.5mm (g)
5.1									
5.5									
5.1									
5.5									
6.3									
6.6									
7	1.3			0	100	184	15.9	0	1.5
7									
7	1.3			0	107	216	1	0.2	1.6
6.8									
7									
7.2	1.3			0	398	20.2	2.4	1.4	7
8									
7.3	1.3			0	385	15.1	1.7	2	8.2
7.3	1.3	10.0	1.8	0	248	22.2	1.8	1.2	3
5.3									
7.2	1.3	12.0	1.8	0	405	12	0.5	0.4	0
7.2									
6.8									
7	1.3	10.0	2	0	411	68	0.3	0.2	0.6
7.4									
7.2	1.3	10.0	2.2	0	468	90.5	0.3	0.2	0.1
7.3									
7.4	1.3	12.0	2.2	0	410	13	0.2	1	0
7.4	1.3	12	2.3	5	400	15	0.4	1.4	0
7.4	1.3	11	2.3	3	390	20	2	3	0.5
6.8	1.3	11.0	2.1	0.7	338.4	61.5	2.4	1.0	2.0
5.1	1.3	10.0	1.8	0.0	100.0	12.0	0.2	0.0	0.0
8.0	1.3	12.0	2.3	5.0	468.0	216.0	15.9	3.0	8.2
0.8	0.0	1.0	0.2	1.7	127.4	73.4	4.5	0.9	2.9
26	11	7	7	11	11	11	11	11	11

Total Mass (g)	Percentage Size Fractions						Mean Crystal Size (mm)	Mass P Removed (g)	Theoretical Mass MAP Grown
	>4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	< 0.5mm			
								49.3	391.3
								21.7	172.5
								19.9	158.3
								43.2	342.5
								43.5	344.9
								44.1	349.8
301.4	0	33.2	61.0	5.3	0	0.5	2.8	49.1	389.3
								41.4	328.2
325.8	0	32.8	66.3	0.3	0.1	0.5	2.8	39.6	314.6
								45.0	357.1
								37.7	299.3
429	0	92.8	4.7	0.6	0.3	1.6	3.6	39.9	316.7
								43.5	345.2
412	0	93.4	3.7	0.4	0.5	2.0	3.6	39.0	309.9
								46.1	366.0
276.2	0	89.8	8.0	0.7	0.4	1.1	3.5		
								44.8	355.3
417.9	0	96.9	2.9	0.1	0.1	0.0	3.7	44.1	350.1
								15.1	119.6
								51.1	405.7
480.1	0	85.6	14.2	0.1	0.0	0.1	3.5	52.4	416.0
								54.2	429.9
559.1	0	83.7	16.2	0.1	0.0	0.0	3.5	56.2	446.1
								51.7	410.0
424.2	0	96.7	3.1	0.0	0.2	0.0	3.7	52.6	417.9
421.8	1.19	94.8	3.6	0.1	0.3	0.0	3.7	50.9	404.3
418.5	0.72	93.2	4.8	0.5	0.7	0.1	3.6	51.7	410.0
406.0	0.2	81.2	17.1	0.7	0.3	0.5	3.4	43.4	344.3
276.2	0.0	32.8	2.9	0.0	0.0	0.0	2.8	15.1	119.6
559.1	1.2	96.9	66.3	5.3	0.7	2.0	3.7	56.2	446.1
80.4	0.4	24.2	23.5	1.5	0.2	0.7	0.3	10.4	82.2
11	11	11	11	11	11	11	11	26	26

Date *Reactor B* *Run 3*	Recyle flow	Temp ° C	Influent Lab results PO_4-P (mg/L)	 NH_4.N (mg/L)	 Mg (mg/L)	Effluent Lab results PO_4-P (mg/L)	 NH_4.N (mg/L)	 Mg (mg/L)	pH
18-Mar-02	9.8	5.0	148.7	332.2	2380.0	12.2	241.2	128.1	7.7
19-Mar-02	9.7	6.0	151.4	325.9	2380.0	12.0	225.2	126.8	7.7
20-Mar-02	9.6	8.0	150.7	322.4	2400.0	12.8	222.5	125.4	7.7
25-Mar-02	9.9	8.0	177.9	305.1	2466.4	11.4	210.0	113.7	7.5
26-Mar-02	8.9	8.0	185.7	350.0	2144.9	103.9	277.1	141.0	6.6
27-Mar-02	9.8	8.0	179.3	350.2	1995.9	9.8	247.0	68.0	7.5
29-Mar-02	7.3	7.0	178.3	340.4	2560.0	14.4	250.8	50.0	7.7
30-Mar-02	24.3	9.0	159.5	239.2	1800.0	43.1	160.5	234.4	7.1
31-Mar-02	11.3	9.0	154.8	237.8	1800.0	44.9	173.5	71.1	7.3
1-Apr-02	10.3	10.0	150.1	217.1	1800.0	32.9	137.1	53.4	7.4
2-Apr-02	9.6	8	171.2	240.0	2110.4	18.7	160.0	40.0	7.6
3-Apr-02	10.7	10	155.4	229.0	1800.0	20.7	145.0	57.7	7.6
4-Apr-02	13.3	11	170.2	228.8	1800.0	13.7	131.6	60.0	7.7
5-Apr-02	10.8	12	179.0	260.0	2322.7	9.7	140.0	50.0	7.9
6-Apr-02	15.5	10	162.5	217.1	2200.0	3.9	123.8	142.5	8.0
7-Apr-02	7.1	10	182.0	220.0	2200.0	36.3	148.1	12.8	7.9
8-Apr-02									
9-Apr-02									
10-Apr-02									
11-Apr-02	12.3	13.0	173.7	300.0	3200.0	9.6	209.3	104.5	7.7
12-Apr-02									
13-Apr-02	10.7	13.0	144.5	300.0	3200.0	5.2	221.3	87.4	7.9
14-Apr-02									
15-Apr-02									
16-Apr-02									
17-Apr-02									
18-Apr-02	8.5	8.0	142.7	220.0	3444.0	8.5	150.2	75.0	7.7
19-Apr-02	11.0	10.0	164.8	202.7	3100.0	8.9	123.4	109.5	7.7
20-Apr-02	10.2	13.0	164.0	198.0	3101.0	7.6	120.1	77.9	7.9
21-Apr-02	10.1	13.0	168.3	200.3	3101.0	9.0	121.7	80.0	7.8
22-Apr-02									
23-Apr-02	9.6	8.0	163.9	282.0	3200.0	6.8	190.0	99.7	7.6
24-Apr-02	15.0	11.0	159.9	280.0	3200.0	9.4	191.3	75.0	7.8
25-Apr-02	10.4	11.0	170.0	280.0	3200.0	12.3	190.0	70.0	7.8
26-Apr-02	10.0	8.0	177.7	300.0	3263.7	5.1	210.1	65.0	7.8
27-Apr-02									
28-Apr-02									
29-Apr-02	11.7	12.0	255.0	377.5	1294.9	19.6	227.8	70.0	7.4
30-Apr-02	6.0	12.0	243.0	371.2	1187.0	144.0	293.6	15.2	7.3
1-May-02									
2-May-02									
3-May-02	11.8	12.0	241.0	362.2	1236.5	19.6	217.8	70.0	7.4
4-May-02	17.0	13.0	240.0	365.7	1157.0	7.2	190.3	167.7	7.5
5-May-02	17.0	10.0	240.0	360.0	1156.0	7.3	186.0	167.7	7.5
6-May-02	17.0	10.0	242.0	360.0	1156.9	7.3	186.0	167.7	7.5
7-May-02									
8-May-02									
9-May-02									
11-May-02									
12-May-02	19.4	18.0	235.0	305.0	1107.6	23.0	169.8	100.0	7.3

Date *Reactor B* *Run 3*	Removal efficiency (%) PO_4-P (mg/L)	 NH_4-N (mg/L)	 Mg (mg/L)	MgCl Flow (mL/min)	Total Influent Flow (mL/min)	N & P Influent Flow (mL/min)	Recycle Flow (mL/min)	Total flow (influent+recycle) (mL/min)
18-Mar-02	90.9	19.8	43.1	32	338	306	3300	3638
19-Mar-02	91.3	23.7	43.4	32	340	308	3300	3640
20-Mar-02	90.6	23.9	43.7	32	345	313	3310	3655
25-Mar-02	92.9	24.2	49.6	32	350	318	3450	3800
26-Mar-02	38.6	13.2	25.6	32	362	330	3238	3600
27-Mar-02	94.0	22.1	64.1	32	337	305	3313	3650
29-Mar-02	91.4	21.8	66.0	23	400	377	2900	3300
30-Mar-02	67.6	19.5	21.9	25	150	125	3650	3800
31-Mar-02	68.5	20.7	50.6	24	300	276	3400	3700
1-Apr-02	76.2	31.4	62.9	24	300	276	3100	3400
2-Apr-02	88.2	28.3	73.2	23	325	302	3125	3450
3-Apr-02	85.5	30.9	61.5	25	300	275	3200	3500
4-Apr-02	91.1	36.7	63.6	24	262	238	3478	3740
5-Apr-02	94.1	41.9	70.8	24	325	301	3525	3850
6-Apr-02	97.3	35.2	46.0	24	200	176	3100	3300
7-Apr-02	78.9	28.9	89.1	24	450	426	3200	3650
8-Apr-02								
9-Apr-02								
10-Apr-02								
11-Apr-02	94.1	25.1	52.8	19	275	256	3375	3650
12-Apr-02								
13-Apr-02	96.2	21.4	55.6	20	325	305	3475	3800
14-Apr-02								
15-Apr-02								
16-Apr-02								
17-Apr-02								
18-Apr-02	93.7	28.1	56.4	20	400	380	3400	3800
19-Apr-02	94.2	34.8	47.0	20	300	280	3300	3600
20-Apr-02	95.1	35.4	58.9	20	327	307	3350	3677
21-Apr-02	94.3	35.6	54.9	20	350	330	3550	3900
22-Apr-02								
23-Apr-02	95.6	28.2	49.4	20	325	305	3125	3450
24-Apr-02	93.7	26.8	64.8	20	300	280	4500	4800
25-Apr-02	92.3	28.0	61.7	20	350	330	3655	4005
26-Apr-02	97.0	25.7	65.1	20	350	330	3500	3850
27-Apr-02								
28-Apr-02								
29-Apr-02	90.8	27.6	67.6	50	300	250	3500	3800
30-Apr-02	34.8	13.0	85.9	50	550	500	3300	3850
1-May-02								
2-May-02								
3-May-02	90.2	27.8	66.0	50	300	250	3550	3850
4-May-02	96.0	30.6	42.0	50	200	150	3400	3600
5-May-02	95.9	31.1	42.0	50	200	150	3400	3600
6-May-02	96.0	31.1	42.0	50	200	150	3400	3600
7-May-02								
8-May-02								
9-May-02								
11-May-02								
12-May-02	87.8	30.4	54.9	50	250	200	4850	5100

Date	Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
	PO_4-P	NH_4-N	Mg	PO_4-P	NH_4-N	Mg	molar ratio	molar ratio		
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(at inlet)	(at inlet)		(at inlet)
Run 3										
18-Mar-02	134.62	300.7	225.3	3.9E-03	4.3E-03	4.0E-03	2.2	4.9	8.8E-07	59.6
19-Mar-02	137.15	295.2	224.0	4.0E-03	5.0E-03	4.0E-03	2.1	4.8	8.7E-07	59.3
20-Mar-02	136.72	292.5	222.6	4.0E-03	5.0E-03	4.0E-03	2.1	4.7	8.5E-07	58.2
25-Mar-02	161.63	277.2	225.5	4.8E-03	4.8E-03	4.6E-03	1.8	3.8	9.7E-07	42.8
26-Mar-02	169.28	319.1	189.6	2.1E-03	3.0E-03	2.0E-03	1.4	4.2	9.8E-07	3.7
27-Mar-02	162.27	316.9	189.5	4.9E-03	5.0E-03	5.0E-03	1.5	4.3	9.4E-07	41.2
29-Mar-02	168.05	320.8	147.2	5.0E-03	5.0E-03	4.0E-03	1.1	4.2	7.6E-07	51.9
30-Mar-02	132.92	199.3	300.0	2.9E-03	2.8E-03	2.7E-03	2.9	3.3	7.6E-07	13.2
31-Mar-02	142.42	218.8	144.0	3.1E-03	3.2E-03	3.0E-03	1.3	3.4	4.3E-07	12.1
1-Apr-02	138.09	199.7	144.0	3.4E-03	4.5E-03	3.7E-03	1.3	3.2	3.8E-07	13.4
2-Apr-02	159.08	223.0	149.4	4.5E-03	4.5E-03	4.5E-03	1.2	3.1	5.1E-07	27.9
3-Apr-02	142.45	209.9	150.0	3.9E-03	4.6E-03	3.8E-03	1.4	3.3	4.3E-07	23.6
4-Apr-02	154.61	207.8	164.9	4.5E-03	5.4E-03	4.3E-03	1.4	3.0	5.1E-07	34.6
5-Apr-02	165.78	240.8	171.5	5.0E-03	7.2E-03	5.0E-03	1.3	3.2	6.6E-07	68.0
6-Apr-02	143.00	191.0	264.0	4.5E-03	4.8E-03	5.0E-03	2.4	3.0	6.9E-07	87.6
7-Apr-02	172.29	208.3	117.3	4.4E-03	4.3E-03	4.3E-03	0.9	2.7	4.0E-07	41.8
8-Apr-02										
9-Apr-02										
10-Apr-02										
11-Apr-02	161.70	279.3	221.1	4.9E-03	5.0E-03	4.8E-03	1.8	3.8	9.6E-07	65.2
12-Apr-02										
13-Apr-02	135.61	281.5	196.9	4.2E-03	4.3E-03	4.5E-03	1.9	4.6	7.2E-07	74.6
14-Apr-02										
15-Apr-02										
16-Apr-02										
17-Apr-02										
18-Apr-02	135.57	209.0	172.2	4.1E-03	4.2E-03	4.0E-03	1.6	3.4	4.7E-07	31.9
19-Apr-02	153.81	189.2	206.7	4.7E-03	4.7E-03	4.0E-03	1.7	2.7	5.8E-07	39.3
20-Apr-02	153.97	185.9	189.7	4.7E-03	4.7E-03	4.6E-03	1.6	2.7	5.2E-07	53.9
21-Apr-02	158.68	188.9	177.2	4.8E-03	4.8E-03	4.0E-03	1.4	2.6	5.1E-07	42.9
22-Apr-02										
23-Apr-02	153.81	264.6	196.9	4.7E-03	5.3E-03	4.0E-03	1.7	3.8	7.7E-07	42.2
24-Apr-02	149.24	261.3	213.3	4.5E-03	5.0E-03	5.7E-03	1.8	3.9	8.0E-07	67.2
25-Apr-02	160.29	264.0	182.9	4.8E-03	5.3E-03	4.6E-03	1.5	3.6	7.4E-07	62.5
26-Apr-02	167.55	282.9	186.5	5.2E-03	5.2E-03	5.0E-03	1.4	3.7	8.5E-07	71.3
27-Apr-02										
28-Apr-02										
29-Apr-02	212.50	314.6	215.8	6.2E-03	6.2E-03	6.0E-03	1.3	3.3	1.4E-06	48.8
30-Apr-02	220.91	337.5	107.9	2.5E-03	3.1E-03	3.8E-03	0.6	3.4	7.7E-07	21.6
1-May-02										
2-May-02										
3-May-02	200.83	301.8	206.1	5.8E-03	6.0E-03	5.6E-03	1.3	3.3	1.2E-06	42.3
4-May-02	180.00	274.3	289.3	5.6E-03	6.0E-03	5.0E-03	2.1	3.4	1.4E-06	60.4
5-May-02	180.00	270.0	289.0	5.6E-03	6.0E-03	5.0E-03	2.1	3.3	1.3E-06	59.4
6-May-02	181.50	270.0	289.2	5.6E-03	6.0E-03	5.0E-03	2.1	3.3	1.4E-06	60.0
7-May-02										
8-May-02										
9-May-02										
11-May-02										
12-May-02	188.00	244.0	221.5	5.3E-03	5.3E-03	5.0E-03	1.5	2.9	9.8E-07	27.3

Date	PO$_4$-P In-Reactor			NH$_4$-N In-Reactor			Mg In-Reactor		
	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Run 3									
18-Mar-02	12.5	11.1	23.6	27.9	218.8	246.7	20.9	116.2	137.2
19-Mar-02	12.8	10.9	23.7	27.6	204.2	231.8	20.9	115.0	135.9
20-Mar-02	12.9	11.6	24.5	27.6	201.5	229.1	21.0	113.6	134.6
25-Mar-02	14.9	10.4	25.2	25.5	190.7	216.2	20.8	103.2	124.0
26-Mar-02	17.0	93.5	110.5	32.1	249.2	281.3	19.1	126.8	145.9
27-Mar-02	15.0	8.9	23.9	29.3	224.2	253.4	17.5	61.7	79.2
29-Mar-02	20.4	12.7	33.0	38.9	220.4	259.3	17.8	43.9	61.8
30-Mar-02	5.2	41.4	46.6	7.9	154.2	162.0	11.8	225.1	237.0
31-Mar-02	11.5	41.3	52.8	17.7	159.4	177.2	11.7	65.3	77.0
1-Apr-02	12.2	30.0	42.2	17.6	125.0	142.6	12.7	48.7	61.4
2-Apr-02	15.0	16.9	31.9	21.0	144.9	165.9	14.1	36.2	50.3
3-Apr-02	12.2	18.9	31.1	18.0	132.6	150.6	12.9	52.7	65.6
4-Apr-02	10.8	12.7	23.6	14.6	122.4	136.9	11.6	55.8	67.3
5-Apr-02	14.0	8.9	22.9	20.3	128.2	148.5	14.5	45.8	60.3
6-Apr-02	8.7	3.7	12.3	11.6	116.3	127.9	16.0	133.9	149.9
7-Apr-02	21.2	31.8	53.1	25.7	129.8	155.5	14.5	11.2	25.7
8-Apr-02									
9-Apr-02									
10-Apr-02									
11-Apr-02	12.2	8.9	21.1	21.0	193.5	214.5	16.7	96.6	113.2
12-Apr-02									
13-Apr-02	11.6	4.8	16.4	24.1	202.4	226.5	16.8	79.9	96.8
14-Apr-02									
15-Apr-02									
16-Apr-02									
17-Apr-02									
18-Apr-02	14.3	7.6	21.9	22.0	134.4	156.4	18.1	67.1	85.2
19-Apr-02	12.8	8.2	21.0	15.8	113.1	128.9	17.2	100.3	117.6
20-Apr-02	13.7	6.9	20.6	16.5	109.4	126.0	16.9	71.0	87.8
21-Apr-02	14.2	8.2	22.4	16.9	110.7	127.7	15.9	72.8	88.7
22-Apr-02									
23-Apr-02	14.5	6.2	20.6	24.9	172.1	197.0	18.6	90.3	108.9
24-Apr-02	9.3	8.8	18.1	16.3	179.4	195.7	13.3	70.3	83.6
25-Apr-02	14.0	11.2	25.2	23.1	173.4	196.5	16.0	63.9	79.9
26-Apr-02	15.2	4.6	19.9	25.7	191.0	216.7	17.0	59.1	76.0
27-Apr-02									
28-Apr-02									
29-Apr-02	16.8	18.1	34.8	24.8	209.8	234.6	17.0	64.5	81.5
30-Apr-02	31.6	123.4	155.0	48.2	251.7	299.9	15.4	13.0	28.4
1-May-02									
2-May-02									
3-May-02	15.6	18.1	33.7	23.5	200.9	224.4	16.1	64.5	80.6
4-May-02	10.0	6.8	16.8	15.2	179.7	194.9	16.1	158.4	174.5
5-May-02	10.0	6.9	16.9	15.0	175.7	190.7	16.1	158.4	174.4
6-May-02	10.1	6.9	17.0	15.0	175.7	190.7	16.1	158.4	174.5
7-May-02									
8-May-02									
9-May-02									
11-May-02									
12-May-02	9.2	21.9	31.1	12.0	161.5	173.4	10.9	95.1	106.0

Date	In-Reactor Concentrations			In-reactor	In-reactor	In-Reactor P_S	Ps (eg)	S.S.Ratio	Effluent SS
	PO_4-P	NH_4-N	Mg	Mg:P	N:P				
Reactor B	(mol/L)	(mol/L)	(mol/L)	(molar ratio)	(molar ratio)			(in-reactor)	
Run 3									
18-Mar-02	7.6E-04	1.8E-02	5.7E-03	7.5	23.2	7.7E-08	1.5E-08	5.2	2.5
19-Mar-02	7.6E-04	1.7E-02	5.7E-03	7.4	21.7	7.2E-08	1.5E-08	4.9	2.2
20-Mar-02	7.9E-04	1.6E-02	5.6E-03	7.1	20.7	7.3E-08	1.5E-08	4.9	2.3
25-Mar-02	8.1E-04	1.5E-02	5.2E-03	6.3	19.0	6.5E-08	2.3E-08	2.9	1.2
26-Mar-02	3.6E-03	2.0E-02	6.1E-03	1.7	5.6	4.4E-07	2.6E-07	1.7	1.5
27-Mar-02	7.7E-04	1.8E-02	3.3E-03	4.3	23.5	4.6E-08	2.3E-08	2.0	0.7
29-Mar-02	1.1E-03	1.9E-02	2.6E-03	2.4	17.4	5.1E-08	1.5E-08	3.5	1.2
30-Mar-02	1.5E-03	1.2E-02	9.9E-03	6.6	7.7	1.7E-07	5.8E-08	3.0	2.7
31-Mar-02	1.7E-03	1.3E-02	3.2E-03	1.9	7.4	6.9E-08	3.6E-08	1.9	1.5
1-Apr-02	1.4E-03	1.0E-02	2.6E-03	1.9	7.5	3.5E-08	2.8E-08	1.2	0.8
2-Apr-02	1.0E-03	1.2E-02	2.1E-03	2.0	11.5	2.6E-08	1.8E-08	1.4	0.6
3-Apr-02	1.0E-03	1.1E-02	2.7E-03	2.7	10.7	3.0E-08	1.8E-08	1.6	0.9
4-Apr-02	7.6E-04	9.8E-03	2.8E-03	3.7	12.9	2.1E-08	1.5E-08	1.4	0.7
5-Apr-02	7.4E-04	1.1E-02	2.5E-03	3.4	14.4	2.0E-08	9.7E-09	2.0	0.7
6-Apr-02	4.0E-04	9.1E-03	6.2E-03	15.7	23.0	2.3E-08	7.9E-09	2.9	0.8
7-Apr-02	1.7E-03	1.1E-02	1.1E-03	0.6	6.5	2.0E-08	9.7E-09	2.1	0.7
8-Apr-02									
9-Apr-02									
10-Apr-02									
11-Apr-02	6.8E-04	1.5E-02	4.7E-03	6.9	22.6	4.9E-08	1.5E-08	3.3	1.4
12-Apr-02									
13-Apr-02	5.3E-04	1.6E-02	4.0E-03	7.6	30.7	3.4E-08	9.7E-09	3.6	1.0
14-Apr-02									
15-Apr-02									
16-Apr-02									
17-Apr-02									
18-Apr-02	7.1E-04	1.1E-02	3.6E-03	5.0	15.8	2.8E-08	1.5E-08	1.9	0.6
19-Apr-02	6.8E-04	9.2E-03	4.9E-03	7.2	13.6	3.1E-08	1.5E-08	2.1	0.8
20-Apr-02	6.7E-04	9.0E-03	3.7E-03	5.5	13.5	2.2E-08	9.7E-09	2.3	0.7
21-Apr-02	7.2E-04	9.1E-03	3.7E-03	5.1	12.6	2.4E-08	1.2E-08	2.1	0.7
22-Apr-02									
23-Apr-02	6.7E-04	1.4E-02	4.5E-03	6.8	21.1	4.3E-08	1.8E-08	2.3	0.7
24-Apr-02	5.9E-04	1.4E-02	3.5E-03	6.0	23.9	2.9E-08	1.2E-08	2.4	1.1
25-Apr-02	8.1E-04	1.4E-02	3.3E-03	4.1	17.2	3.8E-08	1.2E-08	3.2	1.3
26-Apr-02	6.4E-04	1.5E-02	3.2E-03	4.9	24.2	3.1E-08	1.2E-08	2.6	0.6
27-Apr-02									
28-Apr-02									
29-Apr-02	1.1E-03	1.7E-02	3.4E-03	3.0	14.9	6.4E-08	2.8E-08	2.3	1.1
30-Apr-02	5.0E-03	2.1E-02	1.2E-03	0.2	4.3	1.3E-07	3.6E-08	3.6	1.7
1-May-02									
2-May-02									
3-May-02	1.1E-03	1.6E-02	3.4E-03	3.1	14.7	5.9E-08	2.8E-08	2.1	1.0
4-May-02	5.4E-04	1.4E-02	7.3E-03	13.4	25.7	5.5E-08	2.3E-08	2.4	1.0
5-May-02	5.4E-04	1.4E-02	7.3E-03	13.3	25.0	5.4E-08	2.3E-08	2.4	1.0
6-May-02	5.5E-04	1.4E-02	7.3E-03	13.3	24.9	5.4E-08	2.3E-08	2.4	1.0
7-May-02									
8-May-02									
9-May-02									
11-May-02									
12-May-02	1.0E-03	1.2E-02	4.4E-03	4.4	12.4	5.5E-08	3.6E-08	1.5	1.1

Date	Crystal Volume	Harvest Volume	CRT Actual	CRT Averaged In reactor				Harvested Product Data		
				SS Ratio	>4.75mm	>2.83mm	>2 mm	>1mm	>0.5mm	<0.5mm
Reactor B Run 3	(L)	(L)	(days)		(g)	(g)	(g)	(g)	(g)	(g)
18-Mar-02	6									
19-Mar-02	6.8	1.3			0	408.4	50.6	1.5	0.4	0.8
20-Mar-02	6.4	1.3			0	250	81	1.7	1	6
25-Mar-02	6.4									
26-Mar-02	6.8									
27-Mar-02	7.6	1.3			0	222	83.4	1.5	0.4	9.6
29-Mar-02	7.6	1.3			0	323	23	0.4	0.1	3.5
30-Mar-02	6.7									
31-Mar-02	8.2	1.3			0	220	27.8	1	0.2	2
1-Apr-02	8.3									
2-Apr-02	9.3	1.3			0	302	22	1.4	1	10
3-Apr-02	6.7	1.3			0.6	376.3	12.6	0.9	0.1	0.6
4-Apr-02	6.8									
5-Apr-02	7.7	1.3	9.0	2.0	3.8	465	20	0.3	0	0
6-Apr-02	6.7	1.3	7	1.7	6.1	433.6	42.7	0.3	0	0
7-Apr-02	6.7									
8-Apr-02										
9-Apr-02	7.1	1.3	7	1.8	19.6	362.8	52.9	0.1	0	0
10-Apr-02	6.8									
11-Apr-02	6.4									
12-Apr-02										
13-Apr-02	7.9	1.3	10	2.1	73	400	14.8	0.1	0	0
14-Apr-02										
15-Apr-02										
16-Apr-02	7.6	1.3	10		74	405	17	0.5	0	0
17-Apr-02										
18-Apr-02	6.8	1.3	9	2.2	70	386.4	102	0.4	0.2	0
19-Apr-02	6.5									
20-Apr-02	7	1.3	9	2.4	2.2	527	8.5	0.1	0	0
21-Apr-02	7.2									
22-Apr-02										
23-Apr-02	8.2	1.3	11	2.4	100	520	30	1.9	0.1	2.7
24-Apr-02	6.7									
25-Apr-02	8.2	1.3	11	2.6	98	530	35	0.2	0	0
26-Apr-02										
27-Apr-02	6.7	1.3	9	2.5	25	425.6	80	0.5	0	0.1
28-Apr-02										
29-Apr-02	8.5	1.3	11	2.5	20	465.5	65	0.1	0	0
30-Apr-02	7.2									
1-May-02										
2-May-02										
3-May-02	8.5	1.3	12	2.5	0	46.2	215	13.1	0	3.2
4-May-02	8									
5-May-02	8.5	1.3	11	2.6	0	3.5	260.8	20.6	0.1	5.8
6-May-02										
7-May-02										
8-May-02	8.5	1.3	11	2.5	0	92.4	199.5	1.3	0.3	6.2
9-May-02										
11-May-02	8.8	1.3	12	2.5	0	79.2	137.8	7	0	1.2
12-May-02	9.5									

Date	Total Mass	Percentage Size Fractions						Mean Crystal	Mass P	Theoretical
		>4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	< 0.5mm	Size (mm)	Removed	Mass MAP
Reactor B	(g)								(g)	Grown
Run 3										
18-Mar-02									59.6	472.9
19-Mar-02	461.7	0	88.5	11.0	0.3	0.1	0.2	3.5	61.3	486.3
20-Mar-02	339.7	0	73.6	23.8	0.5	0.3	1.8	3.3	61.6	488.6
25-Mar-02									75.7	600.9
26-Mar-02									34.1	270.5
27-Mar-02	316.9	0	70.1	26.3	0.5	0.1	3.0	3.2	74.0	587.2
29-Mar-02	350	0	92.3	6.6	0.1	0.0	1.0	3.6	88.5	702.4
30-Mar-02									19.4	154.0
31-Mar-02	251	0	87.6	11.1	0.4	0.1	0.8	3.5	42.1	334.3
1-Apr-02									45.4	360.7
2-Apr-02	336.4	0	89.8	6.5	0.4	0.3	3.0	3.5	65.7	521.4
3-Apr-02	391.1	0.15	96.2	3.2	0.2	0.0	0.2	3.6	52.6	417.4
4-Apr-02									53.2	421.9
5-Apr-02	489.1	0.8	95.1	4.1	0.1	0.0	0.0	3.7	73.0	579.7
6-Apr-02	482.7	1.3	89.8	8.9	0.1	0.0	0.0	3.6	40.1	317.9
7-Apr-02									88.1	699.4
8-Apr-02										
9-Apr-02	435.4	4.5	83.3	12.2	0.0	0.0	0.0	3.6		
10-Apr-02										
11-Apr-02									60.2	478.0
12-Apr-02										
13-Apr-02	487.9	15.0	82.0	3.0	0.0	0.0	0.0	3.9	61.0	484.4
14-Apr-02										
15-Apr-02										
16-Apr-02	496.5	14.9	81.6	3.4	0.1	0.0	0.0	3.8		
17-Apr-02										
18-Apr-02	559	12.5	69.1	18.2	0.1	0.0	0.0	3.6	73.2	580.9
19-Apr-02									62.6	496.8
20-Apr-02	537.8	0.4	98.0	1.6	0.0	0.0	0.0	3.7	68.9	547.0
21-Apr-02									75.4	598.7
22-Apr-02										
23-Apr-02	654.7	15.3	79.4	4.6	0.3	0.0	0.4	3.8	68.8	546.1
24-Apr-02									60.4	479.5
25-Apr-02	663.2	14.8	79.9	5.3	0.0	0.0	0.0	3.8	74.6	591.9
26-Apr-02									81.9	649.8
27-Apr-02	531.2	4.7	80.1	15.1	0.1	0.0	0.0	3.6		
28-Apr-02										
29-Apr-02	550.6	3.6	84.5	11.8	0.0	0.0	0.0	3.6	83.3	661.4
30-Apr-02									60.9	483.4
1-May-02										
2-May-02										
3-May-02	277.5	0.0	16.6	77.5	4.7	0.0	1.2	2.5	78.3	621.4
4-May-02									49.8	395.0
5-May-02	290.8	0.0	1.2	89.7	7.1	0.0	2.0	2.3	49.7	394.7
6-May-02									50.2	398.2
7-May-02										
8-May-02	299.7	0.0	30.8	66.6	0.4	0.1	2.1	2.7		
9-May-02										
11-May-02	225.2	0.0	35.2	61.2	3.1	0.0	0.5	2.8		
12-May-02									59.4	471.4

Date	Recyle flow	Temp ° C	Influent Lab results			Effluent Lab results			pH
			PO_4-P	NH_4-N	Mg	PO_4-P	NH_4-N	Mg	
Reactor B			(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	
Run 3									
13-May-02									
14-May-02									
15-May-02	14.1	12.0	249.0	394.1	735.8	73.0	209.4	16.0	7.3
16-May-02									
21-May-02									
22-May-02	19.0	15.0	229.0	300.0	2200.0	30.0	194.0	74.0	7.3
23-May-02	19.0	15.0	229.0	300.0	2200.0	29.3	191.6	73.0	7.3
24-May-02	19.0	15.0	224.0	300.0	2200.0	26.1	195.3	72.1	7.3
Average	12.3	10.6	186.8	291.2	2210.9	23.5	188.7	89.5	7.6
Minimum	6.0	5.0	142.7	198.0	735.8	3.9	120.1	12.8	6.6
Maximum	24.3	18.0	255.0	394.1	3444.0	144.0	293.6	234.4	8.0
St.Dev.	4.1	2.8	36.1	58.1	757.5	28.5	44.0	47.1	0.3
Count	37	37	37	37	37	37	37	37	37

Date	Removal efficiency (%)			MgCl	Total	N & P	Recycle	Total flow
	PO_4-P	NH_4-N	Mg	Flow	Influent Flow	Influent Flow	Flow	(influent+recycle)
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mL/min)	(mL/min)	(mL/min)	(mL/min)	(mL/min)
Run 3								
13-May-02								
14-May-02								
15-May-02	65.4	37.2	85.9	50	325	275	4575	4900
16-May-02								
21-May-02								
22-May-02	85.6	29.1	61.8	22	250	228	4750	5000
23-May-02	86.0	30.0	62.3	22	250	228	4750	5000
24-May-02	87.2	28.6	62.8	22	250	228	4750	5000
Average	86.5	27.8	57.2	29.6	309.8	280.1	3568.8	3878.5
Minimum	34.8	13.0	21.9	19.0	150.0	125.0	2900.0	3300.0
Maximum	97.3	41.9	89.1	50.0	550.0	500.0	4850.0	5100.0
St.Dev.	14.5	6.3	14.6	11.5	74.6	76.5	529.0	511.5
Count	37	37	37	37	37	37	37	37

Date	Conditions at the inlet			Molar removal			Mg:P	N:P	Feed P_S	S.S (ratio)
	PO_4_P	NH_4-N	Mg	PO_4_P	NH_4-N	Mg	molar ratio	molar ratio		
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(at inlet)	(at inlet)		(at inlet)
Run 3										
13-May-02										
14-May-02										
15-May-02	210.69	333.4	113.2	4.4E-03	4.0E-03	4.0E-03	0.7	3.5	7.6E-07	21.4
16-May-02										
21-May-02										
22-May-02	208.85	273.6	193.6	5.8E-03	5.7E-03	4.9E-03	1.2	2.9	1.1E-06	29.7
23-May-02	208.85	273.6	193.6	5.8E-03	5.9E-03	5.0E-03	1.2	2.9	1.1E-06	29.7
24-May-02	204.29	273.6	193.6	5.7E-03	5.6E-03	5.0E-03	1.2	3.0	1.0E-06	29.1
Average	166.1	259.3	196.9	4.6E-03	4.9E-03	4.4E-03	1.6	3.5	8.2E-07	43.8
Minimum	132.9	185.9	107.9	2.1E-03	2.8E-03	2.0E-03	0.6	2.6	3.8E-07	3.7
Maximum	220.9	337.5	300.0	6.2E-03	7.2E-03	6.0E-03	2.9	4.9	1.4E-06	87.6
St.Dev.	25.7	45.6	47.9	9.4E-04	9.4E-04	8.0E-04	0.5	0.6	2.8E-07	20.1
Count	37	37	37	37	37	37	37	37	37	37

Date	PO$_4$-P In-Reactor			NH$_4$-N In-Reactor			Mg In-Reactor		
	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total	Feed gives	Recycle gives	Total
Reactor B	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Run 3									
13-May-02									
14-May-02									
15-May-02	14.0	68.2	82.1	22.1	195.5	217.6	7.5	14.9	22.4
16-May-02									
21-May-02									
22-May-02	10.4	28.5	38.9	13.7	184.3	198.0	9.7	70.3	80.0
23-May-02	10.4	27.8	38.3	13.7	182.0	195.7	9.7	69.4	79.0
24-May-02	10.2	24.8	35.0	13.7	185.5	199.2	9.7	68.5	78.2
Average	13.4	21.4	34.8	21.3	173.1	194.3	15.4	82.8	98.1
Minimum	5.2	3.7	12.3	7.9	109.4	126.0	7.5	11.2	22.4
Maximum	31.6	123.4	155.0	48.2	251.7	299.9	21.0	225.1	237.0
St.Dev.	4.4	25.1	27.7	7.9	38.7	44.3	3.4	44.8	45.8
Count	37	37	37	37	37	37	37	37	37

Date	In-Reactor Concentrations			In-reactor	In-reactor	In-Reactor P_S	Ps (eg)	S.S.Ratio	Effluent SS
	PO_4-P	NH_4-N	Mg	Mg:P	N:P				
Reactor B	(mol/L)	(mol/L)	(mol/L)	(molar ratio)	(molar ratio)			(in-reactor)	
Run 3									
13-May-02									
14-May-02									
15-May-02	2.6E-03	1.6E-02	9.4E-04	0.4	5.9	3.9E-08	3.6E-08	1.1	0.7
16-May-02									
21-May-02									
22-May-02	1.3E-03	1.4E-02	3.3E-03	2.7	11.3	5.9E-08	3.6E-08	1.7	1.2
23-May-02	1.2E-03	1.4E-02	3.3E-03	2.7	11.3	5.7E-08	3.6E-08	1.6	1.1
24-May-02	1.1E-03	1.4E-02	3.3E-03	2.9	12.6	5.2E-08	3.6E-08	1.5	1.0
Average	1.1E-03	1.4E-02	4.1E-03	5.2	16.0	6.0E-08	2.8E-08	2.5	1.1
Minimum	4.0E-04	9.0E-03	9.4E-04	0.2	4.3	2.0E-08	7.9E-09	1.1	0.6
Maximum	5.0E-03	2.1E-02	9.9E-03	15.7	30.7	4.4E-07	2.6E-07	5.2	2.7
St.Dev.	8.9E-04	3.2E-03	1.9E-03	3.7	6.9	7.0E-08	4.1E-08	1.0	0.5
Count	37	37	37	37	37	37	37	37	37

Date	Crystal Volume	Harvest Volume	CRT Actual	CRT Averaged In reactor						Harvested Product Data
					>4.75mm	>2.83mm	>2 mm	>1mm	>0.5mm	<0.5mm
Reactor B	(L)	(L)	(days)	SS Ratio	(g)	(g)	(g)	(g)	(g)	(g)
Run 3										
13-May-02	9.5	1.3	11	2.6	0	153.1	72	33.3	0	2.1
14-May-02										
15-May-02										
16-May-02	10.2	1.3	13	2.3	10	610	9.3	3.7	0.1	1.8
21-May-02	10.5	2.6	5	2.0	0	556	3.2	1.1	0.1	0
22-May-02	9.5	1.3	8	2.2	0	253.1	13.2	8.7	0.1	2.3
23-May-02	9.5	1.3	8	1.9	0	233.8	20	13.2	0.7	1.1
24-May-02	9.5	1.3	8	1.7	0.2	144.2	42.5	13.3	0	0
Average	7.8	1.3	9.6	2.2	17.9	328.4	62.2	4.6	0.2	2.1
Minimum	6.0	1.3	5.0	1.7	0.0	3.5	3.2	0.1	0.0	0.0
Maximum	10.5	2.6	13.0	2.6	100.0	610.0	260.8	33.3	1.0	10.0
St.Dev.	1.2	0.2	2.0	0.3	32.1	165.8	66.4	7.8	0.3	2.9
Count	43	28	21	20	28	28	28	28	28	28

Date	Total Mas	Percentage Size Fractions						Mean Crystal	Mass P	Theoretical
		>4.75mm	>2.83-4.75mm	>2-2.83mm	>1-2mm	>0.5-1mm	< 0.5mm	Size (mm)	Removed	Mass MAP
Reactor B	(g)								(g)	Grown
Run 3										
13-May-02	260.5	0.0	58.8	27.6	12.8	0.0	0.8	3.0		
14-May-02										
15-May-02									64.4	511.4
16-May-02	634.9	1.6	96.1	1.5	0.6	0.0	0.3	3.7		
21-May-02	560.4	0.0	99.2	0.6	0.2	0.0	0.0	3.7		
22-May-02	277.4	0.0	91.2	4.8	3.1	0.0	0.8	3.5	64.4	511.0
23-May-02	268.8	0.0	87.0	7.4	4.9	0.3	0.4	3.5	64.6	513.0
24-May-02	200.2	0.1	72.0	21.2	6.6	0.0	0.0	3.3	64.1	509.1
Average	415.4	3.2	75.3	19.1	1.7	0.1	0.7	3.4	62.5	495.6
Minimum	200.2	0.0	1.2	0.6	0.0	0.0	0.0	2.3	19.4	154.0
Maximum	663.2	15.3	99.2	89.7	12.8	0.3	3.0	3.9	88.5	702.4
St.Dev.	139.8	5.5	25.0	24.3	3.0	0.1	0.9	0.4	14.8	117.7
Count	28	28	28	28	28	28	28	28	37	37

APPENDIX E : SOLUBILITY TESTS

Determination of solubility product value for struvite

The equilibrium constant for a reaction involving a precipitate and its constituent ions is known as solubility product. For the case of struvite, Equation A describes this relation.

$$K_{sp} = \{Mg^{+2}\}\ \{NH_4^{+}\}\ \{PO_4^{-3}\} \qquad \text{(A)}$$

where the {} brackets indicate ion activity in moles per liter.

The ionic strength of the solution was determined based on conductivity measurements using the conversion factor described in Equation B[1].

$$\mu = 1.6 \text{ X } 10^{-5}\, EC \qquad \text{(B)}$$

Where μ = Ionic Strength

EC = Electric Conductivity (μS/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 C[2].

$$\gamma = 0.5\ z^2\, \mu\text{^}0.5 \,/\, 1 + \mu\text{^}0.5 \qquad \text{(C)}$$

Equations D to H show the dissociation constants which are used for the partitioning at a temperature of 20°C and 10°C, respectively (Ping Liao, pers comm.). These coefficients are adapted and interpolated to 20°C and 10°C from the literature values.

[1] Tchobanoglous, G. and E.D. Schroeder (1985). *Water Quality.* Addison Wesley Publishing Company, USA.

[2] Sawyer, C., P. McCarty, G. Parkin (1994). *Chemistry for Environmental Engineers.* McGraw-Hill Series in Water Resources and Environmental Engineering, New York.

	At 20°C	At 10°C	
$[H_2PO_4^-][H^+]/[H_3PO_4]$	$= 7.81*10^{-3}$	$8.43 * 10^{-3}$	(D)
$[HPO_4^{2-}][H^+]/[HPO_4^-]$	$= 6.12*10^{-8}$	$5.57 *10^{-8}$	(E)
$[PO_4^{3-}][H^+]/[HPO_4^{2-}]$	$= 5.00*10^{-13}$	$5.00 *10^{-13}$	(F)
$[NH_3][H^+]/[NH_4^+]$	$= 6.05 *10^{-10}$	$6.36 *10^{-10}$	(G)
$[Mg^{2+}][OH^-]/[MgOH^+]$	$= 2.75*10^{-3}$	$2.75 *10^{-3}$	(H)

These acid and base dissociation constants are then substituted into Equations I-K to solve for each individual species concentration.

$$T\text{-}PO_4 = [H_3PO_4] + [H_2PO_4^-] + [HPO_4^{2-}] + [PO_4^{3-}] \quad \text{(I)}$$

$$T\text{-}NH_3 = [NH_3] + [NH_4^+] \quad \text{(J)}$$

$$T\text{-}Mg = [Mg^{2+}] + [MgOH^+] \quad \text{(K)}$$

Once the activity of each individual species of interest is determined, the solubility product is then calculated over a pH range.

Solubility tests using tap water at 10°C

Sample	pH	Conductivity µS/cm	Mg mg/L	NH_4-N mg/L	Sample data PO_4-P mg/L	Mg mol/L	NH_4-N mol/L	PO_4-P mol/L	Mg:P Molar Ratio	N:P Molar Ratio
S1	6.59	1623	142.8	70.5	209.8	0.00588	0.005	0.00677	0.9	0.7
S2	6.96	930	85.5	43.3	103.5	0.00352	0.003	0.00334	1.1	0.9
S3	7.3	640	62.9	28	68.2	0.00259	0.002	0.00220	1.2	0.9
S4	7.42	573	54.3	24.5	60.2	0.00223	0.002	0.00194	1.1	0.9
S5	7.55	474	49	23.6	57	0.00202	0.002	0.00184	1.1	0.9
S6	7.71	344	33.8	14.4	35.1	0.00139	0.001	0.00113	1.2	0.9
S7	8.12	243	25.4	9.5	23.7	0.00105	0.001	0.00077	1.4	0.9
S8	8.45	190	21.6	7.4	19.1	0.00089	0.001	0.00062	1.4	0.9
S9	8.48	186	19.5	7	18.2	0.00080	0.001	0.00059	1.4	0.9
S10	8.57	193	21.6	6.8	18.3	0.00089	0.000	0.00059	1.5	0.8
S11	8.8	232	22.1	6	18.1	0.00091	0.000	0.00058	1.6	0.7
S12	8.85	286	23.2	6.9	19.3	0.00095	0.000	0.00062	1.5	0.8
S13	9.33	529	21.3	13.4	31.3	0.00088	0.001	0.00101	0.9	0.9
S14	9.44	1086	27.6	11.6	72.5	0.00114	0.001	0.00234	0.5	0.4

Solubility tests using tap water at 20°C

Sample	pH	Conductivity µS/cm	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	Mg:P Molar Ratio	N:P Molar Ratio
S1	6.64	1820	152.2	79.7	215.7	0.00626	0.006	0.00696	0.9	0.8
S2	7.25	925	78.8	36.8	101.3	0.00324	0.003	0.00327	1.0	0.8
S3	7.36	752	64.4	32.6	85.9	0.00265	0.002	0.00277	1.0	0.8
S4	7.38	728	71.4	30.7	80.6	0.00294	0.002	0.00260	1.1	0.8
S5	7.96	348	37.6	15	41.6	0.00155	0.001	0.00134	1.2	0.8
S6	7.99	345	37.2	17.2	46.2	0.00153	0.001	0.00149	1.0	0.8
S7	8.14	295	34.1	12.5	35.5	0.00140	0.001	0.00115	1.2	0.8
S8	8.28	267	31.3	11.5	33.4	0.00129	0.001	0.00108	1.2	0.8
S9	8.78	225	23.7	8.6	23.5	0.00098	0.001	0.00076	1.3	0.8
S10	8.98	234	23.9	9.8	25	0.00098	0.001	0.00081	1.2	0.9
S11	9.06	282	23.9	12.1	34.9	0.00098	0.001	0.00113	0.9	0.8
S12	9.43	352	24	15.4	45.5	0.00099	0.001	0.00147	0.7	0.7

Sample	Struvite P_S	Struvite pP_S	Phosphate Dissociation Constants ka_1	ka_2	ka_3	Ammonia ka	MgOH kb	$[H^+]$ mol/L	$[OH^-]$ mol/L
S1	2.0E-07	6.7	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	2.6E-07	3.9E-08
S2	3.6E-08	7.4	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.1E-07	9.1E-08
S3	1.1E-08	7.9	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	5.0E-08	2.0E-07
S4	7.6E-09	8.1	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	3.8E-08	2.6E-07
S5	6.3E-09	8.2	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	2.8E-08	3.5E-07
S6	1.6E-09	8.8	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.9E-08	5.1E-07
S7	5.4E-10	9.3	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	7.6E-09	1.3E-06
S8	2.9E-10	9.5	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	3.5E-09	2.8E-06
S9	2.4E-10	9.6	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	3.3E-09	3.0E-06
S10	2.6E-10	9.6	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	2.7E-09	3.7E-06
S11	2.3E-10	9.6	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.6E-09	6.3E-06
S12	2.9E-10	9.5	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.4E-09	7.1E-06
S13	8.5E-10	9.1	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	4.7E-10	2.1E-05
S14	2.2E-09	8.7	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	3.6E-10	2.8E-05
S1	2.5E-07	6.6	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	2.3E-07	4.4E-08
S2	2.8E-08	7.6	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	5.6E-08	1.8E-07
S3	1.7E-08	7.8	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	4.4E-08	2.3E-07
S4	1.7E-08	7.8	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	4.2E-08	2.4E-07
S5	2.2E-09	8.7	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.1E-08	9.1E-07
S6	2.8E-09	8.6	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.0E-08	9.8E-07
S7	1.4E-09	8.8	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	7.2E-09	1.4E-06
S8	1.1E-09	8.9	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	5.2E-09	1.9E-06
S9	4.5E-10	9.3	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.7E-09	6.0E-06
S10	5.6E-10	9.3	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.0E-09	9.5E-06
S11	9.6E-10	9.0	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	8.7E-10	1.1E-05
S12	1.6E-09	8.8	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	3.7E-10	2.7E-05

Sample	$[Mg^{++}]$ mol/L	$[NH4^{+}]$ mol/L	$[PO4^{---}]$ mol/L	$\{Mg^{++}\}$ mol/L	$\{NH4^{+}\}$ mol/L	$\{PO4^{---}\}$ mol/L	K_{sp}	pK_{sp}	Ionic Strength
S1	5.9E-03	5.0E-03	2.3E-09	3.1E-03	4.3E-03	5.6E-10	7.4E-15	14.1	0.03
S2	3.5E-03	3.1E-03	5.1E-09	2.1E-03	2.7E-03	1.7E-09	9.6E-15	14.0	0.01
S3	2.6E-03	2.0E-03	1.2E-08	1.7E-03	1.8E-03	4.5E-09	1.3E-14	13.9	0.01
S4	2.2E-03	1.7E-03	1.5E-08	1.5E-03	1.6E-03	6.1E-09	1.4E-14	13.8	0.01
S5	2.0E-03	1.6E-03	2.2E-08	1.4E-03	1.5E-03	9.5E-09	2.0E-14	13.7	0.01
S6	1.4E-03	1.0E-03	2.2E-08	1.0E-03	9.2E-04	1.1E-08	9.8E-15	14.0	0.01
S7	1.0E-03	6.3E-04	4.4E-08	8.0E-04	5.9E-04	2.4E-08	1.1E-14	13.9	0.00
S8	8.9E-04	4.5E-04	8.2E-08	7.0E-04	4.2E-04	4.8E-08	1.4E-14	13.9	0.00
S9	8.0E-04	4.2E-04	8.4E-08	6.3E-04	4.0E-04	4.9E-08	1.2E-14	13.9	0.00
S10	8.9E-04	3.9E-04	1.0E-07	7.0E-04	3.7E-04	6.1E-08	1.6E-14	13.8	0.00
S11	9.1E-04	3.1E-04	1.8E-07	7.0E-04	2.9E-04	9.9E-08	2.0E-14	13.7	0.00
S12	9.5E-04	3.4E-04	2.2E-07	7.1E-04	3.2E-04	1.1E-07	2.5E-14	13.6	0.00
S13	8.7E-04	4.1E-04	1.1E-06	5.9E-04	3.7E-04	4.5E-07	9.7E-14	13.0	0.01
S14	1.1E-03	3.0E-04	3.2E-06	6.6E-04	2.6E-04	9.6E-07	1.7E-13	12.8	0.02

S1	6.3E-03	5.7E-03	3.2E-09	3.2E-03	4.8E-03	7.1E-10	1.1E-14	14.0	0.03
S2	3.2E-03	2.6E-03	1.5E-08	2.0E-03	2.3E-03	4.9E-09	2.2E-14	13.7	0.01
S3	2.6E-03	2.3E-03	1.9E-08	1.7E-03	2.0E-03	6.7E-09	2.3E-14	13.6	0.01
S4	2.9E-03	2.2E-03	1.9E-08	1.9E-03	1.9E-03	6.8E-09	2.5E-14	13.6	0.01
S5	1.5E-03	1.0E-03	5.2E-08	1.1E-03	9.4E-04	2.5E-08	2.7E-14	13.6	0.01
S6	1.5E-03	1.2E-03	6.2E-08	1.1E-03	1.1E-03	3.0E-08	3.6E-14	13.4	0.01
S7	1.4E-03	8.2E-04	7.1E-08	1.0E-03	7.7E-04	3.6E-08	2.9E-14	13.5	0.00
S8	1.3E-03	7.4E-04	9.5E-08	9.7E-04	6.9E-04	5.0E-08	3.3E-14	13.5	0.00
S9	9.7E-04	4.5E-04	2.2E-07	7.5E-04	4.2E-04	1.2E-07	3.9E-14	13.4	0.00
S10	9.8E-04	4.4E-04	3.8E-07	7.5E-04	4.2E-04	2.1E-07	6.5E-14	13.2	0.00
S11	9.8E-04	5.1E-04	6.4E-07	7.3E-04	4.7E-04	3.3E-07	1.2E-13	12.9	0.00
S12	9.8E-04	4.2E-04	2.0E-06	7.1E-04	3.9E-04	9.5E-07	2.6E-13	12.6	0.01

Solubility tests using synthetic supernatant at 10^{0}C

Sample	pH	Conductivity µS/cm	Mg mg/L	NH_4-N mg/L	Sample data PO_4-P mg/L	Mg mol/L	NH_4-N mol/L	PO_4-P mol/L	Mg:P Molar Ratio	N:P Molar Ratio
S1	6.62	2970	137.6	194.3	97.8	0.00566	0.014	0.00316	1.8	4.4
S2	6.8	2810	120.8	189.9	68.1	0.00497	0.014	0.00220	2.3	6.2
S3	6.87	2750	114.2	188.6	55.1	0.00470	0.013	0.00178	2.6	7.6
S4	6.91	2760	110.3	187.6	56.5	0.00454	0.013	0.00182	2.5	7.3
S5	7.32	2880	90.5	152.3	25.4	0.00372	0.011	0.00082	4.5	13.3
S6	8.36	2900	42	135	8	0.00173	0.010	0.00026	6.7	37.3
S7	8.66	2600	40	130	6	0.00165	0.009	0.00019	8.5	47.9
S8	9.05	2460	40	120	5.5	0.00165	0.009	0.00018	9.3	48.3
S9	9.31	2430	77.8	118	5	0.00320	0.008	0.00016	19.8	52.2

Solubility tests using synthetic supernatant at 20^o C

S1	6.68	4240	162.9	210	115.1	0.00670	0.015	0.00372	1.8	4.0
S2	6.8	3970	138.4	196.4	85.1	0.00570	0.014	0.00275	2.1	5.1
S3	7	3780	114.8	185.7	53.7	0.00472	0.013	0.00173	2.7	7.6
S4	7.23	3580	97.6	173.6	31.6	0.00402	0.012	0.00102	3.9	12.2
S5	7.72	3510	94	160	12	0.00387	0.011	0.00039	10.0	29.5
S6	7.9	3790	85	158	10	0.00350	0.011	0.00032	10.8	35.0
S7	8.47	3970	55	138	6.5	0.00226	0.010	0.00021	10.8	47.0
S8	9	3400	87.6	123.4	5.5	0.00360	0.009	0.00018	20.3	49.6
S9	9.69	3330	79.6	102.1	16.3	0.00328	0.007	0.00053	6.2	13.9

Sample	Struvite P_S	Struvite pP_S	Phosphate Dissociation Constants ka_1	ka_2	ka_3	Ammonia ka	MgOH kb	$[H^+]$ mol/L	$[OH^-]$ mol/L	$[Mg^{++}]$ mol/L
S1	2.5E-07	6.6	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	2.4E-07	4.2E-08	5.7E-03
S2	1.5E-07	6.8	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.6E-07	6.3E-08	5.0E-03
S3	1.1E-07	6.9	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.3E-07	7.4E-08	4.7E-03
S4	1.1E-07	7.0	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	1.2E-07	8.1E-08	4.5E-03
S5	3.3E-08	7.5	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	4.8E-08	2.1E-07	3.7E-03
S6	4.3E-09	8.4	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	4.4E-09	2.3E-06	1.7E-03
S7	3.0E-09	8.5	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	2.2E-09	4.6E-06	1.6E-03
S8	2.5E-09	8.6	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	8.9E-10	1.1E-05	1.6E-03
S9	4.4E-09	8.4	8.43E-03	5.57E-08	5E-13	6.36E-10	2.75E-03	4.9E-10	2.0E-05	3.2E-03
S1	3.7E-07	6.4	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	2.1E-07	4.8E-08	6.7E-03
S2	2.2E-07	6.7	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.6E-07	6.3E-08	5.7E-03
S3	1.1E-07	7.0	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.0E-07	1.0E-07	4.7E-03
S4	5.1E-08	7.3	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	5.9E-08	1.7E-07	4.0E-03
S5	1.7E-08	7.8	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.9E-08	5.2E-07	3.9E-03
S6	1.3E-08	7.9	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.3E-08	7.9E-07	3.5E-03
S7	4.7E-09	8.3	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	3.4E-09	3.0E-06	2.3E-03
S8	5.6E-09	8.2	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	1.0E-09	1.0E-05	3.6E-03
S9	1.3E-08	7.9	7.81E-03	6.12E-08	5E-13	6.05E-10	2.75E-03	2.0E-10	4.9E-05	3.2E-03

Sample	$[NH4^{+}]$ mol/L	$[PO4^{---}]$ mol/L	$\{Mg^{++}\}$ mol/L	$\{NH4^{+}\}$ mol/L	$\{PO4^{---}\}$ mol/L	K_{sp}	pK_{sp}	Ionic Strength
S1	1.4E-02	1.2E-09	2.5E-03	1.1E-02	1.9E-10	5.4E-15	14.3	0.05
S2	1.4E-02	1.8E-09	2.2E-03	1.1E-02	2.9E-10	7.2E-15	14.1	0.04
S3	1.3E-02	1.9E-09	2.1E-03	1.1E-02	3.2E-10	7.4E-15	14.1	0.04
S4	1.3E-02	2.3E-09	2.0E-03	1.1E-02	3.8E-10	8.5E-15	14.1	0.04
S5	1.1E-02	4.6E-09	1.7E-03	8.8E-03	7.4E-10	1.1E-14	14.0	0.05
S6	8.4E-03	2.7E-08	7.6E-04	6.9E-03	4.4E-09	2.3E-14	13.6	0.05
S7	7.2E-03	4.3E-08	7.5E-04	5.9E-03	7.4E-09	3.3E-14	13.5	0.04
S8	5.0E-03	9.8E-08	7.6E-04	4.1E-03	1.8E-08	5.6E-14	13.3	0.04
S9	3.7E-03	1.6E-07	1.5E-03	3.0E-03	3.0E-08	1.3E-13	12.9	0.04

S1	1.5E-02	2.0E-09	2.6E-03	1.2E-02	2.4E-10	7.2E-15	14.1	0.07
S2	1.4E-02	2.4E-09	2.3E-03	1.1E-02	3.0E-10	7.5E-15	14.1	0.06
S3	1.3E-02	3.3E-09	1.9E-03	1.1E-02	4.3E-10	8.5E-15	14.1	0.06
S4	1.2E-02	4.4E-09	1.7E-03	9.8E-03	6.0E-10	9.7E-15	14.0	0.06
S5	1.1E-02	7.8E-09	1.6E-03	8.9E-03	1.1E-09	1.5E-14	13.8	0.06
S6	1.1E-02	1.1E-08	1.4E-03	8.6E-03	1.4E-09	1.7E-14	13.8	0.06
S7	8.4E-03	2.9E-08	8.9E-04	6.6E-03	3.6E-09	2.2E-14	13.7	0.06
S8	5.5E-03	8.7E-08	1.5E-03	4.4E-03	1.2E-08	8.2E-14	13.1	0.05
S9	1.8E-03	1.3E-06	1.4E-03	1.5E-03	1.8E-07	3.7E-13	12.4	0.05

APPENDIX F : MODEL RESULTS

Run 1 Reactor A

Date	Influent Mg mg/L	Influent NH4 mg/L	Influent PO4 mg/L	pH	Actual Effluent Mg mg/L	Actual Effluent NH4 mg/L	Actual Effluent PO4 mg/L	Predicted Effluent Mg mg/L	Predicted Effluent NH4 mg/L	Predicted Effluent PO4 mg/L
31-Jul-01	45.1	185.2	66.1	7.5	25.7	172.2	36.4	28	176	45
1-Aug-01	56.4	164.7	58.8	7.5	41.8	155.6	40.0	39	155	37
2-Aug-01	57.9	177.8	57.8	7.4	42.0	168.0	36.7	43	169	39
3-Aug-01	58.7	177.6	57.8	7.4	44.1	167.8	38.3	44	169	39
4-Aug-01	49.7	166.0	61.3	7.5	32.9	155.1	38.3	34	157	42
5-Aug-01	61.7	165.4	64.0	7.3	49.5	157.0	46.6	50	159	49
6-Aug-01	68.0	165.4	57.7	7.4	53.2	157.0	38.3	51	156	36
7-Aug-01	47.2	169.4	59.3	7.4	41.1	164.9	46.8	38	164	47
8-Aug-01	81.9	170.1	52.0	7.4	60.0	159.0	27.8	64	160	29
9-Aug-01	55.4	179.6	62.0	7.4	45.0	169.0	42.6	40	171	42
10-Aug-01	60.0	178.5	61.1	7.5	45.0	168.0	40.0	39	166	34
11-Aug-01	105.0	170.0	56.7	7.3	90.4	157.4	35.4	83	158	29
13-Aug-01	58.5	169.3	49.8	7.5	41.0	159.0	32.8	44	161	31
14-Aug-01	65.0	179.1	63.9	7.5	39.7	167.5	36.4	41	165	33
16-Aug-01	55.0	178.1	63.5	7.4	40.4	170.0	42.4	39	169	44
17-Aug-01	69.5	179.0	53.5	7.4	52.5	157.0	30.7	53	169	32
18-Aug-01	72.9	173.7	53.6	7.4	55.9	156.0	30.0	56	164	32
20-Aug-01	52.9	198.9	55.1	7.5	36.6	160.0	29.3	36	189	33
22-Aug-01	90.9	164.7	61.7	7.7	55.4	133.0	19.6	56	145	17
23-Aug-01	117.9	213.9	57.9	7.5	88.8	131.0	18.7	83	194	14
24-Aug-01	65.6	168.4	58.3	7.6	42.3	146.0	22.2	41	154	27
25-Aug-01	79.8	169.3	58.6	7.6	45.4	145.0	20.4	51	153	22
26-Aug-01	82.5	165.5	57.2	7.6	43.6	147.0	19.0	54	149	21
27-Aug-01	117.0	178.9	61.9	7.6	53.0	154.0	16.0	79	157	14
28-Aug-01	117.0	179.3	62.0	7.6	52.0	154.0	16.3	79	158	14
29-Aug-01	97.5	197.0	62.9	7.9	50.0	140.0	12.0	56	173	10
30-Aug-01	97.5	196.1	62.9	8.0	42.0	132.0	9.0	55	171	8
31-Aug-01	97.5	194.3	62.9	8.0	41.5	133.0	9.6	55	170	8
1-Sep-01	58.0	159.3	53.2	8.2	26.4	129.0	11.4	28	142	14
2-Sep-01	141.4	226.6	47.6	8.4	105.0	170.6	3.1	106	206	2
3-Sep-01	78.5	235.0	56.4	8.0	42.0	136.0	10.0	41	213	9
8-Sep-01	74.9	146.3	60.5	8.4	36.0	115.0	6.4	35	124	10
9-Sep-01	121.5	227.5	68.2	8.3	47.0	200.0	3.0	71	198	4
10-Sep-01	115.4	194.6	60.1	8.6	69.2	160.0	1.5	71	169	3
11-Sep-01	125.1	200.2	62.2	8.3	78.9	128.0	5.9	79	174	4

	Influent			Predicted Effluent			$P_S$in	$P_S$eq	$P_S$out	Mol Reduction
Date	Mg mol/L	NH4 mol/L	PO4 mol/L	Mg mol/L	NH4 mol/L	PO4 mol/L				
31-Jul-01	0.0019	0.0132	0.0021	0.0012	0.0125	0.0014	5.2E-08	2.1E-08	2.1E-08	0.0007
1-Aug-01	0.0023	0.0118	0.0019	0.0016	0.0110	0.0012	5.2E-08	2.1E-08	2.1E-08	0.0007
2-Aug-01	0.0024	0.0127	0.0019	0.0018	0.0121	0.0013	5.6E-08	2.8E-08	2.8E-08	0.0006
3-Aug-01	0.0024	0.0127	0.0019	0.0018	0.0121	0.0013	5.7E-08	2.8E-08	2.8E-08	0.0006
4-Aug-01	0.0020	0.0119	0.0020	0.0014	0.0112	0.0013	4.8E-08	2.1E-08	2.1E-08	0.0006
5-Aug-01	0.0025	0.0118	0.0021	0.0020	0.0113	0.0016	6.2E-08	3.6E-08	3.6E-08	0.0005
6-Aug-01	0.0028	0.0118	0.0019	0.0021	0.0111	0.0012	6.1E-08	2.8E-08	2.8E-08	0.0007
7-Aug-01	0.0019	0.0121	0.0019	0.0015	0.0117	0.0015	4.5E-08	2.8E-08	2.8E-08	0.0004
8-Aug-01	0.0034	0.0121	0.0017	0.0026	0.0114	0.0009	6.9E-08	2.8E-08	2.8E-08	0.0008
9-Aug-01	0.0023	0.0128	0.0020	0.0016	0.0122	0.0014	5.8E-08	2.8E-08	2.8E-08	0.0006
10-Aug-01	0.0025	0.0127	0.0020	0.0016	0.0119	0.0011	6.2E-08	2.1E-08	2.1E-08	0.0009
11-Aug-01	0.0043	0.0121	0.0018	0.0034	0.0113	0.0009	9.6E-08	3.6E-08	3.6E-08	0.0009
13-Aug-01	0.0024	0.0121	0.0016	0.0018	0.0115	0.0010	4.7E-08	2.1E-08	2.1E-08	0.0006
14-Aug-01	0.0027	0.0128	0.0021	0.0017	0.0118	0.0011	7.1E-08	2.1E-08	2.1E-08	0.0010
16-Aug-01	0.0023	0.0127	0.0020	0.0016	0.0121	0.0014	5.9E-08	2.8E-08	2.8E-08	0.0006
17-Aug-01	0.0029	0.0128	0.0017	0.0022	0.0121	0.0010	6.3E-08	2.8E-08	2.8E-08	0.0007
18-Aug-01	0.0030	0.0124	0.0017	0.0023	0.0117	0.0010	6.4E-08	2.8E-08	2.8E-08	0.0007
20-Aug-01	0.0022	0.0142	0.0018	0.0015	0.0135	0.0011	5.5E-08	2.1E-08	2.1E-08	0.0007
22-Aug-01	0.0037	0.0118	0.0020	0.0023	0.0103	0.0006	8.8E-08	1.3E-08	1.3E-08	0.0014
23-Aug-01	0.0049	0.0153	0.0019	0.0034	0.0138	0.0004	1.4E-07	2.1E-08	2.1E-08	0.0014
24-Aug-01	0.0027	0.0120	0.0019	0.0017	0.0110	0.0009	6.1E-08	1.7E-08	1.7E-08	0.0010
25-Aug-01	0.0033	0.0121	0.0019	0.0021	0.0109	0.0007	7.5E-08	1.7E-08	1.7E-08	0.0012
26-Aug-01	0.0034	0.0118	0.0018	0.0022	0.0107	0.0007	7.4E-08	1.7E-08	1.7E-08	0.0012
27-Aug-01	0.0048	0.0128	0.0020	0.0033	0.0112	0.0005	1.2E-07	1.7E-08	1.7E-08	0.0015
28-Aug-01	0.0048	0.0128	0.0020	0.0033	0.0112	0.0005	1.2E-07	1.7E-08	1.7E-08	0.0016
29-Aug-01	0.0040	0.0141	0.0020	0.0023	0.0123	0.0003	1.1E-07	8.7E-09	8.7E-09	0.0017
30-Aug-01	0.0040	0.0140	0.0020	0.0022	0.0122	0.0003	1.1E-07	7.3E-09	7.3E-09	0.0018
31-Aug-01	0.0040	0.0139	0.0020	0.0022	0.0121	0.0003	1.1E-07	7.3E-09	7.3E-09	0.0018
1-Sep-01	0.0024	0.0114	0.0017	0.0011	0.0101	0.0005	4.7E-08	5.3E-09	5.3E-09	0.0013
2-Sep-01	0.0058	0.0162	0.0015	0.0043	0.0147	0.0001	1.4E-07	4.2E-09	4.2E-09	0.0015
3-Sep-01	0.0032	0.0168	0.0018	0.0017	0.0152	0.0003	9.9E-08	7.3E-09	7.3E-09	0.0015
8-Sep-01	0.0031	0.0104	0.0020	0.0015	0.0088	0.0003	6.3E-08	4.2E-09	4.2E-09	0.0016
9-Sep-01	0.0050	0.0162	0.0022	0.0029	0.0142	0.0001	1.8E-07	4.7E-09	4.7E-09	0.0021
10-Sep-01	0.0047	0.0139	0.0019	0.0029	0.0121	0.0001	1.3E-07	3.5E-09	3.5E-09	0.0018
11-Sep-01	0.0051	0.0143	0.0020	0.0033	0.0124	0.0001	1.5E-07	4.7E-09	4.7E-09	0.0019

Run 2 Reactor A

Date	Influent Mg mg/L	Influent NH4 mg/L	Influent PO4 mg/L	pH	Actual Effluent Mg mg/L	Actual Effluent NH4 mg/L	Actual Effluent PO4 mg/L	Predicted Effluent Mg mg/L	Predicted Effluent NH4 mg/L	Predicted Effluent PO4 mg/L
24-Sep-01	93.2	184.0	84.6	7.6	51.9	156.0	28.0	46	157	24
25-Sep-01	93.0	180.3	74.1	7.6	51.7	154.0	30.8	52	157	22
26-Sep-01	91.8	184.3	78.6	7.6	50.4	156.7	27.0	48	159	23
27-Sep-01	88.5	186.9	80.6	7.7	35.0	158.0	16.7	42	160	21
28-Sep-01	84.8	193.8	73.8	7.9	44.7	159.0	14.0	38	167	14
29-Sep-01	84.9	180.0	73.8	7.7	60.0	153.0	20.0	43	156	21
30-Sep-01	109.3	181.4	72.4	8.0	50.0	153.0	12.4	59	153	9
1-Oct-01	93.1	184.6	72.8	7.7	60.3	156.0	19.8	50	160	17
2-Oct-01	73.5	184.5	76.9	7.7	46.0	120.0	44.0	33	161	26
3-Oct-01	59.8	201.4	77.1	7.9	16.0	133.0	23.5	20	178	26
4-Oct-01	40.9	179.8	70.8	8.2	13.0	147.0	23.5	11	162	32
5-Oct-01	46.8	207.1	74.4	8.1	10.0	154.0	28.7	12	187	30
6-Oct-01	48.7	195.8	79.1	8.2	8.0	150.0	31.5	11	174	31
7-Oct-01	48.7	207.1	79.1	8.0	8.0	148.0	35.4	13	186	33
8-Oct-01	45.0	194.2	70.8	8.2	16.0	145.0	18.4	11	175	28
9-Oct-01	49.2	212.3	87.2	8.3	10.0	170.0	31.0	8	188	34
10-Oct-01	57.1	206.2	69.7	8.0	14.0	130.6	20.0	19	184	22
11-Oct-01	48.5	168.5	81.4	8.2	10.0	140.0	21.0	11	147	34
12-Oct-01	71.0	168.5	80.0	8.3	27.0	132.0	11.0	21	140	17
13-Oct-01	69.6	173.2	83.3	8.3	25.0	132.0	11.4	19	144	18
14-Oct-01	71.2	207.1	81.9	8.3	26.0	151.2	8.0	19	177	15
15-Oct-01	71.0	207.1	77.9	8.5	22.0	160.0	5.0	19	177	12
16-Oct-01	81.6	200.4	89.1	8.3	33.0	114.9	21.0	22	166	13
17-Oct-01	112.1	193.1	81.6	8.2	63.5	97.6	18.7	53	159	7
18-Oct-01	101.8	178.2	93.1	8.2	54.0	123.0	12.0	37	141	11
19-Oct-01	101.6	178.2	90.5	8.2	53.0	120.0	11.6	39	142	10
24-Oct-01	94.0	202.8	75.6	8.2	33.3	160.0	9.0	41	172	8
25-Oct-01	70.5	207.1	79.1	8.3	24.0	165.1	9.2	20	178	14
26-Oct-01	75.2	207.2	78.7	8.2	24.0	161.0	10.0	24	178	13
27-Oct-01	75.8	206.2	77.8	8.3	22.0	160.0	10.0	24	176	12
28-Oct-01	75.2	207.2	76.9	8.3	24.0	164.2	9.0	24	178	12
29-Oct-01	75.2	206.2	76.9	8.3	25.0	165.0	9.5	24	177	12
30-Oct-01	74.6	206.2	84.7	8.4	23.0	164.0	9.0	19	174	14

	Influent			Predicted Effluent			$P_S$in	$P_S$eq	$P_S$out	Mol Reduction
Date	Mg mol/L	NH4 mol/L	PO4 mol/L	Mg mol/L	NH4 mol/L	PO4 mol/L				
24-Sep-01	0.0038	0.0131	0.0027	0.0019	0.0112	0.0008	1.4E-07	1.7E-08	1.7E-08	0.0019
25-Sep-01	0.0038	0.0129	0.0024	0.0021	0.0112	0.0007	1.2E-07	1.7E-08	1.7E-08	0.0017
26-Sep-01	0.0038	0.0132	0.0025	0.0020	0.0114	0.0007	1.3E-07	1.7E-08	1.7E-08	0.0018
27-Sep-01	0.0036	0.0133	0.0026	0.0017	0.0114	0.0007	1.3E-07	1.3E-08	1.3E-08	0.0019
28-Sep-01	0.0035	0.0138	0.0024	0.0016	0.0119	0.0005	1.2E-07	8.7E-09	8.7E-09	0.0019
29-Sep-01	0.0035	0.0129	0.0024	0.0018	0.0111	0.0007	1.1E-07	1.3E-08	1.3E-08	0.0017
30-Sep-01	0.0045	0.0130	0.0023	0.0024	0.0109	0.0003	1.4E-07	7.3E-09	7.3E-09	0.0021
1-Oct-01	0.0038	0.0132	0.0023	0.0020	0.0114	0.0006	1.2E-07	1.3E-08	1.3E-08	0.0018
2-Oct-01	0.0030	0.0132	0.0025	0.0014	0.0115	0.0008	9.9E-08	1.3E-08	1.3E-08	0.0017
3-Oct-01	0.0025	0.0144	0.0025	0.0008	0.0127	0.0008	8.8E-08	8.7E-09	8.7E-09	0.0016
4-Oct-01	0.0017	0.0128	0.0023	0.0004	0.0116	0.0010	4.9E-08	5.3E-09	5.3E-09	0.0012
5-Oct-01	0.0019	0.0148	0.0024	0.0005	0.0133	0.0010	6.8E-08	6.2E-09	6.2E-09	0.0014
6-Oct-01	0.0020	0.0140	0.0026	0.0004	0.0124	0.0010	7.2E-08	5.3E-09	5.3E-09	0.0016
7-Oct-01	0.0020	0.0148	0.0026	0.0005	0.0133	0.0011	7.6E-08	7.3E-09	7.3E-09	0.0015
8-Oct-01	0.0019	0.0139	0.0023	0.0005	0.0125	0.0009	5.9E-08	5.3E-09	5.3E-09	0.0014
9-Oct-01	0.0020	0.0152	0.0028	0.0003	0.0134	0.0011	8.6E-08	4.7E-09	4.7E-09	0.0017
10-Oct-01	0.0024	0.0147	0.0022	0.0008	0.0132	0.0007	7.8E-08	7.3E-09	7.3E-09	0.0016
11-Oct-01	0.0020	0.0120	0.0026	0.0005	0.0105	0.0011	6.3E-08	5.3E-09	5.3E-09	0.0015
12-Oct-01	0.0029	0.0120	0.0026	0.0009	0.0100	0.0005	9.1E-08	4.7E-09	4.7E-09	0.0020
13-Oct-01	0.0029	0.0124	0.0027	0.0008	0.0103	0.0006	9.5E-08	4.7E-09	4.7E-09	0.0021
14-Oct-01	0.0029	0.0148	0.0026	0.0008	0.0126	0.0005	1.1E-07	4.7E-09	4.7E-09	0.0022
15-Oct-01	0.0029	0.0148	0.0025	0.0008	0.0127	0.0004	1.1E-07	3.8E-09	3.8E-09	0.0021
16-Oct-01	0.0034	0.0143	0.0029	0.0009	0.0119	0.0004	1.4E-07	4.7E-09	4.7E-09	0.0024
17-Oct-01	0.0046	0.0138	0.0026	0.0022	0.0114	0.0002	1.7E-07	5.3E-09	5.3E-09	0.0024
18-Oct-01	0.0042	0.0127	0.0030	0.0015	0.0101	0.0003	1.6E-07	5.3E-09	5.3E-09	0.0027
19-Oct-01	0.0042	0.0127	0.0029	0.0016	0.0101	0.0003	1.6E-07	5.3E-09	5.3E-09	0.0026
24-Oct-01	0.0039	0.0145	0.0024	0.0017	0.0123	0.0003	1.4E-07	5.3E-09	5.3E-09	0.0022
25-Oct-01	0.0029	0.0148	0.0026	0.0008	0.0127	0.0005	1.1E-07	4.7E-09	4.7E-09	0.0021
26-Oct-01	0.0031	0.0148	0.0025	0.0010	0.0127	0.0004	1.2E-07	5.3E-09	5.3E-09	0.0021
27-Oct-01	0.0031	0.0147	0.0025	0.0010	0.0126	0.0004	1.2E-07	4.7E-09	4.7E-09	0.0021
28-Oct-01	0.0031	0.0148	0.0025	0.0010	0.0127	0.0004	1.1E-07	4.7E-09	4.7E-09	0.0021
29-Oct-01	0.0031	0.0147	0.0025	0.0010	0.0126	0.0004	1.1E-07	4.7E-09	4.7E-09	0.0021
30-Oct-01	0.0031	0.0147	0.0027	0.0008	0.0124	0.0004	1.2E-07	4.2E-09	4.2E-09	0.0023

Run 3 Reactor A

Date	Influent Mg mg/L	Influent NH4 mg/L	Influent PO4 mg/L	pH	Actual Effluent Mg mg/L	Actual Effluent NH4 mg/L	Actual Effluent PO4 mg/L	Predicted Effluent Mg mg/L	Predicted Effluent NH4 mg/L	Predicted Effluent PO4 mg/L
2-Apr-02	267.3	209.6	149.5	7.1	194.4	164.0	33.0	170	154	26
3-Apr-02	228.0	200.0	135.7	7.1	155.1	150.0	32.0	145	152	30
4-Apr-02	185.6	205.2	152.7	7.2	91.3	145.3	39.5	95	153	37
5-Apr-02	337.9	222.2	153.0	7.3	240.7	127.2	17.0	227	158	12
6-Apr-02	396.0	178.0	133.3	7.3	298.8	108.5	12.8	300	123	11
7-Apr-02	396.0	180.4	149.2	7.3	311.0	110.4	15.0	289	118	12
8-Apr-02	394.2	187.2	148.4	7.3	309.0	112.0	14.0	287	125	12
9-Apr-02	394.2	180.4	147.6	7.3	307.0	114.0	14.0	288	119	12
10-Apr-02	394.2	183.7	146.0	7.3	300.0	116.0	14.0	289	123	12
13-Apr-02	243.2	277.2	133.5	7.7	146.0	129.8	9.3	143	219	6
17-Apr-02	148.3	194.2	158.0	7.7	51.1	138.6	13.3	47	136	28
18-Apr-02	378.8	195.8	127.0	7.3	290.0	112.4	16.8	287	143	10
19-Apr-02	136.4	193.8	157.5	7.4	41.2	137.8	51.9	50	144	47
20-Apr-02	189.9	185.9	154.0	7.5	102.3	120.1	17.5	88	127	24
21-Apr-02	177.2	188.9	158.7	7.4	80.0	124.4	30.5	78	132	33
22-Apr-02	114.1	223.0	154.3	7.4	28.3	164.6	42.7	35	178	54
24-Apr-02	182.9	264.0	150.8	7.3	110.0	190.0	48.8	84	207	24
25-Apr-02	192.0	263.2	159.8	7.3	94.8	180.0	44.1	86	202	24
29-Apr-02	175.0	326.5	220.5	7.2	40.0	230.0	60.0	42	250	51
30-Apr-02	158.3	321.7	210.6	7.2	38.0	210.0	58.0	37	252	56
1-May-02	163.9	314.3	215.3	7.2	35.0	215.0	59.0	39	242	56
2-May-02	157.3	320.7	216.7	7.2	40.0	221.0	57.0	35	250	61
3-May-02	154.3	313.9	208.9	7.2	38.0	215.0	60.0	37	246	59
4-May-02	156.4	316.3	207.6	7.2	40.0	214.0	60.0	38	248	56
7-May-02	164.3	308.6	205.7	7.2	38.0	240.0	59.0	43	239	51
8-May-02	164.3	304.3	205.7	7.2	38.0	230.0	58.0	44	235	52

Date	Influent Mg mol/L	Influent NH4 mol/L	Influent PO4 mol/L	Predicted Effluent Mg mol/L	Predicted Effluent NH4 mol/L	Predicted Effluent PO4 mol/L	$P_S$in	$P_S$eq	$P_S$out	Mol Reduction
2-Apr-02	0.0110	0.0150	0.0048	0.0070	0.0110	0.0008	7.9E-07	6.4E-08	6.4E-08	0.0040
3-Apr-02	0.0094	0.0143	0.0044	0.0060	0.0109	0.0010	5.9E-07	6.4E-08	6.4E-08	0.0034
4-Apr-02	0.0076	0.0147	0.0049	0.0039	0.0109	0.0012	5.5E-07	5.0E-08	5.0E-08	0.0037
5-Apr-02	0.0139	0.0159	0.0049	0.0093	0.0113	0.0004	1.1E-06	4.0E-08	4.0E-08	0.0046
6-Apr-02	0.0163	0.0127	0.0043	0.0124	0.0088	0.0004	8.9E-07	4.0E-08	4.0E-08	0.0039
7-Apr-02	0.0163	0.0129	0.0048	0.0119	0.0085	0.0004	1.0E-06	4.0E-08	4.0E-08	0.0044
8-Apr-02	0.0162	0.0134	0.0048	0.0118	0.0090	0.0004	1.0E-06	4.0E-08	4.0E-08	0.0044
9-Apr-02	0.0162	0.0129	0.0048	0.0118	0.0085	0.0004	1.0E-06	4.0E-08	4.0E-08	0.0044
10-Apr-02	0.0162	0.0131	0.0047	0.0119	0.0088	0.0004	1.0E-06	4.0E-08	4.0E-08	0.0043
13-Apr-02	0.0100	0.0198	0.0043	0.0059	0.0157	0.0002	8.5E-07	1.7E-08	1.7E-08	0.0041
17-Apr-02	0.0061	0.0139	0.0051	0.0019	0.0097	0.0009	4.3E-07	1.7E-08	1.7E-08	0.0042
18-Apr-02	0.0156	0.0140	0.0041	0.0118	0.0102	0.0003	8.9E-07	4.0E-08	4.0E-08	0.0038
19-Apr-02	0.0056	0.0138	0.0051	0.0020	0.0103	0.0015	3.9E-07	3.2E-08	3.2E-08	0.0036
20-Apr-02	0.0078	0.0133	0.0050	0.0036	0.0091	0.0008	5.2E-07	2.6E-08	2.6E-08	0.0042
21-Apr-02	0.0073	0.0135	0.0051	0.0032	0.0094	0.0011	5.0E-07	3.2E-08	3.2E-08	0.0041
22-Apr-02	0.0047	0.0159	0.0050	0.0014	0.0127	0.0017	3.7E-07	3.2E-08	3.2E-08	0.0032
24-Apr-02	0.0075	0.0188	0.0049	0.0034	0.0148	0.0008	6.9E-07	4.0E-08	4.0E-08	0.0041
25-Apr-02	0.0079	0.0188	0.0052	0.0035	0.0144	0.0008	7.7E-07	4.0E-08	4.0E-08	0.0044
29-Apr-02	0.0072	0.0233	0.0071	0.0017	0.0178	0.0016	1.2E-06	5.0E-08	5.0E-08	0.0055
30-Apr-02	0.0065	0.0230	0.0068	0.0015	0.0180	0.0018	1.0E-06	5.0E-08	5.0E-08	0.0050
1-May-02	0.0067	0.0224	0.0070	0.0016	0.0173	0.0018	1.1E-06	5.0E-08	5.0E-08	0.0051
2-May-02	0.0065	0.0229	0.0070	0.0014	0.0179	0.0020	1.0E-06	5.0E-08	5.0E-08	0.0050
3-May-02	0.0063	0.0224	0.0067	0.0015	0.0176	0.0019	9.6E-07	5.0E-08	5.0E-08	0.0048
4-May-02	0.0064	0.0226	0.0067	0.0016	0.0177	0.0018	9.7E-07	5.0E-08	5.0E-08	0.0049
7-May-02	0.0068	0.0220	0.0066	0.0018	0.0170	0.0017	9.9E-07	5.0E-08	5.0E-08	0.0050
8-May-02	0.0068	0.0217	0.0066	0.0018	0.0168	0.0017	9.8E-07	5.0E-08	5.0E-08	0.0050

Run 1 Reactor B

	Influent				Actual Effluent			Predicted Effluent		
Date	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
31-Jul-01	56.0	181.1	61.3	7.4	41.0	172.7	40.0	41	172	42
1-Aug-01	51.9	165.7	59.2	7.4	46.0	159.0	42.2	41	159	45
2-Aug-01	59.1	177.5	57.7	8.6	29.0	145.0	11.0	22	156	11
3-Aug-01	98.6	169.2	55.0	7.6	52.4	142.0	19.8	69	152	17
9-Aug-01	61.3	178.2	61.5	7.5	45.0	166.0	33.9	40	166	34
10-Aug-01	54.5	179.8	61.5	7.6	44.0	140.0	33.0	32	167	33
11-Aug-01	49.5	185.8	62.0	7.5	28.0	172.0	43.0	32	176	40
15-Aug-01	48.6	210.2	56.1	7.5	27.0	170.0	38.0	32	201	35
16-Aug-01	50.6	179.1	63.8	7.6	28.8	162.3	38.0	29	167	36
17-Aug-01	48.9	183.8	54.9	7.6	34.3	167.0	35.0	31	174	32
18-Aug-01	48.9	179.1	55.2	7.6	34.0	152.0	36.0	31	169	33
20-Aug-01	57.5	197.9	54.8	7.7	33.8	159.0	21.9	33	184	23
22-Aug-01	58.1	170.6	63.9	7.7	33.8	143.0	25.0	31	155	29
23-Aug-01	75.3	221.5	60.0	7.8	34.0	179.5	16.7	39	201	14
24-Aug-01	58.7	169.7	58.7	7.8	32.0	140.0	19.5	31	154	24
25-Aug-01	58.7	173.1	59.9	7.8	31.9	154.7	19.5	30	157	24
26-Aug-01	63.3	168.7	58.3	7.8	38.9	149.0	18.8	34	152	21
27-Aug-01	74.8	185.2	64.1	7.8	35.9	154.0	19.0	38	164	18
28-Aug-01	74.8	185.7	64.2	7.8	35.9	158.0	18.9	38	165	18
29-Aug-01	74.8	200.8	64.1	7.8	35.0	158.0	18.7	38	179	17
30-Aug-01	74.8	199.8	64.1	7.8	34.8	154.0	19.0	38	178	17
31-Aug-01	74.8	197.9	64.1	7.8	35.0	152.0	18.0	38	177	17
2-Sep-01	80.3	241.0	50.6	8.5	50.0	165.0	5.0	44	220	4
3-Sep-01	92.6	232.3	55.8	8.5	48.8	170.0	4.0	52	209	4
7-Sep-01	95.5	232.3	69.7	8.5	55.0	190.0	2.0	44	203	4
9-Sep-01	103.5	230.8	69.2	8.5	55.0	150.0	1.5	52	201	4
10-Sep-01	92.0	199.8	61.7	8.5	60.0	153.6	5.0	47	174	5
11-Sep-01	91.3	205.5	63.8	8.6	50.0	150.0	3.0	45	179	5
12-Sep-01	90.7	205.5	63.5	8.6	55.0	145.0	4.0	45	179	5
13-Sep-01	90.7	205.5	62.6	8.6	52.0	140.0	4.0	45	179	5

	Influent			Predicted Effluent			$P_S$in	$P_S$eq	$P_S$out	Mol Reduction
Date	Mg mol/L	NH4 mol/L	PO4 mol/L	Mg mol/L	NH4 mol/L	PO4 mol/L				
31-Jul-01	0.0023	0.0129	0.0020	0.0017	0.0123	0.0013	5.9E-08	2.8E-08	2.8E-08	0.0006
1-Aug-01	0.0021	0.0118	0.0019	0.0017	0.0114	0.0014	4.8E-08	2.8E-08	2.8E-08	0.0005
2-Aug-01	0.0024	0.0127	0.0019	0.0009	0.0112	0.0003	5.7E-08	3.5E-09	3.5E-09	0.0015
3-Aug-01	0.0041	0.0121	0.0018	0.0028	0.0108	0.0005	8.7E-08	1.7E-08	1.7E-08	0.0012
9-Aug-01	0.0025	0.0127	0.0020	0.0016	0.0118	0.0011	6.4E-08	2.1E-08	2.1E-08	0.0009
10-Aug-01	0.0022	0.0128	0.0020	0.0013	0.0119	0.0011	5.7E-08	1.7E-08	1.7E-08	0.0009
11-Aug-01	0.0020	0.0133	0.0020	0.0013	0.0125	0.0013	5.4E-08	2.1E-08	2.1E-08	0.0007
15-Aug-01	0.0020	0.0150	0.0018	0.0013	0.0143	0.0011	5.4E-08	2.1E-08	2.1E-08	0.0007
16-Aug-01	0.0021	0.0128	0.0021	0.0012	0.0119	0.0012	5.5E-08	1.7E-08	1.7E-08	0.0009
17-Aug-01	0.0020	0.0131	0.0018	0.0013	0.0124	0.0010	4.7E-08	1.7E-08	1.7E-08	0.0007
18-Aug-01	0.0020	0.0128	0.0018	0.0013	0.0121	0.0011	4.6E-08	1.7E-08	1.7E-08	0.0007
20-Aug-01	0.0024	0.0141	0.0018	0.0013	0.0131	0.0007	5.9E-08	1.3E-08	1.3E-08	0.0010
22-Aug-01	0.0024	0.0122	0.0021	0.0013	0.0111	0.0009	6.0E-08	1.3E-08	1.3E-08	0.0011
23-Aug-01	0.0031	0.0158	0.0019	0.0016	0.0143	0.0005	9.5E-08	1.1E-08	1.1E-08	0.0015
24-Aug-01	0.0024	0.0121	0.0019	0.0013	0.0110	0.0008	5.5E-08	1.1E-08	1.1E-08	0.0011
25-Aug-01	0.0024	0.0124	0.0019	0.0012	0.0112	0.0008	5.8E-08	1.1E-08	1.1E-08	0.0012
26-Aug-01	0.0026	0.0120	0.0019	0.0014	0.0109	0.0007	5.9E-08	1.1E-08	1.1E-08	0.0012
27-Aug-01	0.0031	0.0132	0.0021	0.0016	0.0117	0.0006	8.4E-08	1.1E-08	1.1E-08	0.0015
28-Aug-01	0.0031	0.0133	0.0021	0.0016	0.0118	0.0006	8.5E-08	1.1E-08	1.1E-08	0.0015
29-Aug-01	0.0031	0.0143	0.0021	0.0015	0.0128	0.0005	9.1E-08	1.1E-08	1.1E-08	0.0015
30-Aug-01	0.0031	0.0143	0.0021	0.0015	0.0127	0.0005	9.1E-08	1.1E-08	1.1E-08	0.0015
31-Aug-01	0.0031	0.0141	0.0021	0.0016	0.0126	0.0005	9.0E-08	1.1E-08	1.1E-08	0.0015
2-Sep-01	0.0033	0.0172	0.0016	0.0018	0.0157	0.0001	9.3E-08	3.8E-09	3.8E-09	0.0015
3-Sep-01	0.0038	0.0166	0.0018	0.0021	0.0149	0.0001	1.1E-07	3.8E-09	3.8E-09	0.0017
7-Sep-01	0.0039	0.0166	0.0023	0.0018	0.0145	0.0001	1.5E-07	3.8E-09	3.8E-09	0.0021
9-Sep-01	0.0043	0.0165	0.0022	0.0021	0.0144	0.0001	1.6E-07	3.8E-09	3.8E-09	0.0021
10-Sep-01	0.0038	0.0143	0.0020	0.0020	0.0124	0.0002	1.1E-07	3.8E-09	3.8E-09	0.0018
11-Sep-01	0.0038	0.0147	0.0021	0.0018	0.0128	0.0002	1.1E-07	3.5E-09	3.5E-09	0.0019
12-Sep-01	0.0037	0.0147	0.0021	0.0018	0.0128	0.0002	1.1E-07	3.5E-09	3.5E-09	0.0019
13-Sep-01	0.0037	0.0147	0.0020	0.0019	0.0128	0.0001	1.1E-07	3.5E-09	3.5E-09	0.0019

Run 2 Reactor B

Date	Influent Mg mg/L	Influent NH4 mg/L	Influent PO4 mg/L	pH	Actual Effluent Mg mg/L	Actual Effluent NH4 mg/L	Actual Effluent PO4 mg/L	Predicted Effluent Mg mg/L	Predicted Effluent NH4 mg/L	Predicted Effluent PO4 mg/L
24-Sep-01	73.2	187.4	86.2	7.7	24.6	160.0	21.0	29	162	30
25-Sep-01	76.7	183.1	75.2	7.4	54.8	166.0	45.0	47	166	37
26-Sep-01	90.8	184.4	78.6	7.8	46.0	163.0	44.0	42	157	17
27-Sep-01	89.3	186.8	80.5	8.1	22.0	156.0	10.0	35	156	12
28-Sep-01	76.6	195.4	74.4	8.1	23.0	157.0	10.9	29	168	14
29-Sep-01	76.7	181.5	74.4	8.1	25.0	170.0	10.0	30	154	14
30-Sep-01	88.6	184.5	73.6	8.4	40.0	141.0	5.5	37	155	8
1-Oct-01	69.1	189.0	74.5	8.0	27.8	148.9	19.8	25	164	19
2-Oct-01	85.6	182.3	76.0	8.1	37.0	130.0	11.2	35	153	12
3-Oct-01	70.5	199.4	76.3	8.1	17.0	157.4	13.8	23	172	16
4-Oct-01	47.2	178.1	70.1	8.3	9.8	150.1	15.0	12	158	26
5-Oct-01	50.2	206.2	74.0	8.2	12.0	178.2	19.7	12	184	25
6-Oct-01	52.3	194.9	78.7	8.3	11.0	166.9	19.5	11	171	26
7-Oct-01	53.3	205.9	78.6	8.3	10.0	180.7	24.4	11	182	25
8-Oct-01	118.6	186.3	68.0	8.3	70.0	136.2	3.9	69	158	5
10-Oct-01	61.3	205.3	69.4	8.3	20.0	177.3	8.4	19	181	15
11-Oct-01	52.1	167.8	81.1	8.5	10.0	124.0	21.0	10	144	28
12-Oct-01	242.8	143.2	68.0	8.5	194.2	113.0	2.6	191	113	2
13-Oct-01	54.4	175.6	84.5	7.7	43.0	151.0	48.0	21	156	42
14-Oct-01	82.1	205.2	81.1	8.5	25.0	168.8	6.4	26	173	9
15-Oct-01	77.8	205.9	77.4	8.5	29.0	169.5	4.6	24	175	9
16-Oct-01	58.6	205.9	91.5	8.5	10.0	163.9	16.3	8	177	27
17-Oct-01	73.2	202.4	85.6	8.6	24.6	160.4	7.5	17	170	13
24-Oct-01	76.8	205.9	76.8	8.5	29.0	170.0	5.0	24	176	10
25-Oct-01	76.8	205.9	78.6	8.5	30.0	169.0	5.5	23	175	10
26-Oct-01	17.4	146.7	63.2	9.1	3.2	146.9	79.0	5	140	48
28-Oct-01	76.8	206.9	76.8	8.6	28.0	172.0	6.0	24	176	9
29-Oct-01	76.8	205.9	76.8	8.6	30.0	170.0	5.0	24	175	9

	Influent			Predicted Effluent			P_Sin	P_Seq	P_Sout	Mol Reduction
Date	Mg mol/L	NH4 mol/L	PO4 mol/L	Mg mol/L	NH4 mol/L	PO4 mol/L				
24-Sep-01	0.0030	0.0134	0.0028	0.0012	0.0116	0.0010	1.1E-07	1.3E-08	1.3E-08	0.0018
25-Sep-01	0.0032	0.0131	0.0024	0.0019	0.0118	0.0012	1.0E-07	2.8E-08	2.8E-08	0.0012
26-Sep-01	0.0037	0.0132	0.0025	0.0017	0.0112	0.0005	1.2E-07	1.1E-08	1.1E-08	0.0020
27-Sep-01	0.0037	0.0133	0.0026	0.0015	0.0111	0.0004	1.3E-07	6.2E-09	6.2E-09	0.0022
28-Sep-01	0.0031	0.0140	0.0024	0.0012	0.0120	0.0004	1.1E-07	6.2E-09	6.2E-09	0.0020
29-Sep-01	0.0032	0.0130	0.0024	0.0012	0.0110	0.0005	9.8E-08	6.2E-09	6.2E-09	0.0019
30-Sep-01	0.0036	0.0132	0.0024	0.0015	0.0110	0.0003	1.1E-07	4.2E-09	4.2E-09	0.0021
1-Oct-01	0.0028	0.0135	0.0024	0.0010	0.0117	0.0006	9.2E-08	7.3E-09	7.3E-09	0.0018
2-Oct-01	0.0035	0.0130	0.0025	0.0015	0.0110	0.0004	1.1E-07	6.2E-09	6.2E-09	0.0021
3-Oct-01	0.0029	0.0142	0.0025	0.0010	0.0123	0.0005	1.0E-07	6.2E-09	6.2E-09	0.0019
4-Oct-01	0.0019	0.0127	0.0023	0.0005	0.0113	0.0008	5.6E-08	4.7E-09	4.7E-09	0.0014
5-Oct-01	0.0021	0.0147	0.0024	0.0005	0.0132	0.0008	7.3E-08	5.3E-09	5.3E-09	0.0016
6-Oct-01	0.0022	0.0139	0.0025	0.0005	0.0122	0.0008	7.6E-08	4.7E-09	4.7E-09	0.0017
7-Oct-01	0.0022	0.0147	0.0025	0.0005	0.0130	0.0008	8.2E-08	4.7E-09	4.7E-09	0.0017
8-Oct-01	0.0049	0.0133	0.0022	0.0028	0.0113	0.0001	1.4E-07	4.7E-09	4.7E-09	0.0020
10-Oct-01	0.0025	0.0147	0.0022	0.0008	0.0129	0.0005	8.3E-08	4.7E-09	4.7E-09	0.0018
11-Oct-01	0.0021	0.0120	0.0026	0.0004	0.0103	0.0009	6.7E-08	3.8E-09	3.8E-09	0.0017
12-Oct-01	0.0100	0.0102	0.0022	0.0079	0.0081	0.0001	2.2E-07	3.8E-09	3.8E-09	0.0021
13-Oct-01	0.0022	0.0125	0.0027	0.0009	0.0112	0.0014	7.7E-08	1.3E-08	1.3E-08	0.0014
14-Oct-01	0.0034	0.0146	0.0026	0.0011	0.0123	0.0003	1.3E-07	3.8E-09	3.8E-09	0.0023
15-Oct-01	0.0032	0.0147	0.0025	0.0010	0.0125	0.0003	1.2E-07	3.8E-09	3.8E-09	0.0022
16-Oct-01	0.0024	0.0147	0.0030	0.0003	0.0126	0.0009	1.0E-07	3.8E-09	3.8E-09	0.0021
17-Oct-01	0.0030	0.0144	0.0028	0.0007	0.0121	0.0004	1.2E-07	3.5E-09	3.5E-09	0.0023
24-Oct-01	0.0032	0.0147	0.0025	0.0010	0.0125	0.0003	1.2E-07	3.8E-09	3.8E-09	0.0022
25-Oct-01	0.0032	0.0147	0.0025	0.0009	0.0125	0.0003	1.2E-07	3.8E-09	3.8E-09	0.0022
26-Oct-01	0.0007	0.0105	0.0020	0.0002	0.0100	0.0015	1.5E-08	3.3E-09	3.3E-09	0.0005
28-Oct-01	0.0032	0.0148	0.0025	0.0010	0.0126	0.0003	1.2E-07	3.5E-09	3.5E-09	0.0022
29-Oct-01	0.0032	0.0147	0.0025	0.0010	0.0125	0.0003	1.2E-07	3.5E-09	3.5E-09	0.0022

Run 3 Reactor B

Date	Influent Mg mg/L	Influent NH4 mg/L	Influent PO4 mg/L	pH	Actual Effluent Mg mg/L	Actual Effluent NH4 mg/L	Actual Effluent PO4 mg/L	Predicted Effluent Mg mg/L	Predicted Effluent NH4 mg/L	Predicted Effluent PO4 mg/L
18-Mar-02	225.3	300.7	134.6	7.7	128.1	241.2	12.2	124	243	6
19-Mar-02	224.0	295.2	137.2	7.7	126.8	225.2	12	121	236	6
20-Mar-02	222.6	292.5	136.7	7.7	125.4	222.5	12.8	120	234	6
25-Mar-02	225.5	277.2	161.6	7.5	113.7	210.0	11.4	108	210	12
26-Mar-02	189.6	319.1	169.3	6.6	141.0	277.1	103.9	123	281	85
27-Mar-02	189.5	316.9	162.3	7.5	68.0	247.0	9.8	74	250	15
29-Mar-02	147.2	320.8	168.0	7.7	50.0	250.8	14.4	32	255	22
30-Mar-02	300.0	199.3	132.9	7.1	234.4	160.5	43.1	212	149	21
31-Mar-02	144.0	218.8	142.4	7.3	71.1	173.5	44.9	63	172	39
1-Apr-02	144.0	199.7	138.1	7.4	53.4	137.1	32.9	63	153	35
2-Apr-02	149.4	223.0	159.1	7.6	40.0	160.0	18.7	47	164	29
3-Apr-02	150.0	209.9	142.5	7.6	57.7	145.0	20.7	57	157	24
4-Apr-02	164.9	207.8	154.6	7.7	60.0	131.6	13.7	60	147	20
5-Apr-02	171.5	240.8	165.8	7.9	50.0	140.0	9.7	52	172	13
6-Apr-02	264.0	191.0	143.0	8	142.5	123.8	3.9	156	129	5
7-Apr-02	117.3	208.3	172.3	7.9	12.8	148.1	36.3	18	151	45
11-Apr-02	221.1	279.3	161.7	7.7	104.5	209.3	9.6	101	210	8
13-Apr-02	172.2	209.0	135.6	7.7	75.0	150.2	8.5	78	154	15
18-Apr-02	206.7	189.2	153.8	7.7	109.5	123.4	8.9	97	126	15
19-Apr-02	189.7	185.9	154.0	7.9	77.9	120.1	7.6	79	122	12
20-Apr-02	177.2	188.9	158.7	7.8	80.0	121.7	9	66	125	18
21-Apr-02	289.2	270.0	181.5	7.5	167.7	186.0	7.3	154	192	9
23-Apr-02	196.9	264.6	153.8	7.6	99.7	190.0	6.8	86	201	13
24-Apr-02	213.3	261.3	149.2	7.8	75.0	191.3	9.4	102	197	7
25-Apr-02	182.9	264.0	160.3	7.8	70.0	190.0	12.3	66	197	11
26-Apr-02	186.5	282.9	167.5	7.8	65.0	210.1	5.1	64	212	11
29-Apr-02	215.8	314.6	212.5	7.4	70.0	227.8	19.6	66	229	22
30-Apr-02	107.9	337.5	220.9	7.3	15.2	293.6	144	15	284	102
3-May-02	206.1	301.8	200.8	7.4	70.0	217.8	19.6	66	221	23
4-May-02	289.3	274.3	180.0	7.5	167.7	190.3	7.2	155	197	9
5-May-02	289.0	270.0	180.0	7.5	167.7	186.0	7.3	155	193	9
6-May-02	289.2	270.0	181.5	7.5	167.7	186.0	7.3	154	192	9
12-May-02	221.5	244.0	188.0	7.3	100.0	169.8	23	94	171	26
15-May-02	113.2	333.4	210.7	7.3	16.0	209.4	73	17	278	88
22-May-02	193.6	273.6	208.8	7.3	74.0	194.0	30	59	196	37
23-May-02	193.6	273.6	208.8	7.3	73.0	191.6	29.3	59	196	37
24-May-02	193.6	273.6	204.3	7.3	72.1	195.3	26.1	61	197	35

Date	Influent Mg mol/L	Influent NH4 mol/L	Influent PO4 mol/L	Predicted Effluent Mg mol/L	Predicted Effluent NH4 mol/L	Predicted Effluent PO4 mol/L	$P_{S}in$	$P_{S}eq$	$P_{S}out$	Mol Reduction
18-Mar-02	0.0093	0.0215	0.0043	0.0051	0.0173	0.0002	8.7E-07	1.7E-08	1.7E-08	0.0042
19-Mar-02	0.0092	0.0211	0.0044	0.0050	0.0169	0.0002	8.6E-07	1.7E-08	1.7E-08	0.0042
20-Mar-02	0.0092	0.0209	0.0044	0.0049	0.0167	0.0002	8.4E-07	1.7E-08	1.7E-08	0.0042
25-Mar-02	0.0093	0.0198	0.0052	0.0044	0.0150	0.0004	9.6E-07	2.6E-08	2.6E-08	0.0048
26-Mar-02	0.0078	0.0228	0.0055	0.0051	0.0201	0.0027	9.7E-07	2.8E-07	2.8E-07	0.0027
27-Mar-02	0.0078	0.0226	0.0052	0.0030	0.0179	0.0005	9.2E-07	2.6E-08	2.6E-08	0.0048
29-Mar-02	0.0061	0.0229	0.0054	0.0013	0.0182	0.0007	7.5E-07	1.7E-08	1.7E-08	0.0047
30-Mar-02	0.0123	0.0142	0.0043	0.0087	0.0106	0.0007	7.5E-07	6.4E-08	6.4E-08	0.0036
31-Mar-02	0.0059	0.0156	0.0046	0.0026	0.0123	0.0013	4.3E-07	4.0E-08	4.0E-08	0.0033
1-Apr-02	0.0059	0.0143	0.0045	0.0026	0.0109	0.0011	3.8E-07	3.2E-08	3.2E-08	0.0033
2-Apr-02	0.0061	0.0159	0.0051	0.0019	0.0117	0.0009	5.0E-07	2.1E-08	2.1E-08	0.0042
3-Apr-02	0.0062	0.0150	0.0046	0.0024	0.0112	0.0008	4.3E-07	2.1E-08	2.1E-08	0.0038
4-Apr-02	0.0068	0.0148	0.0050	0.0024	0.0105	0.0007	5.0E-07	1.7E-08	1.7E-08	0.0043
5-Apr-02	0.0071	0.0172	0.0054	0.0021	0.0123	0.0004	6.5E-07	1.1E-08	1.1E-08	0.0049
6-Apr-02	0.0109	0.0136	0.0046	0.0064	0.0092	0.0002	6.8E-07	9.3E-09	9.3E-09	0.0045
7-Apr-02	0.0048	0.0149	0.0056	0.0007	0.0108	0.0015	4.0E-07	1.1E-08	1.1E-08	0.0041
11-Apr-02	0.0091	0.0199	0.0052	0.0041	0.0150	0.0003	9.5E-07	1.7E-08	1.7E-08	0.0049
13-Apr-02	0.0071	0.0149	0.0044	0.0032	0.0110	0.0005	4.6E-07	1.7E-08	1.7E-08	0.0039
18-Apr-02	0.0085	0.0135	0.0050	0.0040	0.0090	0.0005	5.7E-07	1.7E-08	1.7E-08	0.0045
19-Apr-02	0.0078	0.0133	0.0050	0.0032	0.0087	0.0004	5.1E-07	1.1E-08	1.1E-08	0.0046
20-Apr-02	0.0073	0.0135	0.0051	0.0027	0.0089	0.0006	5.0E-07	1.4E-08	1.4E-08	0.0046
21-Apr-02	0.0119	0.0193	0.0059	0.0063	0.0137	0.0003	1.3E-06	2.6E-08	2.6E-08	0.0056
23-Apr-02	0.0081	0.0189	0.0050	0.0035	0.0143	0.0004	7.6E-07	2.1E-08	2.1E-08	0.0046
24-Apr-02	0.0088	0.0187	0.0048	0.0042	0.0141	0.0002	7.9E-07	1.4E-08	1.4E-08	0.0046
25-Apr-02	0.0075	0.0188	0.0052	0.0027	0.0140	0.0004	7.3E-07	1.4E-08	1.4E-08	0.0048
26-Apr-02	0.0077	0.0202	0.0054	0.0026	0.0151	0.0003	8.4E-07	1.4E-08	1.4E-08	0.0051
29-Apr-02	0.0089	0.0225	0.0069	0.0027	0.0163	0.0007	1.4E-06	3.2E-08	3.2E-08	0.0061
30-Apr-02	0.0044	0.0241	0.0071	0.0006	0.0203	0.0033	7.6E-07	4.0E-08	4.0E-08	0.0038
3-May-02	0.0085	0.0215	0.0065	0.0027	0.0158	0.0007	1.2E-06	3.2E-08	3.2E-08	0.0057
4-May-02	0.0119	0.0196	0.0058	0.0064	0.0141	0.0003	1.4E-06	2.6E-08	2.6E-08	0.0055
5-May-02	0.0119	0.0193	0.0058	0.0064	0.0138	0.0003	1.3E-06	2.6E-08	2.6E-08	0.0055
6-May-02	0.0119	0.0193	0.0059	0.0063	0.0137	0.0003	1.3E-06	2.6E-08	2.6E-08	0.0056
12-May-02	0.0091	0.0174	0.0061	0.0039	0.0122	0.0008	9.6E-07	4.0E-08	4.0E-08	0.0052
15-May-02	0.0047	0.0238	0.0068	0.0007	0.0199	0.0028	7.5E-07	4.0E-08	4.0E-08	0.0040
22-May-02	0.0080	0.0195	0.0067	0.0024	0.0140	0.0012	1.0E-06	4.0E-08	4.0E-08	0.0056
23-May-02	0.0080	0.0195	0.0067	0.0024	0.0140	0.0012	1.0E-06	4.0E-08	4.0E-08	0.0056
24-May-02	0.0080	0.0195	0.0066	0.0025	0.0141	0.0011	1.0E-06	4.0E-08	4.0E-08	0.0055