AEROBIC TREATMENT OF LANDFILL

LEACHATE USING A SUBMERGED MEMBRANE

BIOREACTOR

By

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A Thesis

Submitted to the Faculty of Graduate Studies in Partial

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"Aerobic Treatment of Landfill Leachate Using a Submerged Membrane Bioreactor"

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ABSTRACT

Submerged membrane bioreactor (MBR) technology for aerobic treatment of landfill leachate was studied in laboratory-scale. The performance evaluation of the system was based on the reduction of organic carbon, nitrogen, overall toxicity, and heavy metals to levels suitable for direct discharge into surface water. A 7.5 L working reactor was constructed and operated under continuous feeding. During the laboratory test, three combinations of solid retention time - hydraulic retention time of 60d-3.5d, 60d-2d and 30d-1d, were examined to evaluate reactor performance under varying loading and biomass conditions. Steady-state was assumed at each operating condition when total and volatile suspended solids in the bioreactor stabilized. COD removal ranged from 51 to 78%. The MBR showed excellent BOD_5 removal of 97% and higher. Complete retention of volatile suspended solids was observed. Also complete nitrification of the incoming ammonia was achieved, despite highly variable loading. Significant removal of iron, lead, manganese, cadmium and aluminum from the incoming leachate was observed. The main effect of changes in SRT-HRT was on the reactor biomass population, rate of leachate consumption and rate of toxicity removal. No significant changes in the removal efficiency of metals, ammonia, COD and BOD_5 were observed at different SRT-HRT. Toxicity removal decreased with increase of HRT.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITRATURE REVIEW

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1.0 INTRODCUTION

1.1 General Overview

Landfill leachate is the fluid that comes into contact with refuse and is collected at the bottom of a landfill. This fluid is mainly produced as the result of the contact of the infiltrated, precipitated and/or irrigation water with the refuse in a landfill. The sap extract of the refuse because of the pressure from its own weight or the weight of daily and final covers, as well as groundwater seep into the landfill, are also responsible for the production of leachate. Presence of moisture in the landfill aids for occurrence of a combination of several physical, chemical, and biological reactions, as well as transfer of many recalcitrant pollutants from the solid phase to the produced leachate (Christensen and Kjeldsen, 1989; Tchobanoglous et al., 2003; Bohdziewicz et al., 2001). Landfill leachate is generally known as a high strength wastewater in terms of content of organic matter (COD and BOD), ammonia, heavy metals, and toxicity. The current practices of landfill leachate treatment are centered on the collection and combined disposal of the leachate with municipal wastewater (Jensen et al., 2001). The City of Winnipeg, Manitoba, Canada is no exception, as leachate from four of the City's landfills is treated at the largest of the three wastewater treatment plants in the city. Although it has been a common strategy in many parts of the world, disposal of leachate at municipal wastewater treatment plants is controversial, since the total organic carbon, nitrogen content and fairly toxic nature of leachate can lead to operational problems within the plant and compromises effluent and bio-solids quality. Therefore, on-site treatment of leachate has been considered by many landfill

1

operators. This, however, may involve costly physical and chemical technologies for removing high contents of organic matter, ammonia, heavy metals, and toxic materials.

Several other methods have been employed for landfill leachate treatment. Due to the high strength of leachate, most methods have comprised of a combination of different stages. Biological, chemical, membrane separation, and thermal processes methods have shown the most effectiveness in landfill leachate treatment (Loukidou and Zouboulis, 2000). Physico-chemical processes are considered to be the most expensive and the least effective methods. Also, conventional suspended growth biological methods, such as traditional activated sludge processes, experience problems with inadequate biomass settling when treating high strength wastewater. Due to the need for longer aeration time and high solid retention time (SRT), large settling tank volumes would be required for total biomass recycling (Gonzalez-Martinez and Garzon-Zungiga, 1996; Cicek, 2003), otherwise, the effluent quality of a liquid with a high food to biomass ratio (as maybe common in leachate) may not yield the desired levels, and biomass loss via the effluent might be significant. This has prompted the investigation of alternative biological methods, such as the use of membrane bioreactors (MBR) for leachate.

MBRs retain the whole biomass within the reactor and produce a compact and versatile environment for the biological degradation of leachate components.

MBRs maintain a wide spectrum of biomass as well as extra-cellular enzymes and soluble oxidants, so that an active biological mixture capable of degrading a wider range of carbon sources can be produced. To the authors' knowledge, the only North American application of the submerged MBR technology for landfill leachate treatment is at the Crane Mountain Landfill which receives municipal solid waste from the City of Saint John, New Brunswick. In this case, the MBR was used as a pretreatment step to a reverse osmosis system to produce water at sufficient quality to discharge directly into the receiving stream year around. Successful BOD and ammonia removal were reported with the MBR pretreatment system (Jensen et al., 2001).

Despite the promising reports from limited previous worldwide studies, it is challenging to extrapolate results from one case to another due to highly fluctuating characteristics of landfill leachate. To obtain the optimum MBR design and operational conditions, pilot-scale testing with a real leachate source is necessary. Additionally, the requirement for effluent water quality might differ for each case, at times rendering sophisticated and costly polishing steps, such as reverse osmosis, unsustainable. For example, if only organic carbon (BOD), ammonia, and toxicity removal are desired, a stand-alone MBR might be sufficient.

1.2 Objectives

The main objectives of this research were:

(1) Evaluation of submerged MBR technology efficiency in TSS, VSS ammonia, COD, BOD5, heavy metals, and toxicity concentration/removal in the aerobic treatment of landfill leachate in laboratory

(2) Studying system's efficiency when dealing with different types of leachate in terms of organic and inorganic contents by feeding the system by leachate pumped randomly from different wells

(3) Investigation and comparison of 3 different leachate loading conditions

(PI: 3.5d HRT: 60d SRT,

 PII: 2d HRT: 60d SRT, and

 PIII: 1d HRT: 30d SRT)

 for optimizing the sludge age in the reactor and increasing leachate consumption rate, and investigating the most efficient loading rate from the engineering design perspective.

1.3 Organization of Thesis

The arrangement of this thesis is as follows: Chapter 2 deals with the literature review of this research including the fundamental definitions and explanations as well as a summary of relevant past researches. Chapter 3 presents details about assembling the system and provides information on leachate supply. Also the

main experiments performed in this research study are explained. Chapter 4

presents the data obtained from experiments. Raw data from the experiments are

provided in the appendices. Chapter 5 provides a discussion of the results and a

comparison with past research findings. Chapter 6 concludes the results and

proposes recommendations for future work in this field.

2.0 LITERATURE REVIEW

2.1 Fundamental Theory

2.1.1 Solid Waste

Solid waste is the "consequence of life" (Tchobanoglous et al., 2003). In fact, solid waste can comprise all normally solid and discarded materials, commonly termed "garbage". According to the U.S. Environmental Protection Agency (EPA), solid waste includes any discarded item; things that can not be reused or recycled any more as well as sludge and hazardous wastes excluding radioactive wastes and in-situ mining wastes (Davis and Cornwell, 1998). Depending on type and source of production, solid waste by itself can be categorized into two groups (1) municipal (residential) and (2) industrial, commercial and institutional (ICI) wastes (Jensen et al., 2001).

2.1.2 Landfill

In early times, solid waste was not a significant problem. With increases in the number of communities and concentration of the population in cities, the problem of increased solid waste has been magnified and the need for solid waste management has become inevitable. Although the amount of solid waste produced per capita changes from town to town and country to country, it fluctuates between 1 kg/capita.day to 3.2 kg/capita.day (Davis and Cornwell, 1998).

Landfills are the most traditional methods for disposal of municipal solid wastes (MSW). Since the 1990's, the disposal of solid wastes has changed from burying

without any containment, leachate collection system, or restriction of incoming materials to the disposal in engineered and constructed landfills. Modern landfills are established with restricted monitoring regulations for the waste flow rate control as well as gas and leachate production monitoring to minimize their environmental impact (Jensen et al., 2001). These practices control the pollution potential to the surrounding environment, particularly groundwater, surface water, and air.

2.1.3 Landfill Leachate

Leachate encompasses any liquid collected at the bottom of a landfill as the by-product of the constitution of landfill, generated when the water content of solid waste buried in the landfill exceeds its field capacity (Wang et al., 2003). According to Reinhart and Townsend (1998), the quality and quantity of landfill leachate depends on site specifics, including type and moisture content of deposited waste; site hydrogeology; landfill design, operation and age of the landfill and/or leachate as well as relative biodegradability of the different organic contaminants present in the landfill solid wastes. Nevertheless, landfill leachate especially young leachate, is generally known as a high strength wastewater characterized by almost neutral pH (6-8), high content of soluble organic and inorganic substances. Consequently, landfill leachate typically has high BOD_5 (4,000-13,000 mg/l) and COD (10,000-60,000mg/l) high content of ammonia, alkalinity, heavy metals and toxicity (Cicek, 2003; Ehrig, 1989; Loukidou and Zouboulis, 2000).

Also, landfill leachate is known as having the highest level (as high as mg/L) of endocrine disrupters or estrogenic compounds (Wintegens et al., 2003). According to Wintegens et al., (2003); endocrine disrupters such as nonylphenol (NP) and bisphenol A (BPA) as well as estradiol, are those portions of soluble organic compounds and chemical substances or mixtures that are able to disturb the hormonal balance of humans, animals, and /or their descendants. These chemicals also are classified as xenoestrogenic compounds.

Landfill leachate treatment methods were developed since early 1960's (Alvarez-Vazquez et al., 2004), however, contaminant variations lead to a wide variety of results of advanced leachate treatment methods, making it impossible to use the data obtained from one site to predict results for another site.

2.1.4 Young vs. Old Leachate

According to Alvarez-Vazquez et al., (2004); main fluctuations of leachate compositions depend on its age and from this aspect leachate can be categorized as old, medium and young.

Table 2.1- Categorizing leachate into 3 different age groups according to the leachate BOD/COD ratio (Alvarez-Vazquez et al., 2004).

Leachate type	Age	BOD/COD ratio
Old	>5years	0-0.3
Medium	1-5years	0.3-0.6
Young	3-12months	0.6-1

Young landfill leachate contains large amount of free volatile fatty acids, resulting in high concentrations of COD, BOD, BOD/COD, NH_3-N and alkalinity, but low ORP and light color (usually yellowish to brownish) (Wang et al., 2003). By the ageing of the refuse, due to the release of the large refractory organic molecules from the solid wastes and degradation of short-chain organic molecules followed by dissolution into the leachate, the BOD/COD ratio decreases rapidly. Old landfill leachate, as well as the biological treated young leachate are characterized by high COD, ORP, pH (>7), and low BOD and BOD/COD ratio and fairly high NH_3-N and alkalinity (Wang et al., 2003). Due to relatively high BOD content in young leachate compared to old leachate, biological treatment processes can be much more commonly employed and effective for young landfill leachate (Forgie, 1998). According to Ahn et al., (2002), it is probable that the amount of ammonia in the leachate increases with landfill age because biological nitrogen removal becomes difficult.

2.1.5 Treated Leachate

One of the best ways of consuming treated leachate is to return it to the landfill (Jensen et al., 2001). Recirculation of treated leachate into the landfill can increase the absorption capacity of the waste, facilitate compaction, and control dust production in the cell (Jensen et al., 2001).

Other methods of treated leachate disposal include leachate evaporation in evaporation ponds and disposal of treated leachate into the wastewater treatment plants. If the high quality of the treated effluent satisfies local surface water regulations, leachate can be discharged to an open river stream directly.

2.1.6 Hydraulic Retention Time and Solid Retention Time

Hydraulic retention time (HRT) is the assessment of the period which the whole volume of a bioreactor is depleted by an assigned flow rate. A very simplified equation of HRT is:

$$\theta = \frac{\upsilon}{Q}$$

Where:

θ = Hydraulic retention time (d)

υ = Volume of bioreactor (m^3)

Q = Flow rate of the effluent pumping pipe (m^3/d)

Solid retention time (SRT) of the bioreactor system is the period that the mixed liquor in a bioreactor is replaced by an assigned amount of wastage from the mixed liquor.

$$\theta_c = \frac{\upsilon}{Q_w}$$

Where:

θ_c = Solid retention time (d)

υ = Volume of bioreactor (cm^3)

Q_w = the amount of mixed liquor which is wasted daily (cm^3/d)

2.2 Important Water Quality Parameters for Landfill Leachate

2.2.1 Introduction

Following the first objective of this research study, major parameters to studied (i.e. BOD, COD, ammonia, TSS, VSS, total metals and toxicity, etc) are further explained in this section. Also, as mentioned before, the amounts of theses parameters are of major concern in landfill leachate.

2.2.2 Biochemical Oxidation Demand (BOD)

One of the serious water resources pollutants is oxygen-demanding material. Oxygen-demanding material can be oxidized in the water, consuming dissolved molecular oxygen and resulting in oxygen depletion in the receiving water. This can result in dangerous conditions for fish and other higher forms of aquatic life. BOD test was developed by sanitary engineers in England to determine how much

oxygen content is required to degrade the waste. Technically, BOD is the amount of oxygen required to oxidize a substance bio-chemically to carbon dioxide and water. The BOD curve is a first order reaction and can be calculated by the following formula;

$$BOD_t = L_0(1 - e^{kt})$$

Where;

BOD_t= BOD content of water at the time t (mg/L)

L_0= Ultimate BOD or oxygen equivalent of organics at time=0 (mg/L)

k = reaction rate constant, d^{-1}

t = time (d)

The ultimate BOD (UBOD) is the maximum BOD exerted by the waste (Davis and Conrwell, 1998). BOD_5 denotes the oxygen consumed over a 5-day period. Since the amount of organics that can be oxidized chemically are normally higher than the amount that can be oxidized biologically, the COD content of one sample of water is normally higher than the BOD content of the same sample.

According to Davis and Cornwell (1998), only under rare controlled circumstances the COD and BOD of one sample can be equal and that is when "the chemical composition of all of the substances in the water is known and they are capable of being completely oxidized both chemically and biologically.

2.2.3 Chemical Oxidation Demand (COD)

Chemical oxidation demand is a test determining the amount of oxygen required in the receiving water body for chemical degradation of the sample waste. COD test is conducted by adding the sample to a strong oxidizing agent such as chromic acid. The difference between the initial amount of chromic acid and that remaining at the end of the test determines the COD content of the water (Davis and Cornwell, 1998). According to Alvarez-Vazquez et al., (2004), the amount of COD in leachate is partially influenced by its age.

2.2.4 Ammonia Concentration

NH_3-N is present in landfill leachate due to the biodegradation of nitrogen-containing organic compounds such as proteins (Lo, 1996). According to Wang et al., (2003), the ammonia concentration in old or biologically treated landfill leachate varies from less than 5 mg/L to 3,400mg/L. High ammonia concentrations can be toxic to both nitrifying bacteria and fish in the receiving water body. Ammonia can be converted to nitrate by autotrophic nitrifying bacteria in a process termed nitrification.

Nitrification is a two-step process where ammonia is converted biologically first to nitrite and then to nitrate. Ammonia is a non-carbonaceous matter that is produced during the hydrolysis of proteins (Tchobanoglous et al., 2003). The overall nitrification reaction is:

$$NH_4^+ + 2O_2 \overset{\text{microorganisms}}{\Leftrightarrow} NO_3^- + H_2O + 2H^+$$
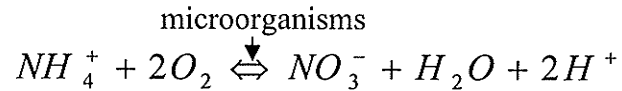
Ammonia is represented in the form of the ammonium cation (NH_4^+) as nitrification occurs at pH values where ammonia is in its ionized form.

Total Kjeldahl Nitrogen (TKN) is a method is a measure of organic nitrogen in the wastewater and it is a sum of organic nitrogen, ammonia, and ammonium compounds. Therefore, TKN is the total organic and ammonia nitrogen.

2.2.5 Total Suspended Solids & Total Volatile Solids

Organic and inorganic particles in the water are measured as suspended solids (SS). Total suspended solids consist of those groups of suspended particles that cause turbidity (Davis and Cornwell, 1998). Because paper filters are used for determining TSS and VSS, the size of filter papers used in TSS and VSS test should be mentioned to make the comparison of results from different cases easier and clearer. Filter's pore sizes vary from 0.45 to 2.0μm. Since colloidal particles rang from 0.001 to 0.1μm, they pass through the TSS and VSS tests filters (Tchobanoglous et al., 2003).

Materials that can be ignited and vaporized from a homogenized water sample, at 550±50°C, are measured as VSS. The major portion of VSS is organic matter,

which is commonly used as a representative value for the concentration of microorganisms within the water or wastewater sample.

2.2.6 Metallic Constituents

Presence of certain metals (regular or heavy) in the wastewater is of concern. Metals such as cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), Mercury (Hg), nickel (Ni), and zinc (Zn) are important constituents to be measured for evaluations in many treatment systems. Some of these elements are required for growth of microorganisms in water. Absence of these elements can limit biological growth, but excess dosage of either of them can pose toxicity. Therefore, it is desirable that their amount be measured in the effluent to make sure that they are kept below standard levels. Metals by themselves are categorized as (1) dissolved (which are those metals present in un-acidified samples and pass through a 0.45μm membrane filter), and (2) suspended (which are those metals that are present in un-acidified samples and are kept on the surface of a 0.45μm membrane filter) (Tchobanoglous et al., 2003). Total metals measurement is an evaluation of both dissolved and suspended metals in a water sample. Appendix 1 shows typical waste metals sources and their effect on the environment.

2.2.7 Toxicity

Toxicity in general, is the test of assessing the amount of hazard to people when exposed to a contaminant (Davis and Cornwell, 1998).

The ammonia content of leachate has been considered to be one of the major toxicants in landfill leachate (Dave and Nilsson, 2005) to the extent that ammonia toxicity can over shadow the toxicity of any other minor toxicant. Therefore, removal of ammonia as a pretreatment stage is suggested by many researchers (Dave and Nilsson, 2005). One effective way to reduce toxicity can be ammonia stripping of leachate before exposing it to the system's microorganisms (Wichitsathian et al., 2004). However, ammonia stripping is not suggested by EPA for wastewater with an ammonia content of higher than 100mg/L (EPA, 2000). Other alternate methods such as steam stripping or biological methods are considered to be more economical than ammonia stripping (EPA, 2000). Other ways to reduce ammonia toxicity are to increase the pH of the leachate, and application of aeration or, filtration through zeolite (EPA, 2000). Nitrification is considered as the most effective and natural technique(s) of toxicity removal among the other methods (Dave and Nilsson, 2005).

2.3 Landfill Leachate Treatment Methods

2.3.1 Introduction

Several methods have been employed for landfill leachate treatment. Due to high strength of leachate in terms of pollutants, most methods have been a combination of different stages. Biological, chemical, membrane separation, and thermal methods have shown the most effectiveness in landfill leachate treatment (Loukidou and Zouboulis, 2000). Application of micro-filtration or ultra-filtration membranes is now a common method for leachate treatment (Wintgens et al.,

2003). Physico-chemical processes are considered to be the most expensive and the least effective methods (Loukidou and Zouboulis, 2000). Also, conventional suspended growth biological methods, such as traditional activated sludge processes have the problem of inadequate settlement of sludge in a reasonable time. They need longer aeration time and a larger volume of settling tank for leachate total biomass recycling (Gonzalez-Martinez and Garzon-Zungiga, 1996; Cicek, 2003). Therefore, a number of innovative biological methods, such as membrane bioreactor treatment methods, have been investigated.

According to studies of Loukidou and Zouboulis, (2000), there are several problems with attached growth biomass method regarding to biomass age. As the biomass ages on the attached film, it detaches from carrier media and accumulates at the bottom of the bioreactor.

According to Alvarez-Vazquez et al., (2004), out of 157 studies reported in the last 30 years based on leachate treatment, less than 30% were based on chemical treatment, less than 10% on physical treatment, and around 60% were based on biological treatment such as aerobic lagoon treatment, activated sludge, UASB, and membrane bioreactors.

2.3.2 Physico-Chemical Treatment

Physico-chemical treatment methods are combinations of physical treatment methods (i.e., screening, filtration, etc) with chemical treatment methods (i.e., RO,

PAC, chemical precipitation, ion exchange, electro-dialysis, distillation, solvent extraction, incineration, etc).

Advanced oxidation processes using ozone (O_3), ozone with hydrogen peroxide (O_3/H_2O_2), ozone with ultraviolet light (O_3/UV), Fenton process (H_2O_2/Fe_2^+), and photo-Fenton process ($H_2O_2/Fe_2^+/UV$), are one category of effective means to deal with the refractory organic compounds in old or biologically treated landfill leachate (Wang et al. 2003).

According to Wang et al., (2003), ozonation for oxidation of refractory contaminants of landfill leachate can not be effective unless a high concentration of ozone and a long time of exposure is applied. In terms of COD removal, ozone with hydrogen peroxide applied at pH of 7 to 8 and hydrogen peroxide ultra violet applied at pH of 2 to 4 are more effective than ozonation alone or ozonation-ultra violet or Fenton processes. In terms of COD removal, the best results were observed with hydrogen peroxide/UV treatment. However, due to slow reaction rate with organics, slow self-decomposition rate, and influence on the subsequent biological treatment systems as well as the ecosystems of the receiving water, hydrogen peroxide- related processes are not desirable (Wang et al., 2003). The only method that is suggested by Wang et al., (2003), for the treatment of high strength leachate, is use of ozone as pretreatment followed by a biological treatment method.

Chaturapruek et al., (2004) investigated ozonation of a medium-aged landfill leachate effluent obtained from a membrane bioreactor process. The MBR efficiency had a COD removal of 70%, ozonation of the MBR effluent showed reduction of further COD up to 73% when an ozone dosage of 4.2 $mgO_3/mgCOD$ was applied. Ozonation was also successful in removal of TOC up to 71% at a contact time of 180 min. However, due to substantial changes that ozone causes in reacting with humic substances and other complex substances in leachate, BOD_5 showed an average of 40% increase when the contact time was less than 45 min. Continuous increase of contact time of ozone with leachate reduced the BOD_5, however, the high cost of ozone in required high contact times was a serious limiting factor (Chaturapruek et al., 2004).

Physico- chemical methods have been successful in removal of fulvic and humic substances from leachate. These pollutants are difficult to be degraded in traditional biological methods, such as activated sludge, due to the short and insufficient solid retention time (SRT) of the system for growth of microorganisms capable of degrading them.

Another physical treatment method studied for landfill leachate is the membrane powdered activated carbon process. In this system, an Ultrafiltration (UF) membrane is coupled with powdered activated carbon (PAC) adsorption. By addition of the PAC to the filtration process, the removal of natural organic matter such as humic substances, taste, odour and colour producing compounds,

and synthetic organic compounds such as Tri-halomethans (THMs), phenols, detergents, cresols, pesticides, become possible at lower filtration pressures. If the PAC usage in the reactor is not desirable, reverse osmosis (RO) treatment is required which gives the same efficiency of removal of natural and synthetic organic matter with the application of higher pressure. The use PAC of in the UF process is referred as Membrane Powdered Activated Carbon or PAC/UF (AWWA, 1996).

Trebouet et al., (2001) tried to treat leachate by pre-filtration and coagulation with FeCl$_3$ to remove potential foulants such as soluble organic and inorganic materials as well as colloidal substances. The results obtained from pre-filtration and coagulation is shown in the following table.

Table 2.2- Characteristics of raw stabilized leachate after pre-filtration and coagulation (Tredouet et al., 2000).

Parameters	Raw leachate	Pre-filtration		Coagulation	
		Effluent	Reduction (%)	Effluent	Reduction (%)
pH	7.5	7.5	-	5	-
Turbidity (NTU)	170	70	58	9	95
COD (mg/L)	620	580	6	280	55
SS (mg/L)	185	27	85	30	83

2.3.3 Biological Treatment

The goals of biological treatment include oxidization of dissolved biodegradable constituents, incorporation of suspended and colloidal solids into a biological floc and removal of nitrogen and phosphorus and other trace nutrients (Tchobanoglous et. al, 2003). In case of leachate, biological treatment can be applied for removal of both organic and inorganic materials as well as nutrients. In terms of metabolic function, biological treatment methods can be classified as aerobic, anaerobic and anoxic, facultative and combined processes (Tchobanoglous et. al., 2003). Anaerobic treatment and aerobic treatment by lagoons, reed beds (such as wetlands), activated sludge and rotating biological contractors as well as membrane bioreactor technology are well documented (Lugowski et al., 1989; Qasim et al., 1994; Engelhardt et al., 1998; Günder et al., 1998).

Leachate has been treated by several biological methods in past research studies; Loukidou and Zouboulis, (2000) investigated and compared two biological systems using attached-growth for treatment of leachate pumped out of a typical municipal solid waste sanitary landfill leachate collection system in Greece. A bench scale sequencing batch (bio) reactor (SBR) was fed by real leachate and aerated by air diffuser. The study, also called "suspended-carrier attached-biofilm" was conducted by two sequencing operational cycles; during the first cycle, the SBR was filled up by cube-shaped waste polyurethane particles as biofilm carriers which were able to follow the water flow pattern, hence, the continuous motion eliminated problems with clogging and dead space. During the

21

second operational cycle, GAC was added to the reactor. A daily aerobic, anoxic, and biomass separation cycle was automatically controlled. At the end of experiments, during the first cycle, 60% COD removal and 90% BOD_5 removal was reported (Table 2.3).

Table 2.3- Treatment results for the first operation cycle of SBR (average values) (Loukidou and Zouboulis, 2000).

Parameter	Leachate Average Values (mg/L)	Removal during the first cycle (Polyurethane)	Removal during the second cycle (GAC)
COD	5000	65%	55%
Ammonia Removal	1800	60%	95%
BOD_5	1000	90%	80%

Ammonia removal during the first operational cycle was lower than expected, possibly because the aeration time in the reactor was not enough to allow full nitrification to occur or because of the high organic load of the leachate, the available time for sufficient biofilm growth was rather short and did not allow adequate colonization of nitrifying bacteria to occur. Another disadvantage of this system was considered to be the large amount of residual suspended solids which have to be subsequently treated and separated. Since the polyurethane was not

successful enough for efficient removal of COD and ammonia, a considerable

amount of GAC had to be consumed to compensate for the shortage from the first

cycle, which resulted in a considerable increase in the system expenses (Loukidou

and Zouboulis, 2000).

Frascari et al. (2003), investigated leachate treatment by two anaerobic and three

facultative lagoons that had been in operation for almost 10 years. Results are

summarized in the following table (Table 2.4).

Table 2.4- Average leachate concentrations and average removals of pollutants in

the lagoon system from 1992 to 2001 (Frascari et al., 2003).

Parameter	Leachate	Lagoon-treated effluent	Removal efficiency (%)
COD (mg/L)	5050	2960	40
BOD (mg/L)	1270	470	64
NH3-N (mg/L)	1330	295	77
NO3—N (mg/L)	21	3.4	63

Although the lagoon treated effluent was suitable for discharge into the

wastewater sewage system, the removal efficiencies of COD and BOD as well as

ammonia were not sufficient for direct discharge into surface waters. The high

expenses of monitoring of rainfall, environmental temperature, and evaporation rate necessary to ensure a stable lagoon ecosystem should not be underestimated.

In aerobic treatment methods, molecular oxygen is required as the terminal electron acceptor. Oxygen allows obligate aerobic microorganisms to grow for decomposition of organic matter. The results of aerobic decomposition are carbon dioxide, water, and biomass. The amount of biomass produced in aerobic treatment is much higher than that in anaerobic treatment systems, requiring extensive waste biomass management. On the other hand, in aerobic systems, annoying to olfactory senses gaseous end products will be kept to a minimum. According to Tchobanoglous et al., (2003), biological aerobic treatment can be formulated as the oxidation or conversion of organic matter to biomass, carbon dioxide and water:

$$\upsilon_1\left(organic\,material\right) + \upsilon_2 O_2 + \upsilon_3 NH_3 + \upsilon_4 PO_4^{3-} \xrightarrow{\text{Microorganisms}} \upsilon_5\left(new\,cells\right) + \upsilon_6 CO_2 + \upsilon_7 H_2 O$$
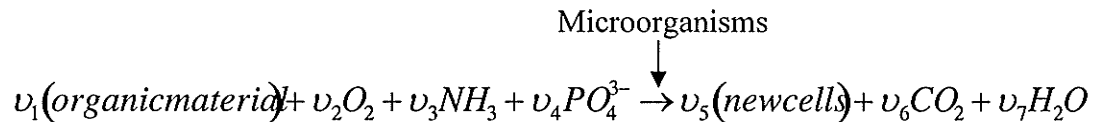
Where υ_i= *the stoichiometric coefficient which refers to the quantities of compounds involved in a reaction.*

In this reaction, aerobic microorganisms are responsible for oxidation of the organic matter and removal of both nitrogen and phosphorous.

It is important to note that the aerobic treatment process would not be completed unless the biomass is removed from the system either by gravity settling or

filtration, since the biomass is considered as organic matter and is measured as BOD in the effluent (Tchobanoglous et al., 2003).

2.3.3.1 Conventional Activated Sludge

Treating landfill leachate using conventional activated sludge is controversial due to differences of leachate composition, nitrogen and ammonia content, and age. Since leachate is a specific type of wastewater with toxic nature and high loading caused by recalcitrant compounds, organic and inorganic substances, in comparison with other sewage wastewaters, it is much more difficult to treat (Bohdziewicz et al., 2000).

Few literatures regarding treatment of leachate by conventional activated sludge (AS) is available. This can be most probably because of the obvious result of treating leachate by conventional activated sludge (i.e. the activated sludge system solely is not sufficient to treat landfill leachate in a way that the effluent meets the standards of treated wastewater). Therefore, hybrid methods are necessary, if treatment by AS is desired.

Bohdziewicz et al., (2000) designed some hybrid systems for studying their efficiencies in treating preliminary landfill leachate. The hybrid systems composed of activated sludge-chemical oxidation, activated sludge-ultrafiltration-chemical oxidation and activated sludge-ultrafiltration-reverse osmosis (Bohdziewicz et al., 2000). Leachate generated from Dąbrowa Górnicza (province

of Katowice, Polnad) was resistant to biodegradation with average BOD_5 of 331mg/L, COD of 1183mg/L and ammonia nitrogen content of 743mgN/L. The first stage of leachate treatment was activated sludge. Activated sludge method was rather unsuccessful in removal of COD from leachate. Only <10% COD removal was observed in the stage of activated sludge. Table 2.5 shows the results obtained from raw landfill leachate treatment by activated sludge in this research.

Table 2.5- Composition of landfill leachate subjected to activated sludge treatment (Bohdziewicz et al., 2000)

Parameter	Raw landfill leachate	Landfill leachate after biological treatment
COD (mg/L)	1600	1600
Dry matter (mg/L)	164	395
pH	8	8.7
Conductivity (mS/m)	9.5	11.2

This research concluded the methods involved in membrane treatment as the most advantageous ones for treating landfill leachate. Also the research showed that the activated sludge stage was almost useless in the whole hybrid treatment processes of landfill leachate treatment.

Geenens et al., (2000), in Belgium, investigated a pilot scale activated sludge system for advanced treatment of ozone pre-treated landfill leachate. High COD removal performance (81%) and decreased nitrification inhibition (21%), during the biological activated sludge stage were reported. Consuming ozone for a full-scale treatment plant for leachate was considered very expensive however, partial degradation, increased biodegradability, and minimized toxicity can be achieved in this stage.

Bae et al., (1999) studied treatment of biologically refractory substances of landfill leachate using activated sludge methods followed by electron-beam (EB) radiation technology. The results obtained from only the AS part revealed that despite removal of 98% of BOD, 295mg/L of DOC and a high concentration of COD (960mg/L) as well as 1470mg/L of VSS were left for the polishing (EB) stage (Bae et al., 1999).

2.3.3.2 Membrane Bioreactors (MBRs)

One of the most promising biological aerobic treatment methods for leachate is the membrane bioreactor (Cicek, 2003). Since MBRs are an important focus in this research study, they are described in detail in the following section.

2.4 Membrane Bioreactors (MBRs)

2.4.1 Introduction

MBRs can be described as the combination of two parts: (1) vessels, where biodegradation of the wastewater occurs and (2) membrane filters which physically retain the biomass and particulate based organic and inorganic contaminants (Cicek et al., 1998). Two main configurations of membrane bioreactors have been widely studied:

(1) Submerged or integrated MBRs: in this configuration an outer skin membrane is installed inside the bioreactor. Filtration occurs by imposing negative pressure by a vacuum pump. Cleaning of the membrane module is achieved by frequent back-pulsing of permeate from the permeate tank to the bioreactor and by less frequent chemical cleaning. In aerobic processes, air is introduced to the system through the same membrane module (Cicek et al., 1999a).

(2) Side-stream, re-circulated or external MBRs: in this configuration an outer or inner skin membrane is installed outside of the bioreactor and flow re-circulates between the membrane module and the bioreactor. The pressure created by high cross-flow velocity along the membrane surface provides the driving force in this configuration (Cicek et al., 1998, 1999b).

From the aspect of global competition, the submerged membrane has been more

successful economically, because it is a less expensive and more compact system,

which requires less pressure and releases higher fluxes (Adham et al., 2001).

Figure 2.1 and 2.2 present an illustration of the side-stream and submerged

membrane bioreactor configurations, respectively.

Figure 2.1- Side stream, or external MBR.
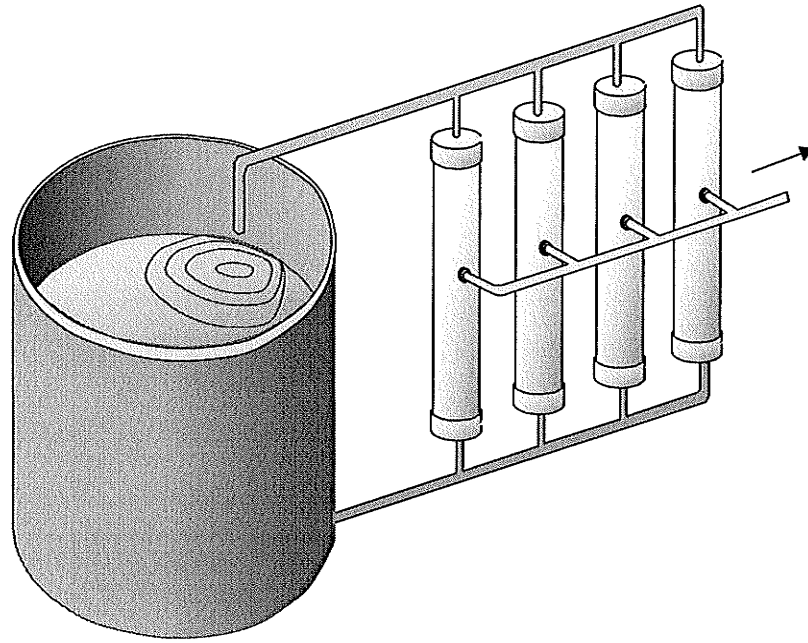
Figure 2.2- Submerged, or integrated MBR.
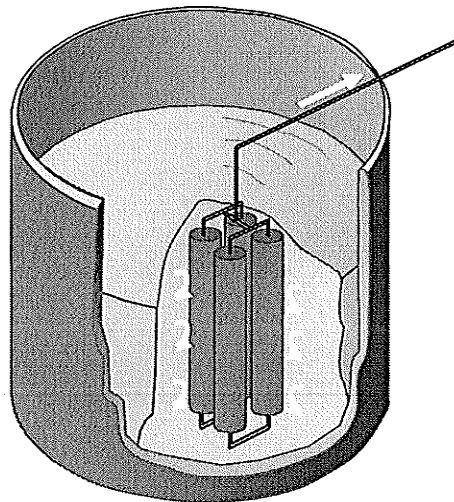
2.4.2 Advantages of MBRs

Advantages of MBRs in treatment of wastewaters are well documented. These advantages are:

(1) Efficient removal of bacteria, pathogens, organics and inorganics

(2) Ability to treat high strength wastewater due to the maintenance of a high population of biomass in the reactor. MBR provides this environment as it is not limited by the settling constraint of biomass encountered in traditional systems.

(3) The need for a gravity-driven clarifier is omitted, and separation occurs by membrane filtration, enabling sensitive, slow-growing organisms (i.e., nitrifying bactria, and bacteria capable of degrading complex compounds) to develop and persist in the system even under short SRTs (Cicek et al., 2001)

(4) Retention of all biomass as well as extracellular enzymes and soluble oxidants by membrane in the reactor, creates a more active biological mixture capable of degrading a wider range of carbon sources (Cicek et al, 1999b).

(5) Smaller footprint due to removal of a settling tank.

(6) Retention of high molecular weight soluble compounds which are not readily biodegradable, making oxidation possible (Welander et al., 1997).

(7) Due to extensive biological acclimation and retention of decaying biomass, the system is able to handle fluctuations in nutrient concentrations and has a lower sensitivity of adverse environmental conditions such as lack of feed, process pause, high pressure, and toxicity (Cicek et al., 1999c).

(8) Cost effective particularly if upgrading an existing plant is required.

(9) Due to the relatively low F/M ratio in membrane bioreactors in comparison with conventional activated sludge system the amount of sludge production in MBRs is much lower than that in conventional aerobic systems.

(10) After an UF process in MBR the effluent is free of suspended solids, bacteria, and viruses.

(11) Solid retention time in MBRs is completely separate from hydraulic retention time (HRT). This advantage is specifically useful for treating of wastewaters with many recalcitrant pollutants (i.e., landfill leachate) that require a long SRT to achieve biodegradation (VanDijk and Roncken, 1997).

2.4.3 Disadvantages of MBRs

The main disadvantage of MBRs is the membrane fouling and concentration polarization which are obstacles to limit the wider application of MBR technology. Compared to activated sludge methods, MBRs require a higher level of energy consumption. Other disadvantages of MBRs are cost related. Capital

costs of membrane modules are high. Operation and maintenance costs associated with fouling control, manual cleaning, and/or chemical cleaning as well as the need for a permanent suction gradient by vacuum pump are rather high. Despite the mentioned factors in cost estimation considerations, many researchers have mentioned MBRs as one of the economically feasible methods for high strength wastewater treatment (Wichitisathian et al., 2004).

Additionally, another disadvantage of MBRs arises when they operate at high SRTs; in those situations the inorganic compounds accumulate in the bioreactor can reach concentration levels that are harmful to the microbial population or to the membrane structure (Cicek et al., 1999a).

Some other disadvantages of MBRs specific to leachate treatment include:

(1) In order to maintain high nitrification rates, there is a need for maintaining high concentrations of dissolved oxygen (DO).

(2) High content of ammonia in leachate can pose problems relating to biomass growth and inhibition of nitrification, especially if nitrite anions accumulate in the system (Welander et al., 1997).

(3) The observations about refractory COD removal, biokinetic aspects and membrane fouling of MBR processes are not well understood, especially for leachate treatment (Wichitisathian et al., 2004).

2.4.4 Membrane fouling

One the most acute problems in using membranes is membrane fouling which can be defined as clogging of membrane pores due to ingress of solids. This will result in an increase in membrane hydraulic resistance (Gander et al., 2000).

Since membranes have to deal with treatment of wastewaters, they are usually in the centre of a high content of mixed liquor suspended solids (i.e., more than 20g/L). But what are widely known as the major foulants in MBR processes, are varying levels of colloidal and dissolved extra-cellular polymeric substances (EPS) (Chang and Lee, 1988; Bouhabila et al., 2001; Chang et al., 2002). Colloids and EPS include proteins, polysaccharides, lipids, and nucleic acids. Therefore, fouling can be defined more comprehensively as the accumulation of colloidal, particulate, and solute materials which may or may not be of microbial origin (such as EPS) on the surface of, or within, the membrane (Judd, 2004).

If the wastewater contains larger microbial particles, the chance of fouling reduces because larger particles will physically attach themselves to the membrane body and form a porous cake layer over it. This cake is a barrier to filter out the EPS and other colloidal foulants (Wichitisathian et al., 2004).

Membrane fouling can be distinguished by a sharp decrease of trans-membrane pressure (TMP) difference. Some researchers suggest that if instead of bacteria in the MBR, yeast be used, because of larger size of yeast cells, the need for cleaning

the membrane module due to fouling stretches over time (Wichitisathian et al., 2004). Depending on accumulation on the surface or inside the membrane pores, the fouling can be classified either as reversible or irreversible. Deposition of sludge cake on the surface of the membrane is referred to as reversible fouling and can be reduced by appropriate washing procedures (Holbrook et al., 2004). Experiments show that fouling has a small relationship with high suspended solids levels than with content of fine colloidal and macromolecular solute fractions of the wastewater (Judd, 2004).

While the colloidal substances block the membrane pores, reversible fouling occurs and can be generally controlled by sodium hypochlorite or citric acid cleaning (Holbrook et al., 2004). With time, reversible fouling turns into irreversible fouling, which has been considered to have the largest effect on membrane service and replacement. In membrane bioreactors, addition of alum in the reactor can bind the EPS material and reduce the membrane irreversible fouling (Holbrook et al., 2004). According to Judd, (2004), fouling could be controlled by common ways; "(1) reducing the flux, (2) increasing membrane aeration, or (3) employing physical or chemical cleaning". Fouling should be differentiated with the more serious problem of "membrane aerator clogging" where the membrane interstices or aerator ports may become blocked with solid particles. Clogging by solid matter is normally ameliorated by intermittent flushing of the aerators.

Despite the rigorous fouling process control demand of the membranes, the commercial success of membranes is striking. According to Judd, (2004); the submerged configuration which has been available commercially only for the last 15 years, has achieved a great global attraction in a way that the 1000th Kubota MBR plant was installed in May 2003 and Zenon MBRs' capacity has been increased from <1,000m³/d in 1993 to almost 40,000 m³/d currently.

2.4.5 Landfill Leachate Treatment with MBRs

The current practices of landfill leachate treatment are centered on the collection and combined disposal of the leachate with municipal wastewater.

In a bench scale study of landfill leachate treatment using a 5L submerged membrane bioreactor by Wichitsathian et al., (2004), in Thailand, leachate was treated in two HRTs of 16 and 24 h, each with and without ammonia stripping. The membrane module was a hollow fiber with nominal pore size of 0.1μm. The results showed a 52-66% COD removal without ammonia stripping and a 72-76% COD removal with ammonia stripping, while the BOD_5 removal was higher than 90% but still the effluent BOD_5 did not meet the standard regulation limit of 30mg/L for discharge to an open river system. The TKN removal of the system increased from the range of 14-28% without ammonia stripping to 82-89% with ammonia stripping. Since the BOD_5/COD was lower in 24 h HRT, longer HRT for the system was suggested (Wichitsathian et al., 2004).

The only full scale landfill leachate treatment system in North America is located at the City of Saint John, New Brunswick, Canada (Jenson et al., 2001). The ZeeWeed ZenoGem process is a proprietary membrane bioreactor (MBR) of Zenon Environmental Incorporation that has been applied for treatment of industrial and commercial wastewaters for over ten years (Hare et al., 1990). The complete facility was established in an area of 50 m×35 m. Raw leachate obtained from the City of Saint John and several surrounding municipalities and rural communities, and was fed from the equalization tank to the bioreactor with a volume of $300m^3$ and submerged ultra-filter hallow fiber membrane. Since disposal of treated leachate into a local stream was desired, the ZenoGem process was accompanied by a RO step. The results obtained from the first stage (ZenoGem) are summarized in the following table.

Table 2.6- ZEEWEED ZENOGEM information (Jensen et al., 2001).

Parameter	Leachate Average Quality	% Removal
Leachate Average BOD5 (mg/L)	408-3328	97.5-99.7
Leachate Average COD (mg/L)	856-4155	76.6-95
HRT (d):SRT(d)	-	2.7-80

After treatment by RO, major pollutants (i.e., TSS, COD, BOD, nitrate, cadmium, chromium, iron, lead, nickel, zinc, and phenol) met water quality objectives criteria in every monitoring for discharge to the river system, however, some

parameters did not meet the required guidelines in every monitoring including: pH, dissolved oxygen, ammonia and copper (Jensen et al., 2001).

In Korea, a full scale landfill leachate treatment plant was installed at Chung-Nam province in 2000 (Ahn et al., 2002). In this study an integrated membrane system composed of MBR submerged membrane configuration named KIMAS (Kolon Immerseed Membrane Activated Sludge) and RO process using spiral wound membrane were used. In the MBR stage, successful BOD_5 removal of 97% was achieved in a level that the effluent average BOD_5 content was 9mg/L. In opposite of good BOD_5 removal in the MBR part, ammonia removal was limited easy and most of it was removed in RO stage. Ammonia concentration of leachate ranged from 250 to 1,300 mg/L and it was reduced to 100-408mg/L in the effluent of the MBR. Since the mgN/L of the wastewater (leachate) was higher than 1000mg/L, treating of this leachate with conventional activated sludge methods could cause many difficulties (Ahn et al., 2002). Effective removal of SS was also observed in the MBR level. This made the MBR effluent an effective pre-treated feed for the RO.

In Europe, Wehrle Environmental Company, originally established in Witney, Oxfordshire, England, has demonstrated some successful full scale MBR systems for treating landfill leachate. Some examples of successful projects of Wehrle Company include: (1) MBR system with volume of $2 \times 120m^3$ in Lorrach, Germany, in 1997 (2) MBR with volume of $140m^3$ in Neuss, Germany, in 1998,

and (3) full-scale MBR with volume of $80m^3$ in Moréac, France, in 2001. The process data of these three full-scale plants are presented in table 2.7.

Table 2.7- MBR application in treatment of landfill leachate (Wehrle, 1997; Wehrle, 1998; Wehrle, 2001).

Process Data	Lorrach, Germany, 1997			Neuss, Germany, 1998			Moréac, France, 2001		
	Input	Output	Removal %	Input	Output	Removal %	Input	Output	Removal %
COD (mg/L)	2,000	<400	>80	4,000	400	90	3,000	125	95.8
BOD (mg/L)	150	<5	>96.7	400	<25	>93.8	NA		
Ammonia (mg/L)	600	<5	>99	1,600	5	99.7	800	30	96.3

Wintgens et al., (2003); in Germany, investigated an ultra-filtration membrane bioreactor followed by GAC polishing stage for removal of endocrine disrupters. Studies showed that 87% of estrogenic compounds including NP and BPA were eliminated by UF and an extra 13% was removed by activated carbon.

Table 2.8 presents some details about MBR systems dealing with landfill leachate all around the world and summarizes the information of section 2.4.5.

Table 2.8- MBR systems treating landfill leachate across the world and their efficiency in removal of COD, BOD₅, and ammonia.

Country	MBR size	Initial COD; % Removal	Initial BOD$_5$; % Removal	Initial Ammonia; % Removal	Other Information
Thailand	Bench-scale	8000; 52-76	0.4; >90	1700; 82-90	HRT: 0.7d-1d
Korea	Full-scale	400-1500; 38	100-500; 97	200-1400; 69-92	Membrane surface:5 m^2
Germany	Full-scale	2000; >80	150; >96.7	600; >99	Bioreactor volume 2*120 m^3 Membrane surface:226 m^2
Germany	Full-scale	4000; 90	400; >93.8	1600; 99.7	Bioreactor volume 140 m^3 Membrane surface:120 m^2
France	Full-scale	3000; 95.8	-	800; 96.3	Bioreactor volume 80 m^3 Membrane surface:30 m^2
Canada	Full-scale	856-4155; 77-95	408-3328; 98-99.9	-; 100	HRT:2.7d; SRT:80d Bioreactor volume 2*303 m^3

2.4.6 Powdered Activated Carbon MBRs

RO process is expensive operationally and requires high pressure. Therefore, the idea of using a cheaper membrane process module with bigger pores such as UF with addition of a polishing stage such as powdered activated carbon (which is able to particulate dissolved organic matter) is developed and considered to be more applicable than the RO in landfill leachate treatment. UF alone is good enough for removing bigger natural suspended particles such as clays and algae. Since organic matter is responsible for colour of wastewater, formation of carcinogenic by- products (DPB) during wastewater disinfection, and reacting with heavy metals, etc (Yiantsis and Karbabelas, 2001), there is a need for organic matter removal from wastewater to the highest possible level. Different researches on PAC adsorption capacity when dealing with a pre-treated leachate (by MBRs) has been addressed (Cecen et al., 2003; Loukiour and Zouboulis, 2000). By addition of PAC to the process, the removal of natural organic matter such as humic substances, taste, odour and colour producing compounds, and synthetic organic compounds such as Tri-halomethans (THMs), phenols, detergents, cresols, pesticides, and other toxic or non-biodegradable material might be feasible. The use of PAC in the UF process is referred to as Membrane Powdered Activated Carbon or PAC/UF.

2.5 Membranes

2.5.1 Membrane Modules

The word "module" was originally an architectural term for a standard unit of measurement. In the water and wastewater treatment industry, the term module refers to a "single operational unit into which membranes are engineered for use" (AWWA, 1996). Normally any membrane module consists of membranes, pressure support structure, feed inlet, permeate outlet and retentate ports, and an overall support structure (Tchobanoglous et al. 2003). Practically, the membranes perform the functions of the secondary settler and tertiary filter of the activated sludge process (Jensen et al., 2001). Successful operation of membrane processes relies on membrane module design and module function analysis in a bench or pilot scale test. Using the membrane module design, it can be determined if sufficient circulation of the flow has been reached, maximum flux has been obtained, and isolation of each feed and permeate tank has been achieved.

Four principal types of membrane modules are used for wastewater treatment. They include: (1) tubular, (2) hollow fiber, (3) spiral wound, and (4) plate and frame (AWWA, 1996). The hollow fiber modules are now the most commonly used in the area of biological wastewater treatment using MBRs.

2.5.1.1 Hollow Fibers

Hollow-fiber membranes consist of hollow, hair-like fibers bundled together into either a U-shape or straight-through configuration. Tube bundles are inside a

pressure vessel and feed material normally flows inside the tubes. However, flow can run from outside to the inside too. Fibers in the straight-through design are somewhat larger with 1000 m^2/m^3 packing density and can accept streams with low levels of suspended solids. U-tubes can be used for reverse osmosis, and the straight-through module can be used for ultra-filtration (AWWA, 1996). Several thousand to several million bundles of fibers can be gathered together in one module.

Having many beneficial features, the hollow fiber modules have become an attractive module in many industries. These advantages include: low pumping power, very high packing density, being self-supported in cleaning as they can be back-flushed (Fellows, 1998), as well as, functioning in laminar flow regime and being free from the recirculation need (they are functioning in dead-end mode) (AWWA, 1996).

Hollow fiber modules have large membrane surface per module volume. Hence, the size of the hollow fiber module is smaller than other type of membrane modules while it can give better performance. Hollow fiber membranes also have a lower operation cost compare to other types of unit operations (OCERP, 2004).

Hollow fiber membranes have some disadvantages, which lead to application constraints. These include the fragility of the fibers, inability to handle suspended solids well, and difficulty in manual cleaning (Fellows, 1998). Membrane fouling

of hollow fiber is more frequent than other membranes due to its configuration.

Also hollow fibers, which are made of polymeric substances, cannot be used

under extreme pH and temperature conditions (OCERP, 2004).

3.0 Materials and Methods

All materials used in the construction of the bench-scale MBR were designed according to the membrane manufacture's (Zenon Environmental Inc.) instructions. Experimental methods were based on standard methods for the examination of water and wastewater, (APHA- AWWA- WEF, 1998). Each component of this experiment is discussed in this chapter.

3.1 Leachate Samples

The landfill leachate used in this study was obtained from Brady Landfill located south of Winning, MB. This municipal solid waste leachate was representative of what is readily available in Manitoba, Canada. During the test, the leachate was pumped out of randomly different wells at the landfill, resulting in leachate derived from refuse at various stages of degradation. As a result, the influent leachate to the MBR varied in its composition with time, enabling the evaluation of the MBR systems under varying loading conditions. Leachate jugs (20 L) were stored in a cold chamber at 4°C (to prevent microbial activity) and brought to room temperature (15-25°C) prior to feeding the system. The leachate (feed) was introduced into the MBR by gravity using a float valve. Samples were taken from each jug at the beginning and end of their use and results were averaged.

3.2 System Setup

A laboratory scale, 7.5 L working volume MBR was constructed and continuously fed with the leachate. One proprietary ZW-1 (ZeeWeed®) hollow fiber membrane module from Zenon Environmental Inc. (nominal pore size of 0.04 μm) was submerged in the reactor vessel to separate the biomass from the treated water. Aeration for membrane surface scouring was provided by a compressed air pump which was connected to the head of the membrane manifold (Figure 3.1). The compressed air pump also provided the oxygen required for biological aerobic digestion. Mixed liquor pH, temperature, and ORP were measured by electrodes separately immersed into the bioreactor. The reactor was seeded with waste activated sludge from the local North-End wastewater treatment plant prior to leachate treatment. Automatic backwashing was employed for 45 sec out of every 580 sec (9.67 min) to maintain a steady permeate flux through the membrane. A simplified flow diagram showing the overall process is presented in Figure 3.1. A picture of the system is shown in Figure 3.2.

3.3 Parameters Studied

The main parameters studied during this investigation were the following:

1. Trans-membrane pressure (TMP), effluent flow rates, mixed liquor pH, ORP and temperature were monitored daily.

2. Decrease of hydraulic and solid retention times. After an initial acclimation period (40 d), a hydraulic retention time (HRT) of 3.5d and solids retention time (SRT) of 60d were maintained in the system for 128

d. At day 168 of operation, the HRT was reduced to 2d to further challenge the system. The last examined HRT was 1d, which was accompanied by a reduction of SRT to 30d after 250 d of system operation.

3. Leachate TSS, VSS, COD, and ammonia, mixed liquor TSS and VSS, effluent COD, TSS, VSS, ammonia, nitrite, and nitrate concentrations were measured weekly.

4. Influent and effluent BOD, heavy metals, and toxicity (Dophnia-LC50) were also analyzed in less frequent intervals.

Figure 3.1- Schematic representation of the laboratory (bench) scale MBR.
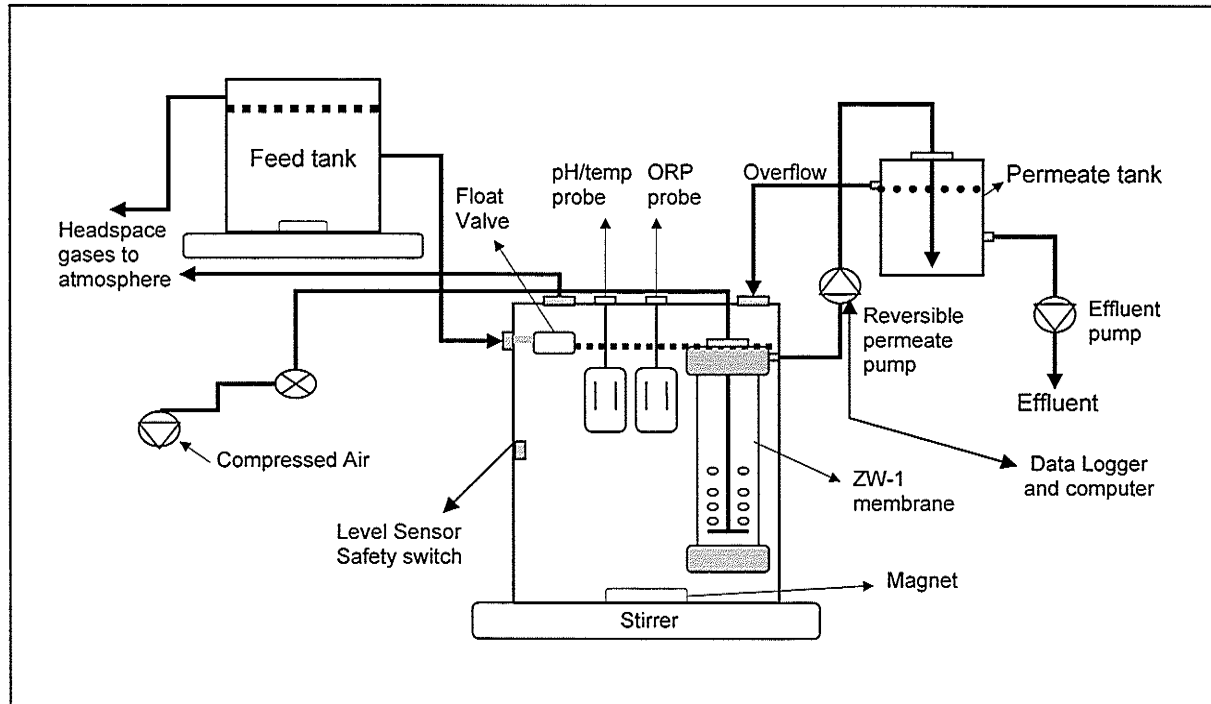
Figure 3.2- Picture of the bench scale system.
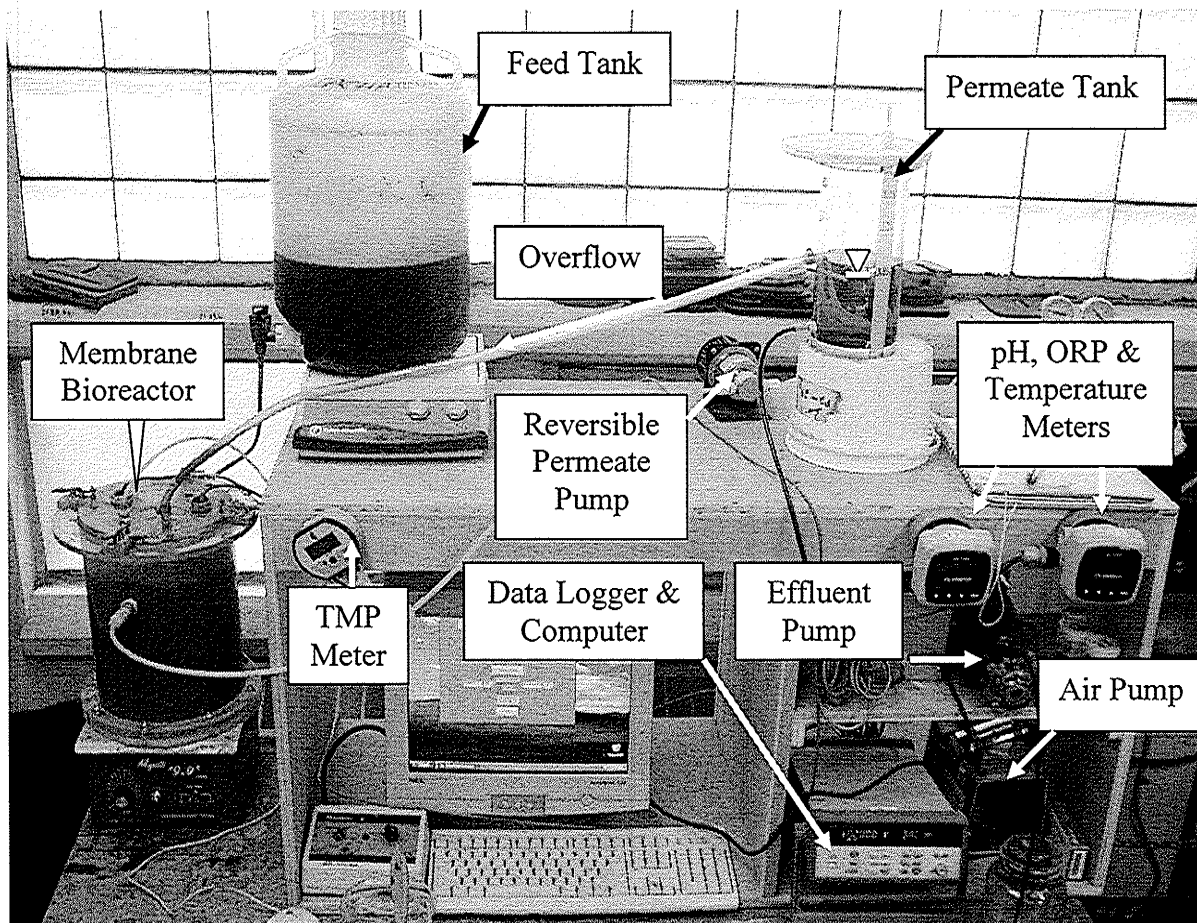
More information on system's details and operation are in the operator's manual for ZenoGem ZW-1 bench scale unit provided by Zenon Environmental Inc (refer to Zenon company for more information). This manual explains systems assemblies in detail. Also, the following list provides the name and catalogue number of components that was used in this experiment according to their availability in market during the period of experiment.

Table 3.1- MBR system compartments details.

Name	Catalogue number	Description	Supplier
1. Micropump	G187GA-X21-JFSG	Model G18	Viking Pump Canada
2. Pressure Gauge	EW-68925-02	Battery powered gauges	LABCOR
3. Data logging system	34970A	Data Acquisition/Switch unit	Agilent Technologies
	34907A	Multifunction Module for the 34970A	
	34901A	20-Chennel Armature multiplexer	
	82350B	High-performance PCL GPIB card for MS Windows	
	10833B	GPIB cable, 2 meter	

Name	Catalogue number	Description	Supplier
4. pH (with temp. display)	PHTX-271-1	pH/OPR Transmitter	OMEGA
	PH-2720-PA	Preamplifier for PHTX-8710	
	PHE-3271	Flat surface pH electrode	
	FP90UM	Universal NPT mount	
5. ORP	PHTX-271-1	pH/OPR Transmitter	OMEGA
	PH-2720-PA	Preamplifier for PHTX-8710	
	ORE-2715	Flat surface ORP electrode	
	FP90UM	Universal NPT mount	
6. Solenoid valve	SV-125	Solenoid valve	OMEGA
7. High-Capacity Vacuum/Pressure Pumps	U-07061-20	Single head, 1.0cfm, 115VAC	Cole Parmer

Name	Catalogue number	Description	Supplier
8. Closure caps	0292315	Filling/Venting with 83mmB Closure, Polypropylene	Fisher Scientific
9. Polypropylene, 20LT Jugs; 2 Packs of 4	029632B	Carboy, Round, Autoclavable, Leakproof, 83B screw size	Fisher Scientific
10. Glass Microfiber Filters (for TSS and VSS tests)	1827 037	Circles of 37mmΦ	Whatman

3.4 Experimental Procedures

The experiment was carried out for almost one year (355 d), beginning August 10th, 2004 and ending July 31st, 2005. A schedule of daily monitoring of the system, including temperature, ORP, pressure and pH with other observed changes in the system is presented in Appendix B.

During operation of the MBR system, the biomass in the bioreactor attached to pH, ORP probes, and bioreactor interior wall as well as membrane module body. Therefore, to prevent the attached growth and making sure that the samples were taken from the bioreactor for different experiments (using the batch method) are representative of a homogenous culture, the bioreactor was cleaned twice a day. Figure 3.3 shows the situation of the bioreactor when the lid was opened everyday at mornings and figure 3.4 shows the cleaned bioreactor working during day.

Figure 3.3- The situation in bioreactor almost every morning before cleaning

Figure 3.4- Bioreactor while working during the day (after daily cleanings)
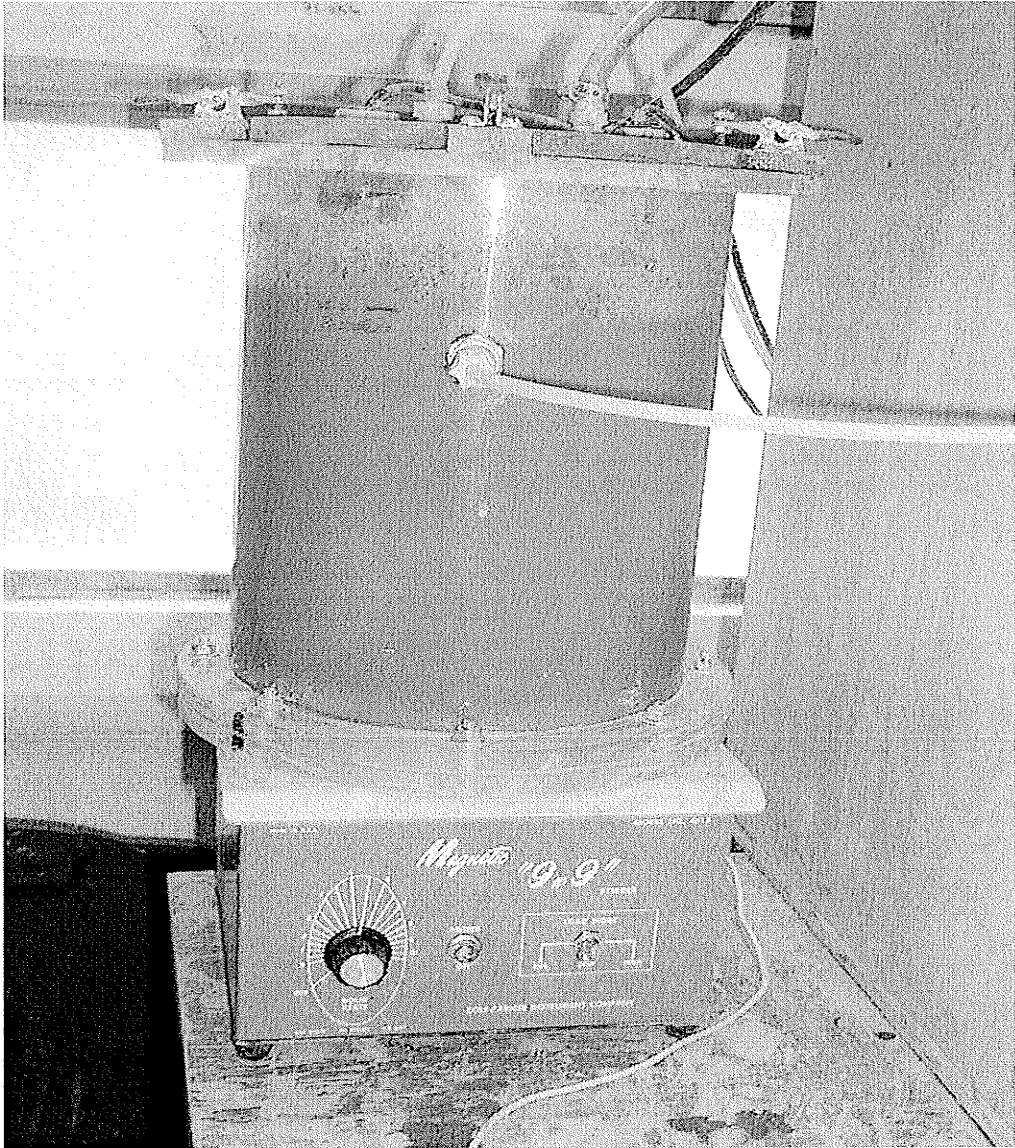
3.4.1 TSS and VSS

Total suspended solids tests were performed on weekly/biweekly basis according to standard methods #2540D (APHA- AWWA- WEF, 1998).

Volatile suspended solids experiments were done on the same schedule as that for TSS according to #2540E (APHA- AWWA- WEF, 1998).

The filter papers used for these series of tests, were provided by Whatman company and had smooth circle surface with surface diameter of 37mm Φ and pore size of 0.3 μm.

3.4.2 Toxicity

The test that was conducted for determining the toxicity was lethal concentration 50% or (Daphnia- LC50). According to standard methods for the water and wastewater treatment (APHA- AWWA- WEF, 1998), LC-50 is defined as the ability of certain amount of toxicant to kill certain proportion of bacteria (here 50%) in certain period of time (here in 48 hr). Daphnia-LC50 test was conducted on a less frequent basis according to standard methods # 8510.

3.4.3 Ammonia

All ammonia tests were performed by the flow injection analysis (Standard methods #4500-NH$_3$ H). Samples from leachate were taken weekly/biweekly and diluted into 1:20 and injected to the ammonia analyzer. Effluent samples were

taken from the effluent pump line, on the same schedule as that for ammonia and injected into the analyzer without any dilution.

3.4.4 Nitrate and Nitrite

Nitrate samples from the effluent were taken from the effluent pumping line every week (or every 2 weeks sometimes), diluted into 1:40 and analyzed using the standard methods #4500-NO_3^- I (APHA- AWWA- WEF, 1998).

Nitrite samples from the effluent were analyzed without any dilution using the same procedure as in nitrate.

3.4.5   Total Metals

Total metals including heavy metals were measured according to standard methods #3010 on a less frequent basis (APHA- AWWA- WEF, 1998).

3.4.6   COD

Samples were taken from leachate diluted into 1:5 while samples taken from the effluent were analyzed without any dilution. After half of a year samples were prepared for measuring the SCOD of leachate and biomass in the bioreactor with a dilution of 1:4. The suggested method was #5220 from the standard methods (APHA- AWWA- WEF, 1998).

3.4.7 TOC

Since the effluent from MBR system was free from suspended particles, in this test, dissolved organic carbon test, showed almost the same results as those from total organic carbon.

The test was conducted according to # 5310C from the standard methods (APHA-AWWA- WEF, 1998).

3.4.8 BOD$_5$

BOD$_5$ test were performed less frequently and according to standard method #5210 (APHA- AWWA- WEF, 1998).

3.4.9 Total Kjeldahl Nitrogen (TKN)

This test was done less frequently according to #4500-N$_{org}$ of standard methods (APHA- AWWA- WEF, 1998).

3.4.10 Changes of HRT-SRT Periods

Three sets of HRT-SRT were examined during this research to study systems response to different loading rates.

The first set was a 3.5-d HRT;60-d SRT and was started from the first day of the experiment, however, the results presented for the first period are those ones obtained after the first 40 d of acclimation period. The second period which

spanned from day 165 to day 250 was a 2-d HRT; 60-d SRT. Finally the last

period was a 1-d HRT; 30-d SRT and started after day 250 and lasted up to the

last day (day 355).

The HRT-SRT of the system has been reduced according to a judgment on

biomass concentration stabilization. After results of TSS/VSS concentration in the

bioreactor have shown that biomass has been reached to a stable level and full

nitrification has been reached in the system, the HRT-SRT of the system has been

decided to be changed.

4.0 RESULTS

4.1 Introduction

Observation for the first 2-3 weeks after switching from one HRT-SRT period to another was a considerable amount of foaming on the mixed liquor surface. Foaming was not only observed after the rapid change of biomass HRT-SRT, but whenever the system was interrupted due to electrical or mechanical failures for few hours to few days. Some reasons for the failures in the system during operation were: micro-pump wear out, disconnection of the computer to the system due to electrical interruptions, over night clog of the feeding tube, break of surface level controller, or stoppage of stir bar over night (which prevented a unified aeration of the biomass).

Figure 3.5 shows a considerable amount of foaming on the biomass surface after system's stoppage due to membrane exhaustion.

Figure 3-5. Foaming on the mixed liquor surface after a few days of problems

with the membrane exhaustion.

4.2 Maintenance of a Steady Biomass within the Reactor

During the MBR operation, excellent removal of suspended solids was achieved. Soluble organic and inorganic particles with size smaller than 0.3 μm (filter pore size) passed through the filter paper. The average mixed liquor total and volatile suspended concentrations during different HRT and SRT operations are presented in Table 4.1. The monitoring results for both the biomass and the filtered effluent are shown in Figures 4.1 and 4.2.

Typically the maximum ZeeWeed® Zeno Gem® design level for TSS of mixed liquor in the bioreactor is 15,000 mg/L (Jensen et al., 2001). Results in Table 4.1, show that the biomass extent exceeded this limit at the 30-d HRT, 2-d SRT. Although the TSS/VSS removal efficiency of the system was not affected by the HRT-SRT, the 60-d HRT, 2-d SRT is not recommended for this system.

Comparing the results from the 3.5-d HRT, 60-d SRT (first period) with the 1-d HRT, 30-d SRT (third period) from Table 4.1, overall less biomass VSS was measured for the first period than the third one. VSS is a measure of active portion of biomass which is microorganisms. The fact that the VSS in the third period is more than that in the first period, whereas the TSS in the third period is less than that it in the first period, conveys this meaning that due to the shorter SRT, more portion of inorganic materials were wasted daily, however, the contact time of nutrients with microorganisms in the third period was good enough to allow them to grow more.

As expected, effluent VSS was generally below the detection limit due to the effective retention of the biomass by the membrane. However, some TSS was observed in the effluent, which was attributed to the precipitation of soluble inorganic matter in the permeate line and tank. Nevertheless, in general the effluent quality in terms of TSS was below 30 mg/L and this level meets Manitoba Surface Water Guidelines for discharge into river stream.

Overall, a steady biomass concentration is maintained in the reactor (Figure 4.1) despite fluctuations in the incoming feed (Figure 4.3). Although the need for membrane manual cleaning increased when HRT was reduced, the efficiency of the module in TSS and VSS removal did not show any changes. Appendix E, presents the TSS and VSS of biomass, leachate and effluent from every time sampling. Figures 4.1, 4.2, and 4.3 are developed using data from Appendix E.

Due to the lack of mixing and high retention times, soluble inorganics such as calcium salts that found their way into the effluent tank could precipitate in the final effluent collection tank. Figures 4-4a and 4-4b show the precipitation in the final effluent tank and Figure 4-4c shows the precipitation in the permeate tank.

Table 4.1- Average total and volatile suspended solids of biomass and effluent

for different operating conditions

	TSS (mg/L)			VSS (mg/L)		
	Biomass	Effluent	RE (%)	Biomass	Effluent	RE (%)
HRT=3.5d; SRT=60d	10206±394	18±4.0	99.8	4920±297	7.1±1	99.9
HRT=2.0d; SRT=60d	21039±730	21±6	99.9	9893±520	9.5±7	99.9
HRT=1.0d; SRT=30d	9719.2±526	17.8±5.6	99.8	5311.1±326	6.8±2.7	99.9

Figure 4.1 - Total and volatile suspended solids in the MBR
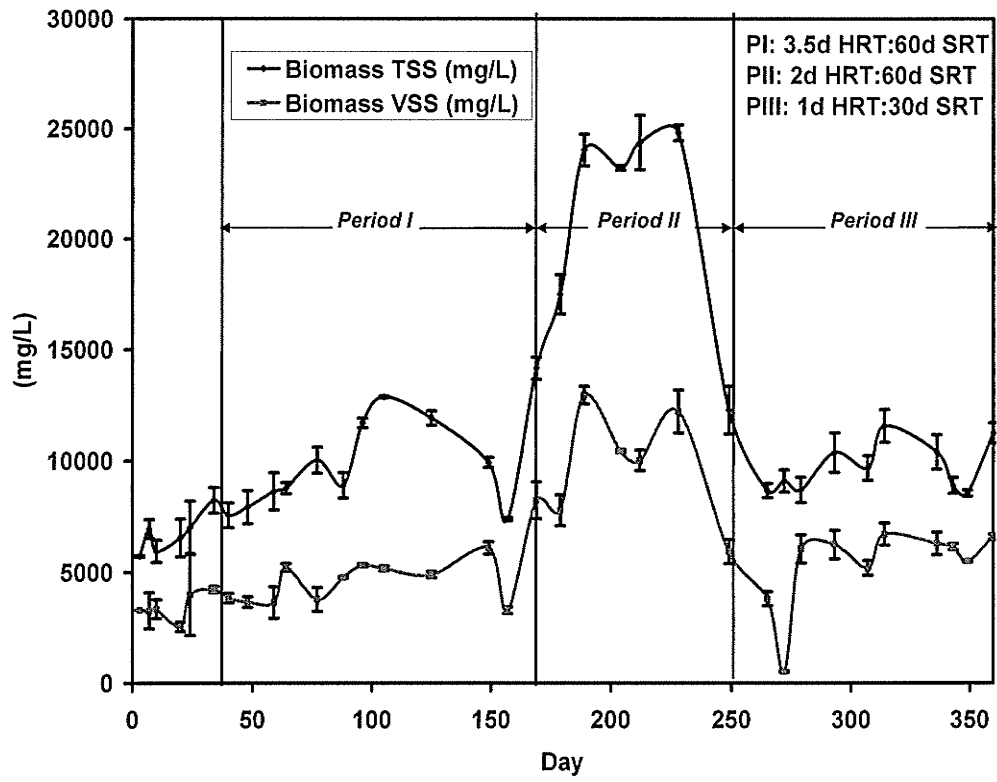
Figure 4.2 - Total and volatile suspended solids in the effluent
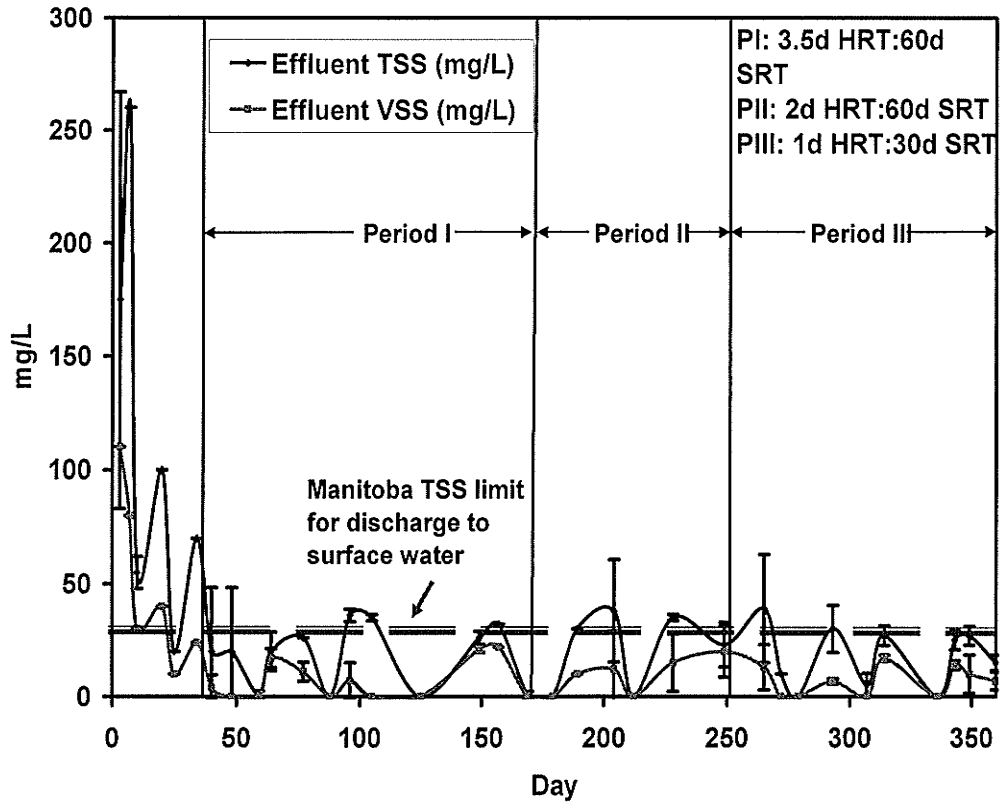
Figure 4.3 - Total and volatile suspended solids in the leachate
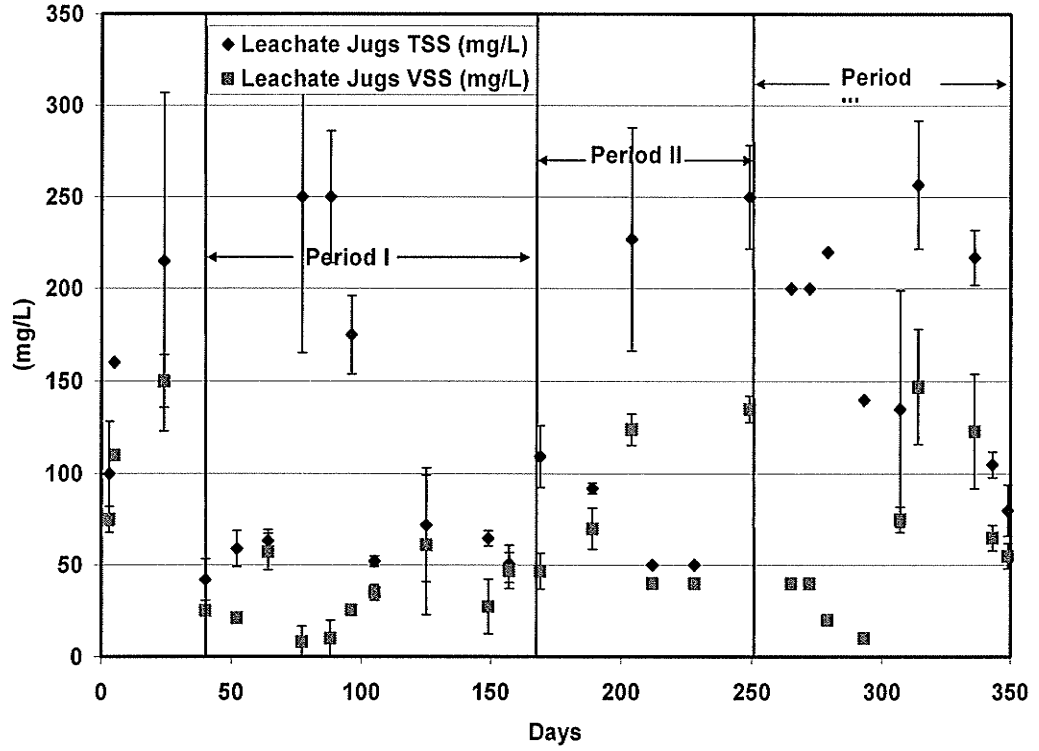
PI: 3.5d HRT:60d SRT
PII: 2d HRT:60d SRT
PIII: 1d HRT:30d SRT

Figure 4.4- (a) Precipitation in the final effluent tank (right); (b) Calcium carbonate salts precipitants (left); (down) (c) soluble

constituents from the pumping line settled in the permeate tank.
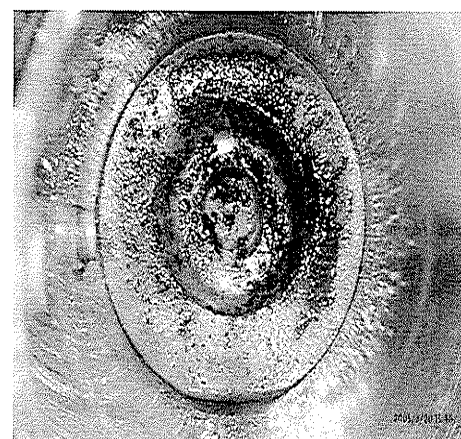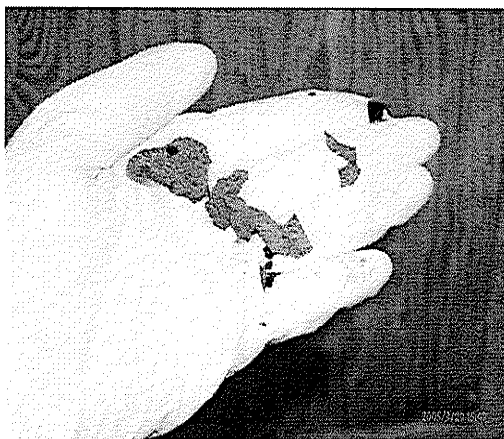
4.2 Effective Removal of COD and BOD$_5$ from Leachate

COD removal from the landfill leachate throughout MBR operation is shown in Figure 4.5. In figure 4.5, also, values of TOC (which is the same as DOC, in this case) are shown. TOC values are presented as the process control values. The variation in temperature within the MBR system did not appear to affect the COD removal efficiencies, as the temperature did not drop below 15°C, even in winter conditions. The BOD was reduced 97.7% at HRT of 3.5-d and SRT of 60-d, 96.8% at HRT of 2-d and SRT of 60-d, and 97.7% for the period of 1-d HRT-30-d SRT. From data presented in Table 4.2, it is possible to conclude that excellent BOD removal was achieved. Depending on the COD content and characteristics of organic matter in the leachate, COD removal ranging from 51% to 78 % was observed.

MBRs are generally expected to be less successful in removal of COD in a great extent as well as other biological methods, however, COD removal greater than 99% can be achieved using multistage biological treatment (MBR/AC/NF) since the amount of COD in leachate has a direct relationship with leachate age, it normally can only be removed up to 60% if the leachate is old (>5years old) (Alvarez-Vazquez et al., 2004). Also, The SCOD of both leachate and biomass were measured (Table 4.2). Since there were a noticeable different between the two values, it can be said that biodegradation was occurring in the bioreactor and the COD removal is primarily due to biodegradation not filtration

Referring to Table 2.1 and comparing the results of BOD/COD obtained from this study, leachate examined through the whole period categorizes as generally old leachate. Appendix C, presents raw data from COD and DOC monitoring.

Table 4.2 - Organic carbon data with three different SRT and HRT.

Parameter (unit)	HRT=3.5d; SRT=60d	HRT=2.0d; SRT=60d	HRT=1.0d; SRT=30d
Leachate Quality			
COD (mg/L)	3208±718	4079±1163	2737±537
BOD$_5$ (mg/L)	528±675	730	300
BOD$_5$/COD	0.16	0.18	0.11
SCOD	na	3444.5±153	2792.4±86
COD/VSS (kg/kg.d)	0.19	0.21	0.84
Nominal flow rate (L/d)	2.14	3.75	7.5
Biomass			
SCOD (mg/L)	1400±123	963.4±80	1669.4±143
Effluent Quality			
COD (mg/L)	1032±200	871±333	1271±190
BOD$_5$ (mg/L)	12±13.5	23	7
BOD$_5$/COD	0.012	0.026	0.006
DOC	222.5±46	214.3±109	273±26
DO (mg/L)	7.5-8.5	7.2-8.0	5.4
pH	8.5	8.3	8.4

Figure 4.5 - Organic carbon of leachate and effluent; RE%, total COD removal

(%)
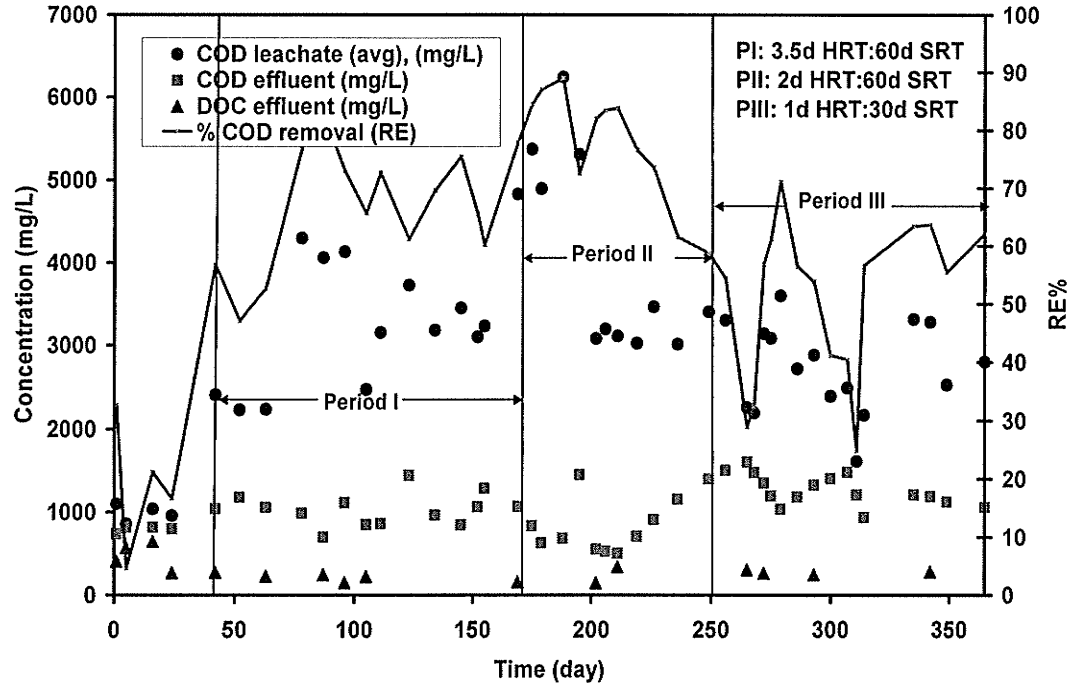
Figure 4.6- Average leachate COD and BOD5, and average effluent COD and

BOD $_5$ during the three test periods and comparing them with the standard BOD5

level (30mg/L) according to Manitoba surface water regulation guideline
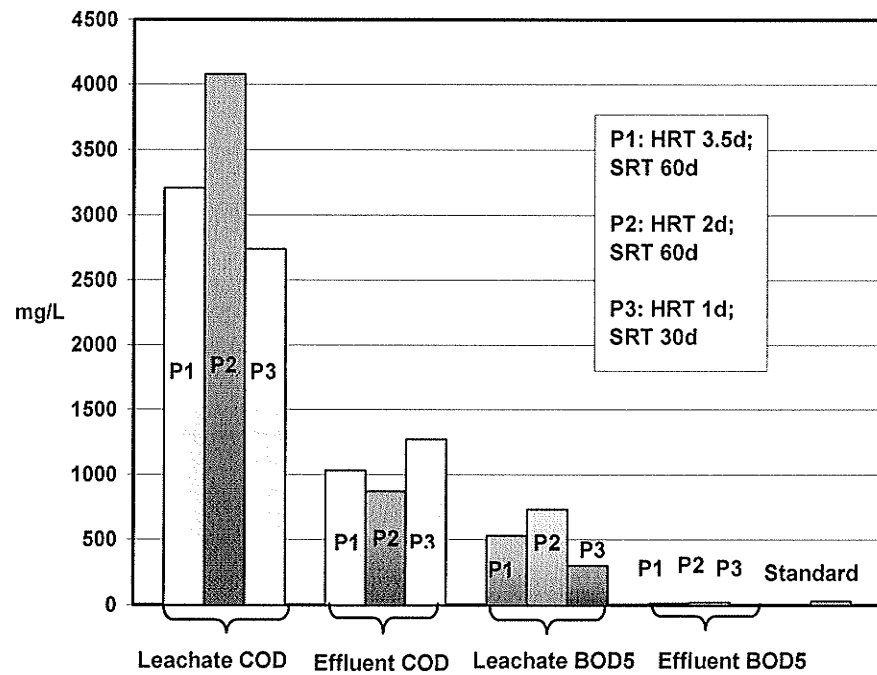
Figure 4.7- Average amount of COD and ammonia loading per kg of biomass per day, during the three assigned HRTs-SRTs.

P1: HRT 3.5d; SRT 60d

P2: HRT 2d; SRT 60d

P3: HRT 1d; SRT 30d

Leachate COD/VSS   Leachate NH3-N/VSS

Kg/Kg.d
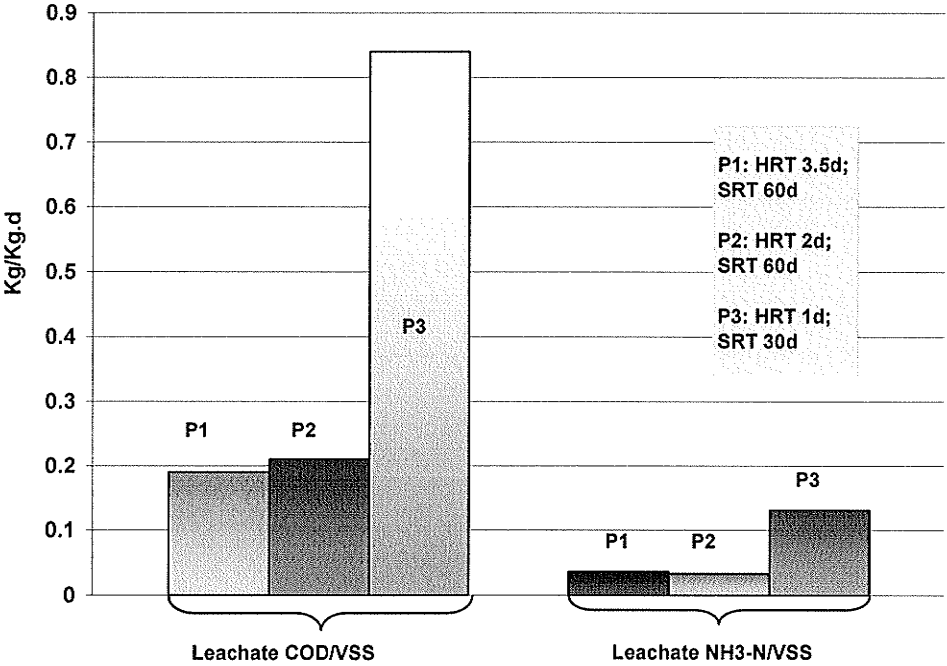
4.3 Evaluation of Ammonia Removal and Nitrification Stability

Approximately 40 days after start-up, full nitrification was achieved (Figure 4.6, Table 4.3). The 40 days also marked the time when steady-state operation was assumed and overall performance of the systems was evaluated.

According to Manitoba Surface Water Guidelines, the suggested amount of ammonia in water is among 5-10 mg/L depending on temperature and pH. Although the effluent quality in this research, generally meets the guideline's standard limit it seems that the trivial amount of effluent ammonia and TKN might still contribute in toxicity of the effluent to some extent. Also, full nitrification was achieved in all three periods of HRT- SRT, for the most of monitoring despite highly variable influent ammonia concentrations of 645±175 mgN/L. Nitrification in the system could not be completely maintained all the times. The consistency of nitrification in the effluent was affected by different interruptions in the system such as membrane fouling, micro-pump crash, feeding line clogging, etc.

The average amount of nitrate in the effluent remains high (660mg/L). No limitation for nitrate content of wastewater for discharge into the river is mentioned in Manitoba surface water guidelines. This high amount can be reduced by adding a post treatment stage such as RO treatment or biological denitrification system. Ammonia monitoring raw data are presented in Appendix D.

Table 4.3 - Average leachate and effluent ammonia and TKN concentrations and

ammonia reduction rate

	HRT=3.5d; SRT=60d	HRT=2.0d; SRT=60d	HRT=1.0d; SRT=30d
Leachate Ammonia (mgN/L)	617.2±224.2	648±169	671±132
Leachate TKN (mgN/L)	na	1150	746
Effluent Ammonia (mgN/L)	1.3	8	6.3
Effluent TKN (mgN/L)	24	13	74
Biomass TKN (mg/L)	na	489	204
NH_3/VSS (kgN/kg.day) (bioreactor)	0.125	0.066	0.126

Figure 4.8 - Ammonia removal during the 3 operational periods of the MBR
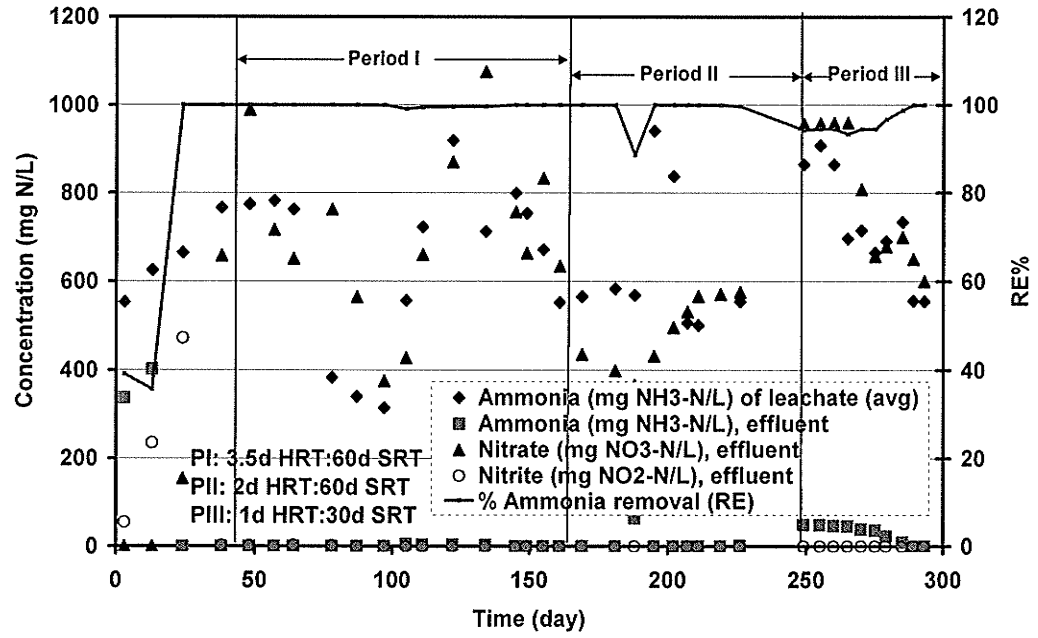
4.4 Retention of Metals in the MBR

Table 4.4 presents the removal a selected group of metals from the incoming leachate. Significant removal of iron, lead, manganese, cadmium and aluminum was observed, along with lesser retention of some other metals within the MBR. The loading rate (HRT) of the MBR did not appear to have a substantial effect on metals retention.

Figure 4.7, represents a visual comparison of major heavy metals in leachate as well as effluents during three periods of HRT; SRT along with Manitoba guidelines for discharge of wastewater into the river. A glimpse of data presented in this figure shows that generally metal concentration of leachate in Manitoba is not of a great concern, however the only troublesome metal seems to be chromium. The reason that chromium is in high concentration even after treatment should be found in the type of waste that is disposed in the landfill. Normally, chromium in the solid waste comes from the industrial activities that are dealing with metal plating (Appendix A). Pre-treatment of industrial waste stream that comes from such industrial activities can result in reduction of chromium level in the leachate produced. Appendix F discloses all details about total metals examinations.

Table 4.4 - Metals removal in the MBR system.

		PI	PII	PIII	PI	PII	PIII	(mg/L)
Metals	Leachate (mg/L) (Average)	Effluent (mg/L) (Average)	Effluent (mg/L) (Average)	Effluent (mg/L) (Average)	Removal efficiency (%)	Removal efficiency (%)	Removal efficiency (%)	Manitoba Surface Water GL
Aluminum(Al)	0.3583	<0.1293	<0.05	0.34	>42.52	>84.85	5.12	0.005-0.1
*Arsenic(As)	0.0173	0.0131	0.014	0.0158	0.00	26.32	8.85	0.05
*Cadmium(Cd)	0.0008	<0.0001	<0.0001	<0.0002	>90.51	>82.14	>73.65	0.001
*Chromium(Cr)	0.0614	0.0428	0.026	0.069	11.39	36.59	0.71	0.02
*Copper(Cu)	0.0168	0.0165	0.012	0.015	29.79	0.00	10.89	0.3
Iron(Fe)-Total	6.9667	<1.735	<1	3.15	>83.79	>75.61	54.78	40
*Lead (Pb)	0.0125	<0.0126	<0.001	0.0046	>16.00	>85.07	63.10	0.2
Manganese(Mn)	0.6575	0.0396	0.067	0.294	93.85	93.50	55.29	0.2
*Nickel(Ni)	0.1419	0.129	0.0786	0.216	0.00	0.00	1.32	0.5
Phosphorus(P)-total	7.5850	0.9000	**na	0.3	90.87	na	96.04	na
*Selenium(Se)	0.0118	<0.008	<0.002	0.015	>5.88	>0.00	0.00	0.01
*Zinc(Zn)	0.5000	0.2895	0.077	0.36	0.00	60.91	28.00	0.5

*heavy metal

**na: Not Available

Figure 4.9- Average leachate, effluent heavy metal concentrations and their comparison with the standard guideline
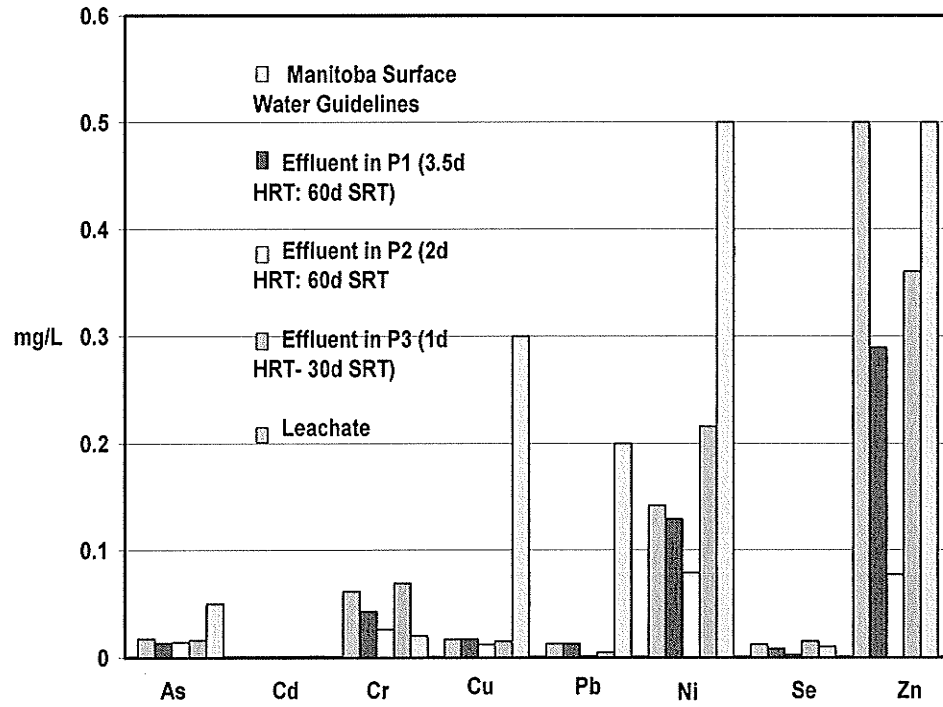
4.5 Toxicity Reduction with the MBR

Analytical studies were done with respect to the overall reduction of toxicity (as Daphnia-LC50) with the use of the MBR. Obtained results for all leachate samples during all three periods showed mortality in all concentrations (from 100-12.5% dilutions).

No mortality was observed in the effluent during the first period (3.5-d HRT, 60-d SRT). However 70% mortality was observed in 0-1:4 dilutions for the effluent from 2-d HRT, 60-d SRT and 0% mortality (no toxicity) was observed in higher dilutions. During the third period 100% mortality was observed in all concentrations of 100, 75 and 50%. 70% mortality was observed in 1:4 dilution (or 25% concentration) and no mortality was observed in dilutions higher than 1:4 (or 25%> concentrations).

Effective reduction of toxicity was primarily attributed to the complete removal of ammonia and reduction of metals from the leachate. Heavy metal components in the effluent from the third period were, in overall, higher than those in the first two periods (Figure 4.7). The toxicity extent observed in the effluent from the last period was expected to be lower that that was reported. There is a probability that since samples were analyzed only after 4 days of a one week period of system pause due to membrane module exhaustion, the effluent quality was reflecting the results from the pause period (not efficient filtration as well as deficient nitrification).

Table 4.5 shows the exact results from toxicity test of leachate and effluent samples during the three loading conditions.

Table 4.5- Toxicity results from leachate samples and effluents

Sample Concentration v/v (%)		100	75	50	25	12.5	0
Percent Immobility	**All Leachate Samples**	100	100	100	100	100	0
	HRT:3.5d-SRT:60d	0	0	0	0	0	0
	HRT: 2d-SRT: 60d	100	75	0	0	0	0
	HRT: 1d-SRT: 30d	100	100	100	70	0	0

4.6 Results from Daily Monitoring

The pH as well as the temperature of the system remained fairly stable at about 8.4, and 22.5°C, respectively. ORP values remained high throughout operation indicating the presence of residual oxygen in the system. Appendix A provides the daily observations of the system in detail.

The trans-membrane daily pressure monitoring results are presented in Figure 4.10.

Figure 4.10- Transmembrane daily monitoring
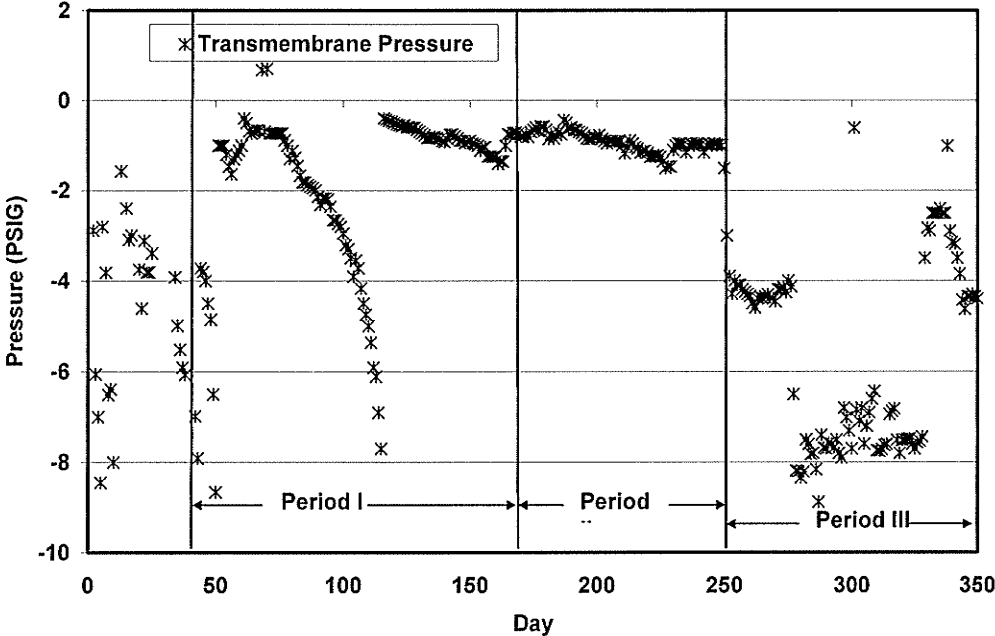
5.0 DISCUSSION

5.1 Current Condition of Treated Leachate

The current water quality guidelines in Manitoba would allow the MBR effluent

to be discharged directly to surface water as effluent BOD, TSS, ammonia, trace

metals, dissolved oxygen, and toxicity levels are below discharge limits. However

future limitations on COD and nitrate discharge as well as toxicity to surface

water bodies would necessitate post-treatment of the MBR effluent. The advanced

treatment stage can be either reverse osmosis (RO) or powdered activated carbon

(PAC) filtration.

The MBR treated effluent could also be used to irrigate part of the landfill. This

would be done to promote biogas production throughout the landfill. As this

alternative would require extensive pumping and piping, the scaling potential of

the effluent will be of importance. After permeate was pumped into the effluent

tank, a considerable amount of precipitation and scaling was noticed. The scaling

materials are comprised of different soluble salts and metals that pass through the

hollow-fiber membranes pores. These will precipitate and act as scaling agents

when mixing and turbulence is reduced. The scaling can be limited if the effluent

pH is adjusted to 6.5 (since metals are insoluble in almost neutral pH) or by

adding anti-scalant to the effluent (Cameron et al., 2001).

Another potential problem is foaming in the bioreactor due to the high variation in

organic loading and rigorous aeration and mixing to provide sufficient dissolved

oxygen to the highly concentrated mixed liquor. In order to prevent foaming in the MBR, some dosage of anti-foam chemical might become necessary during on-site operation (Jensen et al., 2001).

5.2 Comparison of the Results & Other Research Studies

Comparing the COD removal results from this research (51-78% removal), with ozonation process when applied for landfill leachate treatment (with removal efficiency of 50-71%) (Wange et al., (2003)), with a small difference MBR is more effective than ozonation, however, ozonation alone, as well as MBR alone can hardly achieve the discharge requirements. Both methods are suggested to be used as pretreatment stage. In this situation, MBR has priorities to be used as the pretreatment stage over ozonation. MBR is cheaper and is more versatile to pH fluctuations whereas, ozonation is effective in a narrow range of pH (7-8).

Comparing the COD removal of MBR with the hydrogen peroxide/UV method, H_2O_2/UV has a higher COD removal efficiency (85%), however due to considerable disadvantages of this method (i.e., slow reaction and self-decomposition rates, influence on the subsequent biological treatment systems and ecosystems of the receiving water), Wang et al., (2003) did not suggest any hydrogen peroxide-related processes for treatment of landfill leachate.

The COD removal by MBR in this research was higher that that in the MBR system study of Chaturapruek et al., (2004).

If the RO processes is added as the polishing stage to the MBR more removal of the remaining inorganic nitrogenous ions and dissolved non-biodegradable organic matters as well as negatively charged nitrified compounds (Ahn et al., 2002) will be achieved. PAC treatment, also, would reduce effluent COD levels but would also require pre-denitrification to eliminate nitrate. Another possibility is to dose PAC directly into the MBR to further facilitate non-biodegradable COD removal (Yiantsis and Karbabelas, 2001). Such a hybrid system has not yet been tested for landfill leachate treatment.

According to Trebouet et al., (2001), coagulation of landfill leachate was successful to remove COD only up to 6% and SS only up to 27mg/L. Obviously in this case, in term of comparison, MBR has a great priority.

Loukidou and Zouboulis, (2000); investigated and compared two biological systems using attached- growth system for treatment of landfill leachate (section 2.3.3). The GAC polishing stage was accompanied to this research study. Results obtained from this research are summarized in Table 2.3 in terms of COD, ammonia and BOD_5 removal. Comparing removals of COD (65%), ammonia (95%) and BOD_5 (90%) in that research with what were obtained from MBR treatment: COD (71%), ammonia (98%) and BOD_5 (98%), it can be said that the Loukidou and Zouboulis's system even after addition of GAC, could not be as efficient of MBR system even without addition of GAC.

MBR results also are superior to those obtained from treatment of landfill leachate by activated sludge methods. Bohdziewicz et al., (2000) in Poland, Geenens et al., (2000) in Belgium and Bae et al., (1999) investigated leachate treatment by activated sludge method. Bohdziewicz et al., (2000) observed no COD removal. Geenens et al., (2000) achieved up to 81% COD removal for the AS system using ozonation pretreatment stage however ammonia removal in his system was pretty low (21%) and the high cost of ozone also was mentioned to be troublesome in the full-scale system.

Bae et al., (1999) also used the activated sludge system for treating of landfill leachate. Despite a high removal of BOD (98%), high content of COD, DOC and VSS in the system showed the AS alone can not compete with the MBR system.

Comparing the results obtained in the MBR study with other MBR systems (pilot or full scale systems) a similarity in efficiency of this system is noticeable (Wichitsathian et al., 4004; Jensen et al., (2001); Ahn et al., (2002); Wehrle (1997); Wehrle (1998); and Wehrle (2001)).

5.3 Significance of This Research

This research has shown a broad success in terms of refractory pollutants removal from landfill leachate with the simple application of MBRs. Treating leachate by MBR technology is a recent experience in North America and results obtained from this research study are useful for future studies dealing with leachate

treatment, MBR technology for wastewater treatment as well as establishment of a full-scale on-site leachate treatment system for Winnipeg's landfill. This study shows that an MBR operated at HRTs as low as 1d can achieve effluent that can be discharged directly in Manitoba's surface waters, providing on alternative for Winnipeg's landfill operators. The versatile characteristics of MBRs are fully compatible with the highly fluctuating nature of landfill leachate.

6.0 CONCLUSIONS

6.1 Principle Hypothesis and Conclusions

This study has shown that aerobic membrane bioreactor technology can be an effective alternative to traditional activated sludge treatment, or other physcio-chemical methods for treating landfill leachate. COD removal ranged from 51 to 78%, depending on the influent leachate source and hydraulic retention time of the system. The MBR showed excellent BOD_5 removal of 97% and higher, even at HRT as low as 1d. Complete suspended solids removal and nitrification of the incoming ammonia was observed. Significant removal of selected trace metals such as iron, lead, manganese, cadmium and aluminum from the incoming leachate was achieved.

No significant changes in the removal efficiency of metals, ammonia, COD and BOD_5 were observed at different SRT-HRT conditions. 100% of the toxicity was removed from the leachate at the HRT of 3.5d while 75% was removed when the HRT was reduced to 2d. The effluent produced with the MBR met current surface water quality guidelines enabling possible discharge to a natural stream. Future nitrate and COD regulations would require post-treatment which could involve reverse osmosis or powdered activated carbon treatment. Regardless of the landfill leachate age, full nitrification and biodegradable organic carbon removal was achieved in the MBR

Young (originating from fresh solid waste) landfill leachate contains large amount of free volatile fatty acids, resulting in high concentration of COD, BOD, BOD/COD, NH_3-N and alkalinity but low ORP (Wang et. al, 2003). During ageing of the landfill, the BOD/COD decreases rapidly due to the release of the large refractory organic molecules from the solid wastes followed by dissolution into the leachate. Old landfill leachate as well as the biological treated young leachate (in comparison with young leachate) are characterized by high COD, ORP, pH (>7), and low BOD and BOD/COD and fairly high NH_3-N and alkalinity. Therefore, biological treatment processes can be much more effective for young landfill leachate treatment. The leachate treated in this research was generally in old category due to low BOD/COD (=0.1), despite being pumped randomly from different collection wells.

Significant variations in COD, BOD, and ammonia loadings to the MBR showed the effectiveness of the system under fluctuating conditions. The effluent quality is a good indicator that a full-scale, on-site MBR system will be able to handle the fluctuating nature of landfill leachate volume and quality.

6.2 Recommendations for Future Work

Demonstration of an on-site pilot-scale plant will follow the laboratory study. The pilot-scale plant is proprietary to Zenon Environmental Incorporation and is essentially a 25-fold scale-up of the bench-scale MBR system. This unit will be installed at the landfill site in summer 2005 to validate some of the results

obtained with the bench-scale system. The successful demonstration of the pilot-scale MBR will lead to a feasibility study for a full-scale system, at which point issues related to effluent and waste activated sludge disposal will be significant. Since disposing the effluent or waste sludge to the municipal wastewater treatment plant would require the continued practice of daily trucking, alternative disposal is desired (Cameron et al., 2001).

1. In this research, the effect of age of leachate on changes of the MBR performance was not studied. Arranging for the organized feeding to the reactor by certain age of landfill and following a non-arbitrary feeding plan to the MBR is suggested for future studies.

2. When changes in HRT were implemented, a noticeable amount of foaming appeared on the surface of the mixed liquor, which was a sign of biomass stress because of sudden increase in loading . Due to the highly variable nature of the leachate, injection of some dosage of anti foaming chemicals could become necessary in full-scale applications.

3. By putting the final cover on any cell at the landfill as well as any change in landfilling operation and/or design, would impact the amount of leachate produced which causes the leachate production would be expected. Therefore, different monitoring results for the leachate quality

collected from covered cells is expected rather than those from uncovered cells.

4. Future studies on incorporating PAC to the MBR should be conducted to assess additional COD and toxicity removal as well as improvements in membrane flux. It is expected that a hybrid MBR/PAC system will achieve better effluent quality through the removal of natural organic matter and SOCs, color and odor from the leachate.

5. Some researches have suggested that, instead of using bacteria in MBRs, yeast be used (YMBR), which could reduce membrane biofouling extend membrane module life. This avenue could be explored in future work.

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1 Appendix A

Typical waste compounds produced by commercial, industrial, and agricultural activities that have been classified as priority pollutants

Name	Formula	Use	Concern
Arsenic	As	Alloying additive for metals, especially lead and copper as shot, battery grids, cable sheaths, boiler tubes. High-purity (semiconductor) grade.	Carcinogen and mutagen. *Long-term*—sometimes can cause fatigue and loss of energy; dermatitis
Barium	Ba	Getter alloys in vacuum tubes, deoxidizer for copper, Frary's metal, lubricant for anode rotors in x-ray tubes, spark-plug alloys	Flammable at room temperature in powder form. *Long-term*—Increased blood pressure and nerve block
Cadmium	Cd	Electrodeposited and dipped coatings on metals, bearing and low-melting alloys, brazing alloys, fire protection system, nickel-cadmium storage batteries power transmission wire, TV phosphors, basis of pigments used in ceramic glazes, machinery enamels, fungicide, photography and lithography, selenium rectifiers, electrodes for cadmium-vapor lamps and photoelectric cells	Flammable in powder form. Toxic by inhalation of dust or fume. A carcinogen. Soluble compounds of cadmium are highly toxic. *Long-term*—concentrates in the liver, kidneys, pancreas, and thyroid; hypertension suspected effect
Chromium	Cr	Alloying and plating element on metal and plastic substrates for corrosion resistance, chromium-containing and stainless steels, protective coating for automotive and equipment accessories, nuclear and high-temperature research, constituent of inorganic pigments	Hexavalent chromium compounds are carcinogenic and corrosive on tissue. *Long-term*—skin sensitization and kidney damage
Lead	Pb	Storage batteries, gasoline additive, cable covering, ammunition, piping, tank linings, solder and fusible alloys, vibration damping in heavy construction, foil, babbitt and other bearing alloys	Toxic by ingestion or inhalation of dust or fumes. *Long-term*—brain and kidney damage; birth defects
Mercury	Hg	Amalgams, catalyst electrical apparatus, cathodes for production of chlorine and caustic soda, instruments, mercury vapor lamps, mirror coating, arc lamps, boilers	Highly toxic by skin absorption and inhalation of fume or vapor. *Long-term*—toxic to central nervous system, may cause birth defects
Selenium	Se	Electronics, xerographic plates, TV cameras, photocells, magnetic computer cores, solar batteries (rectifiers, relays), ceramics (colorant for glass), steel and copper, rubber accelerator, catalyst, trace element in animal feeds	*Long-term*—red staining of fingers, teeth, and hair; general weakness; depression; irritation of nose and mouth
Silver	Ag	Manufacture of silver nitrate, silver bromide, photochemicals; lining vats and other equipment for chemical reaction vessels, water distillation, etc.; mirrors, electric conductors, silver plating electronic equipment; sterilant, water purification, surgical cements, hydration and oxidation catalyst, special batteries, solar cells, reflectors for solar towers, low-temperature brazing alloys, table cutlery, jewelry, dental, medical, and scientific equipment, electrical contacts, bearing metal, magnet windings, dental amalgams, colloidal silver used as a nucleating agent in photography and medicine, often combined with protein	Toxic metal. *Long-term*—permanent gray discoloration of skin, eyes, and mucous membranes

2 Appendix B- Daily Monitoring

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
12-Aug	11	2	8.39	139	24.7	-2.88	
13-Aug	10:27	3	8.65	139	26.2	-6.06	
14-Aug		4	8.65	130	26.2	-7	
15-Aug	11:00	5	8.67	127	26.3	-8.45	
16-Aug		6	8.68	126	27	-2.8	
17-Aug	10:00	7	8.7	126	27.2	-3.82	
18-Aug	10:00	8	8.74	127	27.1	-6.51	
19-Aug	10:00	9	8.81	129	25.1	-6.39	
20-Aug	10:00	10	8.93	131	23.9	-8	
23-Aug	10:00	13	8.81	439	24.7	-1.57	Membrane Was Changed
25-Aug	10:40	15	8.63	602	24.8	-2.39	
26-Aug	10:40	16	8.4	642	26.3	-3.09	
27-Aug	10:40	17	8.44	634	25.5	-2.99	
30-Aug	10:40	20	8.39	572	25.6	-3.75	
31-Aug	10:40	21	8.45	569	25.3	-4.61	
Sep-01	10:40	22	8.49	565	25.3	-3.11	
Sep-02	10:40	23	8.49	586	26.1	-3.81	
Sep-03	10:40	24	8.45	576	25.6	-3.81	
Sep-04	10:40	25	8.56	415	26.8	-3.39	
Sep-13	10:40	34	8.34	328	25.4	-3.92	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Sep-14	10:40	35	8.53	319	24.6	-4.99	
Sep-15	10:40	36	8.52	328	24.5	-5.52	
Sep-16	10:40	37	8.53	311	24.5	-5.91	PI started
Sep-17	10:40	38	8.53	302	24.9	-6.07	
Sep-21	10:40	42	8.35	269	25.8	-6.98	
Sep-22	10:40	43	8.47	253	24.3	-7.91	Membrane Was Changed
Sep-23	10:40	44	8.44	251	24.8	-3.72	
Sep-24	10:40	45	8.44	251	24.9	-3.8	
Sep-25	10:40	46	8.44	251	25	-4	
Sep-26	10:40	47	8.44	251	25.1	-4.5	
Sep-27	10:40	48	8.44	251	25.3	-4.86	
Sep-28	10:40	49	8.44	248	24.2	-6.5	
Sep-29	10:40	50	8.09	150	24.2	-8.66	Membrane Was Changed
Sep-30	10:40	51	8.2	225	24.3	-1	
Oct-01	10:40	52	8.03	218	23.8	-1	Damage of level control
Oct-02	10:40	53	8.53	282	22.7	-1	
Oct-03	10:40	54	8.45	289	23.7	-1.2	
Oct-04	10:40	55	8.36	306	21.9	-1.46	
Oct-05	10:40	56	8.46	314	21.5	-1.63	
Oct-06	10:40	57	8.44	318	24	-1.3	

2-c

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)
Oct-07	10:40	58	8.04	231	24.5	-1.2
Oct-08	10:40	59	8.45	325	25.7	-1.11
Oct-09	10:40	60	8.4	350	25.9	-1
Oct-10	10:40	61	8.4	400	26	-0.4
Oct-11	10:40	62	8.2	480	26.3	-0.5
Oct-12	10:40	63	8.06	549	26.5	-0.68
Oct-13	10:40	64	8.46	552	25.8	-0.73
Oct-14	10:40	65	8.48	574	22.8	-0.7
Oct-15	10:40	66	8.44	582	24.5	-0.66
Oct-16	10:40	67	8.5	570	23	-0.67
Oct-17	10:40	68	8.59	563	22	0.68
Oct-18	10:40	69	8.6	565	22.5	-0.69
Oct-19	10:40	70	8.62	566	23.3	0.71
Oct-20	10:40	71	8.62	561	23.8	-0.73
Oct-21	10:40	72	8.62	568	23.6	-0.73
Oct-22	10:40	73	8.64	573	23.5	-0.73
Oct-23	10:40	74	8.64	578	23.3	-0.73
Oct-24	10:40	75	8.65	580	23.1	-0.73
Oct-25	10:40	76	8.68	581	23	-0.73
Oct-26	10:40	77	8.5	570	23.5	-0.88
Oct-27	10:40	78	8.42	562	24.1	-1
Oct-28	10:40	79	8.69	569	24.3	-1.29

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)
Oct-29	10:40	80	8.67	581	24.9	-1.12
Oct-30	10:40	81	8.7	560	22	-1.27
Oct-31	10:40	82	8.75	542	21.9	-1.45
Nov-01	10:40	83	8.71	540	22.6	-1.66
Nov-02	10:40	84	8.81	564	22.6	-1.81
Nov-03	10:40	85	8.79	560	22.8	-1.82
Nov-04	10:40	86	8.75	555	22.9	-1.87
Nov-05	10:40	87	8.7	540	23.4	-1.91
Nov-06	10:40	88	8.65	534	23.8	-1.94
Nov-07	10:40	89	8.6	500	23	-1.99
Nov-08	10:40	90	8.6	485	22.7	-2.13
Nov-09	10:40	91	8.58	477	22.1	-2.31
Nov-10	10:40	92	8.64	477	23	-2.16
Nov-11	10:40	93	8.66	466	22	-2.17
Nov-12	10:40	94	8.68	458	21.6	-2.19
Nov-13	10:40	95	8.6	444	21	-2.35
Nov-14	10:40	96	8.54	435	20.5	-2.65
Nov-15	10:40	97	8.61	439	21.2	-2.66
Nov-16	10:40	98	8.65	437	21.5	-2.73
Nov-17	10:40	99	8.6	444	22.5	-2.8
Nov-18	10:40	100	8.56	454	23.5	-2.95
Nov-19	10:40	101	8.57	431	22.9	-3.21
Nov-20	10:40	102	8.61	420	22.8	-3.3

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Nov-21	10:40	103	8.65	415	22.7	-3.5	
Nov-22	10:40	104	8.61	382	21	-3.91	
Nov-23	10:40	105	8.64	371	22.4	-3.55	
Nov-24	10:40	106	8.57	368	21.5	-3.72	
Nov-25	10:40	107	8.47	363	20.9	-4.17	
Nov-26	10:40	108	8.48	365	21.4	-4.5	
Nov-27	10:40	109	8.4	360	21	-4.75	
Nov-28	10:40	110	8.32	345	20.3	-5	
Nov-29	10:40	111	8.28	337	19.7	-5.36	
Nov-30	10:40	112	8.46	365	21.7	-5.91	
Dec-01	10:40	113	8.46	346	21.2	-6.11	
Dec-02	10:40	114	8.46	349	21.7	-6.9	
Dec-03	10:40	115	8.45	352	21.1	-7.7	
Dec-04	10:40	116	8.45	355	20	-0.4	Membrane Was Change
Dec-05	10:40	117	8.45	359	21	-0.42	
Dec-06	10:40	118	8.43	360	21.1	-0.45	
Dec-07	10:40	119	8.43	363	21.2	-0.47	
Dec-08	10:40	120	8.42	366	21.5	-0.5	
Dec-09	10:40	121	8.41	369	22	-0.53	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)
Dec-10	10:40	122	8.4	370	21.2	-0.55
Dec-11	10:40	123	8.48	342	20.6	-0.57
Dec-12	10:40	124	8.37	349	21.3	-0.55
Dec-13	10:40	125	8.44	326	20.8	-0.59
Dec-14	10:40	126	8.44	3.2	21	-0.59
Dec-15	10:40	127	8.44	2.15	21.2	-0.6
Dec-16	10:40	128	8.44	311	21.4	-0.61
Dec-17	10:40	129	8.45	300	21	-0.65
Dec-18	10:40	130	8.46	392	20.5	-0.69
Dec-19	10:40	131	8.47	390	20	-0.73
Dec-20	10:40	132	8.48	286	19.7	-0.77
Dec-21	10:40	133	8.49	302	20.1	-0.83
Dec-22	10:40	134	8.4	295	20.3	-0.83
Dec-23	10:40	135	8.35	290	20.1	-0.82
Dec-24	10:40	136	8.33	285	20.1	-0.81
Dec-25	10:40	137	8.25	290	20.5	-0.83
Dec-26	10:40	138	8.19	310	21.1	-0.85
Dec-27	10:40	139	8.35	305	21.7	-0.9
Dec-28	10:40	140	8.49	300	22.2	-0.92
Dec-29	10:40	141	8.44	301	22	-0.85
Dec-30	10:40	142	8.42	303	23.3	-0.76

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)
Dec-31	10:40	143	8.41	300	22	-0.75
Jan-01	10:40	144	8.4	295	21	-0.79
Jan-02	10:40	145	8.38	292	19.6	-0.84
Jan-03	10:40	146	8.36	291	19.2	-0.89
Jan-04	10:40	147	8.33	250	18.6	-0.9
Jan-05	10:40	148	8.29	228	18.9	-0.94
Jan-06	10:40	149	8.4	230	19.1	-0.92
Jan-07	10:40	150	8.5	241	20.1	-0.9
Jan-08	10:40	151	8.5	236	19.8	-0.95
Jan-09	10:40	152	8.49	245	19.7	-0.97
Jan-10	10:40	153	8.49	248	19.7	-1
Jan-11	10:40	154	8.48	250	20	-1.11
Jan-12	10:40	155	8.41	254	20.6	-1.05
Jan-13	10:40	156	8.54	243	19.7	-1.03
Jan-14	10:40	157	8.39	224	18.2	-1.24
Jan-15	10:40	158	8.45	215	18	-1.24
Jan-16	10:40	159	8.6	210	17.6	-1.25
Jan-17	10:40	160	8.69	209	17.5	-1.25
Jan-18	10:40	161	8.51	223	17.2	-1.4
Jan-19	10:40	162	8.86	226	18	-1.34

2-h

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Jan-20	10:40	163	8.6	230	19	-1.35	
Jan-21	10:40	164	8.43	244	19.4	-1	Membrane Was Changed
Jan-22	10:40	165	8.44	250	19.4	-0.75	
Jan-23	10:40	166	8.45	261	19.3	-0.76	
Jan-24	10:40	167	8.42	265	20.7	-0.72	PII Started
Jan-25	10:40	168	8.45	253	19.7	-0.71	
Jan-26	10:40	169	8.38	261	19.8	-0.73	
Jan-27	10:40	170	8.51	251	20.1	-0.8	
Jan-28	10:40	171	8.4	272	20.2	-0.79	
Jan-29	10:40	172	8.37	269	21.6	-0.75	
Jan-30	10:40	173	8.41	265	21	-0.81	
Jan-31	10:40	174	8.45	260	20.9	-0.7	
Feb-01	10:40	175	8.46	269	20.7	-0.65	
Feb-02	10:40	176	8.18	279	21.1	-0.6	
Feb-03	10:40	177	8.24	276	20.7	-0.68	
Feb-04	10:40	178	8.17	271	20.7	-0.58	
Feb-05	10:40	179	8.27	269	20	-0.58	
Feb-06	10:40	180	8.25	245	17	-0.65	Membrane Was Changed
Feb-07	10:40	181	8.21	237	15.1	-0.85	
Feb-08	10:40	182	8.53	253	18.3	-0.74	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Feb-09	10:40	183	8.28	261	19.1	-0.84	
Feb-10	10:40	184	8.27	261	18.1	-0.77	
Feb-11	10:40	185	8.18	256	21	-0.71	
Feb-12	10:40	186	8.3	247	20	-0.75	
Feb-13	10:40	187	8.4	256	19.6	-0.44	Membrane Was Changed
Feb-14	10:40	188	8.38	245	21	-0.5	
Feb-15	10:40	189	8.34	256	22.1	-0.62	
Feb-16	10:40	190	8.49	260	20.1	-0.6	
Feb-17	10:40	191	8.5	258	19.5	-0.65	
Feb-18	10:40	192	8.5	257	19.3	-0.66	
Feb-19	10:40	193	8.49	256	19	-0.7	
Feb-20	10:40	194	8.48	245	18.6	-0.73	
Feb-21	10:40	195	8.45	250	18.5	-0.78	
Feb-22	10:40	196	8.43	246	18	-0.84	
Feb-23	10:40	197	8.41	242	17.6	-0.86	
Feb-24	10:40	198	8.3	243	18.1	-0.85	
Feb-25	10:40	199	8.35	243	18.6	-0.82	
Feb-26	10:40	200	8.48	235	19.1	-0.82	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)
Feb-27	10:40	201	8.33	237	21.1	-0.77
Feb-28	10:40	202	8.24	255	19.7	-0.86
Mar-01	10:40	203	8.17	253	19.5	-0.9
Mar-02	10:40	204	8.14	250	19.1	-0.95
Mar-03	10:40	205	8.3	244	17.6	-0.9
Mar-04	10:40	206	8.25	240	18	-0.9
Mar-05	10:40	207	8.23	239	18.3	-0.92
Mar-06	10:40	208	8.2	238	18.6	-0.91
Mar-07	10:40	209	8.17	235	19.8	-0.91
Mar-08	10:40	210	8.25	235	20.3	-0.99
Mar-09	10:40	211	8.39	237	17.5	-1.17
Mar-10	10:40	212	8.26	233	20.3	-1.03
Mar-11	10:40	213	8.27	242	20.7	-0.89
Mar-12	10:40	214	8.26	243	18.6	-0.96
Mar-13	10:40	215	8.26	236	19.3	-1.04
Mar-14	10:40	216	8.23	233	19.3	-1.07
Mar-15	10:40	217	8.23	240	17.2	-1.16
Mar-16	10:40	218	8.38	235	21	-1.13
Mar-17	10:40	219	8.05	241	21.2	-1.12
Mar-18	10:40	220	8.16	242	21.5	-1.16

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Mar-19	10:40	221	8.25	244	21.7	-1.25	
Mar-20	10:40	222	8.4	250	21.8	-1.24	
Mar-21	10:40	223	8.6	258	21.9	-1.23	
Mar-22	10:40	224	8.45	256	22.1	-1.22	
Mar-23	10:40	225	8.22	263	23	-1.25	
Mar-24	10:40	226	8.15	264	22.2	-1.35	
Mar-25	10:40	227	8.18	269	20.1	-1.5	
Mar-26	10:40	228	8.6	269	19.9	-1.46	
Mar-27	10:40	229	7.99	269	19.7	-1.47	
Mar-28	10:40	230	8.16	240	20	-1.1	
Mar-29	10:40	231	8.25	230	20.6	-1	
Mar-30	10:40	232	8.36	226	21.1	-0.96	
Mar-31	10:40	233	8.19	219	23.7	-0.96	
Apr-01	10:40	234	8.24	261	23.3	-0.97	
Apr-02	10:40	235	8.08	226	21.7	-1.15	
Apr-03	10:40	236	8.38	209	23.2	-1	Pump Out of order, n⟨ Feeding, no HRT, SRT
Apr-04	10:40	237	8.39	199	24.1	-0.96	
Apr-05	10:40	238	7.93	199	23.3	-1	
Apr-06	10:40	239	8.1	200	23.5	-0.96	
Apr-07	10:40	240	8.2	195	23.6	-0.96	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Apr-08	10:40	241	8.25	200	23.8	-0.97	
Apr-09	10:40	242	8.3	201	24.1	-1.15	
Apr-10	10:40	243	8.35	204	24.1	-1	
Apr-11	10:40	244	8.43	205	24.5	-0.96	
Apr-12	10:40	245	8.45	210	24.6	-1	Pump out of order
Apr-13	10:40	246	8.48	212	24.7	-0.96	
Apr-14	10:40	247	8.51	217	24.8	-0.97	
Apr-15	10:40	248	8.55	220	25	-0.98	
Apr-16	10:40	249	8.6	224	25.1	-1	
Apr-17	10:40	250	8.39	247	23.3	-1.5	PIII Started
Apr-18	10:40	251	8.38	220	24	-3	
Apr-19	10:40	252	8.39	208	24.6	-3.9	
Apr-20	10:40	253	8.56	199	21.3	-4.29	
Apr-21	10:40	254	8.79	202	21.1	-4	
Apr-22	10:40	255	8.36	214	21.7	-4.1	
Apr-23	10:40	256	8.5	230	21.9	-4.1	
Apr-24	10:40	257	8.7	245	22.5	-4.2	
Apr-25	10:40	258	8.93	263	22.7	-4.25	
Apr-26	10:40	259	8.93	270	22.2	-4.3	
Apr-27	10:40	260	8.93	278	22.1	-4.34	
Apr-28	10:40	261	8.9	280	21.8	-4.5	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Apr-29	10:40	262	8.88	285	21.7	-4.6	
Apr-30	10:40	263	8.38	212	22.4	-4.4	
May-01	10:40	264	8.64	206	21.5	-4.36	
May-02	10:40	265	8.34	201	21.9	-4.39	
May-03	10:40	266	8.46	202	21.2	-4.35	
May-04	10:40	267	8.09	241	18.4	-4.31	
May-05	10:40	268	8.15	210	21	-4.38	
May-06	10:40	269	8.33	205	22.8	-4.4	Jug#34
May-07	10:40	270	8.32	209	21.8	-4.46	
May-08	10:40	271	8.42	220	22	-4.2	
May-09	10:40	272	8.55	248	23.3	-4.19	Jug#35
May-10	10:40	273	8.21	235	21	-4.15	
May-11	10:40	274	8.43	271	21.1	-4.26	
May-12	10:40	275	8.41	246	22.1	-4	
May-13	10:40	276	8.81	271	21.4	-4.13	
May-14	10:40	277	8.59	280	21.3	-6.5	Pump Speed Was Increase
May-15	10:40	278	8.37	260	21.6	-8.19	
May-16	10:40	279	8.27	232	22.3	-8.2	
May-17	10:40	280	8.35	260	22.9	-8.34	
May-18	10:40	281	8.42	269	23.4	-8.21	Membrane Was Changed
May-19	10:40	282	8.43	267	23.2	-7.5	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
May-20	10:40	283	8.25	271	21.7	-7.6	
May-21	10:40	284	8.12	273	22.8	-7.82	
May-22	10:40	285	8.39	261	21.6	-7.8	
May-23	10:40	286	8.49	278	21.6	-8.16	Membrane Was Changed
May-24	10:40	287	8.4	274	22.3	-8.88	
May-25	10:40	288	8.85	277	22.2	-7.4	
May-26	10:40	289	8.37	286	21.2	-7.68	
May-27	10:40	290	8.43	289	21	-7.7	
May-28	10:40	291	8.25	284	21.1	-7.58	
May-29	10:40	292	8.38	277	23.2	-7.59	
May-30	10:40	293	8.4	265	24.2	-7.68	
May-31	10:40	294	8.08	274	22.1	-7.5	
Jun-01	10:40	295	8.33	259	23.2	-7.8	
Jun-02	10:40	296	8.38	249	23	-7.9	
Jun-03	10:40	297	8.2	265	23.3	-6.8	
Jun-04	10:40	298	8.36	247	24.5	-7.01	
Jun-05	10:40	299	8.35	250	24.6	-7.3	
Jun-06	10:40	300	8.4	260	22	-7.7	
Jun-07	10:40	301	8.81	271	21.8	-0.61	Membrane Was Changed
Jun-08	10:40	302	8.72	268	23.7	-6.84	
Jun-09	10:40	303	8.39	273	22.2	-7.09	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Jun-10	10:40	304	8.4	271	22.3	-6.8	
Jun-11	10:40	305	8.3	269	23.1	-7.59	
Jun-12	10:40	306	8.35	250	22.9	-7.2	
Jun-13	10:40	307	8.48	240	22.8	-6.9	
Jun-14	10:40	308	8.4	249	23	-6.6	
Jun-15	10:40	309	8.38	238	23.7	-6.43	
Jun-16	10:40	310	8.94	260	23.2	-7.74	
Jun-17	10:40	311	8.24	259	23.7	-7.75	
Jun-18	10:40	312	8.37	258	23.6	-7.72	
Jun-19	10:40	313	8.34	251	25	-7.62	
Jun-20	10:40	314	8.34	255	24.2	-7.6	
Jun-21	10:40	315	8.39	227	22.9	-6.94	Jug#47
Jun-22	10:40	316	8.25	240	24	-6.87	
Jun-23	10:40	317	8.21	255	26.6	-6.82	Jug#48
Jun-24	10:40	318	8.21	253	24.1	-7.51	
Jun-25	10:40	319	8.23	238	22.6	-7.8	
Jun-26	10:40	320	8.39	241	23.8	-7.52	Jug#49
Jun-27	10:40	321	8.4	245	23.5	-7.5	
Jun-28	10:40	322	8.42	252	23.5	-7.49	
Jun-29	10:40	323	8.45	251	23.4	-7.48	
Jun-30	10:40	324	8.48	240	23.2	-7.6	
Jul-01	10:40	325	8.49	245	22.6	-7.7	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)	
Jul-02	10:40	326	8.5	244	22.4	-7.56	
Jul-03	10:40	327	8.51	248	22.3	-7.53	
Jul-04	10:40	328	8.51	251	22.2	-7.44	Pump Speed Was Reduced
Jul-05	10:40	329	8.23	225	23.5	-3.5	
Jul-06	10:40	330	8.61	269	22.8	-2.83	
Jul-07	10:40	331	8.29	259	23.7	-2.89	
Jul-08	10:40	332	8.24	263	24.7	-2.5	
Jul-09	10:40	333	7.97	268	24.3	-2.5	Membrane Exhausted
Jul-10	10:40	334	8	270	24.4	-2.5	
Jul-11	10:40	335	8.1	265	24.5	-2.4	
Jul-12	10:40	336	8.2	275	24.6	-2.5	
Jul-13	10:40	337	8.5	275	24.8	-2.5	
Jul-14	10:40	338	8.87	277	25.1	-1.01	
Jul-15	10:40	339	8.31	264	25.3	-2.9	New Membrane
Jul-16	10:40	340	8.26	254	26.1	-3.15	
Jul-17	10:40	341	8.88	266	25.1	-3.19	
Jul-18	10:40	342	8.14	268	24.6	-3.5	
Jul-19	10:40	343	8.24	268	24.1	-3.85	
Jul-20	10:40	344	8.38	268	25	-4.43	
Jul-21	10:40	345	8.32	269	23.6	-4.63	
Jul-22	10:40	346	8.36	274	25.4	-2.7	

Date	Time (am)	Day	pH	ORP (mV)	Temp (degree C)	Pressure (PSIG)
Jul-23	10:40	347	8.37	282	23.9	-4.35
Jul-24	10:40	348	8.42	284	24.2	-4.3
Jul-25	10:40	349	8.36	269	23.4	-4.35
Jul-26	10:40	350	8.56	284	23.4	-4.4
Jul-27	10:40	351	8.12	285	22.9	-4.25
Jul-28	10:40	352	8.33	279	23.3	-4.25
Jul-29	10:40	353	8.59	285	22.6	-4.55
Jul-30	10:40	354	8.38	267	23.1	-4.6
Jul-31	10:40	355	8.4	280	23.2	-4.74
						End

3 Appendix C Raw Data from COD and DOC tests

leachate , * eff= effluent

Day	COD avg	COD eff	DOC eff	% COD removal	
1	1100.00	740.00	405	32.73	
5	860.00	820.00	570.5	4.65	
16	1040.00	820.00	646.5	21.15	
24	960.00	800.00	267.5	16.67	PI started
42	2410.67	1042.67	271.67	56.75	
52	2232.17	1180.33		47.12	
63	2238.00	1058.00	227	52.73	
78	4297.50	991.33		76.93	
87	4060.17	700.00	244	82.76	
96	4133.00	1113.67	149	73.05	
105	2475.00	849.00	221	65.70	
111	3155.00	862.50		72.66	
123	3727.33	1445.00		61.23	
134	3182.67	966.67		69.63	
145	3450.00	847.00		75.45	
152	3103.75	1066.67		65.63	PII Started
155	3232.00	1286.33		60.20	
169	4830.00	1068.40	158	77.88	
175	5371.67	834.65		84.46	
179	4894.17	632.50		87.08	
188	6243.33	686.50		89.00	

3-a

Day	leachate COD avg	, * eff= effluent COD eff	DOC eff	Day
195	5308.33	1455.50		72.58
202	3080.00	553.50	145	82.03
206	3194.67	528.75		83.45
211	3112.00	504.00	340	83.80
219	3026.00	709.00		76.57
226	3464.00	914.00		73.61
236	3016.70	1158.50		61.60
249	3405.00	1403.00		58.80
256	3305.00	1505.00		54.46
265	2261.70	1607.00	304	28.95
268	2195.00	1481.00		32.53
272	3141.70	1355.00	262	56.87
275	3086.70	1197.00		61.22
279	3597.50	1038.00		71.15
286	2721.70	1184.80		56.47
293	2885.00	1331.50	244	53.85
300	2393.00	1407.80		41.17
307	2493.30	1484.00		40.48
311	1615.00	1212.00		24.95
314	2167.50	940.00		56.63
335	3313.30	1211.70		63.43
342	3280.00	1191.30	280	63.68
349	2530.00	1126.20		55.49
365	2805.00	1061.00		62.17

% COD removal in 3 periods
66.14
77.57
51.47

Appendix C, Raw Data from COD and DOC tests

COD

	SRT1	stdev	SRT2	Stdev	SRT3	Stdev
Leachate	3207.48	717.5285	4078.82	1163.067692	2736.96	537.051
effluent	1031.47	199.68779	870.69	332.9282279	1270.83	190.039

Day	DOC eff		DOC avg	Stdev
1	405	SRT1	222.534	45.56501706
5	570.5	SRT2	214.333	109.0244621
16	646.5	SRT3	272.5	25.63201124

PI
started

24	267.5
42	271.67
63	227
87	244
96	149

PII

105	221
169	158
202	145

PIII

211	340
265	304
272	262
293	244
342	280

4 Appendix D Primarily data from nitrogen tests

Day	NH3-N avg LS	TKN Leachate	TKN eff	TKN Biomass	NH3 (mg/L) eff	NO2-N eff	NO3-Neff	% of ammonia removal
3	553.15				336.90	54.83	0.00	39.09
13	625.24				402.09	236.02	0.00	35.69
24	664.62				0.00	472.46	154.40	100.00
38	766.65				0.00	2.50	657.78	100.00
48	774.285				0.00	1.88	988.44	100.00
57	781.92				0.00	0.00	716.33	100.00
64	762.49				0.00	2.50	650.69	100.00
78	382.90				0.00	1.88	762.45	100.00
87	340.10				0.00	0.00	564.96	100.00
97	314.39				0.00	0.00	375.17	100.00
105	556.99				4.83	0.00	427.40	99.13
111	722.66				3.51	0.00	659.73	99.51
122	918.91		24		3.51	0.00	869.57	99.62
134	712.31				2.50	0.00	1075.25	99.65
145	799.44				0.00	0.00	756.75	100.00
149	753.42				0.00	0.00	663.23	100.00
155	671.25				0.00	0.00	832.73	100.00
161	552.18				0.00	0.00	633.77	100.00
169	565.53		12.1		0.00	0.41	434.82	100.00

Day	NH3-N avg LS	TKN Leachate	TKN eff	TKN Biomass	NH3 (mg/L) eff	NO2-N eff	NO3-Neff	% of ammonia removal
181	583.33				0.00	0.00	398.66	100.00
188	568.90				64.17	0.00	366.07	88.72
195	940.82				0.00	0.00	431.16	100.00
202	837.74	1239.00	13	489	0.00	0.00	496.25	100.00
207	506.37	1060.00			0.00	0.00	531.20	100.00
211	501.13				0.00	0.00	566.15	100.00
219	308.81				0.00	0.00	570.84	100.00
226	554.06				1.78	0.00	575.52	99.68
249	864.46				49.30	0.00	957.09	94.30
255	907.72				48.90	0.00	958.12	94.61
260	864.49				47.10	0.00	958.80	94.55
265	696.14	773.00	67	263	45.98	0.00	959.12	93.40
270	714.50				39.10	0.00	807.82	94.53
275	664.01	832.00	59	287	36.54	0.00	656.51	94.50
279	689.60				22.60	0.00	677.83	96.72
285	733.73				8.70	0.00	699.14	98.81
289	555.80				0.00	0.00	649.60	100.00
293	554.40	635.00	24	247	0.00	0.00	600.00	100.00
300	479.00				0.00	0.00	500	100.00
307	490.00				0.00	0.00	371.50	100.00
310	614.00				1.5	0.00	620.00	99.76
314	637.00				3.00	0.00	340.00	99.53
336	731.30				1.20	0.00	530.40	99.84
342	852.10	376	145	17	5.7	0.00	836.10	99.33
345	477.20				3	0.00	784.10	99.37
349	746.14				0	0.00	732.10	100.00

5 Appendix E TSS and VSS Data

*L= Leachate jug

Day	TSS (mg/L)	stdev	VSS (mg/L)	stdev	Description
3	100	28.284	75	7.07	L1
5	160	0	110	0	L2
24	215	91.92	150	14.14	L4
40	42	11.31	25	1.41	L5
52	59	9.83	21	1.41	L6
64	63.33	6.11	57.33	10.07	L7
77	250	84.85	8	8.49	L8
88	250	36.056	9.8658	9.8658	L9
96	175	21.213	25.3333	1.1547	L10
105	52	2.8284	35	4.2426	L11
125	72	31.11	61	38.18	L13
149	64.67	4.163	27.33	15.01	16
157	50.667	10.263	47	9.8995	L17
169	109.333	16.773	46.667	9.8658	L19
189	92	2.83	70	11.31	L21
204	227	60.81	124	8.49	L23
212	50	0	40	0	L25
228	50	0	40	0	L27

Day	TSS(mg/L)	stdev	VSS (mg/L)	stdev	Description
249	250	28.3	135	7.1	L29
265	200	0	40	0	L32
272	200	0	40	0	L35
279	220	0	20	0	L37
293	140	0	10	0	L40
307	135	64	75	7	L43
314	256.7	35	147	31	L46
336	217	15	123	31	L49
343	105	7	65	7	L51
349	80	14	55	7	L52

Day	TSS(mg/L)	stdev	VSS (mg/L)	stdev	Description
3	5725	35.36	3300	0	Biomass
7	6950	424.26	3275	813.1728	Biomass
10	5950	494.97	3350	424.2641	Biomass
20	6550	848.53	2550	212.132	Biomass
24	7000	1202.08	4000	1838.478	Biomass
34	8233.33	577.3503	4233.3333	145.2966	Biomass
40	7566.6667	550.76	3850	212.132	Biomass
48	7925	742.46	3666.6667	235.7023	Biomass
59	8633.3333	831.16	3644.4444	709.5251	Biomass
64	8775	247.49	5225	176.7767	Biomass
77	10033.33	583.81	3783.3333	539.2897	Biomass
88	8900	565.69	4775	35.3553	Biomass
96	11700	212.132	5320	70.717	Biomass

Day	TSS (mg/L)	stdev	VSS (mg/L)	stdev	Description
105	12875	35.3553	5175	106.066	Biomass
125	11925	318.198	4900	141.421	Biomass
149	9933.33	225.462	6100	278.39	Biomass
157	7400	70.7107	3300	141.42	Biomass
169	14166.667	500.8326	8233.333	828.1505	Biomass
179	17500	884.59	7783.333	693.421	Biomass
189	24033.33	723.42	12950	396.86	Biomass
204	23225	106.07	10450	70.71	Biomass
212	24375	1237.44	10025	459.6	Biomass
228	24816.67	354.73	12216.67	960.9	Biomass
249	12283.33	1075.1	5933.3	539.3	Biomass
265	8666.7	317.5	3816.7	317.5	Biomass
272	9100	495	527.5	35.36	Biomass

Day	TSS(mg/L)	stdev	VSS (mg/L)	stdev	Description
279	8700	565.7	6050	636.4	Biomass
293	10375	884	6250	636.4	Biomass
307	9683.33	550	5200	328	Biomass
314	11566.7	730	6716.7	503	Biomass
336	10400	770	6300	507	Biomass
343	8900	354	6150	141	Biomass
349	8550	141	5500	35	Biomass
360	11250	450	6600	120	Biomass

Day	TSS (mg/L)	stdev	VSS (mg/L)	stdev	Description
3	175	91.92	110	0	Effluent
7	260	0	80	0	Effluent
10	55	7.07	30	0	Effluent
20	100	0	40	0	Effluent
25	20	0	10	0	Effluent
34	70	0	24	0	Effluent
40	20	28.28	4	5.66	Effluent
48	20	28.28	0	0	Effluent
59	1	1.41	0	0	Effluent
64	20	8.49	17	4.24	Effluent
77	26	0	11	4.24	Effluent
88	0	0	0	0	Effluent
96	36	2.8284	7	8	Effluent

Day	TSS (mg/L)	stdev	VSS (mg/L)	stdev	Description
105	35	1.4142	0	0	Effluent
125	0	0	0	0	Effluent
149	26	2.83	21	1.41	Effluent
157	32	0	22	0	Effluent
169	0.67	1.55	0	0	Effluent
179	0	0	0	0	Effluent
189	30	0	10	0	Effluent
204	38	22.63	12	17	Effluent
212	0	0	0	0	Effluent
228	35	1.41	15	12.73	Effluent
249	23	9.9	20	11.31	Effluent
265	39	24	13	10	Effluent
272	10	0	0	0	Effluent

Day	TSS (mg/L)	stdev	VSS (mg/L)	stdev	Description
279	0	0	0	0	Effluent
293	30	10.4	6.7	1.2	Effluent
307	5.3	5	0	0	Effluent
314	27	4.3	17	1.4	Effluent
336	0	0	0	0	Effluent
343	25	4.2	14	2	Effluent
349	27	4.2	10	8.5	Effluent
360	15	3.5	7	4	Effluent

6 Appenidx F Total metal result

all mg/L

Metal	Date	Leachate	effluent	Date	Leachate	effluent	Date	Leachate	effluent
	Mar-30	#28		Oct-26	#7		Nov-08	#9	
Aluminum (Al)		0.3	0.3		0.15	0.038		0.33	<0.05
*Arsenic (As)		0.0095	0.0095		0.0168	0.0167		0.019	0.014
*Cadmium (Cd)		0.0039	<0.0002		<0.00005	<0.00005		0.00056	<0.0001
*Chromium-Total (Cr)		0.053	0.053		0.0436	0.0326		0.041	0.026
*Copper (Cu)		0.026	0.012		0.021	0.021		0.012	0.012
Iron-Total (Fe)		14.7	2.87		6.7	0.6		4.1	<1
*Lead (Pb)		0.0247	0.0247		0.0053	<0.0005		0.0067	<0.001
Manganese (Mn)		0.947	0.0122		0.34	0.067		1.03	0.067
*Nickel (Ni)		0.081	0.081		0.177	0.177		0.0786	0.0786
Phosphorus (P)-Total		9.86	0.9		-	-		-	-
*Selenium (Se)		0.016	0.015		<0.001	<0.001		<0.002	<0.002
*Zinc (Zn)		0.45	0.45		0.129	0.129		0.197	0.077

Total metal result   60-day-SRT and 4-day-HRT   60-day-SRT and 2-day-HRT   30-day-SRT and 1-d-HRT

all mg/L

Metal	Leach avg	Eff avg	% of removal	Leach avg	Eff avg	% of removal	Leach avg	Eff avg	% of removal
Aluminum (Al)	0.2250	0.1293	42.52	0.33	<0.05	84.85	0.52	0.34	34.62
*Arsenic (As)	0.0131	0.0131	0.00	0.019	0.014	26.32	0.0199	0.0158	20.60
*Cadmium (Cd)	0.0013	0.0001	90.51	0.00056	<0.0001	82.14	0.0004	0.0002	50.00
*Chromium-Total (Cr)	0.0483	0.0428	11.39	0.041	0.026	36.59	0.095	0.069	27.37
*Copper (Cu)	0.0235	0.0165	29.79	0.012	0.012	0.00	0.015	0.015	0.00
Iron-Total (Fe)	10.7000	1.7350	83.79	4.1	<1	75.61	6.1	3.15	48.36
*Lead (Pb)	0.0150	0.0126	16.00	0.0067	<0.001	85.07	0.0157	0.0046	70.70
Manganese (Mn)	0.6435	0.0396	93.85	1.03	0.067	93.50	0.299	0.294	1.67
*Nickel (Ni)	0.1290	0.1290	0.00	0.0786	0.0786	0.00	0.218	0.216	0.92
Phosphorus (P)-Total	9.8600	0.9000	90.87	-	-	-	5.31	0.3	94.35
*Selenium (Se)	0.0085	0.0080	5.88	<0.002	<0.002	0.00	0.015	0.015	0.00
*Zinc (Zn)	0.2895	0.2895	0.00	0.197	0.077	60.91	0.61	0.36	40.98