Simulating a Novel Nitrogen Removal Process Using EnviroPro Designer

by

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<u>Author's Declaration</u>

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revision, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Jabeen Waheed

ABSTRACT

Ammonia removal is an important problem that Canadian municipalities are encountering in their wastewater treatment systems due to ammonia's adverse environmental effects and its increasingly stringent discharge standards.

Nitrogen compounds are generally removed from wastewater by a combination of nitrification and denitrification. In full nitrification, ammonia is first biologically oxidized to nitrite, which is then oxidized to nitrate by nitrite-oxidizing bacteria. In denitrification, the resulting nitrate has to be first reduced to nitrite in order to be converted to nitrous oxide, then nitric oxide, and finally to nitrogen gas. Since, nitrite is an intermediary compound in both nitrification and denitrification, it may be more efficient to produce a partial nitrification up to nitrite and then denitrification starting from this nitrite.

In this research, EnviroPro Designer was used to simulate, optimize and compare process models for both full nitrification and partial nitrification. The Full System model simulates the traditional full nitrification followed by denitrification. Partial System-1 model simulates the partial nitrification process followed by denitrification directly from nitrite. Partial System-1 significantly reduced the ammonia and domestic waste concentrations in the effluent while achieving 1.5 times faster denitrification rates and utilizing 33% less oxygen. Partial System-1 was further optimized to develop a novel nitrogen removal process, Partial System-3, which incorporated an additional third anoxic stage while the aerobic stage in sludge treatment was removed. Partial System-3 successfully reduced the ammonia and nitrite concentrations in the effluent to values well within the current guidelines while consuming 50% less oxygen than the Full System, which reflected favorably on utility savings. It also showed 2 times faster denitrification rates, and displayed superior domestic waste consumption. Furthermore, the capital and operational costs were less than other nitrogen removal systems investigated in this thesis. The novel Partial System-3 appears to be the best option for removal of nitrogen from medium to high strength wastewater, and further experimental research is required to confirm the kinetic and yield constants assumed in the simulations.

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Chapter 1

Introduction

The removal of ammonia is an important problem in modern wastewater treatment systems due to adverse environmental effects and its increasingly stringent discharge standards.

The biological full nitrification–denitrification is the most common wastewater procedure to convert ammonia into nitrogen. This treatment is based on natural nitrogen cycle transformations. As with any natural biological treatment, it uses the same tools as nature to transform the pollutants. The only difference is that these reactions are being carried out in bioreactors under favorable conditions to optimize the transformation reactions. Full Nitrification-Denitrification process takes place in two steps. During the first step, that is full nitrification, ammonia is aerobically oxidized to nitrite and then to nitrate by the action of autotrophic microorganisms which obtain their energy from these reactions therefore, in full nitrification, dissolved oxygen is required. The second step is de-nitrification, which is an anoxic process. This process is performed by heterotrophic microorganisms which reduce the nitrate obtained in the first step to gaseous nitrogen. These microorganisms use nitrite and nitrate as final electron acceptors. Although oxygen is not required in this process, however, organic matter (electron donor) is required during denitrification. Hence, the operational costs of the biological nitrogen removal process are to a great extent related to the oxygen and organic matter requirements associated with the treatment.

Currently, many Wastewater Treatment Plants implement Full Nitrification. Some new processes and operational strategies have come up in order to reduce the costs. One of the new technologies being proposed these days is Partial Nitrification in which a partial nitrification is produced up to nitrite and then the process of denitrification starts from this nitrite. The results obtained from the experimental data suggest that Partial Nitrification consumes lower amounts of oxygen and organic matter, reducing the cost of the treatment. It has also been suggested to be a more efficient system in performance than Full Nitrification.

1.1 - Scope of the Research

This work focuses on comparing the currently implemented technology of Full Nitrification to the proposed technology of Partial Nitrification, using process models. This research examines the effects of parameters like pH, Dissolved Oxygen and Temperature to evaluate the optimal values. Based on the values obtained from literature, models for both Full Nitrification and Partial Nitrification, along with the respective Denitrification, are designed to compare the effect on Ammonia removal as nitrogen gas.

EnviroPro Designer is being used for the modeling of these processes. EnviroPro Designer is an environmental process simulator from Intelligen Inc that is used to develop, assess and optimize environmentally beneficial technologies. A superset of EnviroPro Designer, SuperPro Designer is also available to extend the modeling of pollution control processes to include chemical and biochemical manufacturing operations. The software is also able to provide capital and operating cost estimates, which can be useful for process comparisons.

Essentially, this thesis is comprised of two parts. The first part consists of a summary of all the experimental data derived from a literature review, which is used to investigate why Partial Nitrification is potentially a better system. The second part involves process modeling by EnviroPro Designer for several ammonia removal alternatives, and describes the findings of modeling work and experience using EnviroPro Designer.

The modeling of ammonia removal processes can be further divided into the following phases:

- In the first phase, we develop two models, Full System and Partial System-1. Full System implements Full Nitrification with Denitrification from nitrate and Partial System-1 implements the basic Partial Nitrification with Denitrification from nitrite.
- In the second phase, Full System and Partial System-1 are analyzed and compared. An evaluation of the most efficient system with respect to design effectiveness and cost efficiency is performed. This is done by analyzing the simulation results of the effluent and generating following reports from the modeling software:
  - Stream and Material Balance
  - Economical Evaluation

- In third phase, Partial System-1 is further optimized to Partial System-2 and Partial System-3 in an attempt to achieve a novel nitrogen removal treatment.

- In the fourth phase, a sensitivity analysis is conducted on Partial System-3 to determine the most significant factors.

This work compares Full nitrification and Partial nitrification with their respective denitrification. Therefore, it sheds light on the limitation and complexities involved in both nitrification and denitrification processes in each technology.

Since this work does not include laboratory experiments, available values for kinetic parameters have been taken from literature. Where experimental data was not available, an approximation has been employed, based on reasonable analogies. Later on, a sensitivity analysis has been to done to test the effect of the chosen value.

Furthermore, this thesis focuses on steady state, macro scale models. A steady state model is good for design, constant estimation and supporting alternate design processes or scenarios. This thesis does not incorporate dynamics involved in the processes because many of the kinetic parameters involved are not well known. Since the approach taken in this thesis is based on the practical implementation, therefore a steady state model was considered a more feasible and appropriate option.

1.2 - Why Ammonia?

According to the National Pollutant Release Inventory 1996, ammonia was ranked first in terms of amounts released to the Canadian environment. Municipal, industrial, agricultural and natural processes commonly contribute to emissions of ammonia in the environment. Natural sources of ammonia include the decomposition or breakdown of organic waste matter, gas exchange with the atmosphere, forest fires, animal waste, human breath, the discharge of ammonia by biota, and nitrogen fixation processes.

It is estimated that industrial releases have contributed 5,970 metric tons per year of ammonia. Emissions and effluents from a wide variety of industrial plants such as iron and steel mills, fertilizer plants, oil refineries, and meat processing plants are identified as the point sources of ammonia. Other significant point sources of ammonia include the manufacturing of explosives and the use of explosives in mining and construction. The largest non-industrial point sources are sewage treatment plants as per Environment Canada 1999.

According to Environment Canada in 1992, the major anthropogenic source of ammonia entering the Canadian environment is accidental ammonia spills. It was further emphasized that an ammonia spill can occur during the production, processing, storage, application, or disposal stage of the chemical's life cycle. Ammonia has been ranked as the top priority on the Environment Canada 1990 Canadian Chemical Spill Priority List. In addition, ammonia has also been recognized as a priority substance by the Major Industrial Accidents Council of Canada (MIACC).

Agricultural, residential, municipal, and atmospheric releases are identified to be non-point sources of ammonia. Major agricultural sources include areas with intensive farming, accidental releases or spills of ammonia-rich fertilizer, and the decomposition of livestock wastes [68, 69].

Municipal wastewater treatment plants remain the most significant sources of ammonia released to aquatic ecosystems across Canada. The total quantity of ammonia being annually released by municipal wastewater treatment plants has been estimated to be approximately 62,000 tonnes [67].

Ammonia sources in residential and municipal sectors include the use and disposal of cleansing agents that contain ammonia, improper disposal or accidental spills of ammonia products, and urban runoff [69, 70]. Combustion processes increase the atmospheric concentrations of ammonia. These involve the burning of municipal waste, emissions from sewage treatment plants, domestic heating, the decay of vegetation, and the production and use of chemical fertilizers. Mobile sources of ammonia to the atmosphere arise from all forms of transportation [70].

Ammonia in mammals, including humans, is converted to carbamoyl phosphate by the enzyme carbamoyl phosphate synthetase, and then enters the urea cycle to be either incorporated into amino acids or excreted in the urine. This mechanism prevents the build-up of ammonia in the bloodstream. Therefore, the toxicity of ammonia solutions is usually not of any consequence for mammals including humans. However, fish and amphibians lack this mechanism, as they can usually eliminate ammonia from their bodies by direct excretion, consequently, making ammonia highly toxic to aquatic life at even dilute concentrations [66]. This is the reason why ammonia is considered dangerous for aquatic life. Hence, keeping in view the vast sources of ammonia releases in the environment and its toxic properties, it is determined that the terrestrial plants and aquatic organisms are at a potential risk. As per *Canadian Environmental Protection Act, 1999*, (CEPA 1999) ammonia in wastewater effluent was determined to be toxic and harmful to a wide variety of fish, and other aquatic life. Mostly, freshwater organisms are at risk from ammonia released in the aquatic environment. Rainbow trout, freshwater scud, walleye, mountain whitefish and fingernail clams are some of the most sensitive species [5].

1.3 -Target Market

The marketing prospects of Partial Nitrification technology are very bright. This research is focused on obtaining improvement of the currently implemented Full Nitrification technology. Any improvement in the current technology will subsequently make it a better commodity.

1.3.1 - Applications in Waste Water Treatment Plants

Growing decline in water quality, water scarcity, and infrastructure challenges around the globe are a major source of concern. Subsequently, this drives a high demand for patented technologies that can treat virtually any water source providing industrial, agricultural and potable water, while decreasing dependence on fresh water sources. The merger of major North American manufacturers of wastewater treatment plants with small and medium-sized companies is a testimony to the fact that wastewater treatment is the fastest growing sector. The most significant example is the GE acquisition of ZENON Environmental Inc., a Canadian based global leader in advanced membranes for water purification, wastewater treatment and water reuse, in June 2006. GE purchased ZENON in an all cash transaction valued at approximately US $689 million or Cdn $763 million.

Application of Partial Nitrification in wastewater treatment plants is significant. It can be utilized in the capacities described in the following sections:

1.3.1.1 - Municipal Waste Water

Typically, 40-50% of the total nitrogen in a municipal wastewater treatment plant is found as ammonia in the centrate or filtrate streams. The technology of biological Nitrification-denitrification treatment is heavily used in Municipal Wastewater Treatment Plants. Hence, any advancement in this technology with has a beneficial effect in municipal wastewater treatment.

1.3.1.2 - Industrial Waste Water

Many industrial applications use ammonia in their chemical processes therefore, ammonia is can be found as contaminate in the industrial wastewater discharge. The following industries use ammonia in their manufacturing processes [4].

- Anhydrous ammonia is used as a refrigerant in industrial, closed-circuit refrigeration systems.
- Pulp and Paper industry also use ammonia in production of ammonia-based sulfite.
- Phosphate ores use ammonia as a modifying reagent in the froth flotation.
- Ammonia is used in various household cleaning products such liquid window cleaners, liquid all-purpose cleaners and household ammonia.
- Ammonia is also used to manufacture surfactants in detergents used for liquid dishwashing formulations.
- Semiconductor industry uses high purity ammonia in gallium nitride manufacturing processes to provide high brightness blue and white LED's(light emitting diodes), in high performance optoelectronics (such as LCD and flat panel displays) and in high power electronic devices (such as lasers and laser diodes).
- Ammonia is used to scrub sulfur oxide (SOx) and nitrogen oxides (NOx) from industrial and electrical power plant gases.
- Uranium concentrate salt is precipitated prior to drying and calcification by using ammonia.

- Rubber Industry utilizes ammonia for stabilization of natural and synthetic latex to prevent coagulation during transportation and storage.
- By pharmaceutical Industry in order to adjust pH in solvent extraction reactions.
- In food and beverage industry as a source of nitrogen for growth of yeast and microorganisms.
- To control pH in yeast production.
- As a curing agent in production of leather.
- As slime and mold preventive in tanning liquor [4].

1.3.2 - Effect in Aquaculture facilities

High density, semi-closed or closed aquaculture facilities (for example, aquariums) often implement biofiltration for water purification. An increase in fish density causes potential problems of ammonia toxicity and sludge build-up. Therefore, aquaculture systems incorporate biofilters designed to assist the growth of nitrifying bacteria which oxidize ammonia to nitrite and then to nitrate. One of the disadvantages of ammonia removal by Full nitrification is the increase in nitrate concentration. High nitrate concentration is not only toxic to aquatic life but discharge of nitrate rich effluent is prohibited in many countries due to environmental and public health considerations. In Partial nitrification, the ammonia is only oxidized until nitrite hence, inhibiting nitrate accumulation in aquatic tanks. In addition, it has been experimentally found that the amount of sludge generated is considerably less than in Full Nitrification. The technology of Partial nitrification can positively impact aquaculture systems around the world and hence has generated a lot of interest in this sector [3].

Although, nitrite is more toxic than nitrate, denitrification from nitrite has been found to be 1.5 to 2 times faster than denitrification from nitrate [12]. Therefore, conversion into nitrogen gas would be much more effective and efficient when done with nitrite instead of nitrate. Furthermore, nitrite oxidizers require more oxygen than ammonia oxidizers, therefore in instances where the dissolved oxygen concentration is low (as there is a competition for dissolved oxygen by other aquatic organisms present in the aquaculture unit), nitrite accumulation is present even when a Full nitrification-denitrification (Full System) is in place. It is therefore, better to implement Partial nitrification-denitrification process (or Partial System), possibly a simultaneous ammonia oxidation and denitrification from nitrite process. Microorganisms such as *Paracoccus,* acting both as autotrophs and heterotrophs, can be incorporated in such a treatment system.

1.4 - EnviroPro Modeling

EnviroPro Designer has been used to design the Full and Partial nitrification models with their respective denitrification processes. EnviroPro Designer is a subset of SuperPro Designer, a simulation software package from Intelligen Inc, 2326 Morse Avenue - Scotch Plains, NJ 07076 – USA.

EnviroPro Designer is an extensive environmental simulator and design tool that can be used to model various steps of modern wastewater treatment plant. The most important advantage of EnviroPro Designer is that it understands the complex composition of wastewater enabling it to express components of wastewater in traditional environmental language (TSS, BOD, COD) that makes it a perfect tool to model and evaluate the municipal wastewater treatment plants. This software package is also equipped to deal with plants expansions and modifications in order to accommodate increased throughput or changing regulations. It is a competent tool for accomplishing economical evaluations. It estimates comprehensive capital and operating costs of treatment plants. It also incorporates estimation and justification of processing fee of not only existing processes but also predicts the cost and impact of additional treatment steps that may be needed in the future. All in all, EnviroPro Designer has proved to be an efficient design tool for engineers. It gives them the approximate predicted behavior of the real world and assists them to estimate a technology before its implementation.

1.5 - Contribution to Research

This thesis expands on the previous experimental studies done on Full and Partial nitrifications by applying it to Municipal Treatment Plant operations through simulation modeling. It assesses the practicability of the new and innovative technology of Partial nitrification and determines whether it is feasible to replace the existing technology of Full Nitrification.

Additionally, this work does a parallel comparison of the both the Full and Partial nitrifications together with their respective denitrification processes. Therefore, it also studies impact of each nitrification process on its subsequent denitrification, hence the feasibility and limitations associated with each denitrification process and the resulting conversion at the end of each of the whole nitrogen removal technology, thus, giving a more extensive evaluation. Furthermore, this thesis incorporates optimization of Partial Treatment process to develop a modified nitrogen removal treatment for medium to high strength wastewater.

In addition, this thesis can be used as a valuable guideline on the modeling and retrofit design of a municipal wastewater treatment using EnviroPro Designer, and it provides a benchmark for future studies.

Chapter 2

Literature Review

2.1 - Wastewater Treatment Technologies

Municipal wastewater treatment is the process of removing contaminants from wastewater discharged by residences, businesses and industries. Municipal wastewater is a blend of physical, chemical and biological contaminants. It consists of 99.94 percent water while only 0.06 percent is dissolved and suspended solid material. The sewage's cloudy demeanor is due to the suspended particles. The range of suspended particles in an untreated sewage is from 100 to 350 mg/l. The strength of wastewater is measured by biochemical oxygen demand, or BOD_5, which measures the amount of oxygen required by microorganisms to decompose sewage over a five-day period. The BOD_5 of an untreated sewage ranges from 100 mg/l to 300 mg/l. Pathogens or disease-causing organisms are also present in sewage. Coliform bacteria are considered a sign of disease-causing organisms. Nutrients such as ammonia and phosphorus, minerals, and metals are found in sewage. Untreated sewage may contain 12 to 50 mg/l of ammonia and 6 to 20 mg/l of phosphorus. Therefore, municipal wastewater treatment systems use physical, chemical, and biological processes to remove the physical, chemical and biological contaminants [6].

Water treatment is a very important ecosystem service. Wastewater treatment uses microorganisms to decompose organic matter in sewage. If too much untreated sewage or other organic matter is added to a lake or stream, not only will it result in low dissolved oxygen levels, insufficient to support sensitive species of fish and other aquatic life, but ammonia and other nutrients at elevated concentrations are extremely toxic to aquatic life. Wastewater treatment systems are designed to digest much of the organic matter before the wastewater is released to avoid causing damage to the ecosystem.

As previously discussed, in addition to domestic wastewater, many industries handling protein-rich materials or other nitrogen compounds generate effluents with very high loads of ammonia. This makes ammonia a prevalent problem in the Industrial, Agricultural and Municipal wastewaters. The undesirable amount of ammonia in wastewater discharge requires continuing research in order to resolve the issue effectively. This thesis specifically investigates wastewater treatment technologies with respect to nitrogen removal [8].

2.1.1 - Full Nitrification

Nitrogen is one of the principal nutrients found in the wastewater, in a variety of chemical forms including ammonia. Nitrogen containing effluents can seriously damage a water resource and its associated ecosystem. Several physical, chemical and biological processes has been designed and studied for the removal of nitrogen. Our environment encompasses nitrogen in many forms. It can enter water resources as a consequence of either natural or human generated sources. The total nitrogen concentration of an untreated sewage flowing into municipal wastewater treatment plant is in the range of 20 to 85 mg/L. Furthermore, domestic sewage contains 60 percent of the nitrogen in the form of ammonia nitrogen, 40 percent of the nitrogen in the form of organic nitrogen and additionally, small quantities of nitrates [9].

Nitrogen conversion processes are essential for most wastewater treatment processes. The level of nitrogen in treated domestic wastewater depends upon the treatment method employed. Solid removal and cell synthesis are utilized in order to lower the nitrogen levels. It is very important that proper treatment is implemented to lower nitrogen levels otherwise most ammonia nitrogen passes through the system and is discharged in effluent of the facility. The presence of ammonia nitrogen in a wastewater plant's effluent is potentially toxic to aquatic life, causes additional oxygen demand, pose public health risks and decreased sustainability for reuse.

Municipal wastewater treatment plants presently incorporate Full Nitrification in combination with Denitrification as the effective method for converting ammonia into nitrogen gas. This biological nitrogen removal method is based on the natural nitrogen cycle transformation. Microorganisms, particularly bacteria, play a significant role in these nitrogen transformations. These microbial-mediated processes tend to occur much faster than geological processes. However, rates of these reactions are affected by environmental factors that influence microbial activity, such as temperature, moisture, and resource availability [7].

Full Nitrification involves complete aerobic oxidation of reduced nitrogen compound with the assistance of generally autotrophic or mixotrophic microorganisms. The microbes that carry out this reaction gain energy from it. It is generally accepted that instead of ammonium (NH_4^+), ammonia (NH_3) is used as substrate. The growth of the microbes is therefore affected by the ammonia/ammonium ratio. Full Nitrification requires the presence of oxygen, so nitrification can happen only in oxygen-rich environments like aerated, circulating or flowing waters and the very surface layers of soils and sediments. Therefore, oxygen is a very significant factor to be considered in Full Nitrification. Hence, in wastewater treatment plants, oxygen demand contributes to high operational costs [8, 10, 12, 15, 16] due to the need to compress air for injection into the bottom of aeration basins to supply the required oxygen.

Full Nitrification for nitrogen removal is a significant aspect of current wastewater treatment technology. Full nitrification in activated sludge includes a large number of nitrogen compounds, a multitude of reactions and slow growth of bacteria involved in the process, making Full Nitrification a complex process. Despite a century long study of microbes involved in Nitrification, it is not uncommon to receive conflicting and speculative reports in studies of nitrogen conversion. The first reports on microbial oxidation of ammonium were published as early as the end of the nineteenth century. Basic concepts of Nitrification were already established in the beginning of this century [17].

Full Nitrification has been found to be a two-step process. It essentially is comprised of ammonia being oxidized through nitrite to nitrate. A number of various types of nitrifying bacteria have been identified for each step of ammonia oxidation and nitrite oxidation. It is interesting to note that a specific group of bacteria oxidizes either ammonia or nitrite. No single group of microbial organisms was found to exist in nature, which can directly oxidize ammonia to nitrate, consequently making microorganism communities an important factor to consider in Full Nitrification as it divides the process in two steps [17].

The following is the breakdown of the two steps involved in Full Nitrification:

2.1.1.1 - Nitritation

First ammonia-oxidizing bacteria (AOB) oxidizes the ammonia into nitrite. Generally in activated sludge, the dominant ammonia-oxidizing group of bacteria is *Nitrosomanas europaea* [17].

The oxidation of NH_3 to NO_2^- by AOB is again a two-step process that progresses through hydroxylamine. In the first reaction, ammonia monooxygenase (AMO) catalyzes the oxidation of NH_3 to NH_2OH. In the second reaction, hydroxylamine oxidoreductase (HAO) catalyzes the oxidation of NH_2OH to NO_2^-.

The reactions discussed can be described as follows:

Reaction 1:

$$2H^+ + NH_3 + 2e + O_2 \Rightarrow NH_2OH + H_2O$$

Reaction 2:

$$NH_2OH + H_2O \Rightarrow HNO_2 + 4H^+ + 4e-$$

The electron input of the first reaction is compensated by two of the electrons produced in the second reaction. The remaining two electrons generated in the second reaction produce a proton motive force by passing through an electron transport chain to the terminal oxidase, which can be represented by the following reaction:

$2H^+ + 0.5O_2 + 2e- \Rightarrow H_2O$

The sum of the reactions gives the final Nitritation.

$2NH_3 + 3O_2 \Rightarrow 2HNO_2 + H_2O$ [12]

2.1.1.2 - Nitratation

The nitrite obtained from the nitritation is the intermediate product, which is further oxidized by nitrite-oxidizing bacteria (NOB) into nitrate. *Nitrobacter agilis* are mostly attributed to the oxidation of nitrite to nitrate [17].

The nitrite oxidation process is described in the following reaction:

$NO_2^- + 0.5O_2 \Rightarrow NO_3^-$

In the natural environment, nitrite oxidation occurs more rapidly than ammonia oxidation possibly due to the low minimum substrate concentration capable of supporting steady-state biomass and a relatively high substrate-utilization rate of nitrite oxidizers. Hence, nitrite rarely builds-up in nature. Furthermore, nitrite oxidizers have higher affinity of oxygen as compared to ammonia oxidizers [12, 27].

2.1.2 - Denitrification after Full Nitrification

In the denitrification process after Full Nitrification, the oxidation of organic substrates in wastewater treatment uses the nitrate as the electron acceptor instead of oxygen. This process is done in the absence of Dissolved Oxygen or under limited Dissolved Oxygen concentrations the nitrate reductase enzyme is induced in the electron transport respiratory chain and helps to transfer hydrogen and electrons to nitrate as the terminal electron acceptor. The nitrate is reduced first to nitrite, then to nitric oxide, to nitrous oxide and finally to nitrogen gas. This is given as follows [52]:

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

Denitrification is achieved by heterotrophic bacteria. The common genre of heterotrophic organisms include *Achromobacter, Acinetobacter, Agrobacterium, Alcaligenes, Arthrobacter, Bacillus, Chromobacterium, Corynebacterium, Flavobacterium, Hypomicrobium, Moraxella, Neisseria, Propionibacterium, Pseudomonas, Rhizobium, Rhodopseudomonas, Spirillum* and *Vibrio* [53]. Additionally, [54] includes *Halobacterium* and *Methanomonas*. *Pseudomonas* is considered to be the most common denitrifier that consumes a wide range of organic compounds such as methanol, carbohydrates, organic acids, alcohols, benzoates and other aromatic compounds [53]. Most of these bacteria have the ability to use oxygen, nitrate and nitrite [52].

The heterotrophic organisms consume organic carbon source. Typically in biological nitrogen removal process, the electron donor is biodegradable soluble Chemical Oxygen Demand (bsCOD) in raw sewage, bsCOD in generated in the process of endogenous decay and exogenous sources such as methanol or acetate [40, 52]. Reaction stoichiometry for different electron donors is given below. The term $C_{10}H_{19}O_3N$ in each reaction represents the biodegradable organic matter in wastewater [51].

Wastewater:

$C_{10}H_{19}O_3N + 10NO_3^- \rightarrow 5N_2 + 10CO_2 + H_2O + NH_3 + 10H^-$

Methanol:

$5CH_3OH + 6NO_3^- \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$

Acetate:

$5CH_3COOH + 8NO_3^- \rightarrow 4N_2 + 10CO_2 + H_2O + 8OH^-$

[52]

2.1.3 - Partial Nitrification

Oxygen and organic matter requirements involved in the processes of nitrification and denitrification within the nitrogen removal treatment contribute to the operational costs of the biological treatment. Engineers have designed new processes and operational strategies in order to decrease the costs involved.

Partial nitrification is one such strategy that is based on the accumulation of nitrite, which is the intermediary compound in both nitrification and denitrification. In this treatment, ammonia is just partially oxidized to nitrite and the nitrite thus obtained is then denitrified to nitrogen gas [26-31]. This eliminates the extra steps of oxidation to nitrate followed by reduction back to nitrite, found in the standard nitrification/denitrification designs.

Reaction

$$NH_3^{+} + 0.75O_2 \Rightarrow 0.5NH_3^{+} + 0.5NO_2^{-} + 0.5H_2O + 0.5H^{+}$$

(50% Partial Nitrification)

No single group of bacteria can carry out both Nitritation and Nitratation. *Nitrosomonas* (ammonia oxidizers) bacteria oxidized ammonia to nitrite whereas *Nitrobacter* (nitrite oxidizers) oxidized the nitrite to nitrate. In nature, nitrite is rarely accumulated possibly, because due to a low value of minimum substrate concentration capable of supporting steady-state biomass and a relatively high value of substrate utilization rate of nitrite oxidizers [12, 27]. Furthermore, nitrite oxidizers have higher affinity for oxygen as compared to ammonia oxidizers. Therefore, if we somehow inhibit nitrite oxidation without retarding ammonia oxidation, we would be able to achieve nitrite accumulation. One convenient way of doing that is by inhibiting nitrite oxidizers. Various research studies have been conducted on free ammonia concentration, dissolved oxygen, pH and temperature to find the effect of these parameters on nitrite oxidizers. It was found that by controlling these parameters, it would be possible to accumulate nitrite.

Oxygen saturation coefficients of Monod kinetics for Nitritation and Nitratation are found to be 0.3 mg/L and 1.1 mg/L respectively [10-12]. Therefore, Nitrite accumulation can be achieved by controlling a low concentration of Dissolved Oxygen throughout the treatment process. Consequently, it was found that approximately 25% lower oxygen and about 40% lower electron donors are required in Partial Nitrification technology which can proved to be beneficial with respect to operational costs [12, 32].

The effect of concentration of free ammonia on inhibition of nitrite oxidation was also studied by some research work and it has been found that certain concentration of free ammonia does inhibited nitrite oxidation [30, 32, 33, 34]. A high concentration of free ammonia retarded nitrite oxidation in the beginning, however, with time the nitrite oxidizing bacteria adapted to this high concentration of free ammonia [35, 36]. Thus, the free ammonia concentration should be gradually increased. Furthermore, studies suggested that an excessively high concentration of free ammonia would inhibit ammonia oxidation causing treatment to fail [34]. Increase in Total ammonia concentration increases the free ammonia concentration. Although some studies show that in the case of high ammonia content in the influent, the high nitrite concentration inhibited the nitrification biomass [12]. Therefore, Partial Nitrification can be suitable for nitrogen rich high to medium strength wastewaters.

Additionally, some studies infer that the intermediate of ammonia oxidation, free hydroxylamine (NH_2OH), may play an important role in inhibition of nitrite oxidation. [37, 38].

Other significant parameters affecting the nitrite oxidation are pH and temperature. These affect the concentration of free ammonia by involving in the ionization of ammonia. Solid retention time was also found to affect nitrite oxidation [39].

2.1.4 - Denitrification with Partial Nitrification

In the denitrification process after Partial Nitrification, nitrite can be directly used as the electron acceptor by the organic substrates in wastewater treatment. This process is also done in the absence of Dissolved Oxygen or under limited Dissolved Oxygen concentrations. The nitrite reductase enzyme is induced in the electron transport respiratory chain and helps to transfer hydrogen and electrons to nitrite as the terminal electron acceptor. Here, one step is omitted and the nitrite is reduced first to nitric oxide, to nitrous oxide and finally to nitrogen gas.

$NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

As previously discussed, most heterotrophic organisms have the ability to use either, nitrate or nitrite in order to carry out denitrification. Therefore, in case of Partial nitrification, nitrite can be directly used. Experimental studies have shown that as compared to nitrates, the denitrification rates are 1.5 to 2 times faster in case of nitrite [12, 32].

2.1.5 - Parameters Affecting Partial Nitrification

Ammonia is almost always converted to nitrate in nature due to a low value of minimum substrate concentration capable of supporting steady-state biomass and a relatively high value of substrate utilization rate of nitrite oxidizers [12, 27]. If certain parameters are controlled then it is possible to accomplish Partial Nitrification to nitrite only. Experimental research undertakings have been conducted to not only study the critical parameters but also their optimal values that will achieve the maximum results.

2.1.5.1 - Effect of pH on Undissociated Ammonia Concentration

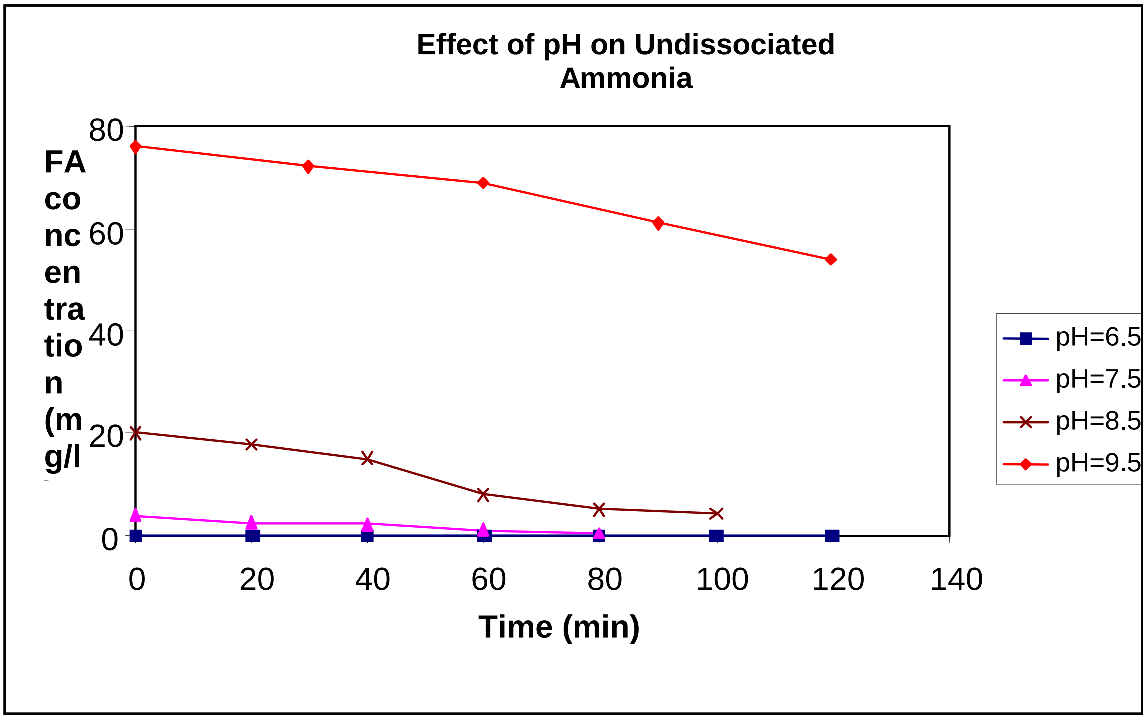
The value of pH is one of the most important parameters to affect Partial Nitrification. High concentration of undissociated ammonia has been considered to cause of nitrite accumulation. Alkaline pH has been known to increase the undissociated ammonia concentration, consequently, causing nitrite accumulation. The effect of pH on undissociated ammonia was investigated [12]. The Dissolved Oxygen was fixed at a concentration of 1.5 mg/L. The pH values 6.5, 7.5, 8.5 and 9.5 were tested. Undissociated Ammonia was calculated using the equation given below [34]:

$$= \frac{17}{14} \times \frac{total\ ammonia\ nitrogen\left(mg/L\right) \times 10^{pH}}{K_b / K_w + 10^{pH}}$$

$$where,\ K_b / K_w = e^{6344/(273+T(^oC))}$$

The Fig. 2.1.5.1 below shows a plot that depicts the variation of undissociated ammonia concentration in mg/L with respect to time in minutes. It is evident from this plot that as pH was increased, the undissociated ammonia concentration increased, and the rate was relatively fast compared to the timescales in wastewater treatment plants.

Fig. 2.1.5.1 : Effect of pH on undissociated Ammonia [12]

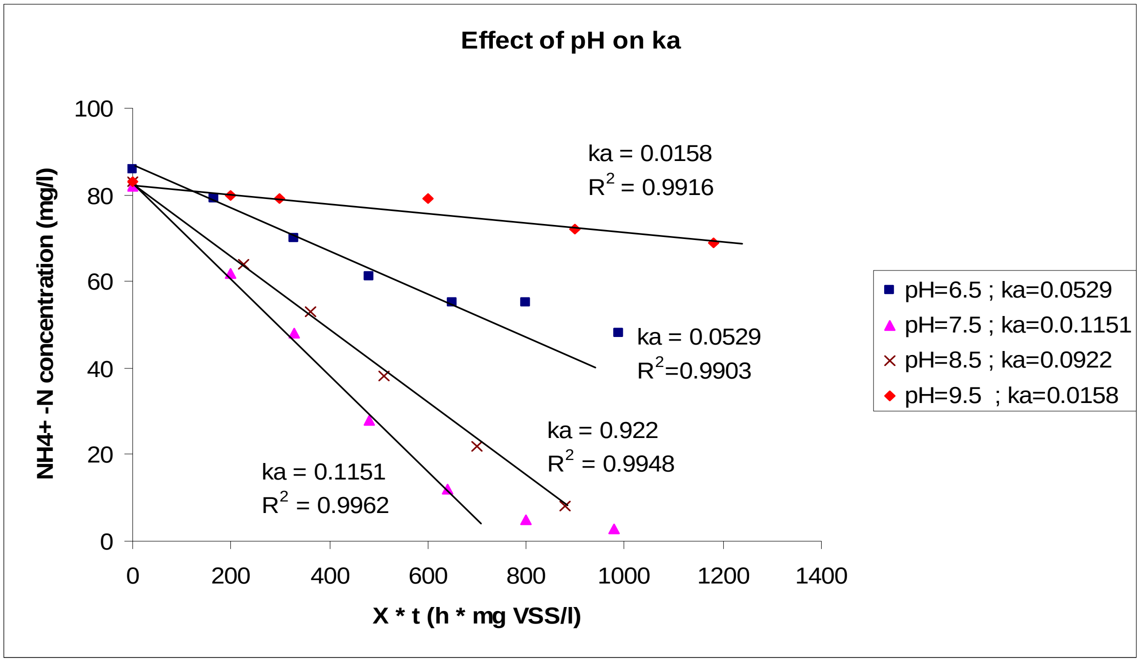


2.1.5.2 - Effect of pH on Ammonium Oxidation Rate (ka)

The effect of pH on ammonium oxidation rate (ka) was studied when the dissolved oxygen concentration was kept fixed at 1.5 mg/L [12]. The maximum ammonium oxidation rate (ka) was evaluated by means of Linear Regression Method in Fig. 2.1.5.2. Ammonia oxidation followed a zero-order equation as in all the cases the correlation coefficient value was high ($R^2 > 0.99$).

As shown in Fig. 2.1.5.2, the ammonium oxidation rate increased when the pH was increased from 6.5 to 7.5. However, ammonium oxidation rate decreased when the pH was further increased from 7.5 to 8.5. This maybe due to the fact that as the pH was increased, the undissociated ammonia concentration increased to a concentration that inhibited ammonia oxidation. Ammonium oxidation rate was significantly decreased when the pH was further increased from 8.5 to 9.5, showing meaningful retardation of ammonia oxidation. Hence, from the results we can say that pH = 7.5, gives an ideal concentration of undissociated free ammonia that will not retard ammonia oxidation while an attempt is being made to inhibit nitrite oxidation by adjusting the pH of wastewater to a slightly alkaline value. Alkaline pH has been found to increase concentration of undissociated ammonia, which in turn inhibits nitrite oxidation [12].

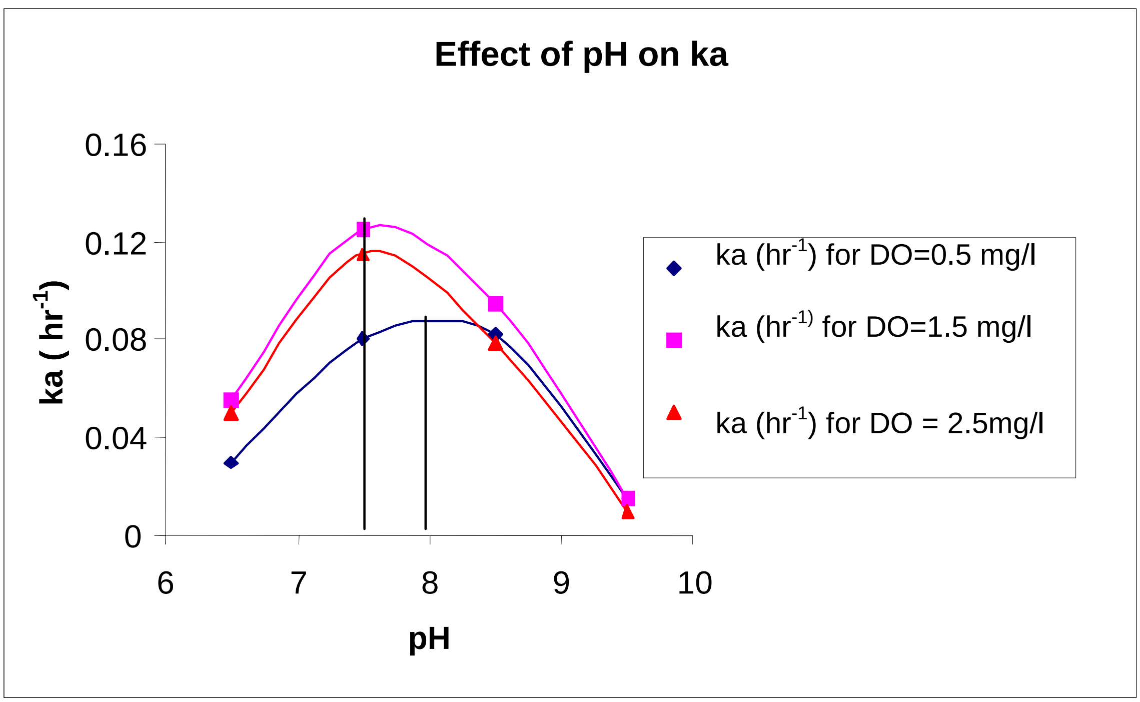
Fig. 2.1.5.2 : Effect of pH on Ammonium Oxidation Rate (ka) [12]



2.1.5.3 - Effect of pH on Ammonia Oxidation Rate at different DO

Fig. 2.1.5.3 shows the effect of pH on ammonia oxidation rate when the dissolved oxygen (DO) was varied. As it can be shown by Fig. 2.1.5.3 below that the maximum ammonia oxidation was achieved when the pH value was near to 8 and dissolved oxygen (DO) was 1.5 mg/L. The pH value is consistent with the result obtained in case of undissociated ammonia concentration. Therefore, from Figure 2.1.5.3 we can conclude that at DO = 1.5 mg/L and pH = 7.5 to 8, will give us the conditions most likely to accomplish maximum ammonia oxidation.

Fig. 2.1.5.3 : Effect of pH on Ammonia Oxidation Rate at different DO concentrations [12]



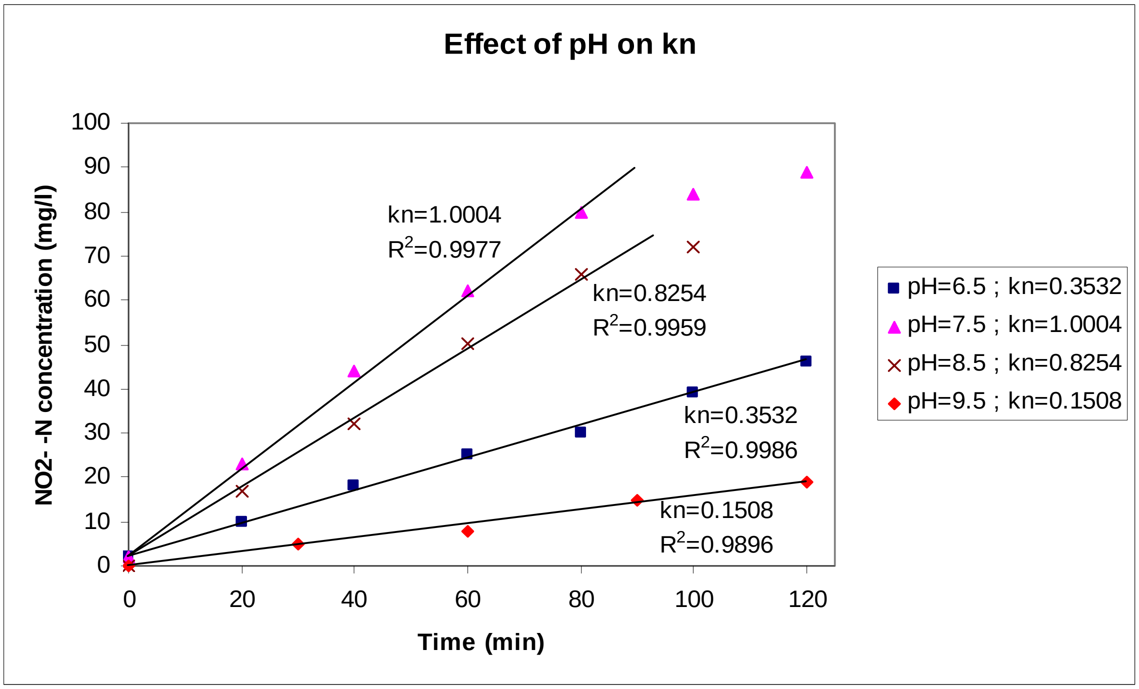
2.1.5.4 - Effect of pH on Nitrite Accumulation

From Fig. 2.1.5.1 and Fig. 2.1.5.4, it is evident that there is a correlation between ammonia oxidation and nitrite accumulation. As can be seen by the Fig. 2.1.5.1 when the pH was 7.5 and 8.5, the ammonia concentration was almost depleted after 80 minutes. Fig. 2.1.5.4 reveals that the nitrite accumulation is high in the corresponding time frame. In experiments conducted in [12], between 100 to 120 minutes, the ammonia-nitrogen decreased 2.27 mg/L, whereas the nitrite-nitrogen increased 2.14 mg/L, suggesting that the ammonia oxidized is being converted to nitrite which in turn, is being accumulated and not further oxidized to nitrate.

The plot also shows that the maximum nitrite accumulation was achieved when the value of pH= 7.5 followed by pH= 8.5. The minimum amount of nitrite accumulation was seen in case of pH= 9.5 which is consistent with the explanation that at high pH, the undissociated ammonia concentration is high resulting in retardation of ammonia oxidation. However, complete retardation is not occurring as can be seen by low concentration of nitrite accumulation present in the system.

Other research studies also revealed interesting observations. One research paper [41] showed that it is possible to achieve nitrite accumulation by controlling pH to a high value. However, another study [13] indicated that when the pH was controlled below 6.45, inhibition of nitrification process occurred. When the pH was kept at 9.05, the nitrification was inhibited with no nitrite accumulation. No significant influence of pH on nitrite accumulation was observed when the pH was maintained between 7.85 and 8.95. This study observed temporal nitrite accumulation after the pH value was changed. However, due to biomass adaption after sufficient time no nitrite accumulation was accomplished at the end of pH value experiment. This indicates that pH alone cannot be considered a key parameter in order to accumulate nitrite on long-term basis.

Fig. 2.1.5.4 : Effect of pH on Nitrite Accumulation [12]



2.1.5.5 - Effect of DO on Ammonia Oxidation Rate

Dissolved oxygen is considered to be very important operational parameter in order to achieve Partial Nitrification. The nitrite oxidizers have low affinity of for oxygen and oxygen saturation coefficients of Monod kinetics for Nitritation and Nitratation are found to be 0.3 mg/L and 1.1 mg/L, respectively [10-12]. Therefore, it has been thought that for Partial Nitrification, a low concentration of dissolved oxygen should be maintained.

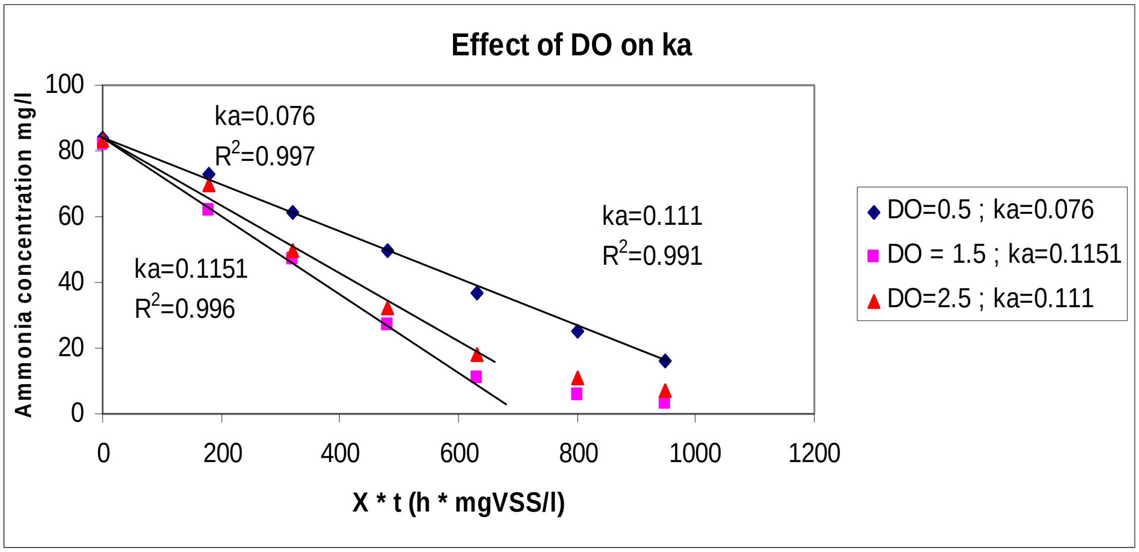
Oxygen is a co-substrate in nitrification reaction, along with ammonia. Therefore, its concentration influences the reaction rate of both ammonia and nitrite oxidation in dual-limitation manner [33, 35, 42].

The effect of dissolved oxygen was studied by keeping the pH fixed at 7.5 and varying the concentration of DO, at levels of 0.5 mg/L, 1.5 mg/L and 2.5 mg/L [12].

Fig 2.1.5.5 shows that when DO was increased from 0.5 mg/L to 1.5 mg/L the specific ammonia oxidation rate increased. The reason for which is that increase in DO will increase the metabolic activity of ammonia oxidizers. However, when it was increased from 1.5 mg/L to 2.5 mg/L, the value of ka decreased a little. Since the oxygen saturation constant for Monod kinetics for ammonia oxidizers lies in the range of 0.3 to 0.5 mgO_2/ L [28, 38, 47], therefore, when the DO is increased to 2.5 mg/L, it is possible that the nitrite oxidizers began competing for the oxygen, reducing the ammonia oxidation rate.

Research [13] studying the impact of consecutive changes in DO value on nitrification reaction also concluded that DO did not influence nitrite accumulation at concentration value in the range of 5.7 mg/L to 2.7 mg/L. Some nitrite accumulation was observed at DO = 1.7 mg/L. At DO = 1.4 mg/L and 0.7 mg/L, nitrite accumulation increased while showing same ammonia consumption, showing a definite correlation between ammonia being consumed to be converted into nitrite.

Fig. 2.1.5.5 : Effect of DO on Ammonia oxidation rate (ka) [12]



2.1.5.6 - Effect of DO on Ammonia Oxidation Rate at various pH

The effect of varying dissolved oxygen concentration on nitrite accumulation in conjunction with differing pH value was also investigated in order to study the behavior. The behavior of nitrification was observed for the DO concentration of 0.5, 1.5 and 2.5 mg/L for the pH values of 6.5, 7.5, 8.5 and 9.5 each.

As depicted by Fig 2.1.5.6 and Table 2.1.5.8 [12], when the DO was increased from 0.5 to 1.5 mg/L for the pH value of 6.5, the ammonia oxidation rate increased 80%. For the pH value of 7.5, an increase in DO from 0.5 to 1.5 mg/L showed an increase of 50% in ammonia oxidation. For the pH value of 8.5, ammonia oxidation rate increased 15% and finally, when the pH was set to 9.5 the ammonia oxidation rate increased about 5%. Hence the impact of DO for pH 6.5 and 7.5 was very significant. This seems to show that although pH=6.5 is considered unfavorable for biomass (ammonia oxidizers and nitrite oxidizers), increase in DO, increases the activity of ammonia oxidizers (AOB) rather than Nitrite Oxidizers (NOB) as NOB have more affinity for oxygen, hence there is a significant increase in ammonia oxidation due to lack of competition from NOB.

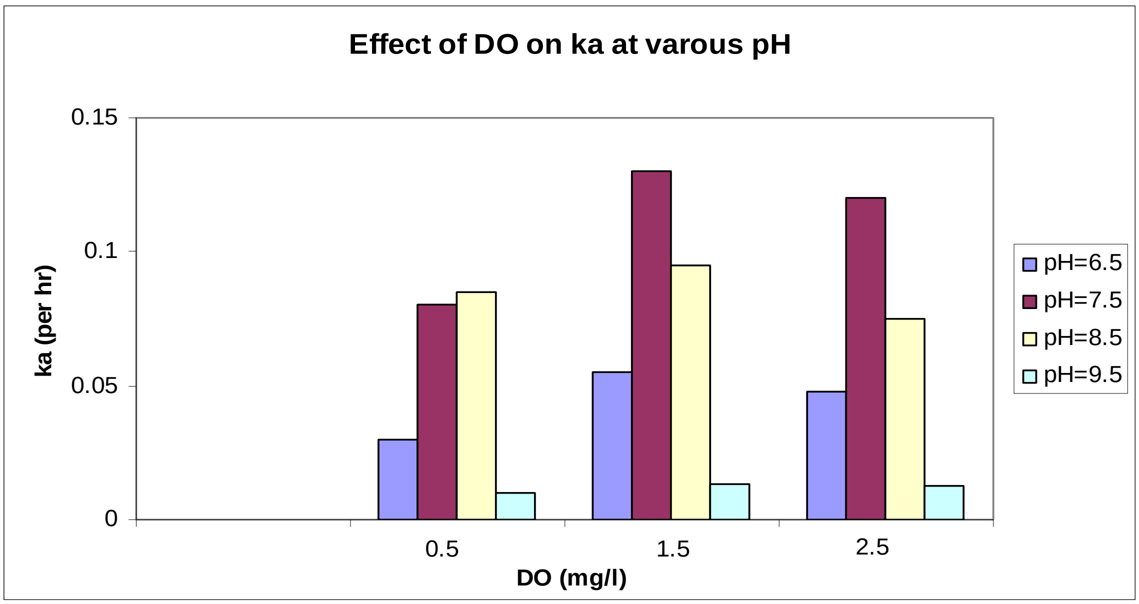
On the other hand, the value pH=7.5 and the DO=1.5 mg/L is considered favorable for AOB and unfavorable for NOB because high pH value increases free ammonia content to a value that is good to inhibit NOB without inhibiting AOB. Also, NOB requires higher concentration of DO to thrive therefore DO=1.5 mg/L is insufficient for NOB. Hence, there is a marked increase in ammonia oxidation by AOB as there is not much competition for resources from NOB.

When the DO was increased from 1.5 to 2.5 mg/L, a different trend was found. For the pH values of 6.5 and 9.5, the specific ammonia oxidation rate remained almost unchanged. This is in accordance with the findings of others [13] that proposed that nitrification is inhibited with no nitrite accumulation at pH below 6.45 and above 8.95. However, for pH 7.5 and 8.5, the specific ammonia oxidation rate increased from 15% to

18%. This shows that the higher concentration of DO is favorable for NOB and there is a competition for oxygen between AOB and NOB. Therefore, the ammonia oxidation increases but not to the extent as in case of DO=1.5 mg/L which is the ideal DO for AOB but inadequate for NOB.

From Fig. 2.1.6.6, we can see that the best results for ammonia oxidation rate are achieved when the pH was set at 7.5 and DO concentration was maintained at 1.5 mg/L

Fig. 2.1.5.6 : Effect of DO on Ammonia oxidation at various pH [12]

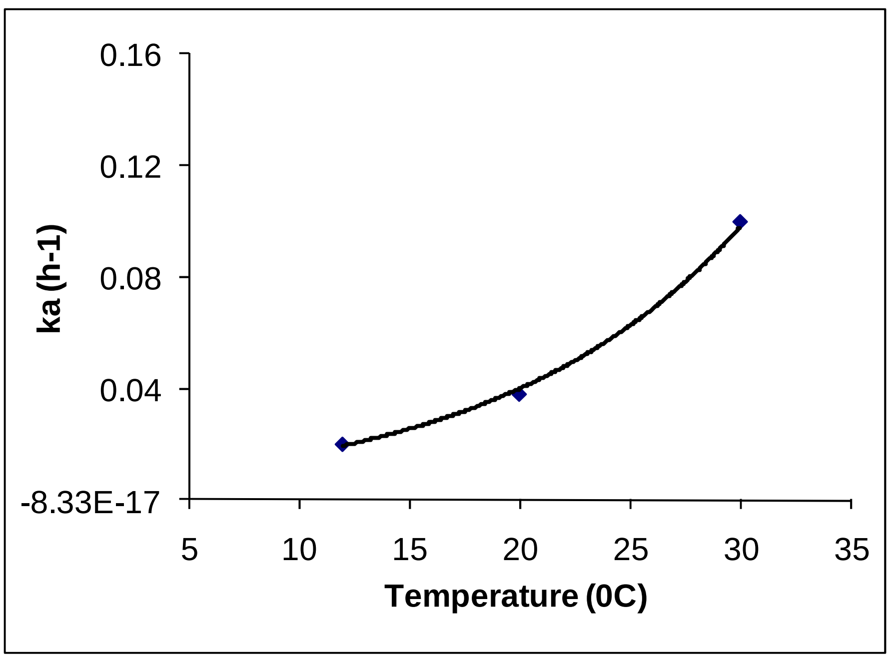


2.1.5.7 - Effect of Temperature on Ammonia Oxidation Rate

The influence of temperature on the maximum specific ammonia oxidation rate was also studied [12]. For that purpose, the other operational parameters (pH and DO) were controlled at their optimal values. The DO was maintained at 1.5 mg/L and pH was fixed at 7.5.

As can be seen from Fig 2.1.5.7 below, raising temperature from 12°C to 30°C, increased the ka 4.5 times. This observation is in agreement with the conclusion derived in one paper [26], where increasing the temperature by 10°C over the range of 5 to 30°C, increases the rate of nitrification by two or three times.

Fig. 2.1.5.7 : Effect of Temperature on Ammonia oxidation rate [12]



2.1.5.8 - Optimal Values of Operational Parameters

A detailed study based on the experimental research has revealed that ammonia oxidation and nitrite accumulation resulting in Partial Nitrification is sensitive to operational conditions like dissolved oxygen, pH, temperature and free ammonia concentration.

Dissolved oxygen is considered the most important factor in achieving Partial nitrification. Ammonia oxidation into nitrite and nitrite oxidation into nitrate are caused by a group of two different microorganisms namely, Ammonia Oxidizing Bacteria (AOB) and Nitrite Oxidizing Bacteria (NOB). No, single group of microorganism can achieve both these steps. Therefore, it is possible to accomplish just ammonia oxidation to accumulate nitrite by inhibiting NOB. Oxygen Saturation coefficient of Minod kinetics for AOB is 0.3 mg O_2 / L, whereas, it is 1.1 mg O_2/L for NOB [45]. Hence, AOB require less amount of dissolved oxygen to thrive when compared to NOB, which require a larger concentration of DO. It was found the DO concentration controlled at 1.5 mg/L was sufficient to encourage growth of AOB and thus, achieve ammonia oxidation. However, this DO concentration was inadequate for NOB to thrive therefore, restricting oxidation of nitrite into nitrate, resulting in nitrite accumulation.

The value of pH was also considered to influence ammonia oxidation and nitrite accumulation but only in conjunction with DO. It is widely believed that higher pH causes higher undissociated ammonia concentration that in turn retards growth of NOB. On the other hand, too high a concentration of undissociated ammonia will result in inhibiting AOB and causing process failure. However, various experimental works, studying the affect of pH on ammonia oxidation and nitrite accumulation concluded that pH alone gave inconsistent results. However, a pH value of 7.5 along with a DO concentration of 1.5 mg/L was considered highly favorable in order to accomplish Partial Nitrification. Maintaining this value of pH is not difficult in wastewaters as the pH of municipal wastewater is commonly in that range. Temperature was also found to influence ammonia oxidation and nitrite accumulation. A temperature of 30°C was considered to achieve maximum ammonia oxidation and nitrite accumulation.

Table.2.1.5.8 summarizes the effect of operational parameters, such as DO, pH and temperature reported in literature [12]. It can be seen that maximum ammonia oxidation and nitrite accumulation was achieved when the DO was controlled at 1.5 mg/L, pH was kept 7.5 and a temperature of 30°C was maintained.

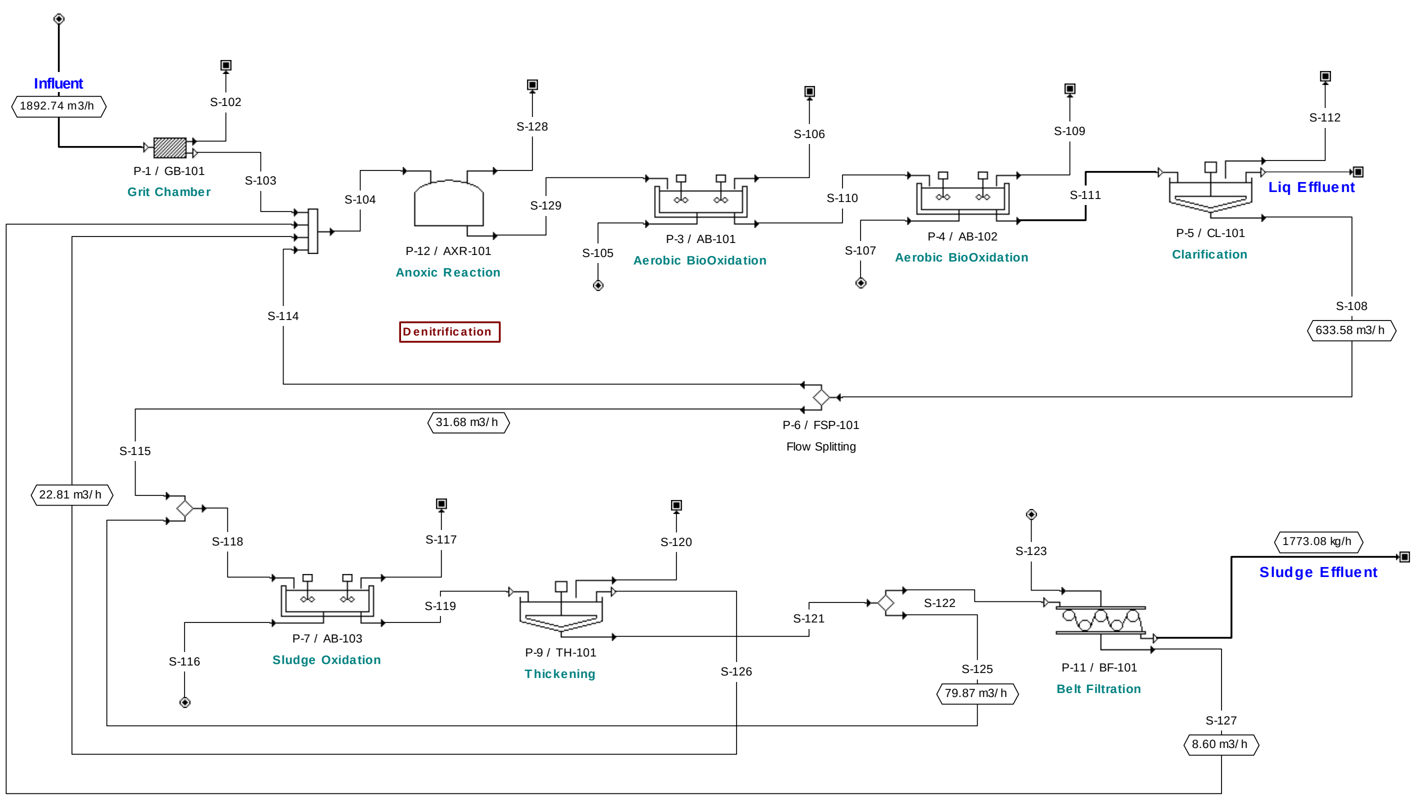
Table 2.1.5.8 :Effect of DO, pH and undissociated Ammonia at 30⁰C on Ammonia Oxidation and Nitrite Accumulation [12]

pH	T	DO	Undissociated Ammonia	Ka	kn	ka/kn
	°C	(mg/L)	(mg/L)	(10^{-3} mg NH4 + -N (mg VSS h)$^{-1}$)	(10^{-3} mg NH4 + -N (mg VSS h)$^{-1}$)	
6.5	30	0.5	0.22	29.2	27.1	1.077
		1.5	0.23	52.9	44.4	1.16
		2.5	0.23	51.7	47.5	1.09
7.5	30	0.5	2.15	76	90.3	0.841
		1.5	2.22	115.1	125.8	0.915
		2.5	2.20	111	114.3	0.97
8.5	30	0.5	20.52	81.1	73.1	1.109
		1.5	20.46	92.2	96.6	0.954
		2.5	20.65	79.2	83.1	0.953
9.5	30	0.5	74.32	11.4	11	1.036
		1.5	73.66	15.8	13.9	1.137
		2.5	73.68	16.3	14.9	1.094

2.2 Wastewater Treatment Retrofit Designs

2.2.1 - Ludzack-Ettinger Process

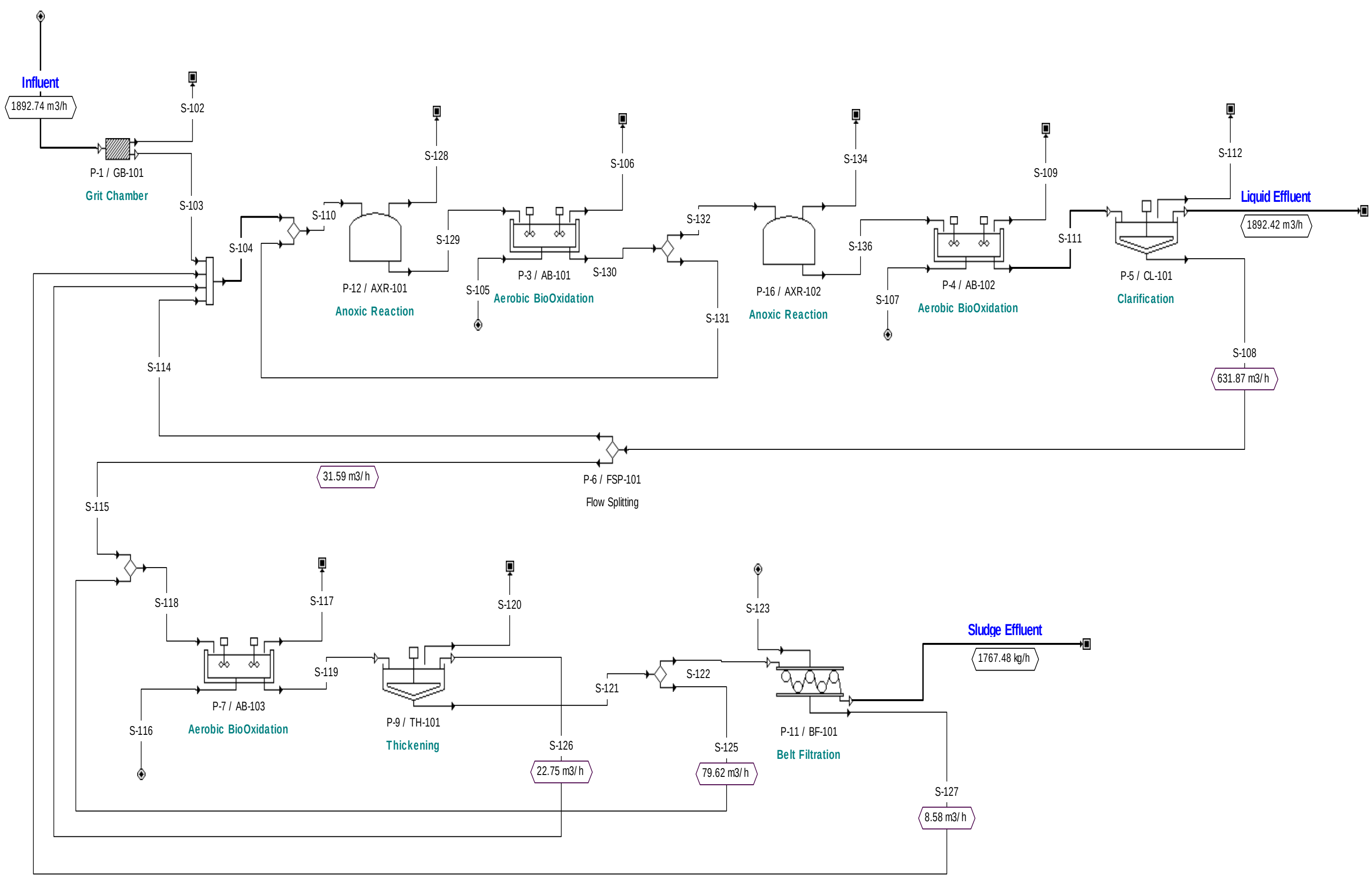
Fig. 2.2.1 : Municipal Wastewater Treatment – Ludzack-Ettinger Process



Ludzack-Ettinger is a basic process used for nitrogen removal in small systems. It is comprised of a two-step nitrification and denitrification process. Nitrification in the Ludzack Ettinger process is carried out in an aerobic zone whereas, Denitrification is achieved in anoxic zone. In this design, the anoxic zone is placed ahead of aerobic zone, which allows the denitrification zone to receive the required organic material from the wastewater plant's influent. This organic material is used to carry out the process of denitrification. The anoxic stage is then followed by an aerobic zone where ammonia is being converted to Nitrate. The nitrate formed in aerobic zone is returned to anoxic zone by return activated sludge (RAS). Once in the anoxic zone, the oxygen in nitrate (NO_3) or nitrite (NO_2) is used by the heterotrophic bacteria to metabolize the organic matter in the wastewater. Since this method relies on RAS to receive nitrate, therefore denitrification is limited by RAS recycle ratio. Recently, increased RAS recycle rates have been implemented in this process to prevent rising sludge in the secondary clarifiers due to gas bubbles from denitrification [55].

2.2.2 - Bardenpho Process

Fig. 2.2.2 : Municipal Wastewater Treatment – Bardenpho Process



The Four-step Bardenpho process is most commonly used for Nitrogen Removal. In this method, an anoxic zone also carries-out denitrification whereas an aerobic zone performs nitrification. However, the Bardenpho process implements pre-anoxic and post-anoxic zones for a more complete denitrification. The size of post-anoxic zone may be similar or larger than pre-anoxic zone. First, partial denitrification takes place in the pre-anoxic zone which is followed by an aerobic zone, where nitrification takes place and ammonia is oxidized into Nitrate or Nitrite. After the aerobic zone there is another anoxic zone called the post-anoxic zone. The Nitrate which was produced in aerobic zone is fed to the post-anoxic zone, where it is reduced to nitrogen gas. After the post-anoxic zone the flow is sent for clarification but before entering the clarifier, it is passed through a re-aeration zone to strip nitrogen gas from the flow in order to prevent the clarifier from becoming oxygen depleted. It is considered a more efficient and comprehensive method for nitrogen removal [55].

2.3 - EnviroPro Designer

For over four decades, computer-aided process design tools have been successfully used for process analysis, evaluation and optimization. It is imperative that similar computer aided process designs be applied to analyze and resolve the complex issues of environmental processes.

Biological wastewater is a combination of mixed microbial population, soluble and suspended organic and inorganic compounds. It is therefore, difficult to predict the properties of its components by using standard thermodynamics and transport phenomena principles. This makes modeling of biological wastewater treatment extremely challenging. Furthermore, most of the modeling work has been focused on kinetic studies based on lumped environmental stream properties (e.g. BOD, COD, TSS) as opposed to biodegradability of individual chemicals present in a multi-component mixture. Insufficient work has been done on VOC volatilization, sorption of heavy metals on the sludge, contribution towards effluent toxicity, etc. Additionally, most pollutants are present in very low concentrations and consequently, require accurate material balances that can predict trace contaminant levels.

EnviroPro Designer, a subset of SuperPro Designer from Intelligen Inc., is an environmental process simulator which has been designed to enhance the productivity of engineers and scientists engaged in the design, development and assessment of integrated waste recycling, treatment, and disposal processes. It is specifically targeted to carry out material balances on components and analyze the issues related to the hazardous chemical (e.g., heavy metals, VOCs) in integrated environmental processes.

This thesis has used EnviroPro Designer in order compare the Full nitrification and Partial nitrification processes along with their respective denitrification process as implemented on real life municipal wastewater treatment plant. EnviroPro Designer can be a very useful tool for the macro scale evaluations of ammonia removal processes and provide insightful conclusions about the practicability of Partial nitrification.

The following key features of EnviroPro Designer were helpful in its selection for this research [1]:

- Intuitive graphical user interface
- Complete simulation facilities including mass and energy balances as well as equipment sizing.
- Model for over 40 unit operations used in the environmental and process industries.
- Comprehensive process economics.
- Characterization of waste stream.
- Prediction of fate of chemical components.
- Extensive databases of process equipment, chemical components, and construction materials.
- Batch operations process scheduling.
- Compatibility with variety of graphics, spreadsheet and word processing packages.
- Rigorous VOC emission calculations from the different treatment units.
- Advanced hypertext on-line help facility.

The general structure of EnviroPro Designer is comprised of the graphical user interface, the process simulation module and the economic evaluation module.

Flowsheets consist of unit operations, material streams and chemical components, and examples of flowsheets were shown in Fig. 2.2.1 & Fig. 2.2.2. A flowsheet can have any number of these objects. The flowsheet is created by selecting equipment from the "Unit Operations" menu, and material streams are then drawn to connect these units. All the input and output information are entered and displayed through dialog windows.

The process simulation module is used to develop and analyze integrated flowsheets for waste recycling, treatment and disposal processes.

A unit operation is represented by a picture on the flowsheet, and each unit operation has a model describing its performance. The main function of the unit operation model is to carry out the material and energy balance around that particular process step. Outlet stream variables are based on the inlet stream variables and operating specifications entered during initialization of unit operations through unit specific dialog windows. Sequential modular approach is used to estimate material balances. Recycle streams can be included to solve the unit operations that are part of the recycle loop, iteratively until the flowsheet calculations converge.

Streams are displayed as polylines on the screen and represent the material flow from one unit operation to another. A stream object stores specific information of the components. These include mass and mole flowrate, weight or mole percentage, stream name and other properties like temperature, pressure, density, etc.

Flow and Composition of material in streams are characterized by chemical components. The reason that make EnviroPro Designer ideal to model biological wastewater treatment is its ability to distinguish between conventional components that can be described with thermodynamics models and non-conventional constituents such as biomass, which cannot be satisfactorily modeled with currently available thermodynamic models. In addition, this designer is linked to a database module that provides access to thermodynamic, environmental (contributions to COD, BOD, TSS, etc) and regulatory properties (e.g. SARA title III) for about four hundred chemicals. The user can also contribute to this database [1, 2].

Summary

The literature shows that the removal of ammonia is an important problem that the Canadian municipalities are encountering in their wastewater treatment systems due to ammonia's adverse environmental effects and its increasingly stringent discharge standards. The treatment of ammonia using a combination of full nitrification and denitrification is an established process, used in a variety of wastewater treatment plants with varying configurations. In full nitrification, ammonia is first oxidized into nitrite by ammonia-oxidizing bacteria. The nitrite is then further oxidized to nitrate by nitrite-oxidizing bacteria. However, in denitritification processes, the nitrate thus obtained from a full nitrification process has to be first converted to nitrite in order to be converted to nitrous oxide and nitric oxide and finally to nitrogen gas. This treatment process involves steep operational costs mostly due to high amounts of oxygen and organic matter required for the biological nitrogen removal process. Furthermore, it is very challenging to dispose of the large magnitude of sludge generated at the end of the treatment in an environmentally friendly manner.

More recently, the concept of partial nitrification until nitrite only and then followed by denitrification has been shown to be potentially useful and more efficient. Partial nitrification avoids the production of nitrate which is then just reduced back to nitrite in the traditional full nitrification treatment. Some optimal operating conditions have been identified for this process. It remains to be quantified how this process design would compare in capital and operating costs compared to traditional processes. Modeling work done in this thesis attempts to make such comparisons. Furthermore, optimization of this technology to develop a novel nitrogen removal treatment process has also been undertaken in this thesis.

Chapter 3

EnviroPro Model Development

In this thesis, EnviroPro Designer has been used to analyze, evaluate and optimize wastewater treatment plant with respect to Full and Partial Nitrification technologies. The flow sheet incorporated in EnviroPro Designer effectively depicts the processes required to convert ammonia into nitrogen gas in municipal wastewater treatment plant. It determines the feasibility of Partial Nitrification with its respective denitrification and compares it with the existing technology of Full Nitrification by performing rigorous mass and energy balances and predicting the treatability and fate of ammonia for each possible technology. The amount of remainder sludge at the end of the each treatment is also investigated as its disposal is an important issue in wastewater treatment engineering. Furthermore, it has given a comprehensive breakdown of materials and streams utilized in each technology, giving valuable information about the amount of oxygen consumed by each method of treatment. Additionally, it performed economic evaluations to estimate the capital and operating costs of each treatment process in the given wastewater treatment system and hence, display a side by side comparison of both the technologies to determine the superior technology.

Essentially this thesis incorporates designs of Full System model representing full nitrification with respective denitrification from nitrate (NO_3) and the basic Partial System-1 model that describes the partial nitrification with its respective denitrification from nitrite (NO_2). The parameters and design specifications for both the models are taken from the experimental research studies conducted in this area.

The basic Partial System-1 model is also optimized to Partial System-2 and Partial System-3 in order to achieve better results. The optimized versions, Partial System-2 and Partial System-3 follow the same design principles as implemented by the basic Partial System-1 with exception of certain operational changes.

Chapter 3 describes the design of Partial System-1 model based on the general partial nitrification technology. Section 4.2 of Chapter 4 discusses the operational changes implemented in Partial System-2 and Partial System-3 in an attempt to improve the partial nitrification treatment process.

3.1 - General Overview

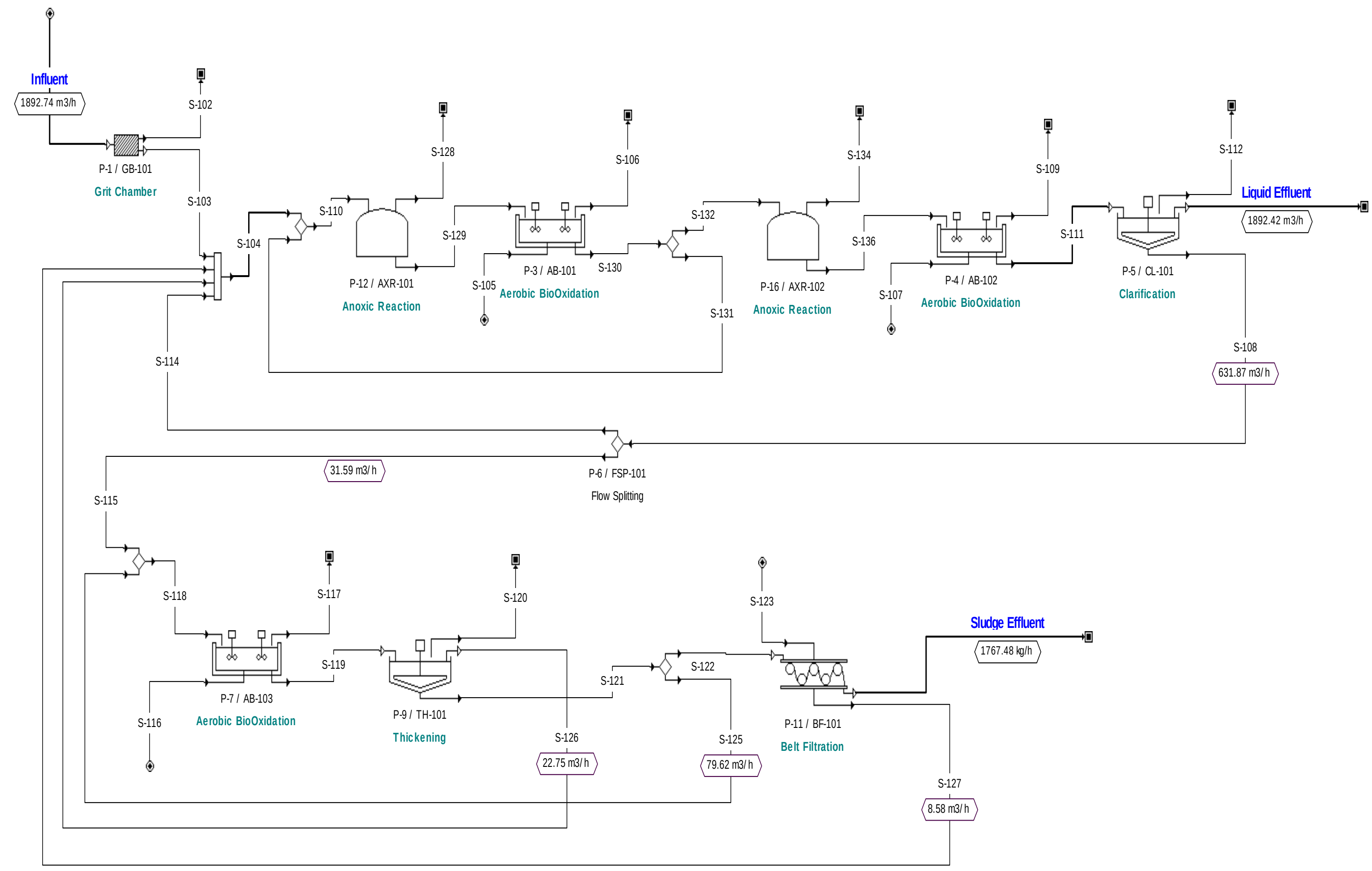
The modeling and retrofit design of municipal wastewater treatment plant incorporated in this thesis represents a four staged Bardenpho process for nitrogen removal. The Bardenpho process has been selected because it has been known to do a better job in terms of NO_3-N removal as well as in terms of overall nitrogen removal, and it is a relatively common design for nitrogen removal. Furthermore, since this thesis investigates partial nitrification therefore, nitrite concentration at the end of the treatment is a concern. Hence, it is considered best to incorporate Bardenpho process with two anoxic stages rather than Ludzack-Ettinger process with only one anoxic process. This existing treatment plant is designed to handle an average flow of 8 MGD.

The EnviroPro Designer flow sheet (Figure 3.2) shows the two anoxic and two aerobic stages as separate process units. In reality, all four stages are accommodated by four initial tanks. More specifically, one of the four tanks, (25% of total volume) is composed of the first anoxic stage, two other tanks (50% of total volume) the first aerobic stage, 80% of the fourth tank (or 20% of the total volume) is the second anoxic zone and the remaining 20% of the fourth tank (or 5% of the total volume) is the second aerobic stage. The flow sheet also indicates a Clarifying stage. There is a Sludge Oxidation and Sludge thickening process stages implemented as well. A belt filter press has also been included in the design. It should be noted that a single icon on the flow sheet may represent multiple identical units operating in parallel.

Since the objective is to study the behavior of nitrification and denitrification when conducted with respect to nitrate and nitrite independently, therefore, it is assumed that plant's influent contains negligible traces of nitrate and nitrite (i.e. the nitrogen is all in the ammonia and organic forms). The first anoxic stage is incorporated in order to convert any nitrate or nitrite being recycled in the respective treatment. It is also assumed that the wastewater has medium ammonia content of approximately 21 mg/L. Domestic waste accounts for the microbial population utilized for the treatment process. This domestic waste accounts for both autotrophic and heterotrophic bacterial population for respective Nitrification and Denitrification processes. The amount of domestic waste concentration in the plant's influent is approximately 157 mg/L (BOD_5 = 295 mg/L). Domestic waste is the biodegradable carbonaceous matter that provides the carbon source for the growth of microorganisms in both Nitrification and Denitrification processes. The oxygen requirement is fulfilled by aeration provided in each of the aerobic stages. An explanation for each stream and operation is provided in the following sections.

3.2 - Flowsheet of Wastewater Treatment Plant

Fig. 3.2: Flowsheet for Bardenpho Process utilized for the Wastewater Treatment Plant



Influent (S-101):

Influent (S-101) represents municipal wastewater coming into the treatment plant. Instream consists of medium strength ammonia and sludge. The details of influent's composition are given in Section 3.3.3.

Grit Chamber (GBX – 101):

The Grit chamber separates the fixed suspended solids in the influent by slowing the flow of the stream. Fixed suspended solids include sand, silt and other non-biodegradable matter. This process removes 20% of the solids and grit.

Anoxic Stage (ANX - 101):

This anoxic stage situated in the beginning of the treatment converts the nitrate or nitrite being recycled in the treatment by S-116 into nitrogen gas. This stage utilizes heterotrophic bacteria to do the conversion. Carbon dioxide is also being emitted from this stage in addition to nitrogen gas.

Aerobic Stage (AB - 102):

The aerobic stage converts ammonia into nitrate or nitrite depending upon the nitrification level required (full or partial). The air is being supplied that makes up the oxygen requirement for this aerobic process. Oxygen, nitrogen and carbon dioxide are being emitted from the stage.

Flow Splitting (FSP - 101):

The flow is then split into halves. Fifty percent of the flow is recycled to AXR 101 while the remaining fifty percent goes to AXR 102. See Fig. 3.2. Splitting is done to recycle the wastewater in order maintain the biomass concentration. Otherwise, biomass will be needed to be grown all over again.

Anoxic Stage (AXR - 102):

The nitrate or nitrite thus obtained from the aerobic stage AB 102 is then denitrified into nitrogen gas in this stage in the heterotrophic microorganisms.

Aerobic Stage (AB - 101):

The remaining unconverted ammonia is then sent to AB 101 in order to be oxidized to nitrate or nitrite.

Clarification Stage (CL -101):

This process clarifies the stream of 98% of fixed suspended solids and the microorganisms X-VSS-h, X-VSS-n and X-VSS-i in the stream. After clarification process in the wastewater is then goes to liquid effluent. Stream S-120 takes the remaining influent to Flow splitter.

Liquid Effluent:

It makes up the effluent from the first stage of treatment from the plant after clarification done in CL 101. This effluent is discharged in the aquatic environment. This thesis is focused on the Liquid Effluent. The concentration of components obtained by the treatment are analyzed and compared with the permissible values provided by Canadian Water Quality for the protection of aquatic life [24, 66].

Flow Splitting (FS - 102):

Given the flow from CL 101, ninety five percent is then sent for recycling back to the first stage to ANX 101. The remaining is sent to the second stage of the treatment.

Aerobic Stage (AB - 103):

It oxidizes the remaining ammonia into nitrate or nitrite from the five percent of the flow coming from CL 101.

Sludge Thickening Stage:

In this stage the sludge is dewatered to be thickened. The amount of fixed suspended solids, X-VSS-h, X-VSS-n and X-VSS-i removed are 99.5 %. The stream S-129 coming out of the thickening stage is recycled back to stage one treatment to ANX 101. The stream S-128 goes to flow splitter.

Flow Splitting (FSP - 104):

It splits the flow. The 10% goes to the belt Filtration via S-131 whereas, the 90% goes for the second stage of treatment to AB 103.

Belt Filtration (BF - 101):

Belt filtration BF 101 is vacuum filter. The water is entering BF 101 from S-132 to wash the filtrate. Stream S-133 takes the wastewater back for recycling in ANX 101 while the remaining goes out of the treatment plant as sludge effluent.

Sludge Effluent

Sludge effluent represents the Sludge obtained after the treatment. This sludge is then further treated and disposed off. This thesis does not analyze the sludge with respect to regulated guidelines.

3.3 - Component Variables

The models designed in this thesis consist of following component variables that have been either imported from EnviroPro Designer's database or user defined as given in Table 3.3.

Table 3.3 : Component Variables of Model Designs

	ALL COMPONENTS VARIABLES	USER DEFINED (mg/L)	EXPLANATION
1	**Ammonia**	**No**	Dissolved NH_3/NH_4 (not NH_3-N)
2	**Carbon Dioxide**	**No**	Dissolved CO_2 (in the form of HCO_3 or H_2CO_3)
3	**DomWaste**	**Yes**	Domestic Waste - (bio-degradable)
4	**FSS**	**Yes**	Fixed Suspended Solids (non-biodegradable)
5	**NO_3**	**Yes**	Nitrate as used in Full Nitrification
6	**NO_2**	**Yes**	Nitrite as used in Partial Nitrification
7	**Oxygen**	**No**	Diffused through aeration
8	**TDS**	**Yes**	Total Dissolved Solids (non-biodegradable)
9	**X-VSS-h**	**Yes**	Active Heterotrophic biomass used in Denitrification
10	**X-VSS-n**	**Yes**	Active Nitrifiers Autotrophic biomass
11	**X-VSS-i**	**Yes**	Inert biomass represents Biomass Decay
12	**Water**	**No**	Total water
13	**Nitrogen**	**No**	End Product in Denitrification

3.3.1 - Register/Edit Pure Components

All the component variables given in Table 3.1 appear in both Full and Partial Systems design models as reactants, products, influents and effluent of the wastewater treatment plants. Any component variables used in the model must be first defined in the special section of the model. EnviroPro Designer incorporates the user-friendly interface of Register/Edit Pure Components to enter these components. The components can only be initialized at this interface in order to be used anywhere in the model for performing any material or energy balance, simulating instreams, effluents or emissions. The EnviroPro Designer consists of a vast databank of around four hundred chemicals. The databank also provides their thermodynamics, environmental and regulatory properties. The components included in the design can either be imported from the databank provided or can also be user defined. The properties of both the component variable imported from the databank as well as user-defined variable can be changed if desired. The state of each component (solid, liquid or gaseous) is specified for appropriate calculation of emissions and effluent components. It is also important to indicate whether a component is Biomass in order for EnviroPro Designer to calculate the sludge residence time. Unless biomass is indicated at this interface, the EnviroPro Designer does not calculate sludge residence time of unit operation. Furthermore, it also fails to provide a drop down menu of available biomass components in reaction kinetics of the unit operation.

3.3.2 - Edit Stock Mixture

A stock mixture is simply a mixture of pure components with a given composition (in mass or molar percentage), which EnviroPro-Designer keeps in its own stock mixture databank. Pre-existing stock mixture can be selected through Edit Stock Mixture interface. It is also possible to register an entirely new stock mixture. Air is the stock mixture in the model designs created for this thesis. Air defined through this interface is then included in the Aerobic BioOxidation stage. Oxygen for aerobic oxidation is retrieved through this air. The remaining oxygen is emitted. The dissolved oxygen concentration and air requirements are however provided in the Aerobic Operation Unit.

3.3.3 - Stream Input

Input stream composition and temperature and pressure are supplied through this interface. The flow rate of each component is also entered here. On the basis of provided information, EnviroPro Designer calculates the concentration and mass composition. This interface also displays the state of each component in the input stream as provided in the Register/Edit Pure Components.

The input streams for both the design scenarios are the same. Since we want to study the how Nitrite and Nitrate affects nitrification and denitrification independently, therefore, for simplicity, it has been assumed that no or negligible traces of nitrate and nitrite are present in the influent. It is also considered that the plant influent has medium strength of ammonia. The Components making up the plant's influent with the initial concentration are given as follows in Table 3.3.3. [18, 56].

Table 3.3.3 Influent Components

INFLUENT COMPONENTS	INITIAL CONC (mg/L)
Ammonia	21
Carbon Dioxide	51
DomWaste	157
FSS	60
TDS	306
X-VSS-h	53
X-VSS-n	3
X-VSS-i	51
Water	999,772

3.4 - Environmental Properties of Domestic Waste

Domestic waste is organic, soluble, biodegradable material that consists of microbial populations and other material. It also serves as the substrate for the bacterial population to conduct Nitrification and Denitrification. Some of the environmental properties of Domestic Waste are given below in Table 3.4 [18].

Table 3.4 : Environmental Properties of Domestic Waste

Property	*Value*	*Units*
COD	**2.00**	**g O_2/g**
ThOD	**2.00**	**g O_2/g**
BODu /COD	**1.00**	**g/g**
BOD5 / BODu	**0.68**	**g/g**
TOC	**0.6**	**g C/g**
TP	**0.00**	**g P/g**
TKN	**0.07**	**g N/g**
NH_3-N	**0.00**	**g N/g**
NO_3-N	**0.00**	**g N/g**

The environmental properties in Table 3.4 can be displayed by selecting the DomWaste Component in Register/Edit Components and selecting the properties option. Although values for these types of properties are already present in component databank for many components, however, these properties can be updated if required. Furthermore, whenever a new component is added, the environmental properties of that component should be included as these properties along with the composition of streams are used to calculate the lumped environmental stream properties (BOD, COD, TKN, TSS, etc).

3.5 - Environmental Reaction Kinetics

In EnviroPro Designer, the kinetics of Environmental Reactions is described as follows:

Equation (1):

Rate	**=**	**k**	×	**{ S-Term}**	×	**{O-Term}**	×	**{B -Term}**
mg/L – h		rate Constant		Substrate Term		Other Term		Biomass Term

3.5.1 - Rate Constant (k)

A specific rate constant (k) of the reaction can be indicated here. Instead, to better fit the experimental data of biodegradation reaction, rate constant can also be calculated as a function of temperature by using the Arrhenius equation or a modified Arrhenius equation.

3.5.2 - S - Term

The S – Term represents a biodegradation reaction being carried out. Through the S-term the user selects the appropriate Substrate's kinetic expression (e.g., Monod, Haldane, Grau, First Order, None). It also identifies the Substrate being utilized in that particular reaction. The value of the Half Saturation Constant (Ks) of the reaction (for Monod and Haldane kinetics) is also specified in this section.

3.5.3 - O - Term

This term is used to define a second substrate (e.g., Oxygen in our case). It specify the impact of the concentration of other component on the reaction. This is helpful in defining aerobic oxidation reactions such as nitrification where oxygen plays an important role in determining whether full or partial nitrification will take place. The kinetic expression and Half Saturation constant also needs to be given for this second substrate.

3.5.4 - B - Term

The B-Term indicates the Biomass component (if any) that affects the kinetics of a reaction. It provides a drop down menu which displays all the components defined as Biomass in Register/Edit Pure Components. Various types of biomass (e.g., heterotrophic biomass, nitrifiers or autotrophic biomass) used in different reactions can be identified and tracked through this term. Hence, the use of appropriate type of biomass to catalyze a certain reaction is enabled through this term.

3.6 - Common Reactions of Full System & the Basic Partial System-1

The models of Full System and Partial System-1 for nitrogen removal involve a set of environmental reactions. The user has to specify the particular reaction or reactions being carried out by the unit operations that are depicted on flow sheet. There is a model for each unit operation that defines its performance. The specifications regarding each unit operation are provided and the stoichiometry of each reaction is also indicated by the user. EnviroPro Designer on the basis of subroutines used to model the unit operation and the variables provided at the inlet calculates the results achieved by that operation and simulate them at the outlet stream of that operation.

This thesis consists of some environmental reactions occurring in aerobic stage operation that is the same for both the Full and Partial systems of nitrogen removal. The calculations and parameters of these common reactions are discussed in detail in this section. The specifications thus obtained for each reaction are then briefly mentioned in each system in tabulated form.

3.6.1 - DomWaste Degradation Reaction

This reaction represents the degradation of Domestic waste present in the municipal wastewater to produce heterotrophic biomass or X-VSS-h. The Domestic waste represents the carbonaceous matter and acts as the substrate for the bacterial growth. This reaction is included in each aerobic stage implemented in both Full Nitrification and Partial Nitrification and forms the starting point for other biological reactions being carried out in each system.

3.6.1.1 - Reaction

This reaction is described as follows [18].

DomWaste	**+**	**NH_3**	**+**	**O_2**	**→**	**X-VSS-h**	**+**	**H_2O**	**+**	**CO_2**
1g		**0.1g**		**1.4g**		**0.8g**		**0.8g**		**0.9g**

The stoichiometry of this reaction, and many others, is on a mass basis, since there is no accurate way to characterize the molar mass of many surrogate parameters such as DomWaste.

3.6.1.2 - Yield Coefficient

Yield coefficients can be derived from the above reaction stoichiometry to give:

Y = 0.8 mg vss / mg DomWaste

From Table 3.4,

1 mg of DomWaste = 2 × 0.68

= 1.36 mg BOD_5

Therefore, yield coefficient Y becomes;

Y = 0.8/1.36

Y = 0.588 mg vss / mg BOD_5

3.6.1.3 - Kinetics of the Reaction

In domestic waste degradation the Substrate-Term follows the Monod Kinetics in the **Equation (1)** mentioned in Section 3.5. The O-term (second substrate) in this particular reaction has been neglected, whereas the B-term (biomass) follows first order kinetics and the biomass component used is heterotrophic bacteria.

3.6.1.4 - Rate Constant

$k = 2.61\ BOD_5$ / (mg vss –d) [18]

$k = 0.109$ mg BOD_5 / (mg vss –h)

$k = 0.109 / 1.36$ (since 1 mg of DomWaste = 1.36 mg BOD_5 from Table 3.4)

$k = 0.08$ mg DomWaste / mg vss – h

The above rate constant is assumed to be k_{max}, applicable at $T_o = 20^oC$

This value can be adjusted according to temperature variations by assuming a value of $\theta = 1.04$ [18].

And using the following expression:

$$k = kmax\ \theta^{T-T_0}$$

3.6.1.5 - Half Saturation Constant

The half Saturation constant is used in the S-term, following Monod's kinetics.

Ks = 6.8 mg BOD_5 /L [18]

Ks = 6.8 / 1.36

Ks = 5 mg DomWaste / L

3.6.2 - Heterotrophic Biomass (X-VSS-h) Decay Reaction

The decay of biomass (i.e. loss of activity) in any biological reaction is a common phenomenon that needs to be accommodated in the system design to realistically simulate the process occurring in real world. X-VSS-h Decay reaction has been created to represent the heterotrophic biomass decay occurring in both Full and Partial Systems.

3.6.2.1 - Reaction

The reaction with its mass based stoichiometry can be described as follows [18]:

X-VSS-h	+ O_2	➔ NH_3	+ CO_2	+ H_2O	+ X-VSS-i
1.05 g	**1.15 g**	**0.1 g**	**1.45 g**	**0.45 g**	**0.20 g**

3.6.2.2 - Kinetics of the Decay Reaction

In heterotrophic biomass decay, the Substrate-Term follows first order kinetics in the ***Equation (1)*** mentioned in Section 3.5. The O-term and B-term in this particular reaction has been neglected.

3.6.2.3 - Rate Constant

The decay constant for heterotrophic biomass is well documented in literature. The value of the decay constant (kd_{max} = 0.002 h^{-1} at 20^0C) in both Full and Partial systems are the same as only one type of bacteria is involved, and it has been taken from [57]. The value of k with respect to the temperature is then calculated by the following expression:

$$k = kmax\ \theta^{T-T_0}$$

The value of theta has been taken from [58]. All the values are tabulated in Section 3.7.2.

3.6.3 - Autotrophic Biomass (X-VSS-n) Decay Reaction

The decay of autotrophic biomass used for nitrifying have also been accommodated in both Full and Partial systems of nitrogen removal as X-VSS-n. In Full Nitrification X-VSS-n represents *Nitrosomonas* and *Nitrobacter* whereas, in Partial Nitrification, X-VSS-n represents *Nitrosomonas* only. In both the cases, the reaction has been included in the aerobic stages.

3.6.3.1 - Reaction

The reaction with its mass based stoichiometry can be described as follows [18]:

X-VSS-n	**+ O_2**	**➔**	**NH_3**	**+ CO_2**	**+ H_2O**	**+**	**X-VSS-i**
1.05 g	**1.15 g**		**0.1 g**	**1.45 g**	**0.45 g**		**0.20 g**

Here, X-VSS-i represents the dead or inactive autotrophic biomass.

3.6.3.2 - Kinetics of the Reaction

In autotrophic biomass Decay, the Substrate-Term follows first order kinetics in **Equation (1)** mentioned in Section 3.5, where the substrate is autotrophic bacteria. The O-term in this particular reaction is neglected whereas, B-term is also neglected.

3.6.2.3 - Rate Constant

The decay constant for autotrophic biomass is also well established in literature. [60] gives the value of decay constant for overall *Nitrosomonas* and *Nitrobacter* cultures as kd = 0.002 h^{-1}, which applies to Full Nitrification. However, due to unavailability of decay constants for *Nitrosomonas* bacteria alone, the same value has been assumed for Partial Systems. These values have been tabulated in Section 3.7.2.4, and this value is subjected to a sensitivity analysis as part of the results.

3.7 – Full System For Nitrogen Removal

The model for the Full System for nitrogen removal essentially implements an aerobic stage that achieve Full Nitrification of the ammonia into nitrate and an Anoxic stage that carries out denitrification from nitrate into nitrogen gas.

In this thesis, it is assumed that the ideal conditions exist where ammonia converts completely into nitrate due to rapid oxidation of nitrite and therefore, there is no significant nitrite accumulation. Similarly, all the denitrification being accomplished is from nitrate only.

Table 3.7 lists the general specifications implemented throughout the model for the Full system of Nitrogen removal.

Table 3.7 : Operational Parameters of Full System of Nitrogen Removal

Property		Value	Unit	Reference
Pressure	**P**	**1.013**	**bar**	[18]
Room Temperature	**To**	**20**	**^{0}C**	
Set Temperature	**T**	**15**	**^{0}C**	[18]
pH	**pH**	**7.2**		[59]

3.7.1 - Aerobic Oxidation Stage

Aerobic oxidation comprises a set of reactions that represents the process of ammonia being oxidized into nitrate with the help of autotrophic microorganisms. Since it is an aerobic reaction therefore, this process occurs in the presence of oxygen. This stage includes production and growth of the microbial population that includes autotrophic and heterotrophic microorganism, as they require oxygen to grow. This stage also accommodates reaction that represents decay of these microorganisms as well.

The following operating conditions are implemented throughout the reactions involved in this stage.

Table 3.7.1: Operating Conditions for Aerobic Oxidation

	Components	Value	Unit	Reference
1	**Dissolved Oxygen**	**2**	**mg/L**	[62]
2	**Aeration Requirement**	**0.010**	**m^3 air m^3 (liq/min)**	[63]

Reactions are described in following sections.

3.7.1.1- DomWaste Degradation Reaction

The DomWaste Degradation reaction represents the growth of heterotrophic microorganisms to be utilized in the denitrification process in the Full System of nitrogen removal, which was explained in detail in Section 3.6.1

Table 3.7.1.1.A - General Specifications for Domestic Waste Degradation in Full System

1	**Substrate**	**DomWaste**	**Domestic Waste**
2	**Product Biomass**	**X-VSS-h**	**Heterotrophic**

Table 3.7.1.1.B - Kinetic Parameter for Domestic Waste Degradation in Full System

	Parameter		Value	Unit	Reference
1	**Half Saturation Constant**	**Ks**	**5**	**mg/l**	As calculated in 3.6.15
2	**Rate of substrate utilization @ 20 ^{0}C**	**kmax**	**0.08**	**h^{-1}**	As calculated in 3.6.14
3	**Theta**	**θ**	**1.04**		[58]
4	**Rate of substrate utilization @ 15 ^{0}C**	**k**	**0.065761**	**h^{-1}**	Calculated by EnviroPro (See section 3.6.14)
5	**Yield**	**Y**	**0.8**	**mg vss / mg DomWaste**	As calculated in Section 3.6.12

3.7.1.2 - Full Nitrification Reaction

The design of full nitrification in wastewater treatment requires that the sludge age in the bioreactor be considerably more than the minimal growth time of the nitrifying bacteria. For that reason, the volume of the nitrifying bioreactor is kept relatively larger to generate low loading rates. One consequence is that a large size of bioreactors contributes to high capital costs [14]. This reaction also includes the growth of nitrifying bacteria.

3.7.1.2.1 - Reaction

NH_3	**+**	**O_2**	**+**	**CO_2**	**➔**	**X-Vss-n**	**+**	**H_2O**	**+**	**NO_3**
(7.5 g)		**(29.46 g)**		**(2.19 g)**		**(1.12 g)**		**(11.29 g)**		**(26.74 g)**

3.7.1.2.2 - Yield Coefficient

Yield Coefficient for Full nitrification has been taken from the table provided in [60].

$Y = 0.2$ mg VSS/ (18/14) mg NH_4

$= 0.155$ mg VSS/ mg NH_4

$= 0.155$ mg VSS/ (17/18) mg NH_3

$Y = 0.15$ mg VSS/ mg NH_3

<u>3.7.1.2.3 - Kinetics of the Reaction</u>

In Full Nitrification, the Substrate-Term follows Monod's kinetics in the ***Equation (1)*** mentioned in Section 3.5, where the substrate is ammonia. The O-term in this particular reaction is with respect to oxygen and follows Monod's kinetics, whereas the B-term follows first order kinetics and the biomass component used is autotrophic bacteria (X-VSS-n), which represents both *Nitrosomonas* and *Nitrobacter*.

<u>3.7.1.2.4 - Rate Constant</u>

<u>Calculating growth rate of overall microorganisms (μ'_m) under the stated conditions of T, pH and DO:</u>

From [60],

μ_m overall for *Nitrosomonas & Nitrobacter* = 1 day^{-1}

From [61],

$$\mu'_m = \mu_m \;*\; e^{0.098(T-15)} \;*\; DO/\,Ko + DO \;*\; [1 - 0.833(7.2 - pH)]$$

Temperature correction factor	Dissolved Oxygen correction factor	pH correction factor

= (1) * (1) * 2/(1.3+2) * (1)

μ'_m = 0.606 day-1

μ'_m = 0.025 h-1

<u>Calculating Rate of substrate utilization @ 15 ^{0}C:</u>

From [61],

$k = \mu'_m / Y$

= 0.025/0.2

k = 0.12 h^{-1}

3.7.1.2.5 - Half Saturation Constant

Both the S-Term and O-term follow Monod's kinetics in this reaction, therefore there are two half saturation constants used. The half Saturation constant for the S-Term (Ks) is taking into account the overall reaction of *Nitrosomonas* and *Nitrobacter*. The half Saturation constant for the O-Term (Ko) considers the oxygen behavior. Both Ks and Ko are well documented. Ks = 1.4 mg/L {0.2 – 5.0 mg NH_4 – N, mg/l}[60] and Ko=1.3 mg/L [61].

3.7.1.2.6 - Parameters

Table 3.7.1.2.6.A : General Specifications for Full Nitrification Reaction

1	**Substrate**	**Ammonia**	Dissolved NH_3 or NH_4 but not NH_3-N
2	**Product Biomass**	**X-VSS-n**	*Nitrosomonas & Nitrobacter*
3	**End Product**	**Nitrate**	

Table 3.7.1.2.6.B - Kinetic Parameters for Full Nitrification Reaction

	Parameter		**Value**	**Unit**	**Reference**
1	**Half Saturation Constant**	**Ks**	**1.4**	**mg/L**	[60]
2	**Half Saturation Constant for DO**	**Ko**	**1.3**	**mg/L**	[61]
3	**Yield**	**Y**	**0.15**	**mg VSS/ mg NH_3**	[60]
4	**Max. Specific growth rate**	**μ_m**	**1.0**	**day^{-1}**	[60]
5	**Growth rate under the specific conditions of Temperature, DO, pH**	**μ'_m**	**0.025**	**h^{-1}**	Calculated in section 3.7.1.2.3
6	**Rate of substrate utilization @ 15 ^{0}C**	**k**	**0.12**	**h^{-1}**	Calculated in section 3.7.1.2.3

3.7.1.3 - Heterotrophic Biomass (X-VSS-h) Decay Reaction

X-VSS-h Decay reaction represents the decay of the heterotrophic microbial population being used in denitrification. All the parameters chosen for this process are taken with respect to heterotrophic bacteria. Calculations done in order to design this reaction are explained in detail in Section 3.6.2

Table 3.7.1.3.A : General Specification for Heterotrophic Biomass Decay in Full System

1	**Substrate**	**X-VSS-h**	**Heterotrophic Bacteria**
2	**Product Biomass**	**X-VSS-i**	**Dead Heterotrophic Bacteria**

Table 3.7.1.3.B -Kinetic Parameter for Heterotrophic Biomass Decay in Full System

	Parameter		Value	Unit	Reference
1	**Decay Constant for Heterotrophic Biomass @ 20 ^{0}C**	**kmax**	**0.002**	**h^{-1}**	[57]
2	**Theta**	**θ**	**1.04**		[58]
3	**Decay Constant for Heterotrophic Biomass @ 15 ^{0}C**	**k**	**0.001644**	**h^{-1}**	Calculated by EnviroPro as shown in 3.6.14

3.7.1.4 - Autotrophic Biomass (X-VSS-n)Decay Reaction

X-VSS-n Decay reaction depicts the decay of autotrophic bacteria used in the full nitrification process. In Full nitrification, X-VSS-n represents both *Nitrosomonas* and *Nitrobacter* and X-VSS-i represents dead *Nitrosomonas* and *Nitrobacter*. In selecting the parameters therefore, the overall behavior of combined *Nitrosomonas* and *Nitrobacter* is taken in view. The calculations done for this reaction are explained in detail in Section 3.6.3.

Table 3.7.1.4.A -General Specification for Autotrophic Biomass in Full System

1	**Substrate**	**X-VSS-n**	**Autotrophic Bacteria**
2	**Product Biomass**	**X-VSS-i**	**Dead Autotrophic Bacteria**

Table 3.7.1.4.B -Kinetic Parameter for Autotrophic Biomass in Full System

	Parameter		Value	Unit	Reference
1	**Decay Constant for Overall *Nitrosomonas* and *Nitrobacter* @ 20^0C**	**kmax**	**0.002**	**h^{-1}**	[57]
2	**Theta**	**θ**	**1.04**		[64]
3	**Decay Constant for Overall *Nitrosomonas* and *Nitrobacter* @ 15^0C**	**k**	**0.001644**	**h^{-1}**	As calculated in 3.6.14

3.7.2 - Anoxic Stage

The anoxic stage in this model is comprised of the denitrification reaction since it is an anoxic reaction therefore, this process occurs in the absence of oxygen. The growth and death of the microbial population has already been accommodated in the reactions included in aerobic stage.

3.7.2.1 - Denitrification Reaction

The denitrification reaction represents the process of nitrate (NO_3) being first reduced to nitrite (NO_2), then to nitric oxide (NO) and nitrous oxide (N_2O) and finally into nitrogen gas (N_2) with the help of heterotrophic microorganisms. The heterotrophic bacteria require carbon as electron donor in order to perform denitrification. In these designs domestic waste in the municipal wastewater provides sufficient source of carbon for this reaction.

3.7.2.1.1 - Reaction:

The mass of each component can be evaluated by the stoichiometry of the reaction. This reaction is taken based on the Yield coefficient derived in the next section.

DomWaste	**+**	**NO_3**	**→**	**CO_2**	**+**	**N_2**	**+**	**H_2O**	**+**	**X-Vss-h**
(34.6 g)		**(108 g)**		**(48 g)**		**(17 g)**		**(61.4 g)**		**(16.2 g)**

(142.6 g) → **(142.6 g)**

3.7.2.1.2 - Yield Coefficient

Yield Coefficient of heterotrophic bacteria has been taken from [57].

Y=0.4 to 0.9 g VSS/g NO_3-N

Y= 0.7 × (14/62)

$Y=0.15$ g VSS / g NO_3

This value is also reported in other literature [21].

The domestic waste yield has been taken as 0.32 g Domestic waste / g NO_3 as indicated by [52].

3.7.2.1.3 - Kinetics of the Reaction

In denitrification from nitrate, the Substrate-Term follows Monod's kinetics in ***Equation (1)*** mentioned in Section 3.5, where now the substrate is nitrate (NO_3). The O-term is neglected because it is an anoxic reaction, while the B-term follows first order kinetics and the biomass component used is heterotrophic bacteria.

3.7.2.1.4 - Rate Constant

The value of kmax has been taken as 0.05 h^{-1} from [22] which also falls in the range mentioned by [18].

The k value adjusted according to the temperature is then calculated by EnviroPro Designer by: $k = kmax\ \theta^{T-T_0}$

3.7.2.1.5 - Half Saturation Constant

The half Saturation constant for denitrification from nitrate is estimated as follows:

From [57],

Ks for denitrification = 0.1 $NO_3 - N$, mg/l

= 0.1 * 62/ 14

= 0.44 NO_3 mg/L

3.7.2.1.6 - Parameters

Table 3.7.2.1.6.A – General Specification for Denitrification in Full System

1	**Substrate**	**NO_3**
2	**Biomass Product**	**X-VSS-h**
3	**End Product**	**N_2**

Table 3.7.2.1.6.B - Kinetic Parameters for Denitrification in Full System

	Parameter		**Value**	**Unit**	**Reference**
1	**Half Saturation Constant**	**Ks**	**0.440**	**mg NO_3 /L**	As Calculated above
2	**Rate of substrate utilization @ 20^0C**	**kmax**	**0.05**	**h^{-1}**	[18] [22] 1.29 day-1
3	**Temperature Coefficient**	**θ**	**1.16**		[65]
4	**Rate of substrate utilization @ 15^0C**	**k**	**0.02381**	**h^{-1}**	Calculated by EnviroPro
5	**Yield**	**Y**	**0.15**	**g VSS/g NO_3**	[21, 57]

3.8 - The Basic Partial System-1 For Nitrogen Removal

The model for the basic Partial System-1 for nitrogen removal involves an aerobic stage that achieves Partial Nitrification of the ammonia to nitrite and an Anoxic stage that performs denitrification from nitrite to nitrogen gas.

Parameters such as Temperature, pH and Dissolved Oxygen concluded to be significant for Partial System (as discussed in Chapter 2) are implemented strictly throughout the process design and it is assumed that almost all ammonia is converted into nitrite.

The plant's influent is considered to contain no significant traces of nitrate, to study the independent affect of nitrite on the nitrification and denitrification. Hence, it is assumed that all the denitrification being accomplished is from nitrite only.

The general specifications of Partial System-1 of nitrogen removal are given below:

Table 3.8 : General Specification for Partial System-1 of Nitrogen Removal

Property		Value	Unit	Reference
Pressure	**P**	**1.013**	**bar**	[18]
Room Temperature	**To**	**20**	**^{0}C**	
Set Temperature	**T**	**30**	**^{0}C**	[12]
PH	**pH**	**7.2**		[57]

3.8.1 - Aerobic Oxidation Stage

The aerobic oxidation reaction occurs in the presence of oxygen and comprises of set of reactions that represents the process of ammonia being oxidized into nitrite with the help of autotrophic *Nitrosomonas* bacteria only. It is an important design requirement that the growth of the *Nitrobacter* population of autotrophic bacteria present in the wastewater be suppressed in order to prevent oxidation of nitrite into nitrate. This is done by controlling the Dissolved Oxygen content to 1.5 mg/L, as *Nitrobacter* requires higher dissolved oxygen content to thrive. In this thesis, the Dissolved Oxygen is controlled by controlling aeration requirements. Hence, reducing the aeration requirement in case of Partial System-1 also reduces the Dissolved Oxygen content.

The aerobic oxidation stage of the Partial System-1 also accommodates production and growth of the microbial population that includes both *Nitrobacter* bacteria and heterotrophic microorganism, as they require oxygen to grow. This stage includes reactions that represent decay of these microorganisms as well.

The following operating conditions are implemented throughout the reactions involved in this stage of the basic Partial System-1.

Table 3.8.1: Operating Conditions of Aerobic Oxidation for Partial System-1

	Components	Value	Unit	Reference
1	**Dissolved Oxygen**	**1.5**	**mg/L**	[12]
2	**Aeration Requirement**	**0.0070**	**m3 liq/min**	[14]

3.8.1.1 - DomWaste Degradation

There is a reaction to depict DomWaste Degradation in Partial System-1 as well. This reaction represents the growth of heterotrophic microorganisms to be utilized in the denitrification process. A detailed explanation is given in Section 3.6.1.

Table 3.8.1.1.A : General Specifications of Domestic Degradation for Partial System-1

1	**Substrate**	**DomWaste**	**Domestic Waste**
2	**Product Biomass**	**X-VSS-h**	**Heterotrophic**

Table 3.8.1.1.B - Kinetic Parameter of Domestic Degradation for Partial System-1

	Parameter		Value	Unit	Reference
1	**Half Saturation Constant**	**Ks**	**5**	**mg/L**	As calculated in 3.6.15
2	**Rate of substrate utilization @ 20 ^{0}C**	**kmax**	**0.08**	**h^{-1}**	As calculated in 3.6.14
3	**Temperature Coefficient**	**θ**	**1.04**		[58]
4	**Rate of substrate utilization @ 30^{0}C**	**k**	**0.118365**	**h^{-1}**	As calculated in 3.6.14
5	**Yield**	**Y**	**0.8**	**mg vss / mg DomWaste**	As calculated in Section 3.6.12

3.8.1.2 - Partial Nitrification Reaction

Initially, the loading rates or the size of the bioreactor is kept same in the Partial Nitrification design. The size is then changed to observe the effect on ammonia conversion. Changing the size of the bioreactor will decrease the capital cost. In this reaction, ammonia is oxidized to nitrite by *Nitrosomonas* bacteria only. For this purpose, the dissolved oxygen level is kept to 1.5 mg/L to inhibit growth of *Nitrobacter* and therefore, discourage nitrite oxidation. Although, nitrite oxidation is not inhibited completely, however, it is assumed that the nitrate being formed is negligible when compared to being nitrite accumulated. This reaction also accounts for the growth of *Nitrosomonas* bacteria.

3.8.1.2.1 - Reaction

The process reaction is given by:

NH_3 +	**O_2 +**	**CO_2**	**➔**	**X-Vss-n +**	**H_2O**	**+**	**NO_2**
(7.5 g)	**(22.97 g)**	**(1.76 g)**		**(0.91 g)**	**(11.4 g)**		**(19.92 g)**
	(32.23 g)				**(32.23 g)**		

3.8.1.2.2 - Yield Coefficient

Yield coefficient of *Nitrosomonas* is **0.04 to 0.13 g VSS/ g NH_3 – N** [20].

Y = 0.1 g VSS/ g NH_3 - N

Y = 0.1 g VSS/ (17/14) g NH_3

Y = 0.12 g VSS/ g NH_3

The yield coefficient is taken into consideration when evaluating the reaction for Partial Nitrification.

3.8.1.2.3 - Kinetics of Reaction

In Partial Nitrification, the Substrate-Term follows Monod's kinetics in ***Equation (1)*** mentioned in Section 3.5, where the substrate is Ammonia. The O-term in this particular reaction is with respect to oxygen and it follows Monod's kinetics, whereas the B-term follows first order kinetics and the biomass component used is autotrophic bacteria (X-VSS-n) which represents only *Nitrosomonas*.

3.8.1.2.4 - Rate Constant

The rate constant for partial nitrification can be calculated as follows:

Calculating growth rate of overall microorganisms (μ'_m) under the stated conditions of T, pH and DO:

From [61],

$$\mu'_m = \mu_m \; * \; e^{0.098(T-15)} \; * \; DO/\,Ko + DO \; * \; [1 - 0.833(7.2 - pH)]$$

Temperature correction factor — Dissolved Oxygen correction factor — pH correction factor

$$= (0.7) \; * \; e^{0.098(30-15)} \; * \; 1.5/(0.3+1.5) \; * \; (1)$$

μ'_m = 2.537 day-1

μ'_m = 0.106 h^{-1}

Calculating Rate of substrate utilization @ 30 ^{0}C:

From [61],

$k = \mu'_m \; / \; Y$

= 0.106/0.12

k = 0.88 h^{-1}

3.8.1.2.5 - Half Saturation Constant

In Partial nitrification, the reaction S-Term and O-term are following Monod's kinetics, and therefore two half saturation constants (Ks and Ko) are required with respect to each term. The half saturation constant of the S-Term (Ks) takes into account only the behavior of *Nitrosomonas* while the half saturation constant for the O-Term (Ko) considers the oxygen behavior. Both Ks and Ko are well documented in literature. Ks = 0.6 mg/L {0.2 – 2.0 mg NH_4 – N, mg/L}[60] and Ko=0.3 mg/L [12].

3.8.1.2.6 – Parameters

Table 3.8.1.2.6.A – General Specifications for Partial Nitrification Reaction:

1	**Substrate**	**Ammonia**
2	**Product Biomass**	**X-VSS-n (Nitrosomonas)**
3	**End Product**	**NO_2**

Table 3.8.1.2.6.B : Kinetic Parameters for Partial Nitrification Reaction:

	Parameter		**Value**	**Unit**	**Reference**
1	**Half Saturation constant**	**Ks**	**0.6**	**NH_4 – N mg/L**	[60]
2	**Half Saturation Constant for DO**	**Ko**	**0.3**	**mg/L**	[12]
3	**Yield Coefficient**	**Y**	**0.12**	**g VSS/ g NH_3**	[20]
4	**Max. Specific growth rate**	**μ_m**	**0.7**	**day^{-1}**	[60] *(Nitrosomonas)*
5	**Growth rate under the specific conditions of Temperature, DO, pH**	**μ'_m**	**0.106**	**h^{-1}**	As calculated in Section 3.8.1.2.4
6	**Rate of substrate utilization**	**k**	**0.88**	**h^{-1}**	As calculated in Section 3.8.1.2.4

3.8.1.3 - Heterotrophic Biomass (X-VSS-h) Decay Reaction

The X-VSS-h Decay reaction represents the decay of the heterotrophic microbial population being used in denitrification. All the parameters chosen for this process are taken with respect to heterotrophic bacteria. Calculations done in order to design this reaction are explained in detail in Section 3.6.2.

Table 3.8.1.3.A – General Specifications for Heterotrophic Decay in Partial System-1

1	**Substrate**	**X-VSS-h**	**Heterotrophic Bacteria**
2	**Product Biomass**	**X-VSS-i**	**Dead Heterotrophic Bacteria**

Table 3.8.1.3.B - Kinetic Parameter for Heterotrophic Decay in Partial System-1

	Parameter		**Value**	**Unit**	**Reference**
1	**Decay Constant for Heterotrophic Biomass @ 20 ^{0}C**	**kmax**	**0.002**	**h^{-1}**	[57]
2	**Theta**	**θ**	**1.04**		[58]
3	**Decay Constant for Heterotrophic Biomass @ 30 ^{0}C**	**k**	**0.002959**	**h^{-1}**	Calculated by EnviroPro as shown in 3.6.14

3.8.1.4 - Autotrophic Biomass (X-VSS-n) Decay Reaction

In the Partial System-1, the X-VSS-n decay reaction depicts the decay of *Nitrosomonas* bacteria used to oxidize ammonia into nitrite. The calculations done for this reaction are explained in detail in Section 3.6.3.

Table 3.8.1.4.A : General Specifications for Autotrophic Biomass in Partial System-1

1	**Substrate**	**X-VSS-n**	***Nitrosomonas* Bacteria**
2	**Product Biomass**	**X-VSS-I**	**Dead *Nitrosomonas* Bacteria**

Table 3.8.1.4.B: Kinetic Parameter for Autotrophic Biomass in Partial System-1

	Parameter		Value	Unit	Reference
1	**Decay Constant for Nitrosomonas @ 20 ^{0}C**	**kmax**	**0.002**	**h^{-1}**	[57]
2	**Theta**	**θ**	**1.04**		[64]
3	**Decay Constant for Nitrosomonas @ 15 ^{0}C**	**k**	**0.002959**	**h^{-1}**	As calculated by EnviroPro

3.8.2 - Anoxic Stage

The anoxic stage in the Partial System-1 model includes the denitrification reaction only. Since it is an anoxic reaction, this process occurs in the absence of oxygen. The growth and death of the microbial population has already been accommodated in the reactions included in Aerobic stage.

3.8.2.1 - Denitrification

Denitrification reaction in the Partial System-1 model represents the process of nitrate (NO_2) being reduced to nitric oxide (NO) and nitrous oxide (N_2O) and finally into nitrogen gas (N_2) with the help of heterotrophic microorganism. The heterotrophic bacteria require carbon as electron donor in order to perform denitrification. In these designs domestic waste in the municipal wastewater provides sufficient source of carbon for this reaction.

3.8.2.1.1 - Reaction

This reaction is based on the Yield Coefficient calculated below

DomWaste	**+**	**NO_2**	**➔**	**CO_2**	**+**	**N_2**	**+**	**H_2O**	**+**	**X-Vss-h**
(34.6 g)		**(108 g)**		**(46 g)**		**(16.3 g)**		**(58.7 g)**		**(21.6 g)**

(142.6 g) **(142.6 g)**

3.8.2.1.2 - Yield Coefficient

Yield coefficient has been taken from literature as 0.2 g VSS/g NO_2 [21].

Due to unavailability of yield coefficient for domestic waste, it has been assumed to be 0.32 g domestic waste/g NO_2, which is same as the value taken in case of Full System. It is recommended that experimental work should be conducted to evaluate the domestic waste yield for Partial System.

3.8.2.1.3 - Kinetics of Reaction

The Partial System-1 implements denitrification from nitrite, and the Substrate-Term follows Monod's kinetics in ***Equation (1)*** as mentioned in Section 3.5, where the substrate is nitrate (NO_2). The O-term is neglected because it is an anoxic reaction, while the B-term follows first order kinetics and the biomass component used is heterotrophic bacteria.

3.8.2.1.4 – Rate Constant

The k_{max} has been taken from [22] as k_{max} = 0.89 day^{-1} or 0.037 h^{-1} and converted with respect to temperature by EnviroPro Designer. By the following expression:
$k = kmax\ \theta^{T-T_0}$

3.8.2.1.5 – Half Saturation Constant

Research papers [21] & [23] give values of half saturation constants for both Full and Partial Systems. The Ks range of values of Full System in both the papers deviated greatly from the already established range of values documented by Metcalf & Eddy for municipal wastewater. Therefore, the Ks values of Partial System-1 deduced from these research papers were considered to be incomparable and were not implemented. It can be seen from [21] & [23] that there is not a lot of difference between the values of Ks obtained from Full and Partial systems therefore, due to unavailability of Ks values for Partial System-1 from authentic sources, the same value as in the Full System has been taken. Later sensitivity analysis has been done to determine the significance of this parameter and documented in Section 4.3 of Chapter 4.

3.8.2.1.6 - Parameters

Table 3.8.2.1.6.A – General Specifications for Denitrification in Partial System-1

1	**Substrate**	**NO_2**
2	**Biomass**	**X-VSS-h**
3	**End Product**	**N_2**

Table 3.8.2.1.6.B - Kinetics of Reaction for Denitrification in Partial System-1

	Parameter		**Value**	**Units**	**Reference**
1	**Half Saturation Constant**	**Ks**	**0.44**	**mg/L**	See Section 3.8.2.1.5
2	**Rate of substrate utilization @ 20^{0}C**	**k_{max}**	**0.037**	**h^{-1}**	[22]
3	**Temperature Coefficient**	**θ**	**1.16**		
4	**Rate of substrate utilization @ 30^{0}C**	**k**	**0.162939**	**h^{-1}**	Calculated by EnviroPro Designer
5	**Yield**	**Y**	**0.2**	**g VSS/ g NO_2**	[21]

Chapter 4

Comparison of Models

Over the years, a number of experimental research studies have been conducted to explore the feasibility of partial nitrification. The studies done on lab-scale and pilot-scale reactors have shown that it is possible to achieve partial nitrification by selectively reducing the nitrite oxidizing bacteria by means of controlling certain critical parameters such as dissolved oxygen, temperature and pH. These research studies have also affirmed the advantages of partial nitrification in conjunction with the respective denitrification. It has been found experimentally, that the Partial System required approximately a 25% lower aeration requirement. It was also observed that the denitrification rates from nitrites were 1.5 to 2 times faster [12].

In the Chapter 3, EnviroPro Designer flowsheeting and the parameters for various process designs were described, and this has been used to implement the experimental findings for municipal wastewater treatment plant design. Two design models were developed. The Full System model reflected the traditional technology of full nitrification with its respective denitrification, whereas the Partial System-1 model incorporated basic partial nitrification with its respective denitrification process.

Partial System-1 showed extremely superior results with respect to ammonia and domestic waste concentrations after the treatment. This made it possible for us to optimize the Partial System-1 for improved results. Hence, the basic Partial System-1 was further optimized as Partial System-2 and Partial System-3 to determine the best case scenario. Partial System-2 and Partial System-3 follow the same design principles as the basic Partial System-1 described in Chapter 3 except for certain operational changes carried out in the design to reflect improved results.

Chapter 4 consists of three parts. In the first part, a parallel comparison between the simulation results of Full System and Partial System-1 was performed and discussed in depth. The second part describes and discusses the optimized versions Partial System-2 and Partial System-3. Part 3 of this chapter incorporates a sensitivity analysis for the unavailable kinetic parameters for Partial System. The values of these parameters are not studied in literature as most of the research done on partial nitrification has been focused on factors like dissolved oxygen, temperature, pH and initial free ammonia concentration. In such a case where the value of parameters for the Partial System were missing in literature, the same values as those taken for the Full System have been selected to draw initial results. Sensitivity analysis is then performed to compare the initial results against the current values obtained to check for any significant changes in the overall conclusions. The sensitivity analysis is also done with respect to temperature. For Partial System, the temperature is set to be 30^{o}C. In some wastewater treatment plants it is not practical to control this temperature therefore Partial System is tested for 15^{o}C. For sensitivity analysis conducted on Partial System, Partial System-3 model has been chosen as it was found to be the best design achieved by this thesis.

4.1 - Simulation Results Discussion

This section analyzes the simulation results obtained for both the Full System and Partial System-1 of Nitrogen Removal, using EnviroPro Designer. The Partial System-1 model is shown to give better results than the Full System model in order to remove nitrogen from the municipal wastewater treatment plant, and therefore, it supports the experimental claims that this technology is more efficient.

The Partial System-1 model designed with the help of EnviroPro Designer, shows several advantages over the Full System model. The most important aspect was a significant reduction in aeration requirement due to the lower dissolved oxygen level utilized in the Partial System-1. This consequently means lesser utility charges for the Partial Treatment process, especially for the air compression required to provide aeration. The simulation results show that the concentration of ammonia left in the effluent is also significantly lower in the Partial System-1 as compared to the Full System. Domestic waste consumption was also found to be much more effective in Partial System-1. The simulation results show that almost all the domestic waste is depleted in the Partial System-1. Hence, the amount of the surplus sludge remaining at the end of the treatment is reduced. Denitrification rates are also shown to be much faster. Details for these parameters are given in the following sub-sections.

4.1.1 - Liquid Effluent Comparison

An analysis of the Liquid Effluent simulation results obtained by EnviroPro Designer was done for both Full System and Partial System-1. This thesis is focused on the analysis Liquid Effluent as this effluent is discharged in the aquatic environment. The concentrations of components found in Liquid Effluent were compared against the permissible concentrations regulated for aquatic environment.

It was found that the Partial System-1 was more successful in reducing the concentration of the influent's components. The concentrations are tabulated in Table 4.1.1.A and Table 4.1.1.B given at the end of this section. The Liquid Effluents of both the treatments are analyzed with respect to following components.

4.1.1.1- Ammonia

The municipal wastewater influent was assumed to contain a moderate concentration of ammonia. The initial concentration of ammonia (21 mg/L) was reduced to 0.2 mg/L after treatment with Full System in liquid effluent. However, the basic Partial System-1 was able to reduce the ammonia content to 0.0056 mg/L in the liquid effluent. Please refer to Table 4.2.2.1.A. The equipment volumes employed for both the systems were approximately the same in the case of AB-101. AB-102 in case of Partial System-1 was slightly bigger (0.04%) than in Full System. The volume of AB-103 in Partial System-1 was 12% less than the one in Full System. AXR-101 was approximately 32% lesser and AXR-102 was 33% lesser in the Partial System-1 as compared to the Full System. Refer to Fig. 4.2.2.A, Table 4.2.1.1.B and Table 4.2.1.2. The aeration requirement was also 30% less in Partial System-1. Hence, the concentration of ammonia in Liquid Effluent was 97% lesser in the Partial System-1 as compared to Full System's Liquid Effluent. See Table 4.2.1.1.A and Table 4.2.2.1.A.

This gives us an opportunity to optimize the basic Partial System-1 to incur savings in capital and operational cost. The basic Partial System-1 was optimized twice in an effort to achieve improved results. Details about the Partial System-2 and Partial System-3 are given in Section 4.2.

4.1.1.2 - Carbon Dioxide

Carbon Dioxide existed in the influent as dissolved CO_2 in the form of HCO_3 or H_2CO_3. The influent's concentration of CO_2 in the liquid form was 51 mg/L. In addition, the stages AXR-101, AB-102, AB-101 and AXR-102 (see Figure 4.2.2.A) all generated and consumed CO_2 to conduct the various reactions. These reactions are also releasing CO_2 in gaseous form. The remaining dissolved CO_2 in liquid effluent also varied in the Full System and Partial System-1. Simulation results showed that the dissolved CO_2 concentration in Full System to be 0.180 mg/L, whereas, a concentration of 0.0930 mg/L was evaluated for Partial System-1. The concentration in Liquid Effluent of Partial System-1 showed a 48% decrease in the dissolved CO_2 as compared to Full System. See Table 4.1.1.A and Table 4.1.1.B.

4.1.1.3 - Domestic Waste

The domestic waste is also one of the most important factors that affirmed Partial System-1 effectiveness over Full System. EnviroPro Designer simulation results demonstrated that the Full treatment was able to reduce the domestic waste concentration from 157 mg/L to 0.64 mg/L. Partial treatment was found to reduce the concentration to 0.017 mg/L. Refer to Table 4.2.2.1.A. This can prove to be very beneficial as it will significantly contribute in reducing the surplus sludge at the end of the treatment. This also suggests that for the same amount of domestic waste, lesser number of treatment operations will be required in partial System as compared to Full System. Since domestic waste is biodegradable therefore, it causes oxygen depletion in the water. Hence, maximum consumption of domestic waste is desired by the engineers in municipal wastewater treatments.

4.1.1.3 - Fixed Suspended Solids

In case of Fixed Suspended Solids (FSS) both the systems reduced the initial concentration of 60 mg/L to final liquid effluent concentration of approximately 14.5 mg/L. See Table 4.1.1.A and Table 4.1.1.B.

4.1.1.4 - Nitrate And Nitrite

The Full System of nitrogen removal produces nitrate in the liquid effluent as opposed to nitrite which is being accumulated in Partial System-1. To study the affect of nitrate and nitrite on nitrogen removal process, it is already assumed that the plant's influent contains negligible traces of nitrate and nitrite in Full System and Partial System-1, respectively. All the nitrate concentration in the liquid effluent of the Full System is due to the full nitrification of ammonia to nitrate being done in aerobic stages. All the concentration of nitrite in the liquid effluent of Partial System-1 is because of the partial nitrification of ammonia to nitrite, caused by controlling the dissolved oxygen and temperature. EnviroPro Designer evaluated the nitrate concentration to be 1.01 mg/L in the Full Liquid's effluent. There are currently no national guidelines for the nitrate for the protection of aquatic life [24]. Liquid effluent of Partial System-1 demonstrated the nitrite concentration to be 0.30 mg/L. Refer to Table 4.2.2.1.A. This is a cause of concern because nitrite is toxic and therefore strict regulations are implemented to control the nitrite concentration in aquatic life. Canadian Water Quality Guidelines for the protection of aquatic life for nitrite are regulated at 60 micro-g/L [24].

4.1.1.5 - Total Dissolved Solids (TDS)

There is no difference in the concentration of TDS in Liquid Effluent and plant's influent, since the removal of TDS has not been incorporated in either of the treatment processes. This result is to be expected since TDS is primarily related to dissolved salts, which are not significantly affected by organic or nitrogen oxidation. See Table 4.1.1.A and Table 4.1.1.B

4.1.1.6 - Microorganisms (Heterotrophic, Autotrophic and dead)

Initially, 53 mg/L of heterotrophic, 3 mg/L of autotrophic and 51 mg/L of dead microorganisms have been set for a typical municipal wastewater influent for both Full System and Partial System-1 [18]. The various stages implemented in both the Full and Partial systems involve growth and death of this microbial population. The difference between both the systems with respect to microbial population was found to be negligible. The Liquid Effluent of Full System show the concentration of heterotrophic bacteria to be 50 mg/L, autotrophic bacteria to be 2.3 mg/L and dead microbial population to be 16 mg/L. In case of Partial System-1, it is 49 mg/L for heterotrophic, 2 mg/L for autotrophic and 16 mg/L for dead microbial population. See Table 4.1.1.A and Table 4.1.1.B

Table 4.1.1.A : Component Concentration in Liquid Effluent of Full System

Component	Flow Rate (kg/h)	Mass Comp (%)	Concentration (mg/L)
Ammonia	0.37	0.0000	0.195
Carbon Dioxide	0.33	0.0000	0.175
Domestic Waste	1.22	0.0001	0.643
Fixed Suspended Solids	27.63	0.0015	14.575
Nitrate	1.92	0.0001	1.012
Total Dissolved Solids	579.51	0.0306	305.754
Water	1891475.99	99.9609	997957.943
Heterotrophic Bacteria	94.97	0.0050	50.108
Autotrophic Bacteria	4.30	0.0002	2.269
Dead Microorganisms	30.09	0.0016	15.878

Table 4.1.1.B : Component Concentration in Liquid Effluent of Partial System-1

Component	Flow Rate (kg/h)	Mass Comp (%)	Concentration (mg/L)
Ammonia	0.01	0.0000	0.0056
Carbon Dioxide	0.18	0.0000	0.0933
Domestic Waste	0.03	0.0000	0.0171
Fixed Suspended Solids	27.63	0.0015	14.4949
Nitrite	0.64	0.0000	0.3375
Total Dissolved Solids	579.54	0.0306	304.0802
Water	1891597.54	99.9611	992503.1989
Heterotrophic Bacteria	92.78	0.0049	48.6822
Autotrophic Bacteria	3.87	0.0002	2.0300
Dead Microorganisms	30.78	0.0016	16.1516

4.1.2 - Sludge Effluent Comparison

This thesis is more focused on the Liquid Effluent being discharged into the aquatic environment and has studied wastewater treatment plant with respect to the rules and regulation implemented for aquatic environment.

The analysis of simulation results obtained from Sludge Effluent has been discussed in detail below. It can be deduced that the Partial System-1 is the more efficient one of the two technologies because the concentration achieved in case of ammonia and domestic waste were far lower than those achieved in Full System. The values of concentration of components achieved are tabulated in Table 4.1.2.A and Table 4.1.2.B given at the end of this section. The sludge effluent was analyzed as follows:

4.1.2.1 - Ammonia

The concentration of ammonia was already very low in the liquid effluent of the Partial System, and therefore the volume of aerobic stage AB-103 was reduced to 12% in Partial System-1 as compared to Full System leading to reduction in capital costs. Also, the sludge residence time was 146 hours as compared to 159 hours in Full System, making it a faster process. Refer to Table 4.2.1.1.B and Table 4.2.1.2.

The ammonia concentration in Partial System-1 was 0.0078 mg/L whereas in Full System was 0.076 mg/L. Hence, the ammonia concentration achieved after the sludge treatment in Partial System-1 was approximately 90% lesser than the concentration achieved in the Full System. Please see Table 4.2.2.1.B

4.1.2.2 - Carbon Dioxide

The sludge effluent also showed better concentration of liquid CO_2 in Full System as compared to Partial System-1. Partial System-1 showed a concentration of 28 mg/L whereas, Full System indicates a concentration of 18.7 mg/L of liquid CO_2. The Partial System-1 shows a 33% increase when compared with Full System. See Table 4.1.2.A and Table 4.1.2.B.

4.1.2.3 - Domestic Waste

The domestic waste was found to be almost depleted by the end of both Full System and Partial System-1. In case of Full System it is 0.000053 mg/L and in Partial System-1, it is 0.000007 mg/L. These values are negligible**.** See Table 4.2.2.1.B.

4.1.2.4 - Fixed Suspended Solids

The amount of Fixed Suspended solids were slightly greater in the sludge effluent obtained from the Partial System-1, but the difference of 6% is considered negligible. See Table 4.1.2.A and Table 4.1.2.B.

4.1.2.5 - Nitrate or Nitrite

The concentration of nitrate achieved in Sludge Effluent of Full System is approximately 313 mg/L. The concentration of nitrite remaining in sludge effluent of Partial System-1 is found to be 334 mg/L. Refer to Table 4.2.2.1.B.

4.1.2.6 - Total Dissolved Solids

Partial System-1 showed a slightly lower concentration of total dissolved solids as compared to Full System. The negligible difference of 1% in the concentration of total dissolved solids was detected. See Table 4.1.2.A and Table 4.1.2.B.

4.1.2.7 - Microorganisms (Heterotrophic, Autotrophic and dead)

In the plant's influent the initial concentration of heterotrophic (53 mg/L), autotrophic (3 mg/L) and dead microorganisms (51 mg/L) went through process of growth and cessation through out the different stages being performed in the various treatment processes included in both the Full System and Partial System-1. The Sludge Effluent of both Full System and Partial System-1 showed similar concentrations of heterotrophic, autotrophic and dead microorganism [18]. See Table 4.1.2.A and Table 4.1.2.B.

Table 4.1.2.A : Component Concentration in Sludge Effluent of Full System

Component	Flow Rate (kg/h)	Mass Comp (%)	Concentration (mg/L)
Ammonia	**0.0002**	**0.0000**	**0.0764660**
Carbon Dioxide	**0.0404**	**0.0019**	**18.713246**
Domestic Waste	**0.0000**	**0.0000**	**0.000053**
Fixed Suspended Solids	**64.4627**	**2.9913**	**29870.600504**
Nitrate	**0.6754**	**0.0313**	**312.975516**
Total Dissolved Solids	**0.4895**	**0.0227**	**226.853004**
Water	**1830.5702**	**84.9441**	**848245.767800**
Heterotrophic Bacteria	**177.3134**	**8.2279**	**82163.094512**
Autotrophic Bacteria	**2.7967**	**0.1298**	**1295.915004**
Dead Microorganisms	**78.6818**	**3.6511**	**36459.399290**

Table 4.1.2.B : Component Concentration in Sludge Effluent of Partial System-1

Component	Flow Rate (kg/h)	Mass Comp (%)	Concentration (mg/L)
Ammonia	0.00002	0.0000	0.007760
Carbon Dioxide	0.05685	0.0028	27.892333
Domestic Waste	0.0000	0.0000	0.000007
Fixed Suspended Solids	64.49655	3.1818	31644.215058
Nitrite	0.68088	0.0336	334.064442
Total Dissolved Solids	0.45640	0.0225	223.927659
Water	1721.81267	84.9411	844780.216199
Heterotrophic Bacteria	153.28912	7.5621	75208.888541
Autotrophic Bacteria	2.32446	0.1147	1140.457546
Dead Microorganisms	83.94990	4.1414	41188.693278

4.1.3 - Environmental Properties Comparison

EnviroPro Designer can also calculate the environmental properties of the effluent stream in comparison with the influent stream. This comparison gives us valuable information about the percentage removal of a particular environmental property included in all the soluble and suspended compounds in the municipal wastewater. Therefore, a parallel comparison between environmental properties of influent and effluent of Full and Partial Systems can give useful insight into the efficiency and feasibility of the Partial System-1 when compared against the Full System.

The Partial System-1 implements a 30% reduction in aeration requirements, reducing utilities charges. There is also a reduction in the volume of aerobic and anoxic stages that favorably affected the capital costs. Furthermore, it gives more desirable concentration of ammonia and domestic waste in its effluents. In addition to all these advantages, it was found that Partial System-1 managed to show a similar or slightly better percentage removal of environmental properties as compared to Full System. The most important aspect of this comparison is that in the Partial System-1, almost all the nitrogen existing as ammonia is retrieved. Also, nitrogen existing as nitrate in Full System is 0.23 mg/L whereas the nitrogen remaining in the effluent of Partial System-1 as nitrite is about 0.08 mg/L. There seems to be a slight increase in TDS concentration in the effluent of Full System. This is due to the calculation error. The comparisons are tabulated in Table 4.1.3.A and Table 4.1.3.B which is given below:

Table 4.1.3.A: Comparison of Environmental Properties in Full System

Property	Influent (mg/L)	Effluent (mg/L)	Removal (%)
BOD_5	**297.62**	**49.65**	**83**
COD	**540.01**	**91.61**	**83**
TSS	**167.73**	**82.83**	**51**
TDS	**305.92**	**306.767**	**0**
TKN	**41.22**	**8.39**	**80**
NH_3-N	**17.30**	**0.16**	**99**
NO_3-N	**0.000**	**0.23**	

Table 4.1.3.B: Comparison of Environmental Properties in Partial System-1

Property	Influent (mg/L)	Effluent (mg/L)	Removal (%)
BOD_5	**295.98**	**47.81**	**84**
COD	**573.04**	**87.90**	**85**
TSS	**166.81**	**81.36**	**51**
TDS	**304.24**	**304.08**	**0.05**
TKN	**40.99**	**8.03**	**80**
NH_3-N	**17.21**	**0.004**	**99.9**
NO_2-N	**0.000**	**0.08**	

4.1.4 – Aeration Requirement

The experimental studies suggested that the aeration requirement was reduced to approximately 25% in Partial System-1 as compared to Full System [12, 14].

In case of EnviroPro Designer, the aeration requirement for the Full System was fixed at 0.010 m^3 air per (m^3 liq/min) according to values for aeration rate provided in the literature to maintain aerobic conditions [63]. Aeration requirement was reduced to 30% for Partial System-1 and thus, was set at 0.007 m^3 air per (m^3 liq/min). See Table 4.2.1.1.A.

The report for Stream and Material balance for Full System, Report 4.1.A (Appendix A) showed the oxygen utilized was 9.1×10^6 kg/yr. The report for Stream and Material balance for the Partial System-1 showed the oxygen utilized was 6.1×10^6 kg/yr while reducing the ammonia concentration in liquid effluent to 0.0056 mg/L in Partial System-1 as opposed to 0.20 mg/L in Full System. Also, refer to Table 4.2.3

Furthermore, ammonia concentration in Sludge Effluent was reduced to 0.0078 mg/L in Partial System-1 as opposed to 0.076 mg/L in Full System.

This indicates that every year approximately 33% less oxygen was utilized by the Partial System-1 to reduce 97% more ammonia in Liquid effluent and approximately 90% lesser ammonia in sludge effluent as compared to Full System. The kg Oxygen / kg Ammonia removed in Full System is 29.1. The kg Oxygen / kg Ammonia removed in Partial System-1 is 19.4. See Table 4.2.3.

This 33% reduction in oxygen usage will reflects positively on utilities savings in the case of Partial System. However, the nitrite concentration achieved in the liquid effluent of Partial System-1 was found to be approximately 0.34 mg/L (see Table 4.2.2.1.A) which is a cause of concern as Canadian Water Quality Guidelines for the protection of aquatic life for nitrite are regulated at 60 μ g/L or 0.06 mg/L. In Section 4.2, Partial

System-3, an optimized version of basic Partial System-1, has been designed to tackle this problem.

4.1.5 - Denitrification Rates

The experimental research studies suggested that the denitrification rates are 1.5 to 2 times faster from nitrite than with nitrate [12, 14].

The simulation results evaluated by EnviroPro Designer seem to support this claim. For Full System, the sludge residence time calculated in anoxic stage, AXR-101 and AXR-102 were found to be approximately 11.4 hours and 9 hours. For Partial System, the sludge residence time for AXR-101 and AXR-102 were calculated to be approximately 7.7 and 6 hours respectively, indicating a 1.5 times faster denitrification rate. Refer to Fig 4.2.2.A and Table 4.2.1.2.

4.1.6 - Capital Cost

The capital cost evaluated by EnviroPro Designer in case of Full System through Report 4.2.A (Appendix A) is $108,171, 000. Report 4.2.B (Appendix A) presents the capital cost involved in Partial System-1 that is calculated to be $ 105,075,000. There is approximately a 3% reduction in the capital cost of the Partial System-1. Also see Table 4.2.3.

4.2 - Optimization of Partial System-1

Partial System-1 showed superior results with respect to ammonia and domestic waste concentrations in the liquid effluent. The dissolved oxygen used in the basic Partial System-1 was 33% less than Full System. This gave us the opportunity to optimize the Partial System-1 to reflect savings in aeration cost. Furthermore, the nitrite concentration found in the Liquid Effluent of Partial System-1 was a cause of concern. Therefore, Partial System-1 was further optimized as Partial System-2 and Partial System-3 for improved results.

4.2.1 - Partial System-2

Dissolved oxygen concentration of 1.5 mg/L due to aeration requirement of 0.007 m3 air / m3 (liq/min) in Partial System-1 was found to reduce 97% more ammonia as compared to Full System. In Partial System-2, the aeration requirement was further decreased to 0.005 m^3 air per (m^3 liq/min) in order to incur savings in utility costs. This aeration requirement is 50% less than amount set in the Full System. The dissolved oxygen concentration is thus expected to be approximately 1 mg/L. See Table 4.2.1.1 A.

The simulation results showed the ammonia concentration to be 8.1 mg/L and nitrite concentration to be 10.78 mg/L in the liquid effluent. See Table 4.2.2.1 A. The Partial System-2 showed a significant rise in both ammonia and nitrite concentrations which are outside the guidelines provided by Canadian Water Quality for the protection of aquatic life [24, 66]. Therefore, aeration of 0.005 m^3 air per (m^3 liq/min) is not enough to maintain required aerobic condition. Hence, the ammonia and nitrite concentrations obtained at the end of the treatment do not fall within the desired criteria.

Report 4.3.A (Appendix A) shows the amount of oxygen and utilized and amount of ammonia removed during this process. Report 4.3.B shows the capital and operational costs involved in this method.

4.2.2 - Partial System-3

One of the biggest limitations of the basic Partial System-1 is that the nitrite concentration achieved at the end of the treatment falls outside the permissible range implemented by Canadian Water Quality for the protection of aquatic life for Nitrite and Nitrate [24]. Refer to Table 4.2.2.1.A, we can see from the simulation results that ammonia concentration achieved in Liquid Effluent by Partial System-3 is sufficiently decreased to 0.0052 mg/L. This ammonia concentration is 97% lower than that achieved in Full System and lies well within the permissible range provided by the Canadian Water Quality for the protection of aquatic life for Ammonia [66]. Therefore, it is insignificant to further decrease this ammonia concentration of 0.0052 mg/L in the sludge treatment. See Table 4.2.2. A third aerobic stage, AB-103 (see Figure 4.2.2.A) is therefore considered to be expendable in the sludge treatment. Removing AB-103 will result in lower oxygen consumption and reflect positively on utility charges associated with it. Instead, an additional anoxic stage would contribute effectively towards reducing the undesirable nitrite concentration in the liquid effluent found in Partial System-1. See Table 4.2.2.1.A.

The design of Partial System-1 and Partial System-2 implemented two aerobic stages AB-102 and AB-101 for partial nitrification and two anoxic stages AXR-101 and AXR-102 for denitrification from nitrite in the Primary Treatment, which results in Liquid Effluent. Both the Partial System-1 and Partial System-2 included an aerobic stage AB-103 in the Secondary Treatment employed for the treatment of sludge. See Figure 4.2.2.A. The design of Partial System-3 involves two aerobic stages AB-102 and AB-101 for partial nitrification and three anoxic stages AXR-101, AXR102 and AXR-103 for denitrification from nitrite. No aerobic stage has been incorporated in the Secondary Treatment to treat sludge. See Figure 4.2.2.B.

As expected, the Partial System-3 showed superior results than all of the nitrogen removal treatment process examined in this research. The ammonia concentration achieved in the Liquid Effluent was 0.0052 mg/L which is still 97% lower than that of Full System. The nitrite concentration was reduced to 0.00121 mg/L or 1.2 micro-g/L) which is now significantly lower than 60 micro-g/L value provided by Canadian Water Quality for the protection of aquatic life for Nitrite and Nitrate [24]. Refer to Table 4.2.2.1 A.

Partial System-3 consumed 4.4×10^6 kg of oxygen per year, which is approximately 50% less than Full System. Additionally, the kg Oxygen /kg Ammonia removed ratio for Partial System-3 is 13.9 as opposed to 29.1 obtained in Full System and 19.4 obtained in Partial System-2. See Table 4.2.3 and Report 4.4.A. This reflects positively on utility savings.

Additionally, Partial System-3 displayed 2 times faster denitrification rates.

Furthermore, the capital cost is $ 93,101,000 and operating cost is $ 21,217,000. Both theses costs are the least among the values obtained from all the treatment models tested in this research. See Table 4.2.3 and Report 4.4.B

Hence, Partial System-3 presents the best-case scenario for the nitrogen removal from medium to high strength municipal wastewater treatment.

This research is the first one to have designed a Partial System model by using EnviroPro Designer. No previous study has designed Partial System simulation model by using EnviroPro Designer. Therefore, there are no existing results available for comparison with the results obtained by this thesis. However, this research can be considered as a bench mark for any future study.

Fig. 4.2.2.A: Flowsheet For Bardenpho Process applied in Full System, Partial System-1 and Partial System-2

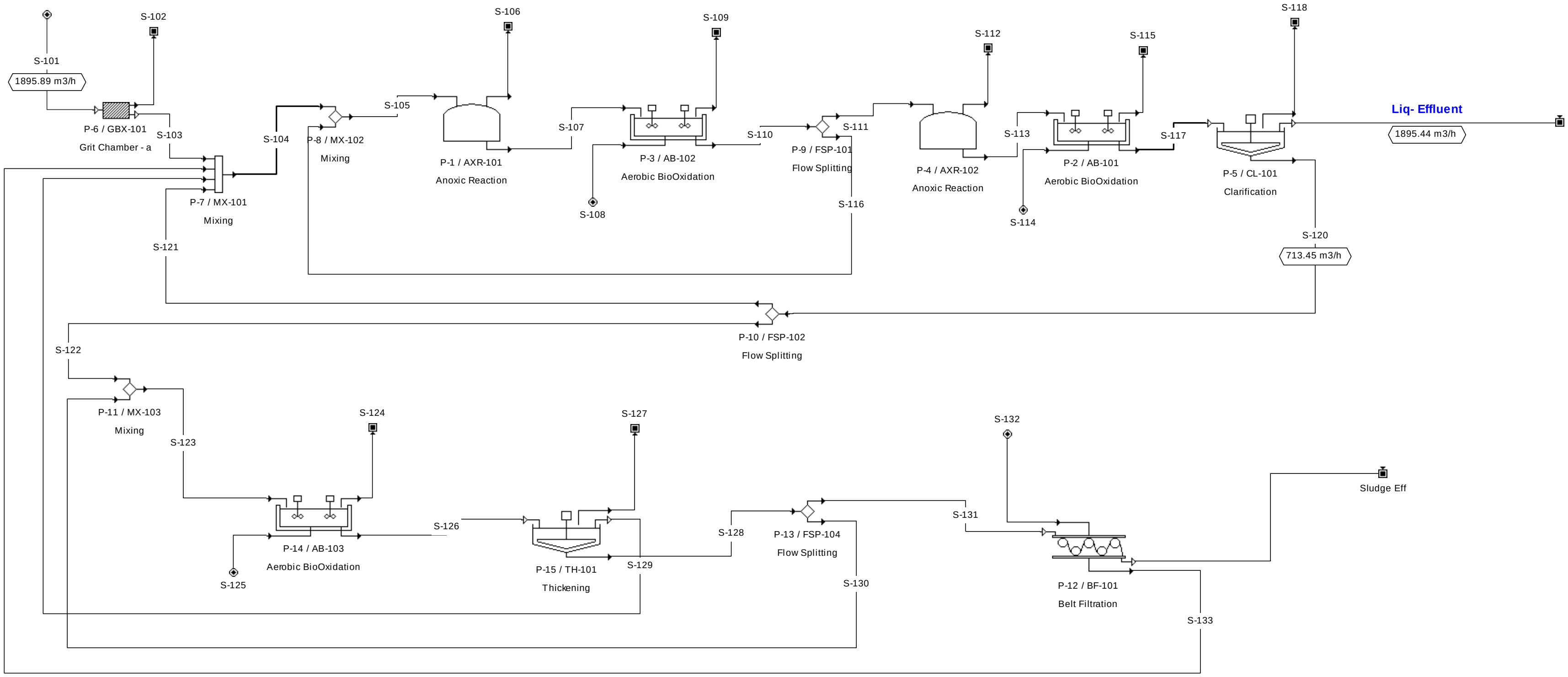
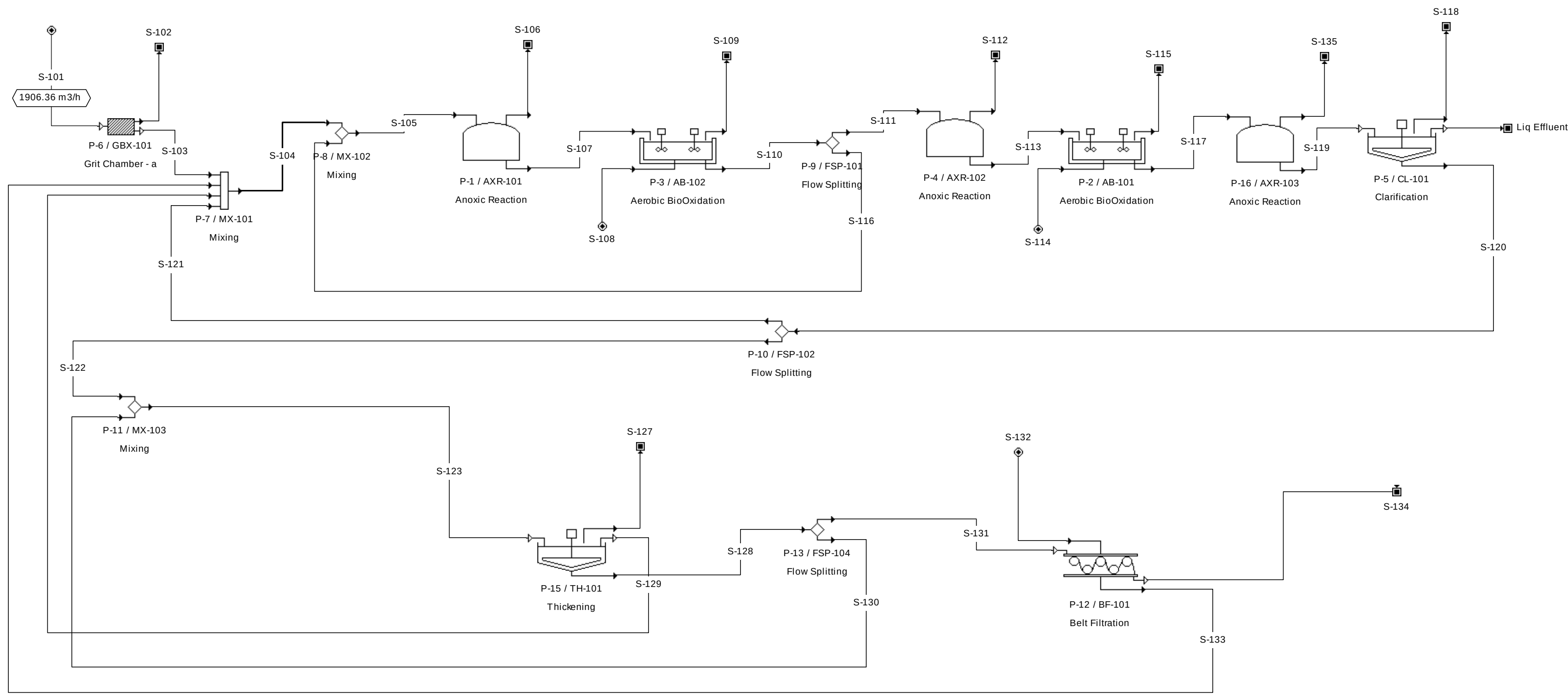


Fig 4.2.2.B : Flowsheet for Partial System-3



Comparison of Design Specifications

Table 4.2.1.1.A: Comparison of Parameters for Aerobic Oxidation System

System	Dissolved Oxygen (mg/L)	Temp ^0C	Aeration Requirement m^3 Air per (m^3 Liq/min)
Full System	2.00	15	0.010
Partial System-1	1.5	30	0.007
Partial System-2	1.0	30	0.005
Partial System-3	1.5	30	0.007

Table 4.2.1.1.B : Comparisons of Volumes and Sludge Residence Times for Aerobic Stages

	Liquid Effluent			Sludge Effluent		
	Name	Sludge Residence Time (h)	Volume (L)	Name	Sludge Residence Time (h)	Volume (L)
Full System	AB-102	23.16	4263223	AB-103	159.00	2125000
	AB-101	2.898	532852			
Partial System-1	AB-102	23.18	4264944	AB-103	146.12	1864726
	AB-101	2.897	532852			
Partial System-2	AB-102	23.17	4240215	AB-103	146.02	1837079
	AB-101	2.914	532852			
Partial System-3	AB-102	32.642	4272202	N/A		
	AB-101	4.072	532852			

Table 4.2.1.2 : Comparison of Volumes and Sludge Residence Times for Anoxic Stages:

System	Name	Sludge Residence Time (h)	Volume (L)
Full System	AXR-101	11.36	2125000
	AXR-102	9.14	1682182
Partial System-1	AXR-101	7.696	1439466
	AXR-102	6.1	1119596
Partial System-2	AXR-101	7.696	1431118
	AXR-102	6.1	1113072
Partial System-3	AXR-101	5.4	1441913
	AXR-102	4.3	1121503
	AXR-103	4.3	1121494

Comparison of Components' Concentration

Table 4.2.2.1.A : Comparison of Components' Concentration in Liquid Effluent

Components	Full System Concentration (mg/L)	Partial System-1 Concentration (mg/L)	Partial System-2 Concentration (mg/L)	Partial System-3 Concentration (mg/L)
Ammonia	0.20	0.0056	8.1	0.0052
Domestic Waste	0.64	0.017	0.25	0.0000
Nitrate	1.01	N/A	N/A	N/A
Nitrite	N/A	0.34	10.78	0.00121 (or 1.21 μ-g/L)

Table 4.2.2.1.B : Comparison of Components' Concentration in Sludge Effluent

Components	Full System Concentration (mg/L)	Partial System-1 Concentration (mg/L)	Partial System-2 Concentration (mg/L)	Partial Nitrification-3 Concentration (mg/L)
Ammonia	0.076	0.0078	0.0106	0.0039
Domestic Waste	0.000053	0.000007	0.000013	0.0000
Nitrate	313	N/A	N/A	N/A
Nitrite	N/A	334.06	354.32	0.00091 (0.91 μg/L)

Table 4.2.3 : Comparison Economics Generated by Reports (Appendix A)

Components	Full System Air req =0.010 m^3 air (m^3 liq/min)	Partial System-1 Air req = 0.007 m^3 air (m^3 liq/min)	Partial System-2 Air req = 0.005 m^3 air (m^3 liq/min)	Partial System-3 Air req = 0.007 m^3 air (m^3 liq/min)
Oxygen (kg/yr) 1	9,130,053	6,146,846	4,352,297	4,390,288
Ammonia Removed (kg/yr) 2	313,865	316,715	163,308	316,721
Oxygen per Ammonia Removed	29.1	19.4	26.7	13.9
Total Capital Investment ($) 3	108,171, 000	105,075,000	104,916,000	93,101,000
Operating Cost ($/yr) (aeration costs are not included) 4	23,940, 000	23,369,000	23,339,000	21,217,000

1 – Oxygen in kg/yr is calculated for Full System by Report 4.1 A, for Partial System -1 by Report 4.2 A, for Partial System-2 by Report 4.3 A and for Partial System-3 by Report 4.4 A. Reports are found in Appendix A

2 – Ammonia Removed in kg/yr is calculated for Full System by Report 4.1 A, for Partial System -1 by Report 4.2 A, for Partial System-2 by Report 4.3 A and for Partial System-3 by Report 4.4 A. Reports are found in Appendix A

3 – Total Capital Investment is calculated for Full System by Report 4.1 B, for Partial System -1 by Report 4.2 B, for Partial System-2 by Report 4.3 B and for Partial System-3 by Report 4.4 B. Reports are found in Appendix A

4 – Operating Cost is calculated for Full System by Report 4.1 B, for Partial System -1 by Report 4.2 B, for Partial System-2 by Report 4.3 B and for Partial System-3 by Report 4.4 B. Reports are found in Appendix A

4.3 - Sensitivity Analysis

The numerous experimental studies have been performed to study the behavior of Partial nitrification. The majority of the work has revolved around the effects of dissolved oxygen, temperature, pH and ammonia concentration. These parameters are considered the most critical factors in order to restrain the nitrification of ammonia to nitrite only. Many laboratory research studies have emphasized these to be the most important parameters to affect the process of nitrification. The appropriate values of these parameters required to incur Partial nitrification are well established in the literature. There are some kinetic parameters associated with the Partial nitrification that have been overlooked as they are believed to have negligible effect on the process. For simplicity, the same values as in the Full System have been taken for these parameters in the Partial System-1. Later on, a sensitivity analysis was conducted on the best design achieved, Partial System-3, in order to see the magnitude of the effect of these parameters on the behavior of partial nitrification. These parameters and their sensitivity analysis are as follows:

4.3.1 - Decay Constant of *Nitrosomonas* in Partial System-3

The decay constant of overall *Nitrosomonas* and *Nitrobacter* bacteria to cause Full Nitrification is well known through out the literature. The table in [60] gives the value of Overall *Nitrosomonas* and *Nitrobacter* decay to be kd = 0.002 h^{-1}. This value was implemented for the Full System model, used by EnviroPro Designer. It has been mentioned in literature [59] that Full Nitrification is controlled by the oxidation of ammonia to nitrite because the growth rate of *Nitrobacter* is considerably greater than *Nitrosomonas*. Therefore, due to unavailability of decay constant of only *Nitrosomonas* bacteria to induce Partial nitrification, we have used the same value in our Partial System-1, Partial System-2 and Partial System-3 as provided for overall reaction by [60].

A sensitivity analysis was conducted for this parameter. The value of kd was first halved from 0.002 h^{-1} to 0.001 h^{-1}. The analysis of Liquid Effluent is summarized in Table 4.3.1.A and that of Sludge Effluent is summarized in Table 4.3.1.B. Both the tables are given at the end of this section.

As we can see from Table 4.3.1.A and Table 4.3.1.B, when the decay constant for *Nitrosomonas* was halved to kd= 0.001 h^{-1}, the concentration of ammonia in Liquid and Sludge Effluents was decreased to approximately 56%. The concentration of domestic waste remained the same and the concentration of nitrite decreased 50% in Liquid Effluent and 59% in Sludge Effluent. Since the concentrations are being decreased therefore, halving the value of kd did not affect the conclusion of this thesis.

When the kd was doubled, kd=0.004 h^{-1}, the ammonia concentration increased 45% in both Liquid and Sludge Effluents. The concentration of domestic waste remained the same and nitrite concentration increased 40% in Liquid Effluent and 35% in Sludge Effluent. However, the values obtained are significantly lower than those accomplished by Full System therefore, this increase does not affect the conclusion of this thesis. See Table 4.3.1.A and Table 4.3.1.B.

Hence, taking the same kd value as in case of Overall *Nitrosomoas* and *Nitrobacter* given for Full System for just *Nitrosomonas* for Partial System-3, did not affect conclusion of this thesis. See Table 4.3.1.A.

Table 4.3.1.A : The Effect of Decay Constant kd on Liquid Effluent

Components	Full System	Partial System-3		
	@ kd = 0.002 h^{-1}	@ kd = 0.002 h^{-1}	@ kd=0.001 h^{-1}	@ kd=0.004 h^{-1}
Ammonia (mg/L)	0.20	0.0052	0.0023	0.0095
Domestic Waste (mg/L)	0.64	0.000	0.0000	0.0000
Nitrite (mg/L)	N/A	0.00121	0.0006	0.002

Table 4.3.1.B : The Effect of kd on Sludge Effluent

Components	Full System	Partial System-3		
	@ kd = 0.002 h^{-1}	@ kd = 0.002 h^{-1}	@ kd=0.001 h^{-1}	@ kd=0.004 h^{-1}
Ammonia (mg/L)	0.076	0.0039	0.0017	0.0071
Domestic Waste (mg/L)	0.000053	0.00091	0.0000	0.0000
Nitrite (mg/L)	N/A	0.00098	0.0004	0.0015

4.3.2 - Half Saturation Constant (Ks) of Denitrification in Partial System-3

Insufficient research and experimental studies were available to obtain a definitive value for the half saturation constant (Ks) of the denitrification process for the Partial nitrification process. Some literature [21, 23] reviewed, studied, analyzed and compared the phenomenon of denitrification performed with nitrate and nitrite in groundwater using a fluidized bed reactor. In one research study [21], the half saturation constant (Ks) value obtained in case of denitrification from nitrate was found to be Ks= 3.59 NO_3 mg/L which is abnormal and inconsistent with the already established range of values available in the literature. The most reliable range is considered 0.266 to 0.886 NO_3 mg/L with a typical value of 0.44 NO_3 mg/L [57]. Hence, the Ks value achieved in the parallel experiments for denitrification performed from nitrite that was found to be 4.1 NO_2 mg/L, was also rejected. However, it can be observed from these experiments that there is not much difference between the two values of Ks of denitrification for Full and Partial System for experiments performed under similar conditions. Hence, the Ks value for denitrification from nitrite was also set to be 0.44 mg/L in the Partial System-1, Partial System-2 and Partial System-3 models.

A sensitivity analysis was also carried out for the Ks parameter of denitrification in the Partial System-3 and the results were analyzed for both Liquid and Sludge Effluents.

The analysis of Liquid and Sludge streams with respect to ammonia, domestic waste and nitrite is given below. The simulation results obtained for Liquid and Sludge Effluents are summarized in Table 4.3.2.A and Table 4.3.2.B respectively.

The Ks value was first halved to Ks = 0.22 mg/L. The ammonia concentration remained approximately the same in Liquid and Sludge Effluents. On doubling the Ks value to Ks = 0.88 mg/L, the ammonia concentration remained the same as well. This was expected as the parameter for denitrification should mostly affect the anoxic reaction of the process. Please refer to Table 4.3.2.A and Table 4.3.2.B.

Similarly, in case of domestic waste, halving and doubling the Ks for denitrification did not change the concentration of domestic waste in the Liquid and Sludge Effluents. The domestic waste completely depleted in AXR-103 (see Fig. 4.2.2.B) in both the cases.

Halving the Ks for denitrification, the nitrite concentration decreased 52% in Liquid Effluent and 14% in Sludge Effluent. On doubling the Ks value, the nitrite concentration in the Liquid Effluent increased to a value of 2.6 micro-g/L, indicating 53% increase. In Sludge Effluent, the concentration of nitrite increased to 1 micro-g/L, indicating increase of 9%. This increase can be neglected as the value 2.6 micro-g/L obtained is well within the guidelines provided by Canadian Water Quality for the protection of aquatic life [24].

The changes in nitrite concentration in the Partial System-3 due to doubling and halving the value of Ks are negligible and fail to deter the end conclusion regarding the comparison between the Full and Partial System-3 therefore, we conclude that the value of Ks of denitrification taken in Partial System-3 is sufficient to make a reasonable interpretation of the behavior and comparison of Full and Partial System models for nitrogen removal.

Table 4.3.2.A : The Effect of Ks of Denitrification on Liquid Effluent

Components	Full System	Partial System-3		
	@ Ks = 0.44 (mg/L)	@ Ks = 0.44 (mg/L)	@ Ks=0.22 (mg/L)	@ Ks=0.88 (mg/L)
Ammonia (mg/L)	0.20	0.0052	0.0053	0.0052
Domestic Waste (mg/L)	0.64	0.000	0.000	0.000
Nitrite (mg/L)	N/A	0.00121	0.00058	0.0026

Table 4.3.2.B : The Effect of Ks of Denitrification on Sludge Effluent

Components	Full System	Partial System-3		
	@ Ks = 0.44 (mg/L)	@ Ks = 0.44 (mg/L)	@ Ks=0.22 (mg/L)	@ Ks=0.88 (mg/L)
Ammonia (mg/L)	0.076	0.0039	0.0039	0.0039
Domestic Waste (mg/L)	0.000053	0.000	0.000	0.000
Nitrite (mg/L)	N/A	0.00091	0.00078	0.001

4.3.3 - Effect of Temperature in Partial System-3

From the literature review of experimental research studies on partial nitrification, we found that a temperature of 30^{o}C was recommended in order to successfully inhibit nitrite oxidation without retarding ammonia oxidation [12]. Therefore, in the designs of Partial System-1, Partial System-2 and Partial System-3 models, the temperature was regulated at 30^{o}C through out the treatment.

In many of the wastewater treatment plants, this temperature would not be a challenge to maintain. Hence, a sensitivity analysis was also carried out to see whether there will be a significant difference in the results if the temperature was set to 15^{o}C which is the temperature maintained in Full System.

The Liquid Effluent was analyzed and the simulation results achieved are summarized in Table 4.3.3.A which is given at the end of the section.

When the temperature of Partial System-3 was set to 15^{o}C, the ammonia concentration was completely depleted in the unit AB-101 (see Fig.4.2.2B). Hence, the Liquid Effluent also shows the ammonia concentration to be depleted.

The domestic waste concentration increased to 0.86 mg/L in the Liquid Effluent, while it was found to be completely depleted when the temperature was 30^{o}C. This concentration of domestic waste is higher than the concentration achieved in Full System. On examining the simulation input and results of AXR-103, it was found that no anoxic reaction took place in AXR-103 because the nitrite was depleted after AB-101. See Fig.4.2.2.B.

The nitrite concentration in Liquid Effluent was completely depleted. The nitrite concentration entering the second anoxic stage, AXR-102 (see Fig.4.2.2.B) was 6.8 mg/L and leaving AXR-102 was 0.41 mg/L. The nitrite concentration entering the second aerobic stage, AB-101 (see Fig.4.2.2.B) was 0.41 mg/L and was completely depleted after treatment in AB-101. This is odd as ammonia oxidation to nitrite should be taking place in AB-101 therefore, nitrite concentration should be increasing at the end of AB-101. On close examination of simulations of AB-101, it was found that the ammonia concentration entering AB-101 was 0.031 mg/L and depleted after treatment in AB-101. Therefore, some reaction with ammonia is taking place in AB-101. It is possible that ammonia is being oxidized to nitrate instead of nitrite in AB-101 and consequently shown as depleted after AB-101. Although, the first aerobic stage, AB-102 shows an increase in nitrite concentration while ammonia's concentration decreased indicating that nitrite accumulation at a low temperature of 15^{o}C. Experimental studies have indicated that increased temperature of about 30^{o}C is required for partial nitrification as this temperature increases the concentration of undissociated ammonia causing inhibition of nitrite-oxidizing microorganisms resulting in nitrite accumulation [12]. A possible explanation is that in the beginning of the treatment when the concentration of undissociated ammonia is high, it is possible to accumulate nitrite (thus, causing partial nitrification) in the first aerobic stage AB-102 (see Fig.4.2.2.B) by controlling dissolved oxygen and pH. However, as the treatment proceeds and ammonia concentration depletes, nitrite-oxidizing microorganisms are no longer inhibited in the second aerobic stage AB-101 (see Fig.4.2.2.B) and begin oxidizing nitrite to nitrate.

Therefore, we have come to a conclusion that Partial System may not work effectively at a temperature of 15^{0}C and will give inconsistent results when the concentration of ammonia is medium strength. A more detailed analysis of temperature effects may be required to understand the mechanisms, both using simulation and experimental work.

Table 4.3.3.A : The Effect of Temperature on Liquid Effluent

Components	Full System	Partial System-3	
	@ T = 15 °C	@ T = 30 °C	@ T = 15 °C
Ammonia (mg/L)	0.20	0.0052	0.00
Domestic Waste (mg/L)	0.64	0.000	0.86
Nitrite (mg/L)	N/A	0.00121	0.00

Table 4.3.3.B : The Effect of Temperature on Sludge Effluent

Components	Full System	Partial System-3	
	@ T = 15 °C	@ T = 30 °C	@ T = 15 °C
Ammonia (mg/L)	0.076	0.0039	0.00
Domestic Waste (mg/L)	0.000053	0.0000	0.65
Nitrite (mg/L)	N/A	0.00091	0.00

Chapter 5

Limitations, Conclusion and Recommendations

5.1 - Limitations and Challenges

The Partial System technology appears to be an efficient and effective method to remove ammonia from the wastewater but it comes with some challenges. The implementation of a Partial System technology is possible only if certain parameters and conditions are strictly maintained through out the wastewater treatment plant. These parameters are as follows:

5.1.1 - Dissolved Oxygen

The most significant and challenging aspect of Partial nitrification is maintaining a rigid dissolved oxygen concentration of 1.5 mg/L. *Nitrobacter* bacteria thrive in dissolved oxygen higher than 1.5 mg/L. When the population of *Nitrobacter* bacteria is left unrestricted, they will begin oxidizing nitrite into nitrate preventing nitrite accumulation and causing full nitrification. Dissolved oxygen concentrations less than 1.5 mg/L will not be enough to maintain aerobic conditions for *Nitrosomonas* bacteria to oxidize ammonia into nitrite and hence the ammonia removal system will fail entirely.

5.1.2 – Undissociated Ammonia

It has been found in experimental studies [12, 25] that the high concentration of undissociated ammonia (0.1 to 10 mg/L) successfully inhibited nitrite oxidation at first to accumulate nitrite. However, a gradual increase in undissociated ammonia concentration is required for two reasons. First, it was found that with time, the nitrite oxidizing bacteria was able to adapt to even higher undissociated ammonia concentration of 22 mg NH3-N/L. Secondly, some experimental studies suggested that in case of very high undissociated ammonia concentration, there is a very high nitrite accumulation that may inhibit the biomass involved in the treatment process. It is found that the initial concentration of undissociated ammonia above 10-150 mg/L can inhibit ammonia oxidation and therefore cause process failure.

Since undissociated ammonia concentration rises with increased total ammonia concentration in the wastewater, Partial nitrification can only be implemented for treatment of wastewater with a high ammonium concentration or low C/N ratio.

5.1.3 -Temperature

Temperature of the wastewater needs to be maintained to 30^0C through out the treatment process in order to accomplish Partial nitrification. This is because temperature affects the formation of undissociated ammonia by changing the ionization rate of ammonia. This can become a problem to maintain in winter.

5.1.4 - pH

The pH value of the wastewater to be treated by Partial technology should be established between 7 – 7.5. The value of pH also affects the formation of undissociated ammonia by involving in the ionization of ammonia.

5.15 - High Nitrite Concentration

Another limitation of Partial System is that concentration of nitrite in the municipal wastewater treatment plant's effluent. Nitrite at high concentration is very toxic. Care should be taken in order to ensure that the nitrite concentration is managed well within the guidelines provided by Canadian Water Quality Guidelines for the protection of aquatic life [24].

Also, another concern with this respect has been suggested by some studies. It was found that high ammonia concentration caused consequently high nitrite concentration. High nitrite concentration in the stream of wastewater inhibited the biomass used for nitrification causing process failure [12].

5.2 - Conclusion

Ammonia is the highest ranked pollutant released to Canadian environment [71] and especially, ammonia dissolved in wastewater effluents was found to be toxic to the aquatic life *(Canadian Environmental Protection Act, 1999, CEPA 1999).* Since the municipal wastewater treatment plants are the major source of ammonia released to Canadian aquatic ecosystem therefore, it is imperative that the ammonia concentration be reduced from the effluents of municipal treatment plants.

Presently, Full nitrification technology is being implemented in municipal wastewater treatment plants. A Full System involves oxidation of ammonia to nitrite by *Nitrosomonas* bacteria and then further oxidation of nitrite to nitrate with the help of *Nitrobacter* bacteria in an aerobic process. The nitrate thus obtained, undergoes a denitrification treatment which is an anoxic process conducted with the help of heterotrophic bacteria. In denitrification, the nitrate is first denitrified back to nitrite and then further reduced to gaseous form of N such as, nitric oxide, nitrous oxide and finally dinitrogen gas which is released in the atmosphere. This technology however, incorporates high costs pertaining to high oxygen requirements in aerobic process. Additionally, in denitrification involves an extra step of reducing nitrate to nitrite. These factors make it an expensive treatment.

For few years, scientists have been working on many new operational strategies in order to improve the efficiency of the ammonia removal treatment and reduce the costs of the treatment. Partial nitrification is one such technology which has shown promising results in research studies. In Partial nitrification technology, the ammonia is oxidized until nitrite only by *Nitrosomonas* bacteria. This can be done by inhibiting the nitrite oxidizers, (*Nitrobacter* bacteria) to accumulate nitrite. The nitrite thus obtained can then be denitrified to dinitrogen gas. *Nitrobacter* (nitrite oxidizers) require larger amount of oxygen to survive as compared to *Nitrosomonas* (ammonia oxidizers). Based on this knowledge, it was found experimentally that Partial nitrification is possible at a lab-scale, provided dissolved oxygen is strictly limited to 1.5 mg/L. Any increase in dissolved oxygen will cause the *Nitrobacter* to flourish which subsequently will begin oxidizing nitrite into nitrate, preventing nitrite accumulation. Furthermore, Partial System can only be implemented in a wastewater influent with a medium to high total ammonia content as high free ammonia concentration inhibits nitrite oxidizers. Additionally, maintaining a temperature of 30^0C and pH of 7 to 7.5 in the wastewater is equally important to inhibit *Nitrobacter* as it helps in maintaining desired free ammonia concentration. The experimental results proclaimed Partial technology to be a more efficient technology. The technology required a 25% lower oxygen consumption and 40% lower electron donors. The denitrification rates in Partial Systems were 1.5-2 times faster than in Full System.

In order to apply the experimental results to a design case, two models Full System and Partial System-1, were developed to represent Full nitrification and Partial nitrification technologies respectively. Both the models also included their respective denitrification processes in order to evaluate the overall effect on the nitrogen removal process. Both the plants were considered to accommodate the nitrogen removal treatment of 8 MGD of municipal wastewater. The influent was assumed to be a typical medium strength municipal wastewater. Initial properties of the municipal wastewater influent were set to be similar in both the models. It was also assumed that there are no or negligible traces of nitrate and nitrite in the plants' influent. The treatment procedure, conditions and parameters were selected on the basis of established research literature.

The simulation results of the Full System model and Partial System-1 models were analyzed to draw comparisons. It was found that the Partial System-1 did reduce the ammonia concentration in the effluent significantly as compared to Full System. The ammonia concentration was 97% lesser in the Partial System-1 when compared to Full System. This is an enormous difference and therefore, gives us the option to optimize the plants operations to reflect reduction in equipment and utility costs. Although, Partial System-1 prove to be very effective in reducing the ammonia concentration in the effluent however, the nitrite concentration achieved at the end of the treatment was 0.34 mg/L. Nitrite is considered toxic and therefore is regulated to a concentration of 0.06 mg/L in the aquatic environment by Canadian Water Quality for the protection of aquatic life for Nitrite and Nitrate [24]. Thus, the concentration of 0.34 mg/L was a source of concern.

The significant decrease in dissolved oxygen requirements as suggested by the experimental research was also verified by EnviroPro Designer. The reports generated by EnviroPro suggested a 33% decrease in oxygen consumption when the Partial System-1 was implemented. The reduction in oxygen requirement suggests a substantial amount of utilities savings for Partial System-1.

The denitrification process was also found to be the more effective and efficient in case of Partial System-1. Experiments studies observed the denitrification rates to be 1.5-2 times faster in case Partial System-1. This experimental evidence was also confirmed by the simulation results obtained by EnviroPro Designer which showed the denitrification rates of Partial System-1 to be 1.5 faster.

Furthermore, many research studies implied better domestic waste consumption by Partial System-1 which in turn would positively affect the amount of surplus sludge at the end of the treatment. The Partial System-1 model demonstrated significantly lower concentration of biodegradable domestic waste. Biodegradable organics in the effluents discharged in the aquatic ecosystem competes for oxygen which adversely affects the aquatic life. Additionally, amount of domestic waste add to the surplus sludge remaining at the end of treatment, the disposal of which becomes a problem. In many cases, the surplus sludge can only be disposed off by incineration or landfill. These methods pose a threat to the environment. Therefore, this low complete utilization of domestic waste in Partial System-1 makes it a more efficient system for the municipal wastewater treatment.

The capital costs associated with Full System and Partial System-1 does indicate Partial System-1 to be more economical of two. However, a 3% reduction as evaluated by EnviroPro Designer is not a significant number as proposed by the research literature.

The ammonia concentration in Partial System-1 is significantly low therefore, that made it possible for us to optimize the design to incur positive results with respect to economics. Furthermore, concern for high nitrite concentration in the effluent after the treatment required an effective solution to lower this concentration according to the permissible values. Hence, the basic Partial System-1 was optimized as Partial System-2 and Partial System-3 in an attempt to incur better results.

Partial System-2 implemented halved the air requirement of Full System. The aeration requirement was set to be 0.005 m^3 air/ m^3 (liq/min) (representing DO =1 mg/L) as opposed to 0.010 m^3 air/ m^3 (liq/min) (representing DO=1.5 mg/L). This did not give desirable results as both the concentration of ammonia and nitrite in the Liquid Effluent surpassed the permissible concentrations provided by Canadian Water Quality for the protection of aquatic life [24,66]. This result confirmed the claim of experimental research that the DO of 1.0 mg/L is not sufficient to carry out effective partial nitrification and its subsequent denitrification [12].

Partial System-3 was designed to tackle the high nitrite concentration in the effluent while implementing measures to lower the oxygen requirements. In Partial System-3, an additional anoxic stage was added. The aerobic stage included in sludge treatment was considered expendable and thus was removed. This novel design, provided superior results. It managed to save 50% of oxygen utilized per year for the treatment when compared to Full System. The oxygen in kg per ammonia removed ratio was 13.9 in Partial System-3 as opposed to 19.4 in case of Partial System-1 and 29.1 in case of Full System. Furthermore, it reduced the nitrite concentration to a mere 0.0012 mg/L when the permissible value is 0.06 mg/L [24]. Additionally, denitrification rates were 2 times faster in Partial System-3. The capital cost was reduced to 14%. The domestic waste was also found to be completely depleted. This shows that for the same domestic concentration Partial System-3 would require lesser number of treatment stages as compared to Full System. Hence, this research put forwards Partial System-3 as the most effective and efficient design to reduce medium to high ammonia concentration in wastewater.

Hence, in order to achieve Partial System, it is important that ammonia content in the wastewater should be from medium to high strength (20 to 50 mg/L). This treatment is not feasible for wastewater with a low ammonia concentration. Furthermore, the pH of the wastewater should be in the range of 7 to 7.5. This is manageable as the pH of a typical municipal wastewater falls in this range. Additionally, maintaining a temperature of 30^0C through out the treatment is also important in order establish Partial System. It is possible to maintain this temperature uniformly by implementing an effective cooling and heating system and thorough mixing system through out the operation process. The most important and challenging parameter is concentration of dissolved oxygen which should be precisely and uniformly maintained to a concentration of 1.5 mg/L. If the concentration of dissolved oxygen is allowed to be more than 1.5 mg/L, *Nitrobacter* bacteria will oxidize the nitrite into nitrate preventing nitrite accumulation and hence, full nitrification will commence. If dissolved oxygen is less than 1.5 mg/L, *Nitrosomonas* would be unable to oxidize ammonia into nitrite, also hindering nitrite accumulation as shown by Partial System-2. In this thesis the DO is depicted by controlling the aeration requirement. In order to reflect a DO concentration of 2 mg/L in Full Nitrification, the aeration requirement was set to 0.010 m^3 air/ m^3 (liq/min) [63]. Hence, it can be inferred that Partial System-3 would be applicable to municipal wastewater treatment plant treating a medium to high treatment plants where it can maintain a dissolved oxygen to 1.5 mg/L by aeration requirement of 0.007 m^3 air/ m^3 (liq/min).

In the light of literature review, further confirmed by simulation results evaluated by EnviroPro Designers, we can conclude that Partial System is definitely a more efficient technology than Full System. Especially, Partial System-3 showed extremely effective results. It significantly reduces ammonia concentration, amount of domestic waste in the effluent and nitrite concentration while substantially reduced oxygen consumption. It shows better capital costs. It will be practical and beneficial to implement Partial System-3 in municipal wastewater treatment plants handling wastewater with medium to high ammonia concentration and a pH of 7 to 7.2.

5.3 - Recommendations

In order to improve the credibility and productivity of the Partial System, following measures are recommended:

It is recommended that experimental work should be carried out in order to find the Decay Constant of *Nitrosomonas* and Half Saturation Constant of Denitrification from nitrite. Although a sensitivity analysis conducted to find the overall significance of these kinetic parameters suggested that the conclusions of the thesis are not significantly affected by these parameters, it will be helpful to have accurate kinetic parameters for Partial System to derive authentic results and for any future development.

In this thesis, dissolved oxygen is set by controlling the aeration requirement. EnviroPro Designer also provides for the dissolved oxygen to be controlled by defining a specific value for it. In future, this approach can be taken to define the aerobic conditions and observe and deviations from the conclusion of this thesis.

It would be useful to explore additional process configurations for other influent ammonia levels i.e. the optimal sequencing of aerobic and anoxic reactors might be different, depending on the concentration.

For the future research, it would be beneficial to demonstrate the minimum temperature required to be maintained through out the treatment in order to meet the Canadian Water Quality guidelines for the protection of aquatic life.

Modeling of fixed film reactors where the partial nitrification might be controlled within the depth of the biofilm is also recommended for future studies.

In DomWaste Degradation Reaction (Section 3.6.1), the yield, Y=0.8 mg vss / mg DomWaste taken from [18]. A high yield of 0.8 from domestic waste seems unrealistic as the theoretical yield of biomass from pure glucose is about 0.5 g biomass/ g glucose. It is possible that the yield, Y=0.8 mg vss / mg DomWaste assumed in [18], considers the capture of colloidal waste. It is best that in future studies, the yield from domestic waste should be investigated for more accurate results.

Due to unavailability of yield for domestic waste in denitrification from NO_2 (Section 3.8.2.1.1), the domestic waste yield of 0.32 g domestic waste/ g NO_2 has been assumed which is same as the one taken in denitrification from NO_3. Experimental work needs to be done in order to evaluate an accurate value.

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APPENDIX A
REPORT 4.1.A – STREAM & MATERIAL BALANCE FOR FULL SYSTEM

Materials & Streams Report

for Thesis - Full System – Bardenpho

1.OVERALL PROCESS DATA

Annual Operating Time	7,920.00 h
Annual Throughput	0.00 kg MP
Operating Days per Year	330.00

MP = Main Product = Undefined

2.2 BULK MATERIALS (ENTIRE PROCESS)

Material	kg/yr	kg/h	kg/kg MP
Air	39,204,611	4,950.077	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,042,320,573	1,899,282.901	

2.3 BULK MATERIALS (PER SECTION)

SECTIONS IN: Main Branch

Main Section

Material	kg/yr	kg/h	kg/kg MP
Air	39,204,611	4,950.077	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,042,320,573	1,899,282.901	

2.4 BULK MATERIALS (PER MATERIAL)

Air				
Air	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-2	7.62	2,986,533	377.087	
P-3	60.95	23,894,536	3,016.987	
P-14	31.43	12,323,542	1,556.003	
TOTAL	100.00	39,204,611	4,950.077	

Ammonia				
Ammonia	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	316,800	40.000	
TOTAL	100.00	316,800	40.000	

Carb. Dioxide				
Carb. Dioxide	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

DomWaste				
DomWaste	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	2,376,000	300.000	
TOTAL	100.00	2,376,000	300.000	

FSS				
FSS	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	910,800	115.000	
TOTAL	100.00	910,800	115.000	

TDS				
TDS	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	4,593,600	580.000	
TOTAL	100.00	4,593,600	580.000	

Water				
Water	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	99.92	14,980,680,000	1,891,500.000	
P-12	0.08	11,862,762	1,497.823	
TOTAL	100.00	14,992,542,762	1,892,997.823	

X-VSS-h				
X-VSS-h	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	792,000	100.000	
TOTAL	100.00	792,000	100.000	

X-VSS-i				
X-VSS-i	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

X-VSS-n				
X-VSS-n	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	47,520	6.000	
TOTAL	100.00	47,520	6.000	

2.5 BULK MATERIALS (kg/h): SECTION TOTALS

Raw Material	Main Section
Air	4,950.077
Ammonia	40.000
Carb. Dioxide	97.000
DomWaste	300.000
FSS	115.000
TDS	580.000
Water	1,892,997.823
X-VSS-h	100.000
X-VSS-i	97.000
X-VSS-n	6.000
TOTAL	1,899,282.901

2.6 BULK MATERIALS (kg/yr): SECTION TOTALS

Raw Material	Main Section
Air	39,204,611
Ammonia	316,800
Carb. Dioxide	768,240
DomWaste	2,376,000
FSS	910,800
TDS	4,593,600
Water	14,992,542,762
X-VSS-h	792,000
X-VSS-i	768,240
X-VSS-n	47,520
TOTAL	15,042,320,573

3. STREAM DETAILS

Stream Name	S-101	S-102	S-103	S-110
Source	INPUT	P-6	P-6	P-3
Destination	P-6	OUTPUT	P-7	P-9
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	998.36	1,000.00	998.36	998.35
Component Flowrates (kg/h averaged)				
Ammonia	40.000	0.000	40.000	3.353
Carb. Dioxide	97.000	0.000	97.000	13.281
DomWaste	300.000	0.000	300.000	32.059
FSS	115.000	23.000	92.000	2,762.527
NO3	0.000	0.000	0.000	46.187
TDS	580.000	0.000	580.000	1,624.771
Water	1,891,500.000	0.000	1,891,500.000	5,303,087.081
X-VSS-h	100.000	0.000	100.000	9,482.240
X-VSS-i	97.000	0.000	97.000	3,008.872
X-VSS-n	6.000	0.000	6.000	430.138
TOTAL (kg/h)	1,892,835.000	23.000	1,892,812.000	5,320,490.508
TOTAL (L/h)	1,895,938.160	23.000	1,895,915.160	5,329,265.216

Stream Name	S-111	S-116	S-112	S-113
Source	P-9	P-9	P-4	P-4
Destination	P-4	P-8	OUTPUT	P-2
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	998.35	998.35	6.43	998.35
Component Flowrates (kg/h averaged)				
Ammonia	1.676	1.676	0.000	1.676
Carb. Dioxide	6.640	6.640	15.830	0.833
DomWaste	16.030	16.030	0.000	8.805
FSS	1,381.264	1,381.264	0.000	1,381.264
Nitrogen	0.000	0.000	3.550	0.000
NO3	23.094	23.094	0.000	0.542
TDS	812.385	812.385	0.000	812.385
Water	2,651,543.049	2,651,543.049	0.000	2,651,555.870
X-VSS-h	4,741.102	4,741.102	0.000	4,744.485
X-VSS-i	1,504.434	1,504.434	0.000	1,504.434
X-VSS-n	215.085	215.085	0.000	215.085
TOTAL (kg/h)	2,660,244.758	2,660,244.758	19.380	2,660,225.378
TOTAL (L/h)	2,664,632.112	2,664,632.112	3,013.962	2,664,611.810

Stream Name	S-114	S-115	S-117	Liq- Effluent
Source	INPUT	P-2	P-2	P-5
Destination	P-2	OUTPUT	P-5	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	1.18	1.25	998.35	998.35
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.000	0.519	0.370
Carb. Dioxide	0.000	8.833	0.465	0.332
DomWaste	0.000	0.000	1.708	1.219
FSS	0.000	0.000	1,381.264	27.625
Nitrogen	289.271	289.271	0.000	0.000
NO3	0.000	0.000	2.690	1.919
Oxygen	87.817	73.728	0.000	0.000
TDS	0.000	0.000	812.385	579.510
Water	0.000	0.000	2,651,563.154	1,891,476.197
X-VSS-h	0.000	0.000	4,748.601	94.972
X-VSS-i	0.000	0.000	1,504.745	30.095
X-VSS-n	0.000	0.000	215.104	4.302
TOTAL (kg/h)	377.087	371.831	2,660,230.635	1,892,216.541
TOTAL (L/h)	319,711.408	298,592.448	2,664,618.509	1,895,346.604

Stream Name	S-120	S-121	S-122	S-130
Source	P-5	P-10	P-10	P-13
Destination	P-10	P-7	P-11	P-11
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	998.36	998.36	998.36	998.40
Component Flowrates (kg/h averaged)				
Ammonia	0.149	0.141	0.007	0.010
Carb. Dioxide	0.133	0.127	0.007	2.351
DomWaste	0.490	0.465	0.024	0.000
FSS	1,353.638	1,285.956	67.682	580.745
NO3	0.771	0.733	0.039	39.325
TDS	232.875	221.231	11.644	28.503
Water	760,086.956	722,082.609	38,004.348	93,097.455
X-VSS-h	4,653.629	4,420.947	232.681	1,597.437
X-VSS-i	1,474.650	1,400.918	73.733	708.847
X-VSS-n	210.802	200.262	10.540	25.194
TOTAL (kg/h)	768,014.094	729,613.389	38,400.705	96,079.868
TOTAL (L/h)	769,271.905	730,808.310	38,463.595	96,234.312

Stream Name	S-123	S-125	S-124	S-126
Source	P-11	INPUT	P-14	P-14
Destination	P-14	P-14	OUTPUT	P-15
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	998.39	1.22	1.27	998.39
Component Flowrates (kg/h averaged)				
Ammonia	0.017	0.000	0.000	0.014
Carb. Dioxide	2.358	0.000	62.923	3.312
DomWaste	0.024	0.000	0.000	0.000
FSS	648.427	0.000	0.000	648.515
Nitrogen	0.000	1,193.638	1,193.638	0.000
NO3	39.362	0.000	0.000	55.390
Oxygen	0.000	362.365	292.989	0.000
TDS	40.147	0.000	0.000	40.147
Water	131,101.110	0.000	0.000	131,128.033
X-VSS-h	1,830.099	0.000	0.000	1,783.849
X-VSS-i	782.577	0.000	0.000	791.566
X-VSS-n	35.735	0.000	0.000	35.486
TOTAL (kg/h)	134,479.857	1,556.003	1,549.549	134,486.311
TOTAL (L/h)	134,697.190	1,275,000.000	1,223,829.449	134,703.846

Stream Name	S-129	S-128	S-131	S-132
Source	P-15	P-15	P-13	INPUT
Destination	P-7	P-13	P-12	P-12
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	998.35	998.40	998.40	998.35
Component Flowrates (kg/h averaged)				
Ammonia	0.003	0.011	0.001	0.000
Carb. Dioxide	0.699	2.612	0.261	0.000
DomWaste	0.000	0.000	0.000	0.000
FSS	3.243	645.272	64.527	0.000
NO3	11.695	43.695	4.369	0.000
TDS	8.477	31.670	3.167	0.000
Water	27,686.416	103,441.617	10,344.162	1,497.823
X-VSS-h	8.919	1,774.930	177.493	0.000
X-VSS-i	3.958	787.608	78.761	0.000
X-VSS-n	7.493	27.994	2.799	0.000
TOTAL (kg/h)	27,730.902	106,755.409	10,675.541	1,497.823
TOTAL (L/h)	27,776.833	106,927.014	10,692.701	1,500.300

Stream Name	Sludge Eff	S-133	S-104	S-105
Source	P-12	P-12	P-7	P-8
Destination	OUTPUT	P-7	P-8	P-1
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	15.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	998.59	998.35	998.36	998.36
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.001	40.145	41.821
Carb. Dioxide	0.040	0.221	98.047	104.687
DomWaste	0.000	0.000	300.465	316.495
FSS	64.463	0.065	1,381.264	2,762.527
NO3	0.675	3.694	16.122	39.215
TDS	0.490	2.677	812.385	1,624.771
Water	1,830.583	10,011.402	2,651,280.427	5,302,823.476
X-VSS-h	177.316	0.177	4,530.044	9,271.146
X-VSS-i	78.682	0.079	1,501.954	3,006.389
X-VSS-n	2.797	0.003	213.757	428.841
TOTAL (kg/h)	2,155.045	10,018.319	2,660,174.610	5,320,419.369
TOTAL (L/h)	2,158.081	10,034.920	2,664,535.233	5,329,167.348

Stream Name	S-106	S-107	S-108	S-109
Source	P-1	P-1	INPUT	P-3
Destination	OUTPUT	P-3	P-3	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	15.00	15.00	25.00	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	23.70	998.36	1.18	1.32
Component Flowrates (kg/h averaged)				
Ammonia	0.000	41.821	0.000	0.000
Carb. Dioxide	115.277	6.067	0.000	252.335
DomWaste	0.000	304.488	0.000	0.000
FSS	0.000	2,762.527	0.000	0.000
Nitrogen	5.899	0.000	2,314.385	2,314.385
NO3	0.000	1.736	0.000	0.000
Oxygen	0.000	0.000	702.602	257.951
TDS	0.000	1,624.771	0.000	0.000
Water	0.000	5,302,844.783	0.000	0.000
X-VSS-h	0.000	9,276.768	0.000	0.000
X-VSS-i	0.000	3,006.389	0.000	0.000
X-VSS-n	0.000	428.841	0.000	0.000
TOTAL (kg/h)	121.177	5,320,298.192	3,016.987	2,824.671
TOTAL (L/h)	5,112.313	5,329,030.193	2,557,934.493	2,143,913.521

4. OVERALL COMPONENT BALANCE (kg/yr)

COMPONENT	IN	OUT	OUT-IN
Ammonia	316,800	2,935	- 313,865
Carb. Dioxide	768,240	3,608,114	2,839,874
DomWaste	2,376,000	9,651	- 2,366,349
FSS	910,800	911,497	697
Nitrogen	30,074,558	30,149,397	74,839
NO3	0	20,549	20,549
Oxygen	9,130,053	4,947,371	- 4,182,682
TDS	4,593,600	4,593,596	- 4
Water	14,992,542,762	14,994,989,700	2,446,938
X-VSS-h	792,000	2,156,517	1,364,517
X-VSS-i	768,240	861,513	93,273
X-VSS-n	47,520	56,221	8,701
TOTAL	15,042,320,573	15,042,307,062	- 13,512

5. EQUIPMENT CONTENTS

This section will be skipped (overall process is continuous)

REPORT 4.1.B - ECONOMIC EVALUATION FOR FULL SYSTEM

Economic Evaluation Report
for Thesis - Full System – Bardenpho

1.EXECUTIVE SUMMARY (2009 prices)

Total Capital Investment	108,171,000	$
Capital Investment Charged to This Project	108,171,000	$
Operating Cost	23,940,000	$/yr
THE MAIN REVENUE STREAM HAS NOT BEEN IDENTIFIED. PRICING AND PRODUCTION/PROCESSING UNIT COST DATA HAVE NOT BEEN PRINTED		
Total Revenues	0	$/yr
Gross Margin	- 1.00	%
Return On Investment	- 13.11	%
Payback Time	- 1.00	years
IRR (After Taxes)	Out of search interval	(0-1000%)
NPV (at 7.0% Interest)	0	$

MT = Metric Ton (1000 kg)

2. MAJOR EQUIPMENT SPECIFICATION AND FOB COST (2009 prices)

Quantity/ Standby/ Staggered	Name	Description	Unit Cost ($)	Cost ($)
1 / 0 / 0	AXR-101	Anoxic Reactor	2,186,000	2,186,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	AB-101	Aeration Basin	1,288,000	1,288,000
		Vessel Volume = 626885.11 L		
1 / 0 / 0	AB-102	Aeration Basin	4,876,000	4,876,000
		Vessel Volume = 5015557.83 L		
1 / 0 / 0	AXR-102	Anoxic Reactor	1,882,000	1,882,000
		Vessel Volume = 1979037.94 L		
1 / 0 / 0	CL-101	Clarifier	827,000	827,000
		Surface Area = 1998.46 m2		
3 / 0 / 0	GBX-101	Generic Box	0	0
		Size/Capacity = 630945.00 kg/h		
4 / 0 / 0	MX-101	Mixer	0	0
		Size/Capacity = 665043.65 kg/h		
8 / 0 / 0	MX-102	Mixer	0	0
		Size/Capacity = 665052.42 kg/h		
8 / 0 / 0	FSP-101	Flow Splitter	0	0
		Size/Capacity = 665061.19 kg/h		
2 / 0 / 0	FSP-102	Flow Splitter	0	0
		Size/Capacity = 384007.05 kg/h		
1 / 0 / 0	BF-101	Belt Filter	224,000	224,000
		Belt Width = 1.50 m		
1 / 0 / 0	FSP-104	Flow Splitter	0	0
		Size/Capacity = 360000.00 kg/h		
1 / 0 / 0	AB-103	Aeration Basin	3,123,000	3,123,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	MX-103	Mixer	0	0
		Size/Capacity = 134479.86 kg/h		
2 / 0 / 0	TH-101	Thickener	238,000	476,000
		Surface Area = 250.00 m2		
		Unlisted Equipment		3,721,000
			TOTAL	18,603,000

3. FIXED CAPITAL ESTIMATE SUMMARY (2009 prices in $)

3A. Total Plant Direct Cost (TPDC) (physical cost)	
1. Equipment Purchase Cost	18,603,000
2. Installation	2,233,000
3. Process Piping	6,511,000
4. Instrumentation	7,441,000
5. Insulation	558,000
6. Electrical	1,860,000
7. Buildings	8,371,000
8. Yard Improvement	2,790,000
9. Auxiliary Facilities	7,441,000
TPDC	55,808,000

3B. Total Plant Indirect Cost (TPIC)	
10. Engineering	13,952,000
11. Construction	19,533,000
TPIC	33,485,000

3C. Total Plant Cost (TPC = TPDC+TPIC)	
TPC	89,293,000

3D. Contractor's Fee & Contingency (CFC)	
12. Contractor's Fee	4,465,000
13. Contingency	8,929,000
CFC = 12+13	13,394,000

3E. Direct Fixed Capital Cost (DFC = TPC+CFC)	
DFC	102,687,000

4. LABOR COST - PROCESS SUMMARY

Labor Type	Unit Cost ($/h)	Annual Amount (h)	Annual Cost ($)	%
Operator	69.00	55,063	3,799,337	100.00
TOTAL		55,063	3,799,337	100.00

5. MATERIALS COST - PROCESS SUMMARY

THE COST OF ALL MATERIALS IS ZERO. PLEASE CHECK THE MATERIAL BALANCES AND THE PURCHASING COST OF RAW MATERIALS.

6. VARIOUS CONSUMABLES COST (2009 prices) - PROCESS SUMMARY

THE CONSUMABLES COST IS ZERO

7. WASTE TREATMENT/DISPOSAL COST (2009 prices) - PROCESS SUMMARY

THE TOTAL WASTE TREATMENT/DISPOSAL COST IS ZERO.

REPORT 4.2.A – STREAM & MATERIAL BALANCE FOR PARTIAL SYSTEM-1

Materials & Streams Report

for Thesis - Partial System (1)- Bardenpho

1.OVERALL PROCESS DATA

Annual Operating Time	7,920.00 h
Annual Throughput	0.00 kg MP
Operating Days per Year	330.00

MP = Main Product = Undefined

2.1 STARTING MATERIAL REQUIREMENTS

Section	Starting Material	Active Product	Amount Needed (kg Sin/kg MP)	Molar Yield (%)	Mass Yield (%)	Gross Mass Yield (%)
Main Section	(none)	(none)	Unknown	Unknown	Unknown	Unknown

Sin = Section Starting Material, Aout = Section Active Product

2.2 BULK MATERIALS (ENTIRE PROCESS)

Material	kg/yr	kg/h	kg/kg MP
Air	26,394,666	3,332.660	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,029,510,628	1,897,665.483	

2.3 BULK MATERIALS (PER SECTION)

SECTIONS IN: Main Branch

Main Section			
Material	**kg/yr**	**kg/h**	**kg/kg MP**
Air	26,394,666	3,332.660	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,029,510,628	1,897,665.483	

2.4 BULK MATERIALS (PER MATERIAL)

Air				
Air	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-2	7.92	2,090,573	263.961	
P-3	63.40	16,732,988	2,112.751	
P-14	28.68	7,571,105	955.948	
TOTAL	100.00	26,394,666	3,332.660	

Ammonia				
Ammonia	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	316,800	40.000	
TOTAL	100.00	316,800	40.000	

Carb. Dioxide				
Carb. Dioxide	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

DomWaste				
DomWaste	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	2,376,000	300.000	
TOTAL	100.00	2,376,000	300.000	

FSS				
FSS	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	910,800	115.000	
TOTAL	100.00	910,800	115.000	

TDS				
TDS	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	4,593,600	580.000	
TOTAL	100.00	4,593,600	580.000	

Water				
Water	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	99.92	14,980,680,000	1,891,500.000	
P-12	0.08	11,862,762	1,497.823	
TOTAL	100.00	14,992,542,762	1,892,997.823	

X-VSS-h				
X-VSS-h	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	792,000	100.000	
TOTAL	100.00	792,000	100.000	

X-VSS-i				
X-VSS-i	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

X-VSS-n				
X-VSS-n	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	47,520	6.000	
TOTAL	100.00	47,520	6.000	

2.5 BULK MATERIALS (kg/h): SECTION TOTALS

Raw Material	Main Section
Air	3,332.660
Ammonia	40.000
Carb. Dioxide	97.000
DomWaste	300.000
FSS	115.000
TDS	580.000
Water	1,892,997.823
X-VSS-h	100.000
X-VSS-i	97.000
X-VSS-n	6.000
TOTAL	1,897,665.483

2.6 BULK MATERIALS (kg/yr): SECTION TOTALS

Raw Material	Main Section
Air	26,394,666
Ammonia	316,800
Carb. Dioxide	768,240
DomWaste	2,376,000
FSS	910,800
TDS	4,593,600
Water	14,992,542,762
X-VSS-h	792,000
X-VSS-i	768,240
X-VSS-n	47,520
TOTAL	15,029,510,628

3. STREAM DETAILS

Stream Name	S-101	S-102	S-103	S-110
Source	INPUT	P-6	P-6	P-3
Destination	P-6	OUTPUT	P-7	P-9
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	30.00	30.00	30.00	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.88	1,000.00	992.88	992.91
Component Flowrates (kg/h averaged)				
Ammonia	40.000	0.000	40.000	0.181
Carb. Dioxide	97.000	0.000	97.000	14.432
DomWaste	300.000	0.000	300.000	12.639
FSS	115.000	23.000	92.000	2,762.575
NO2	0.000	0.000	0.000	36.986
TDS	580.000	0.000	580.000	1,616.587
Water	1,891,500.000	0.000	1,891,500.000	5,276,439.255
X-VSS-h	100.000	0.000	100.000	9,276.046
X-VSS-i	97.000	0.000	97.000	3,077.274
X-VSS-n	6.000	0.000	6.000	386.986
TOTAL (kg/h)	1,892,835.000	23.000	1,892,812.000	5,293,622.960
TOTAL (L/h)	1,906,410.085	23.000	1,906,387.085	5,331,435.331

Stream Name	S-111	S-116	S-112	S-113
Source	P-9	P-9	P-4	P-4
Destination	P-4	P-8	OUTPUT	P-2
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.91	992.91	6.86	992.91
Component Flowrates (kg/h averaged)				
Ammonia	0.091	0.091	0.000	0.091
Carb. Dioxide	7.216	7.216	14.308	0.753
DomWaste	6.319	6.319	0.000	0.418
FSS	1,381.288	1,381.288	0.000	1,381.288
Nitrogen	0.000	0.000	2.780	0.000
NO2	18.493	18.493	0.000	0.073
TDS	808.293	808.293	0.000	808.293
Water	2,638,218.136	2,638,218.136	0.000	2,638,228.147
X-VSS-h	4,638.009	4,638.009	0.000	4,641.693
X-VSS-i	1,538.634	1,538.634	0.000	1,538.634
X-VSS-n	193.498	193.498	0.000	193.498
TOTAL (kg/h)	2,646,809.975	2,646,809.975	17.088	2,646,792.887
TOTAL (L/h)	2,665,716.093	2,665,716.093	2,490.320	2,665,695.314

Stream Name	S-114	S-115	S-117	Liq- Effluent
Source	INPUT	P-2	P-2	P-5
Destination	P-2	OUTPUT	P-5	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.00	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	1.18	1.18	992.91	992.89
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.000	0.015	0.011
Carb. Dioxide	0.000	4.715	0.248	0.178
DomWaste	0.000	0.000	0.045	0.033
FSS	0.000	0.000	1,381.288	27.626
Nitrogen	202.489	202.489	0.000	0.000
NO2	0.000	0.000	0.898	0.644
Oxygen	61.472	56.868	0.000	0.000
TDS	0.000	0.000	808.293	579.543
Water	0.000	0.000	2,638,230.143	1,891,599.570
X-VSS-h	0.000	0.000	4,639.247	92.785
X-VSS-i	0.000	0.000	1,539.179	30.784
X-VSS-n	0.000	0.000	193.421	3.868
TOTAL (kg/h)	263.961	264.072	2,646,792.776	1,892,335.040
TOTAL (L/h)	223,797.985	223,970.473	2,665,694.897	1,905,887.780

Stream Name	S-120	S-121	S-122	S-130
Source	P-5	P-10	P-10	P-13
Destination	P-10	P-7	P-11	P-11
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.94
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.96	992.96	992.96	993.10
Component Flowrates (kg/h averaged)				
Ammonia	0.004	0.004	0.000	0.001
Carb. Dioxide	0.070	0.067	0.004	3.323
DomWaste	0.013	0.012	0.001	0.000
FSS	1,353.662	1,285.979	67.683	581.048
NO2	0.254	0.241	0.013	39.794
TDS	228.750	217.313	11.438	26.687
Water	746,630.572	709,299.044	37,331.529	87,195.800
X-VSS-h	4,546.462	4,319.139	227.323	1,381.533
X-VSS-i	1,508.395	1,432.975	75.420	756.344
X-VSS-n	189.553	180.075	9.478	20.939
TOTAL (kg/h)	754,457.735	716,734.849	37,722.887	90,005.470
TOTAL (L/h)	759,807.118	721,816.762	37,990.356	90,630.847

Stream Name	S-123	S-125	S-124	S-126
Source	P-11	INPUT	P-14	P-14
Destination	P-14	P-14	OUTPUT	P-15
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.97	15.00	29.94	29.94
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	993.05	1.22	1.27	993.05
Component Flowrates (kg/h averaged)				
Ammonia	0.001	0.000	0.000	0.001
Carb. Dioxide	3.328	0.000	90.188	4.747
DomWaste	0.001	0.000	0.000	0.000
FSS	648.732	0.000	0.000	648.854
Nitrogen	0.000	733.325	733.325	0.000
NO2	39.794	0.000	0.000	56.849
Oxygen	0.000	222.623	129.108	0.000
TDS	38.125	0.000	0.000	38.125
Water	124,527.883	0.000	0.000	124,566.418
X-VSS-h	1,608.894	0.000	0.000	1,542.751
X-VSS-i	831.762	0.000	0.000	844.605
X-VSS-n	30.417	0.000	0.000	29.913
TOTAL (kg/h)	127,728.936	955.948	952.620	127,732.263
TOTAL (L/h)	128,622.400	783,310.414	751,386.936	128,625.666

Stream Name	S-129	S-128	S-131	S-132
Source	P-15	P-15	P-13	INPUT
Destination	P-7	P-13	P-12	P-12
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.94	29.94	29.94	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.89	993.10	993.10	998.35
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.001	0.000	0.000
Carb. Dioxide	1.055	3.692	0.369	0.000
DomWaste	0.000	0.000	0.000	0.000
FSS	3.244	645.609	64.561	0.000
NO2	12.633	44.215	4.422	0.000
TDS	8.472	29.653	2.965	0.000
Water	27,682.196	96,884.223	9,688.422	1,497.823
X-VSS-h	7.714	1,535.037	153.504	0.000
X-VSS-i	4.223	840.382	84.038	0.000
X-VSS-n	6.648	23.266	2.327	0.000
TOTAL (kg/h)	27,726.185	100,006.078	10,000.608	1,497.823
TOTAL (L/h)	27,924.725	100,700.941	10,070.094	1,500.300

Stream Name	S-134	S-133	S-104	S-105
Source	P-12	P-12	P-7	P-8
Destination	OUTPUT	P-7	P-8	P-1
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	28.00	28.00	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	994.55	993.60	992.90	992.91
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.000	40.004	40.095
Carb. Dioxide	0.057	0.312	98.434	105.650
DomWaste	0.000	0.000	300.012	306.332
FSS	64.496	0.065	1,381.288	2,762.575
NO2	0.681	3.741	16.615	35.108
TDS	0.457	2.509	808.294	1,616.587
Water	1,722.181	9,464.065	2,637,945.304	5,276,163.440
X-VSS-h	153.350	0.154	4,427.006	9,065.014
X-VSS-i	83.954	0.084	1,534.282	3,072.916
X-VSS-n	2.324	0.002	192.725	386.223
TOTAL (kg/h)	2,027.500	9,470.931	2,646,743.965	5,293,553.940
TOTAL (L/h)	2,038.603	9,531.948	2,665,660.501	5,331,376.591

Stream Name	S-106	S-107	S-108	S-109
Source	P-1	P-1	INPUT	P-3
Destination	OUTPUT	P-3	P-3	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	25.00	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	24.68	992.92	1.18	1.32
Component Flowrates (kg/h averaged)				
Ammonia	0.000	40.095	0.000	0.000
Carb. Dioxide	114.482	6.025	0.000	274.201
DomWaste	0.000	295.156	0.000	0.000
FSS	0.000	2,762.575	0.000	0.000
Nitrogen	5.265	0.000	1,620.729	1,620.729
NO2	0.000	0.225	0.000	0.000
Oxygen	0.000	0.000	492.022	29.054
TDS	0.000	1,616.587	0.000	0.000
Water	0.000	5,276,182.400	0.000	0.000
X-VSS-h	0.000	9,071.991	0.000	0.000
X-VSS-i	0.000	3,072.916	0.000	0.000
X-VSS-n	0.000	386.223	0.000	0.000
TOTAL (kg/h)	119.747	5,293,434.194	2,112.751	1,923.985
TOTAL (L/h)	4,852.576	5,331,200.766	1,791,283.457	1,461,800.753

4. OVERALL COMPONENT BALANCE (kg/yr)

COMPONENT	IN	OUT	OUT-IN
Ammonia	316,800	85	- 316,715
Carb. Dioxide	768,240	3,945,185	3,176,945
DomWaste	2,376,000	258	- 2,375,742
FSS	910,800	911,767	967
Nitrogen	20,247,820	20,311,536	63,715
NO2	0	10,488	10,488
Oxygen	6,146,846	1,703,039	- 4,443,807
TDS	4,593,600	4,593,594	- 6
Water	14,992,542,762	14,995,108,268	2,565,506
X-VSS-h	792,000	1,949,390	1,157,390
X-VSS-i	768,240	908,723	140,483
X-VSS-n	47,520	49,046	1,526
TOTAL	15,029,510,628	15,029,491,378	- 19,250

5. EQUIPMENT CONTENTS

This section will be skipped (overall process is continuous).

REPORT 4.2.B - ECONOMIC EVALUATION FOR PARTIAL SYSTEM-1

Economic Evaluation Report

for Thesis - Partial System (1)- Bardenpho

1.EXECUTIVE SUMMARY (2009 prices)

Total Capital Investment	105,075,000	$
Capital Investment Charged to This Project	105,075,000	$
Operating Cost	23,369,000	$/yr
THE MAIN REVENUE STREAM HAS NOT BEEN IDENTIFIED. PRICING AND PRODUCTION/PROCESSING UNIT COST DATA HAVE NOT BEEN PRINTED		
Total Revenues	0	$/yr
Gross Margin	- 1.00	%
Return On Investment	- 13.22	%
Payback Time	- 1.00	years
IRR (After Taxes)	Out of search interval	(0-1000%)
NPV (at 7.0% Interest)	0	$

MT = Metric Ton (1000 kg)

2. MAJOR EQUIPMENT SPECIFICATION AND FOB COST (2009 prices)

Quantity/ Standby/ Staggered	Name	Description	Unit Cost ($)	Cost ($)
1 / 0 / 0	AXR-101	Anoxic Reactor	2,186,000	2,186,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	AB-101	Aeration Basin	1,288,000	1,288,000
		Vessel Volume = 626885.11 L		
1 / 0 / 0	AB-102	Aeration Basin	4,877,000	4,877,000
		Vessel Volume = 5017600.72 L		
1 / 0 / 0	AXR-102	Anoxic Reactor	1,450,000	1,450,000
		Vessel Volume = 1317177.36 L		
1 / 0 / 0	CL-101	Clarifier	828,000	828,000
		Surface Area = 1999.27 m2		
3 / 0 / 0	GBX-101	Generic Box	0	0
		Size/Capacity = 630945.00 kg/h		
4 / 0 / 0	MX-101	Mixer	0	0
		Size/Capacity = 661686.15 kg/h		
8 / 0 / 0	MX-102	Mixer	0	0
		Size/Capacity = 661694.24 kg/h		
8 / 0 / 0	FSP-101	Flow Splitter	0	0
		Size/Capacity = 661702.49 kg/h		
2 / 0 / 0	FSP-102	Flow Splitter	0	0
		Size/Capacity = 377228.87 kg/h		
1 / 0 / 0	BF-101	Belt Filter	224,000	224,000
		Belt Width = 1.50 m		
1 / 0 / 0	FSP-104	Flow Splitter	0	0
		Size/Capacity = 360000.00 kg/h		
1 / 0 / 0	AB-103	Aeration Basin	3,123,000	3,123,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	MX-103	Mixer	0	0
		Size/Capacity = 127731.29 kg/h		
2 / 0 / 0	TH-101	Thickener	238,000	476,000
		Surface Area = 250.00 m2		
		Unlisted Equipment		3,613,000
			TOTAL	18,065,000

3. FIXED CAPITAL ESTIMATE SUMMARY (2009 prices in $)

3A. Total Plant Direct Cost (TPDC) (physical cost)	
1. Equipment Purchase Cost	18,065,000
2. Installation	2,179,000
3. Process Piping	6,323,000
4. Instrumentation	7,226,000
5. Insulation	542,000
6. Electrical	1,807,000
7. Buildings	8,129,000
8. Yard Improvement	2,710,000
9. Auxiliary Facilities	7,226,000
TPDC	54,207,000

3B. Total Plant Indirect Cost (TPIC)	
10. Engineering	13,552,000
11. Construction	18,972,000
TPIC	32,524,000

3C. Total Plant Cost (TPC = TPDC+TPIC)	
TPC	86,730,000

3D. Contractor's Fee & Contingency (CFC)	
12. Contractor's Fee	4,337,000
13. Contingency	8,673,000
CFC = 12+13	13,010,000

3E. Direct Fixed Capital Cost (DFC = TPC+CFC)	
DFC	99,740,000

4. LABOR COST - PROCESS SUMMARY

Labor Type	Unit Cost ($/h)	Annual Amount (h)	Annual Cost ($)	%
Operator	69.00	55,063	3,799,337	100.00
TOTAL		55,063	3,799,337	100.00

5. MATERIALS COST - PROCESS SUMMARY

THE COST OF ALL MATERIALS IS ZERO. PLEASE CHECK THE MATERIAL BALANCES AND THE PURCHASING COST OF RAW MATERIALS.

6. VARIOUS CONSUMABLES COST (2009 prices) - PROCESS SUMMARY

THE CONSUMABLES ARE ZERO.

7. WASTE TREATMENT/DISPOSAL COST (2009 prices) - PROCESS SUMMARY

THE TOTAL WASTE TREATMENT/DISPOSAL COST IS ZERO.

8. UTILITIES COST (2009 prices) - PROCESS SUMMARY

Utility	Annual Amount	Reference Units	Annual Cost ($)	%
Electricity	343,823	kWh	34,382	100.00
Steam	0	kg	0	0.00
Steam (High P)	0	kg	0	0.00
Cooling Water	0	kg	0	0.00
Chilled Water	0	kg	0	0.00
TOTAL			34,382	100.00

9. ANNUAL OPERATING COST (2009 prices) - PROCESS SUMMARY

Cost Item	$	%
Raw Materials	0	0.00
Labor-Dependent	3,799,000	16.26
Facility-Dependent	18,965,000	81.16
Laboratory/QC/QA	570,000	2.44
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	34,000	0.15
Transportation	0	0.00
Miscellaneous	0	0.00
Advertising/Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
TOTAL	23,369,000	100.00

REPORT 4.3.A – STREAM & MATERIAL BALANCE FOR PARTIAL SYSTEM-2

Materials & Streams Report
for Thesis - Partial System (2)- Bardenpho

1.OVERALL PROCESS DATA

Annual Operating Time	7,920.00 h
Annual Throughput	0.00 kg MP
Operating Days per Year	330.00

MP = Main Product = Undefined

2.1 STARTING MATERIAL REQUIREMENTS

Section	Starting Material	Active Product	Amount Needed (kg Sin/kg MP)	Molar Yield (%)	Mass Yield (%)	Gross Mass Yield (%)
Main Section	(none)	(none)	Unknown	Unknown	Unknown	Unknown

Sin = Section Starting Material, Aout = Section Active Product

2.2 BULK MATERIALS (ENTIRE PROCESS)

Material	kg/yr	kg/h	kg/kg MP
Air	18,688,843	2,359.702	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,021,804,805	1,896,692.526	

2.3 BULK MATERIALS (PER SECTION)

SECTIONS IN: Main Branch

Main Section			
Material	**kg/yr**	**kg/h**	**kg/kg MP**
Air	18,688,843	2,359.702	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,021,804,805	1,896,692.526	

2.4 BULK MATERIALS (PER MATERIAL)

Air				
Air	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-2	7.99	1,493,266	188.544	
P-3	63.55	11,877,667	1,499.705	
P-14	28.45	5,317,910	671.453	
TOTAL	100.00	18,688,843	2,359.702	

Ammonia				
Ammonia	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	316,800	40.000	
TOTAL	100.00	316,800	40.000	

Carb. Dioxide				
Carb. Dioxide	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

DomWaste				
DomWaste	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	2,376,000	300.000	
TOTAL	100.00	2,376,000	300.000	

FSS				
FSS	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	910,800	115.000	
TOTAL	100.00	910,800	115.000	

TDS				
TDS	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	4,593,600	580.000	
TOTAL	100.00	4,593,600	580.000	

Water				
Water	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	99.92	14,980,680,000	1,891,500.000	
P-12	0.08	11,862,762	1,497.823	
TOTAL	100.00	14,992,542,762	1,892,997.823	

X-VSS-h				
X-VSS-h	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	792,000	100.000	
TOTAL	100.00	792,000	100.000	

X-VSS-i				
X-VSS-i	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

X-VSS-n				
X-VSS-n	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	47,520	6.000	
TOTAL	100.00	47,520	6.000	

2.5 BULK MATERIALS (kg/h): SECTION TOTALS

Raw Material	Main Section
Air	2,359.702
Ammonia	40.000
Carb. Dioxide	97.000
DomWaste	300.000
FSS	115.000
TDS	580.000
Water	1,892,997.823
X-VSS-h	100.000
X-VSS-i	97.000
X-VSS-n	6.000
TOTAL	1,896,692.526

2.6 BULK MATERIALS (kg/yr): SECTION TOTALS

Raw Material	Main Section
Air	18,688,843
Ammonia	316,800
Carb. Dioxide	768,240
DomWaste	2,376,000
FSS	910,800
TDS	4,593,600
Water	14,992,542,762
X-VSS-h	792,000
X-VSS-i	768,240
X-VSS-n	47,520
TOTAL	15,021,804,805

3. STREAM DETAILS

Stream Name	S-101	S-102	S-103	S-110
Source	INPUT	P-6	P-6	P-3
Destination	P-6	OUTPUT	P-7	P-9
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	30.00	30.00	30.00	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.88	1,000.00	992.88	992.92
Component Flowrates (kg/h averaged)				
Ammonia	40.000	0.000	40.000	78.649
Carb. Dioxide	97.000	0.000	97.000	14.680
DomWaste	300.000	0.000	300.000	13.276
FSS	115.000	23.000	92.000	2,761.850
NO2	0.000	0.000	0.000	0.335
TDS	580.000	0.000	580.000	1,606.603
Water	1,891,500.000	0.000	1,891,500.000	5,243,687.713
X-VSS-h	100.000	0.000	100.000	9,047.831
X-VSS-i	97.000	0.000	97.000	3,071.495
X-VSS-n	6.000	0.000	6.000	283.527
TOTAL (kg/h)	1,892,835.000	23.000	1,892,812.000	5,260,565.958
TOTAL (L/h)	1,906,410.085	23.000	1,906,387.085	5,298,066.569

Stream Name	S-111	S-116	S-112	S-113
Source	P-9	P-9	P-4	P-4
Destination	P-4	P-8	OUTPUT	P-2
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.92	992.92	525.06	992.92
Component Flowrates (kg/h averaged)				
Ammonia	37.556	37.556	0.000	37.556
Carb. Dioxide	7.221	7.221	6.867	0.361
DomWaste	6.784	6.784	0.000	6.778
FSS	1,380.928	1,380.928	0.000	1,380.928
Nitrogen	0.000	0.000	0.003	0.000
NO2	0.018	0.018	0.000	0.000
TDS	803.309	803.309	0.000	803.309
Water	2,621,866.389	2,621,866.389	0.000	2,621,866.399
X-VSS-h	4,521.167	4,521.167	0.000	4,521.170
X-VSS-i	1,535.755	1,535.755	0.000	1,535.755
X-VSS-n	142.150	142.150	0.000	142.150
TOTAL (kg/h)	2,630,301.277	2,630,301.277	6.870	2,630,294.407
TOTAL (L/h)	2,649,053.441	2,649,053.441	13.084	2,649,042.718

Stream Name	S-114	S-115	S-117	Liq- Effluent
Source	INPUT	P-2	P-2	P-5
Destination	P-2	OUTPUT	P-5	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.00	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	1.18	1.18	992.92	992.90
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.000	26.863	19.380
Carb. Dioxide	0.000	6.807	0.358	0.258
DomWaste	0.000	0.000	0.780	0.563
FSS	0.000	0.000	1,380.928	27.619
Nitrogen	144.635	144.635	0.000	0.000
NO2	0.000	0.000	27.511	19.848
Oxygen	43.908	0.744	0.000	0.000
TDS	0.000	0.000	803.309	579.550
Water	0.000	0.000	2,621,888.133	1,891,571.402
X-VSS-h	0.000	0.000	4,523.277	90.466
X-VSS-i	0.000	0.000	1,536.284	30.726
X-VSS-n	0.000	0.000	143.321	2.866
TOTAL (kg/h)	188.544	152.186	2,630,330.764	1,892,342.677
TOTAL (L/h)	159,855.704	128,988.266	2,649,090.036	1,905,876.627

Stream Name	S-120	S-121	S-122	S-130
Source	P-5	P-10	P-10	P-13
Destination	P-10	P-7	P-11	P-11
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.96
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.97	992.97	992.97	993.09
Component Flowrates (kg/h averaged)				
Ammonia	7.483	7.108	0.374	0.001
Carb. Dioxide	0.100	0.095	0.005	3.232
DomWaste	0.217	0.206	0.011	0.000
FSS	1,353.309	1,285.644	67.665	580.651
NO2	7.663	7.280	0.383	42.105
TDS	223.759	212.571	11.188	26.302
Water	730,316.731	693,800.895	36,515.837	85,935.426
X-VSS-h	4,432.811	4,211.170	221.641	1,346.850
X-VSS-i	1,505.559	1,430.281	75.278	752.085
X-VSS-n	140.455	133.432	7.023	16.103
TOTAL (kg/h)	737,988.087	701,088.682	36,899.404	88,702.755
TOTAL (L/h)	743,213.409	706,052.738	37,160.670	89,319.538

Stream Name	S-123	S-125	S-124	S-126
Source	P-11	INPUT	P-14	P-14
Destination	P-14	P-14	OUTPUT	P-15
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.97	15.00	29.96	29.96
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	993.05	1.22	1.31	993.05
Component Flowrates (kg/h averaged)				
Ammonia	0.375	0.000	0.000	0.002
Carb. Dioxide	3.239	0.000	87.521	4.606
DomWaste	0.011	0.000	0.000	0.000
FSS	648.317	0.000	0.000	648.410
Nitrogen	0.000	515.084	515.084	0.000
NO2	42.461	0.000	0.000	60.015
Oxygen	0.000	156.369	64.393	0.000
TDS	37.490	0.000	0.000	37.490
Water	122,451.903	0.000	0.000	122,489.929
X-VSS-h	1,568.510	0.000	0.000	1,504.020
X-VSS-i	827.376	0.000	0.000	839.849
X-VSS-n	23.135	0.000	0.000	22.953
TOTAL (kg/h)	125,602.819	671.453	666.998	125,607.274
TOTAL (L/h)	126,481.306	550,193.681	507,397.619	126,486.418

Stream Name	S-129	S-128	S-131	S-132
Source	P-15	P-15	P-13	INPUT
Destination	P-7	P-13	P-12	P-12
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.96	29.96	29.96	15.00
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.88	993.09	993.09	998.35
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.001	0.000	0.000
Carb. Dioxide	1.016	3.591	0.359	0.000
DomWaste	0.000	0.000	0.000	0.000
FSS	3.242	645.168	64.517	0.000
NO2	13.232	46.783	4.678	0.000
TDS	8.266	29.225	2.922	0.000
Water	27,006.122	95,483.807	9,548.381	1,497.823
X-VSS-h	7.520	1,496.500	149.650	0.000
X-VSS-i	4.199	835.650	83.565	0.000
X-VSS-n	5.061	17.892	1.789	0.000
TOTAL (kg/h)	27,048.657	98,558.617	9,855.862	1,497.823
TOTAL (L/h)	27,242.488	99,243.931	9,924.393	1,500.300

Stream Name	S-134	S-133	S-104	S-105
Source	P-12	P-12	P-7	P-8
Destination	OUTPUT	P-7	P-8	P-1
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	27.98	27.98	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	994.56	993.60	992.91	992.91
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.000	47.109	84.665
Carb. Dioxide	0.055	0.304	98.414	105.636
DomWaste	0.000	0.000	300.206	306.990
FSS	64.452	0.065	1,380.951	2,761.879
NO2	0.718	3.961	24.473	24.490
TDS	0.448	2.474	803.311	1,606.619
Water	1,694.368	9,351.837	2,621,658.853	5,243,525.243
X-VSS-h	149.500	0.150	4,318.840	8,840.007
X-VSS-i	83.481	0.084	1,531.564	3,067.319
X-VSS-n	1.787	0.002	144.494	286.644
TOTAL (kg/h)	1,994.810	9,358.875	2,630,308.215	5,260,609.491
TOTAL (L/h)	2,005.726	9,419.124	2,649,101.418	5,298,154.859

Stream Name	S-106	S-107	S-108	S-109
Source	P-1	P-1	INPUT	P-3
Destination	OUTPUT	P-3	P-3	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	25.00	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	33.17	992.92	1.18	1.40
Component Flowrates (kg/h averaged)				
Ammonia	0.000	84.665	0.000	0.000
Carb. Dioxide	110.200	5.800	0.000	278.927
DomWaste	0.000	299.194	0.000	0.000
FSS	0.000	2,761.879	0.000	0.000
Nitrogen	3.673	0.000	1,150.451	1,150.439
NO2	0.000	0.156	0.000	0.000
Oxygen	0.000	0.000	349.255	0.000
TDS	0.000	1,606.619	0.000	0.000
Water	0.000	5,243,538.469	0.000	0.000
X-VSS-h	0.000	8,844.874	0.000	0.000
X-VSS-i	0.000	3,067.319	0.000	0.000
X-VSS-n	0.000	286.644	0.000	0.000
TOTAL (kg/h)	113.873	5,260,495.618	1,499.705	1,429.365
TOTAL (L/h)	3,432.566	5,297,984.821	1,271,516.357	1,021,730.153

4. OVERALL COMPONENT BALANCE (kg/yr)

COMPONENT	IN	OUT	OUT-IN
Ammonia	316,800	153,492	- 163,308
Carb. Dioxide	768,240	3,885,836	3,117,596
DomWaste	2,376,000	4,455	- 2,371,545
FSS	910,800	911,361	561
Nitrogen	14,336,546	14,365,561	29,015
NO2	0	162,880	162,880
Oxygen	4,352,297	515,886	- 3,836,411
TDS	4,593,600	4,593,588	- 12
Water	14,992,542,762	14,994,664,892	2,122,129
X-VSS-h	792,000	1,900,530	1,108,530
X-VSS-i	768,240	904,520	136,280
X-VSS-n	47,520	36,859	- 10,661
TOTAL	15,021,804,805	15,022,099,859	295,054

5. EQUIPMENT CONTENTS

This section will be skipped (overall process is continuous).

REPORT 4.3.B – ECONOMIC EVALUATION FOR PARTIAL SYSTEM-2

Economic Evaluation Report

for Thesis - Partial System (2)- Bardenpho

1. EXECUTIVE SUMMARY (2009 prices)

Total Capital Investment	104,916,000	$
Capital Investment Charged to This Project	104,916,000	$
Operating Cost	23,339,000	$/yr
THE MAIN REVENUE STREAM HAS NOT BEEN IDENTIFIED. PRICING AND PRODUCTION/PROCESSING UNIT COST DATA HAVE NOT BEEN PRINTED		
Total Revenues	0	$/yr
Gross Margin	- 1.00	%
Return On Investment	- 13.23	%
Payback Time	- 1.00	years
IRR (After Taxes)	Out of search interval	(0-1000%)
NPV (at 7.0% Interest)	0	$

MT = Metric Ton (1000 kg)

2. MAJOR EQUIPMENT SPECIFICATION AND FOB COST (2009 prices)

Quantity/ Standby/ Staggered	Name	Description	Unit Cost ($)	Cost ($)
1 / 0 / 0	AXR-101	Anoxic Reactor	2,186,000	2,186,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	AB-101	Aeration Basin	1,288,000	1,288,000
		Vessel Volume = 626885.11 L		
1 / 0 / 0	AB-102	Aeration Basin	4,862,000	4,862,000
		Vessel Volume = 4994106.64 L		
1 / 0 / 0	AXR-102	Anoxic Reactor	1,446,000	1,446,000
		Vessel Volume = 1311287.43 L		
1 / 0 / 0	CL-101	Clarifier	825,000	825,000
		Surface Area = 1990.38 m2		
3 / 0 / 0	GBX-101	Generic Box	0	0
		Size/Capacity = 630945.00 kg/h		
4 / 0 / 0	MX-101	Mixer	0	0
		Size/Capacity = 658625.85 kg/h		
8 / 0 / 0	MX-102	Mixer	0	0
		Size/Capacity = 658600.73 kg/h		
8 / 0 / 0	FSP-101	Flow Splitter	0	0
		Size/Capacity = 658750.57 kg/h		
2 / 0 / 0	FSP-102	Flow Splitter	0	0
		Size/Capacity = 371092.88 kg/h		
1 / 0 / 0	BF-101	Belt Filter	224,000	224,000
		Belt Width = 1.50 m		
1 / 0 / 0	FSP-104	Flow Splitter	0	0
		Size/Capacity = 360000.00 kg/h		
1 / 0 / 0	AB-103	Aeration Basin	3,123,000	3,123,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	MX-103	Mixer	0	0
		Size/Capacity = 126235.73 kg/h		
2 / 0 / 0	TH-101	Thickener	238,000	476,000
		Surface Area = 250.00 m2		
		Unlisted Equipment		3,608,000
			TOTAL	18,038,000

3. FIXED CAPITAL ESTIMATE SUMMARY (2009 prices in $)

3A. Total Plant Direct Cost (TPDC) (physical cost)	
1. Equipment Purchase Cost	18,038,000
2. Installation	2,176,000
3. Process Piping	6,313,000
4. Instrumentation	7,215,000
5. Insulation	541,000
6. Electrical	1,804,000
7. Buildings	8,117,000
8. Yard Improvement	2,706,000
9. Auxiliary Facilities	7,215,000
TPDC	54,124,000

3B. Total Plant Indirect Cost (TPIC)	
10. Engineering	13,531,000
11. Construction	18,943,000
TPIC	32,474,000

3C. Total Plant Cost (TPC = TPDC+TPIC)	
TPC	86,598,000

3D. Contractor's Fee & Contingency (CFC)	
12. Contractor's Fee	4,330,000
13. Contingency	8,660,000
CFC = 12+13	12,990,000

3E. Direct Fixed Capital Cost (DFC = TPC+CFC)	
DFC	99,588,000

4. LABOR COST - PROCESS SUMMARY

Labor Type	Unit Cost ($/h)	Annual Amount (h)	Annual Cost ($)	%
Operator	69.00	55,063	3,799,337	100.00
TOTAL		55,063	3,799,337	100.00

5. MATERIALS COST - PROCESS SUMMARY

THE COST OF ALL MATERIALS IS ZERO. PLEASE CHECK THE MATERIAL BALANCES AND THE PURCHASING COST OF RAW MATERIALS.

6. VARIOUS CONSUMABLES COST (2009 prices) - PROCESS SUMMARY

THE CONSUMABLES COST IS ZERO.

7. WASTE TREATMENT/DISPOSAL COST (2009 prices) - PROCESS SUMMARY

THE TOTAL WASTE TREATMENT/DISPOSAL COST IS ZERO.

8. UTILITIES COST (2009 prices) - PROCESS SUMMARY

Utility	Annual Amount	Reference Units	Annual Cost ($)	%
Electricity	341,980	kWh	34,198	100.00
Steam	0	kg	0	0.00
Steam (High P)	0	kg	0	0.00
Cooling Water	0	kg	0	0.00
Chilled Water	0	kg	0	0.00
TOTAL			34,198	100.00

9. ANNUAL OPERATING COST (2009 prices) - PROCESS SUMMARY

Cost Item	$	%
Raw Materials	0	0.00
Labor-Dependent	3,799,000	16.28
Facility-Dependent	18,936,000	81.13
Laboratory/QC/QA	570,000	2.44
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	34,000	0.15
Transportation	0	0.00
Miscellaneous	0	0.00
Advertising/Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
TOTAL	23,339,000	100.00

REPORT 4.4.A – STREAM & MATERIAL BALANCE FOR PARTIAL SYSTEM-3

Materials & Streams Report
for Thesis - Partial System (3)

1. OVERALL PROCESS DATA

Annual Operating Time	7,920.00 h
Annual Throughput	0.00 kg MP
Operating Days per Year	330.00

MP = Main Product = Undefined

2.1 STARTING MATERIAL REQUIREMENTS

Section	Starting Material	Active Product	Amount Needed (kg Sin/kg MP)	Molar Yield (%)	Mass Yield (%)	Gross Mass Yield (%)
Main Section	(none)	(none)	Unknown	Unknown	Unknown	Unknown

Sin = Section Starting Material, Aout = Section Active Product

2.2 BULK MATERIALS (ENTIRE PROCESS)

Material	kg/yr	kg/h	kg/kg MP
Air	18,851,977	2,380.300	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,021,967,939	1,896,713.124	

2.3 BULK MATERIALS (PER SECTION)

SECTIONS IN: Main Branch

Main Section			
Material	**kg/yr**	**kg/h**	**kg/kg MP**
Air	18,851,977	2,380.300	
Ammonia	316,800	40.000	
Carb. Dioxide	768,240	97.000	
DomWaste	2,376,000	300.000	
FSS	910,800	115.000	
TDS	4,593,600	580.000	
Water	14,992,542,762	1,892,997.823	
X-VSS-h	792,000	100.000	
X-VSS-i	768,240	97.000	
X-VSS-n	47,520	6.000	
TOTAL	15,021,967,939	1,896,713.124	

2.4 BULK MATERIALS (PER MATERIAL)

Air				
Air	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-2	11.09	2,090,573	263.961	
P-3	88.91	16,761,404	2,116.339	
TOTAL	100.00	18,851,977	2,380.300	

Ammonia				
Ammonia	**% Total**	**kg/yr**	**kg/h**	**kg/kg MP**
Main Section (Main Branch)				
P-6	100.00	316,800	40.000	
TOTAL	100.00	316,800	40.000	

Carb. Dioxide				
Carb. Dioxide	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

DomWaste				
DomWaste	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	2,376,000	300.000	
TOTAL	100.00	2,376,000	300.000	

FSS				
FSS	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	910,800	115.000	
TOTAL	100.00	910,800	115.000	

TDS				
TDS	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	4,593,600	580.000	
TOTAL	100.00	4,593,600	580.000	

Water				
Water	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	99.92	14,980,680,000	1,891,500.000	
P-12	0.08	11,862,762	1,497.823	
TOTAL	100.00	14,992,542,762	1,892,997.823	

X-VSS-h				
X-VSS-h	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	792,000	100.000	
TOTAL	100.00	792,000	100.000	

X-VSS-i				
X-VSS-i	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	768,240	97.000	
TOTAL	100.00	768,240	97.000	

X-VSS-n				
X-VSS-n	% Total	kg/yr	kg/h	kg/kg MP
Main Section (Main Branch)				
P-6	100.00	47,520	6.000	
TOTAL	100.00	47,520	6.000	

2.5 BULK MATERIALS (kg/h): SECTION TOTALS

Raw Material	Main Section
Air	2,380.300
Ammonia	40.000
Carb. Dioxide	97.000
DomWaste	300.000
FSS	115.000
TDS	580.000
Water	1,892,997.823
X-VSS-h	100.000
X-VSS-i	97.000
X-VSS-n	6.000
TOTAL	1,896,713.124

2.6 BULK MATERIALS (kg/yr): SECTION TOTALS

Raw Material	Main Section
Air	18,851,977
Ammonia	316,800
Carb. Dioxide	768,240
DomWaste	2,376,000
FSS	910,800
TDS	4,593,600
Water	14,992,542,762
X-VSS-h	792,000
X-VSS-i	768,240
X-VSS-n	47,520
TOTAL	15,021,967,939

3.STREAM DETAILS

Stream Name	S-101	S-102	S-103	S-110
Source	INPUT	P-6	P-6	P-3
Destination	P-6	OUTPUT	P-7	P-9
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	30.00	30.00	30.00	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.88	1,000.00	992.88	992.91
Component Flowrates (kg/h averaged)				
Ammonia	40.000	0.000	40.000	0.179
Carb. Dioxide	97.000	0.000	97.000	14.680
DomWaste	300.000	0.000	300.000	12.774
FSS	115.000	23.000	92.000	2,762.393
NO2	0.000	0.000	0.000	35.494
TDS	580.000	0.000	580.000	1,619.351
Water	1,891,500.000	0.000	1,891,500.000	5,285,328.013
X-VSS-h	100.000	0.000	100.000	9,397.222
X-VSS-i	97.000	0.000	97.000	3,060.227
X-VSS-n	6.000	0.000	6.000	382.140
TOTAL (kg/h)	1,892,835.000	23.000	1,892,812.000	5,302,612.473
TOTAL (L/h)	1,906,410.085	23.000	1,906,387.085	5,340,490.655

Stream Name	S-111	S-116	S-112	S-113
Source	P-9	P-9	P-4	P-4
Destination	P-4	P-8	OUTPUT	P-2
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.91	992.91	7.03	992.91
Component Flowrates (kg/h averaged)				
Ammonia	0.089	0.089	0.000	0.089
Carb. Dioxide	7.340	7.340	14.126	0.743
DomWaste	6.387	6.387	0.000	0.723
FSS	1,381.197	1,381.197	0.000	1,381.197
Nitrogen	0.000	0.000	2.668	0.000
NO2	17.747	17.747	0.000	0.068
TDS	809.675	809.675	0.000	809.675
Water	2,642,663.518	2,642,663.518	0.000	2,642,673.127
X-VSS-h	4,698.599	4,698.599	0.000	4,702.134
X-VSS-i	1,530.112	1,530.112	0.000	1,530.112
X-VSS-n	191.081	191.081	0.000	191.081
TOTAL (kg/h)	2,651,305.744	2,651,305.744	16.794	2,651,288.949
TOTAL (L/h)	2,670,244.832	2,670,244.832	2,390.579	2,670,224.274

Stream Name	S-114	S-115	S-117	S-135
Source	INPUT	P-2	P-2	P-16
Destination	P-2	OUTPUT	P-16	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	25.00	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	1.18	1.18	992.91	6.37
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.000	0.014	0.000
Carb. Dioxide	0.000	4.983	0.262	0.580
DomWaste	0.000	0.000	0.078	0.000
FSS	0.000	0.000	1,381.197	0.000
Nitrogen	202.489	202.489	0.000	0.123
NO2	0.000	0.000	0.828	0.000
Oxygen	61.472	56.529	0.000	0.000
TDS	0.000	0.000	809.675	0.000
Water	0.000	0.000	2,642,675.316	0.000
X-VSS-h	0.000	0.000	4,699.875	0.000
X-VSS-i	0.000	0.000	1,530.662	0.000
X-VSS-n	0.000	0.000	191.002	0.000
TOTAL (kg/h)	263.961	264.002	2,651,288.909	0.703
TOTAL (L/h)	223,797.985	223,708.446	2,670,223.941	110.451

Stream Name	S-119	Liq Effluent	S-120	S-121
Source	P-16	P-5	P-5	P-10
Destination	P-5	OUTPUT	P-10	P-7
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.91	992.89	992.96	992.96
Component Flowrates (kg/h averaged)				
Ammonia	0.014	0.010	0.004	0.004
Carb. Dioxide	0.031	0.022	0.009	0.008
FSS	1,381.196	27.624	1,353.573	1,285.894
NO2	0.003	0.002	0.001	0.001
TDS	809.675	579.451	230.225	218.713
Water	2,642,675.584	1,891,252.571	751,423.013	713,851.862
X-VSS-h	4,700.038	94.001	4,606.038	4,375.736
X-VSS-i	1,530.662	30.613	1,500.048	1,425.046
X-VSS-n	191.002	3.820	187.182	177.823
TOTAL (kg/h)	2,651,288.205	1,891,988.114	759,300.092	721,335.087
TOTAL (L/h)	2,670,223.104	1,905,539.030	764,684.074	726,449.870

Stream Name	S-122	S-130	S-123	S-129
Source	P-10	P-13	P-11	P-15
Destination	P-11	P-11	P-15	P-7
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	992.96	993.10	993.07	992.89
Component Flowrates (kg/h averaged)				
Ammonia	0.000	0.001	0.001	0.000
Carb. Dioxide	0.000	0.001	0.002	0.000
FSS	67.679	579.964	647.642	3.238
NO2	0.000	0.000	0.000	0.000
TDS	11.511	31.419	42.930	8.020
Water	37,571.151	102,547.694	140,118.218	26,176.336
X-VSS-h	230.302	1,973.393	2,203.677	11.018
X-VSS-i	75.002	642.708	717.708	3.589
X-VSS-n	9.359	25.548	34.908	6.521
TOTAL (kg/h)	37,965.005	105,800.727	143,765.086	26,208.723
TOTAL (L/h)	38,234.204	106,535.487	144,769.041	26,396.278

Stream Name	S-128	S-131	S-132	S-134
Source	P-15	P-13	INPUT	P-12
Destination	P-13	P-12	P-12	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	29.99	29.99	15.00	28.29
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	993.10	993.10	998.35	994.47
Component Flowrates (kg/h averaged)				
Ammonia	0.001	0.000	0.000	0.000
Carb. Dioxide	0.001	0.000	0.000	0.000
FSS	644.404	64.440	0.000	64.376
NO2	0.000	0.000	0.000	0.000
TDS	34.910	3.491	0.000	0.549
Water	113,941.882	11,394.188	1,497.823	2,025.846
X-VSS-h	2,192.659	219.266	0.000	219.047
X-VSS-i	714.120	71.412	0.000	71.341
X-VSS-n	28.386	2.839	0.000	2.836
TOTAL (kg/h)	117,556.363	11,755.636	1,497.823	2,383.993
TOTAL (L/h)	118,372.763	11,837.276	1,500.300	2,397.240

Stream Name	S-133	S-104	S-105	S-106
Source	P-12	P-7	P-8	P-1
Destination	P-7	P-8	P-1	OUTPUT
Stream Properties				
Activity (U/ml)	0.00	0.00	0.00	0.00
Temperature (°C)	28.29	29.99	29.99	29.99
Pressure (bar)	1.01	1.01	1.01	1.01
Density (g/L)	993.51	992.90	992.91	43.06
Component Flowrates (kg/h averaged)				
Ammonia	0.000	40.004	40.093	0.000
Carb. Dioxide	0.000	97.009	104.349	106.269
DomWaste	0.000	300.000	306.387	0.000
FSS	0.064	1,381.197	2,762.393	0.000
Nitrogen	0.000	0.000	0.000	2.662
NO2	0.000	0.001	17.748	0.000
TDS	2.942	809.676	1,619.351	0.000
Water	10,866.166	2,642,394.364	5,285,057.882	0.000
X-VSS-h	0.219	4,486.973	9,185.572	0.000
X-VSS-i	0.071	1,525.706	3,055.817	0.000
X-VSS-n	0.003	190.347	381.428	0.000
TOTAL (kg/h)	10,869.467	2,651,225.276	5,302,531.020	108.932
TOTAL (L/h)	10,940.522	2,670,173.714	5,340,418.543	2,529.517

Stream Name	S-107	S-108	S-109
Source	P-1	INPUT	P-3
Destination	P-3	P-3	OUTPUT
Stream Properties			
Activity (U/ml)	0.00	0.00	0.00
Temperature (°C)	29.99	25.00	29.99
Pressure (bar)	1.01	1.01	1.01
Density (g/L)	992.92	1.18	1.32
Component Flowrates (kg/h averaged)			
Ammonia	40.093	0.000	0.000
Carb. Dioxide	5.593	0.000	278.923
DomWaste	300.736	0.000	0.000
FSS	2,762.393	0.000	0.000
Nitrogen	0.000	1,623.481	1,623.481
NO2	0.107	0.000	0.000
Oxygen	0.000	492.857	23.550
TDS	1,619.351	0.000	0.000
Water	5,285,067.470	0.000	0.000
X-VSS-h	9,189.100	0.000	0.000
X-VSS-i	3,055.817	0.000	0.000
X-VSS-n	381.428	0.000	0.000
TOTAL (kg/h)	5,302,422.089	2,116.339	1,925.955
TOTAL (L/h)	5,340,254.074	1,794,325.369	1,459,977.789

4. OVERALL COMPONENT BALANCE (kg/yr)

COMPONENT	IN	OUT	OUT-IN
Ammonia	316,800	79	- 316,721
Carb. Dioxide	768,240	3,206,838	2,438,598
DomWaste	2,376,000	0	- 2,376,000
FSS	910,800	910,799	- 1
Nitrogen	14,461,688	14,504,883	43,194
NO2	0	18	18
Oxygen	4,390,288	634,228	- 3,756,060
TDS	4,593,600	4,593,596	- 4
Water	14,992,542,762	14,994,765,058	2,222,296
X-VSS-h	792,000	2,479,335	1,687,335
X-VSS-i	768,240	807,474	39,234
X-VSS-n	47,520	52,714	5,194
TOTAL	15,021,967,939	15,021,955,023	- 12,915

5. EQUIPMENT CONTENTS

THIS SECTION WILL BE SKIPPED (OVERALL PROCESS IS CONTINUOUS).

REPORT 4.4.B – ECONOMIC EVALUATION FOR PARTIAL SYSTEM-3

Economic Evaluation Report
for Thesis - Partial System (3)

1. EXECUTIVE SUMMARY (2009 prices)

Total Capital Investment	93,101,000	$
Capital Investment Charged to This Project	93,101,000	$
Operating Cost	21,217,000	$/yr
THE MAIN REVENUE STREAM HAS NOT BEEN IDENTIFIED. PRICING AND PRODUCTION/PROCESSING UNIT COST DATA HAVE NOT BEEN PRINTED		
Total Revenues	0	$/yr
Gross Margin	- 1.00	%
Return On Investment	- 13.78	%
Payback Time	- 1.00	years
IRR (After Taxes)	Out of search interval	(0-1000%)
NPV (at 7.0% Interest)	0	$

MT = Metric Ton (1000 kg)

2. MAJOR EQUIPMENT SPECIFICATION AND FOB COST (2009 prices)

Quantity/ Standby/ Staggered	Name	Description	Unit Cost ($)	Cost ($)
1 / 0 / 0	AXR-101	Anoxic Reactor	2,186,000	2,186,000
		Vessel Volume = 2500000.00 L		
1 / 0 / 0	AB-101	Aeration Basin	1,288,000	1,288,000
		Vessel Volume = 626885.11 L		
1 / 0 / 0	AB-102	Aeration Basin	4,882,000	4,882,000
		Vessel Volume = 5026121.48 L		
1 / 0 / 0	AXR-102	Anoxic Reactor	1,452,000	1,452,000
		Vessel Volume = 1319415.09 L		
1 / 0 / 0	CL-101	Clarifier	828,000	828,000
		Surface Area = 2002.67 m2		
3 / 0 / 0	GBX-101	Generic Box	0	0
		Size/Capacity = 630945.00 kg/h		
4 / 0 / 0	MX-101	Mixer	0	0
		Size/Capacity = 662806.32 kg/h		
8 / 0 / 0	MX-102	Mixer	0	0
		Size/Capacity = 662816.38 kg/h		
8 / 0 / 0	FSP-101	Flow Splitter	0	0
		Size/Capacity = 662826.44 kg/h		
2 / 0 / 0	FSP-102	Flow Splitter	0	0
		Size/Capacity = 379650.05 kg/h		
1 / 0 / 0	BF-101	Belt Filter	224,000	224,000
		Belt Width = 1.50 m		
1 / 0 / 0	FSP-104	Flow Splitter	0	0
		Size/Capacity = 360000.00 kg/h		
1 / 0 / 0	MX-103	Mixer	0	0
		Size/Capacity = 143765.09 kg/h		
2 / 0 / 0	TH-101	Thickener	238,000	476,000
		Surface Area = 250.00 m2		
1 / 0 / 0	AXR-103	Anoxic Reactor	1,452,000	1,452,000
		Vessel Volume = 1319404.77 L		
		Unlisted Equipment		3,197,000
			TOTAL	15,985,000

3. FIXED CAPITAL ESTIMATE SUMMARY (2009 prices in $)

3A. Total Plant Direct Cost (TPDC) (physical cost)	
1. Equipment Purchase Cost	15,985,000
2. Installation	1,971,000
3. Process Piping	5,595,000
4. Instrumentation	6,394,000
5. Insulation	480,000
6. Electrical	1,599,000
7. Buildings	7,193,000
8. Yard Improvement	2,398,000
9. Auxiliary Facilities	6,394,000
TPDC	48,008,000

3B. Total Plant Indirect Cost (TPIC)	
10. Engineering	12,002,000
11. Construction	16,803,000
TPIC	28,805,000

3C. Total Plant Cost (TPC = TPDC+TPIC)	
TPC	76,813,000

3D. Contractor's Fee & Contingency (CFC)	
12. Contractor's Fee	3,841,000
13. Contingency	7,681,000
CFC = 12+13	11,522,000

3E. Direct Fixed Capital Cost (DFC = TPC+CFC)	
DFC	88,335,000

4. LABOR COST - PROCESS SUMMARY

Labor Type	Unit Cost ($/h)	Annual Amount (h)	Annual Cost ($)	%
Operator	69.00	55,063	3,799,337	100.00
TOTAL		55,063	3,799,337	100.00

5.MATERIALS COST - PROCESS SUMMARY

THE COST OF ALL MATERIALS IS ZERO. PLEASE CHECK THE MATERIAL BALANCES AND THE PURCHASING COST OF RAW MATERIALS.

6. VARIOUS CONSUMABLES COST (2009 prices) - PROCESS SUMMARY

THE CONSUMABLES COST IS ZERO.

7. WASTE TREATMENT/DISPOSAL COST (2009 prices) - PROCESS SUMMARY

THE TOTAL WASTE TREATMENT/DISPOSAL COST IS ZERO.

8. UTILITIES COST (2009 prices) - PROCESS SUMMARY

Utility	Annual Amount	Reference Units	Annual Cost ($)	%
Electricity	455,380	kWh	45,538	100.00
Steam	0	kg	0	0.00
Steam (High P)	0	kg	0	0.00
Cooling Water	0	kg	0	0.00
Chilled Water	0	kg	0	0.00
TOTAL			45,538	100.00

9. ANNUAL OPERATING COST (2009 prices) - PROCESS SUMMARY

Cost Item	$	%
Raw Materials	0	0.00
Labor-Dependent	3,799,000	17.91
Facility-Dependent	16,803,000	79.19
Laboratory/QC/QA	570,000	2.69
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	46,000	0.21
Transportation	0	0.00
Miscellaneous	0	0.00
Advertising/Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
TOTAL	21,217,000	100.00