Selection and optimization of carriers in biological wastewater treatment applications

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Selection and Optimization of Carriers in Biological Wastewater Treatment Applications

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School of Civil & Environmental Engineering

A thesis submitted to Nanyang Technological University
in fulfillment of the requirements for the degree of Master of Engineering

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Abstract

The Integrated Wastewater Treatment (IWWT) plant is SUT Sakra Pte Ltd's second industrial biological wastewater treatment plant on Jurong Island in Singapore. The facility was designed to treat an influent at a flow rate of $110 \text{ m}^3 \text{ h}^{-1}$ with chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5) concentrations at 2878 mg/L and 1870 mg/L respectively. The influent is made up of 7 chemical wastewater streams from several chemical manufacturing plants. The treatment system uses a two-stage biological process, which is a three-phase fluidized bed aerobic reactor (TPFBR), and the second is a conventional activated sludge process.

During commissioning, the plant was found to be able to perform up to only 80% of the design capacity of $317 \text{ kg COD h}^{-1}$, provided that the final effluent COD and BOD_5 were less than 100 mg/L and 50 mg/L respectively. The cause for the underperformance was identified as inadequate biofilm attachment to the carriers in the fluidized bed reactors.

A pilot study that simulated the two-stage process was conducted on site in IWWT to select a carrier with the best performance of COD and BOD_5 removal efficiencies. Altogether, there were three types of carrier studied; i.e. type I - the existing carrier made of Polyvinyl Alcohol (PVA) coated with layers of powder activated carbon (PAC); type II - a Bio-carrier Plastic (BCP) made of plastic and type III - Kaldnes carrier made of polyethylene. In order to compare the performances of the three types of carriers, actual industrial wastewater, equivalent to 100% of the IWWT design hydraulic load and 100~110% of organic load, was fed to each pilot plant throughout the study.

The total biofilm on each type of carrier and the relevant surface area loadings applied in each three-phase fluidized bed reactors (TPFBRs), in addition to the functions of activated carbon powder (ACP), were investigated in this study. The results clearly indicated that the Kaldnes carriers could maintain the most biofilm

which reached up to 10.8 mg/per piece and the relevant specific surface area loading was 8.3 g total organic carbon (TOC) $\text{m}^2 \cdot \text{d}^{-1}$. In the meantime, the average removal efficiencies of COD & BOD₅ were 86% & 88.9% respectively, with final effluent average COD & BOD₅ concentrations of 71 mg/L and 10 mg/L respectively, well within the regulatory limit of 100 mg/L and 30 mg/L. As a result, the Kaldnes carrier was considered as the most likely to meet the performance requirements of the full-scale plant.

Based on the positive pilot study results, all the original type I carriers in the first stage process in IWWT were replaced with the Kaldnes carriers. In order to further verify and prove the success of the carrier replacement project, a full scale performance test was subsequently conducted. Results obtained from the full-scale performance test showed, after the carriers' replacement, the organic removal efficiency for IWWT was increased by 20 - 30% and the design capacity would be exceeded without any deterioration in performance; the corresponding average COD and BOD₅ for the final effluent were 51 mg /L, and 14 mg/L respectively, which matched the stringent effluent discharge limits. With the Kaldnes carriers, the plant was finally able to achieve its original design capacity.

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CHAPTER ONE

INTRODUCTION

1.1 Background

SUT SAKRA PTE LTD (SUT), the utilities arm of SembCorp Industries (SCI), is an established centralized utilities, power, industrial water, industrial wastewater treatment and chemical feedstock company in Singapore. Wastewater treatment is one of the core businesses for the company, which has four industrial wastewater treatment plants.

1.1.1 SUT Sakra Integrated Wastewater Treatment Plant

SUT operates a wastewater treatment plant named as the Integrated Wastewater Treatment Plant (IWWT) on Jurong Island, Singapore. The facility was designed to treat influent 110 m³/hr of wastewater and the soluble maximum concentrations of chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD₅) were 2878 and 1870 mg/L respectively. (BOD₅/COD = 0.6 ~ 0.65). The influent consists of seven chemical wastewater streams from several chemical manufacturing plants. The main composition of the waste organics is mostly alcohols, aldehydes, organic salts, iso-phthalic acid, phenol as well as some minor components such as acetone, benzylaldehyde, m-toluic acid, benzene and xylene. These streams of wastewater are mixed and equalized in an equalization tank (Table 1-1) with a retention time of approximately 24 hours prior to biological treatment process. The existing plant utilizes a two-stage biological process, three-phase fluidized bed aerobic reactors (TPFBRs) followed by activated sludge basins.

IWWT Process Description

The IWWT facility consists of four sections, i.e. 1) Pre-treatment section 2) biological treatment section 3) post-treatment section and 4) sludge treatment section. The scheme of the process is shown in Figure 1-1.

Pre-treatment Biological-treatment Post -treatment Sludge-treatment

- * Three-Phase Fluidized Bed Reactor;
- ** Activated sludge basin

Figure 1-1 IWWT Process Diagram

Table 1-1 Specifications for Equalization Tank TK001

Tank No	Sources	Effective Volume	Retention time
TK001	1,2,3,--7	2,850 m ³	24 hrs

Wastewater from various sources is initially stored at the equalization tank (TK001) to minimize large fluctuation of flow rate and organic composition and to adjust pH.

Wastewater from TK001 is fed to the TPFBRs at a constant flow rate and an online total organic carbon (TOC) analyzer automatically analyzes the influent TOC every 15 minutes. The temperature of mixed wastewater in TK001 ranges from 36 ~ 42 °C. Two online temperature probes monitor the influent temperatures before and after the cooler prior to the distributors from where the wastewater is transferred equally to each TPFBR. The wastewater is cooled to 31 ~ 33 °C at the cooler. The treated final effluent may be recycled back to TK001 and adjust its level or dilute the wastewater with high COD concentration probably due to customer's process start-up or shutdown as when necessary.

Biological Treatment Section in IWWT

The biological treatment section consists of two series of TPFBRs working in parallel, namely Train A and Train B (See Fig 1.1). Each train has six chambers in parallel with each capacity of 100 m³. The reactors in Train A are named from A to F and in Train B from G to L respectively. Following TPFBRs there are two activated sludge reactors to receive the effluents from the Train A and Train B separately. As the equalized wastewater is fed to the TPFBRs equally to each chamber through the two distributors, urea and phosphoric acid are also fed to the distributors as nutrients for the microorganisms' growth. In order to keep the desired concentration of microorganisms and increase the efficiency of the biological treatment in the TPFBRs, the settled sludge in clarifier is returned to the distributors.

Post- Treatment Section in IWWT

The treated water from the activated sludge basin is fed to the coagulation basin by gravity. In the coagulation basin, the sludge aggregates and coagulates into larger flocs with the addition of a coagulant (aluminum sulfate) and pH adjustment by hydrochloric acid or sodium hydroxide when necessary. Anionic polymer is injected to the water before it flows into the clarifier to enhance the flocs and improve sedimentation efficiency in the clarifier. A portion of the precipitated sludge as

mentioned above is returned from the clarifier to TPFBRs and the excess sludge is diverted into the sludge treatment section.

Sludge Treatment Section in IWWT

The excess sludge is transferred into a sludge storage tank in which retention time is one day. Three pumps (one on standby most of the time) are provided to pump the sludge to the dehydrators with polymer dosage for dewatering. The dewatered sludge cakes are then sent out for incineration.

1.1.2 Plant Design Conditions

The specifications of design parameters for IWWT, incoming wastewater from the customers and effluent discharge limits are shown in Table 1-2 and Table 1-3.

Table 1-2 Specifications of Design Parameters for IWWT & Influent Chemical Compositions

	Design Conditions	Actual Conditions
Flow rate	$\leq 110 \text{ m}^3/\text{h}$	$70 \sim 110 \text{ m}^3/\text{h}$
pH	$6 \sim 9$	$6 \sim 9$
Temperature	$\leq 42 \text{ }^\circ\text{C}$	$39 \sim 42 \text{ }^\circ\text{C}$
Suspended solids	$\leq 3 \text{ mg/L}$	$3 \sim 8 \text{ mg/L}$
BOD	$\leq 1607 \text{ ppm}$	$1660 \sim 2018 \text{ ppm}$
COD	$\leq 2281 \text{ ppm}$	$2760 \sim 3360 \text{ ppm}$
Total dissolved solid (TDS)	$\leq 6433 \text{ ppm}$	$4500 \sim 6990 \text{ ppm}$
Organic and Metal Contents		
Poly Iso Phthalic Acid	$\leq 409 \text{ ppm}$	$50 \sim 409 \text{ ppm}$
Acetic Acid	$\leq 145 \text{ ppm}$	$80 \sim 145 \text{ ppm}$
m-Toluic Acid	$\leq 45 \text{ ppm}$	$5 \sim 45 \text{ ppm}$
3-Carboxyl Benzaldehyde	$\leq 82 \text{ ppm}$	$10 \sim 82 \text{ ppm}$
Methyl Acetate	$\leq 91 \text{ ppm}$	$20 \sim 91 \text{ ppm}$
Iso-Butyl Acetate	$\leq 18 \text{ ppm}$	$0 \sim 18 \text{ ppm}$
m-Xylene	$\leq 9 \text{ ppm}$	$0 \sim 9 \text{ ppm}$
Sodium Acetate	$\leq 618 \text{ ppm}$	$45 \sim 618 \text{ ppm}$
Formaldehyde	$\leq 136 \text{ ppm}$	$10 \sim 136 \text{ ppm}$
Methanol Sodium	$\leq 14 \text{ ppm}$	$0 \sim 14 \text{ ppm}$
Format Ethylene	$\leq 14 \text{ ppm}$	$0 \sim 14 \text{ ppm}$
Glycol	$\leq 14 \text{ ppm}$	$0 \sim 14 \text{ ppm}$
Phenol	$\leq 205 \text{ ppm}$	$20 \sim 205 \text{ ppm}$
Acetone	$\leq 11 \text{ ppm}$	$0 \sim 11 \text{ ppm}$
Cyanide	$\leq 3.6 \text{ ppm}$	$0 \sim 3.6 \text{ ppm}$
Copper	$\leq 1.5 \text{ ppm}$	$0 \sim 1.5 \text{ ppm}$
Zinc	$\leq 1.1 \text{ ppb}$	$0 \sim 1.1 \text{ ppb}$
Manganese	$\leq 3.6 \text{ ppm}$	$1 \sim 3.6 \text{ ppm}$
Iron	$\leq 11.5 \text{ ppm}$	$3 \sim 11.5 \text{ ppm}$

Table 1-3 Effluent Discharge Limits

Discharge parameters	
Temperature	$\leq 45^\circ \text{C}$
pH value	$6 \sim 9$
BOD ₅	$\leq 30 \text{ ppm}$
Total dissolved solids	$\leq 2000 \text{ ppm}$
COD	$\leq 100 \text{ ppm}$
Total suspended solids	$\leq 50 \text{ ppm}$

1.1.3 Existing Problem

During the commissioning period, three rounds of performance test were conducted separately in IWWT from 27th July 99 to 30th July 99, 5th Aug 99 to 8th Aug 99 and 11th Aug 99 to 16th Aug 99. The results are summarized in Table 1-4.

The first round of the test with the COD load from 70% to 80% of the design capacity produced a generally acceptable effluent. The average effluent concentrations of COD, BOD₅ and TSS were 83, 28 and 25 mg/L respectively, maintaining below the regulatory discharge limits of 100, 50 and 50 mg/L respectively. The 2nd and 3rd rounds, targeting at 100% design capacity, however, produced high concentrations of the COD, BOD₅ in the effluent. The average concentrations of COD and BOD₅ in the two rounds were 116, 122, 36 and 76 mg/L respectively. The results over the two rounds are illustrated in Figure 1-2, therefore the last two rounds were considered to be failed.

Table 1- 4 Results of Three Performance Tests in IWWT

R*	Load	Flow	Influent				Effluent			
			pH	COD	BOD ₅	BOD ₅ /COD	pH	COD	BOD ₅	TSS
	Design	m ³ /hr		mg/L	mg/L			mg/L	mg/L	mg/L
1	70%	110	10.18 (8.59-11.68)	2017 (1236-2816)	1311 (805-1830)	0.65 (0.63-0.70)	8.25 (8.07-8.47)	83 (63-100)	24 (18-30)	25 (18-33)
2	93%	110	8.43 (7.27-9.75)	2666 (1690-3250)	1488 (1100-1900)	0.55 (0.45-0.70)	8.02 (7.58-8.42)	116 (92-130)	38 (32-60)	38 (26-57)
3	99%	110	8.57 (7.22-9.53)	2838 (2470-3325)	1675 (1584-2142)	0.66 (0.55-0.70)	7.63 (7.36-7.96)	122 (108-145)	37 (29-56)	42 (15-45)
ENV discharge limits							6 - 9	100	30	50

*: R stands for round of test;

Figure 1-2 Results of Three Full-scale Performance Tests in IWWT

An investigation was conducted and confirmed that the operating conditions were well controlled during the performance tests. A testing on the SOUR of the biofilm and suspended sludge in the three-phase fluidized reactor indicated the feeding wastewater was not toxic.

Figure 1-2 indicates that the effluent qualities can comply with ENV standards when the incoming COD load was less than 80% of design capacity. However, when the COD load exceeded 80% of design, the effluent COD and BOD₅ were off the limits. The root cause of the under-performance was identified later: the biofilm on the carrier did not grow sufficiently on the surface of the existing poly vinyl alcohol (PVA) carriers. The original carriers used in IWWT consisted of PVA as the core with powder activated carbon (PAC) as surface coating. The configurations of the virgin existing carriers are shown in Figure 1-3. Through the comparison between the virgin carrier and used carrier, it was observed that most of PAC coated on PVA core disappeared. Details are elucidated in Figure 1-3 & 1-4.

Figure 1-3 Existing Virgin Carriers

Figure 1- 4 Used Existing Carrier

The carrier is maintained in a fluidized state in the reactor by the turbulence generated by mixing of the injected substrate and incoming air stream. Biofilm formation in the three-phase fluidized bed reactor is a dynamic process. At any one time, some bacteria in the suspended phase may attach to the surface, while some attached bacteria may detach from the surface (Yu et al., 2001). The biofilm provides robust organic treatment efficiency due to many layers of microorganisms enmeshed in a bacteria-produced extracellular polysaccharide matrix (Christensen et al., 1990). Conceptually, the organic load should be biodegraded mainly in the first stage in IWWT. A diagram of a TPFBR, which consists of wastewater, carrier, and air, is shown in Figure 1-5.

Figure 1-5 IWWT Three Phase Fluidized Bed Reactor

1.2 Objectives and Scope

1.2.1 Project Objectives

As the process can not meet the design capacity and ENV's effluent discharge standards, appropriate type of carrier become a critical factor. In view of this, the purposes of this study are:

1. Evaluate the performance of different types of carriers under same operation conditions, which are similar to IWWT plant in the pilot study devices.
2. Choose the carrier that has the best performance during the pilot study to replace the existing carriers in IWWT. Conduct a full-scale test by applying the best carriers in IWWT to further assess the plant performance.

The detailed objectives of this study are as follows:

1. To study the general performance of different carriers for treating organics under the same conditions, which are similar to the IWWT and choose one for plant replacement.
2. To investigate the efficiencies of TOC, COD and BOD₅ removal of the new carrier under the same conditions, which are similar to the IWWT.
3. Reconfirm the new carrier performance in full-scale IWWT plant after the carrier replacement.

1.2.2 Scope of Study

To achieve the above objectives, four integrated pilot study devices were set up on site in IWWT, configurations of which are fabricated according to the design for IWWT. All the operational parameters were same as those in IWWT. The scope of the study included:

1. Conduct pilot plant study and compare the performance of different carriers;
2. Replace the existing carrier with a new carrier selected from the pilot study;
3. Conduct a performance test with the replaced carrier to confirm the plant capacity.

1.3 Organization of Thesis

The thesis is organized as follows:

Chapter 1 Introduction

The process of SUT integrated wastewater treatment plant (IWWT) and the existing problems in the process are mainly introduced in Chapter 1. The objectives and scopes of the study are also addressed.

Chapter 2 Literature Review

The history of biological wastewater treatment processes is delineated and the methods of biological wastewater treatment processes are described, especially on the three-phase fluidized bed reactor, which is one branch of the aerobic attached-growth treatment processes. In addition, several factors affecting the performance of the three-phase fluidized bed reactors are reviewed.

Chapter 3 Pilot Study

This chapter introduces the pilot study, elucidates the experimental methodology of the pilot study, as well as the study's results. Based on the results, discussions are carried out and conclusions are drawn.

Chapter 4 Full Scale Plant

Based on the positive pilot study results obtained, the existing carriers were replaced by the selected carriers. To evaluate the performance and effectiveness of Kaldnes carrier, a performance test was executed. Base on the test results gained from the full-scale performance test, a discussion is carried out and the conclusion is elicited.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background

Wastewater collected from municipalities, communities and industries must ultimately be returned to receiving water or to the land. The complex question arises when contaminant in wastewater must be removed to protect the environment. Although the collection of storm water and drainage dates from ancient times, collection of wastewater can only be traced to the early 1800s. Systematic treatment of wastewater followed in the late 1800s and early 1900s. Development of the germ theory by Koch and Pasteur in the latter half of the nineteenth century marked the beginning of a new era in sanitation. Methods of treatment in which the application of physical forces predominates are known as unit operations. Methods of treatment in which the removal of contaminants is brought about by chemical or biological reactions are known as unit processes. At the present time, unit operations and processes are grouped together to provide what is known as primary, secondary, and advanced (or tertiary) treatment (Metcalf and Eddy. 2003). Historically, the term “preliminary” and /or “primary” referred to physical unit operations; “secondary” referred to chemical and biological unit processes; and “advanced” or “tertiary” referred to combinations of all three.

2.2 Various Unit Operations and Processes in Wastewater Treatment

A rational approach is first to establish the level of contaminant removal (treatment) required before the wastewater can be reused or discharged to the environment. The required unit operations and processes necessary to achieve that required level of treatment are then grouped together on the basis of fundamental considerations. The contaminants of major interest in wastewater and the unit operations, processes, or methods applicable to the removal of these contaminants are shown in Table 2 -1.

Table 2-1 Unit Operations, Processes and Treatment Systems Used to Remove Major Contaminants Found in Wastewater. (Metcalf & Eddy, 2003)

Contaminants	Unit operation, unit process, or treatment system
Suspended solids	Screening and comminution
	Grit removal
	Sedimentation
	Filtration
	Flotation
	Chemical polymer addition
	Coagulation/sedimentation
	Natural systems (land treatment)
Biodegradable Organics	Activated-sludge variations
	Fixed –film reactor: trickling filters, rotating biological contactors
	Lagoon variations
	Intermittent sand filtration
	Physical-chemical systems
	Natural systems
Volatile organics	Air stripping
	Off gas treatment
	Carbon adsorption
Pathogens	Chlorination
	Hypochlorination
	Bromine chloride
	Ozonation
	UV radiation
	Natural systems
Nutrients: Nitrogen	Suspended-growth nitrification and denitrification variations
	Fixed-film nitrification and denitrification Variation.
	Ammonia stripping
	Ion exchange
	Breakpoint chlorination
	Natural systems
Nutrients: Phosphorus	Metal-salt addition
	Lime coagulation/sedimentation
	Biological phosphorus removal
	Biological-chemical phosphorus removal
	Natural systems
Nitrogen and Phosphorous	Biological nutrient removal
Refractory organics	Carbon adsorption
	Tertiary ozonation
	Natural systems
Heavy metals	Chemical precipitation
	Ion exchange
	Natural systems
Dissolved organic solids	Ion exchange
	Reverse osmosis
	Electrodialysis

2.3 Basic Microbiology in Biological Wastewater Treatment

Microorganisms

The activated-sludge process was developed in England in 1914 by Arden and Lockett and was so named, because it involved the production of an activated mass of microorganisms capable of stabilizing waste aerobically (Arden and Lockett, 1914). Various adaptations of the activated sludge process are in use today but most are similar in principle.

In order for the microbes to accomplish biodegradation of the organics, the organic materials must be soluble or made soluble so that the process is not hampered by the hindered access of the substrate molecules to the microbial cells. All the primary feeders (bacteria) in the population use soluble food. The primary and secondary feeders, which ingest particulate food, along with other particulate matter contained in the waste or passed into the aeration tank, are collectively termed “activated sludge”. In general, the bacteria in the activated sludge process include a number of the genera *Pseudomonas*, *Zoogloea*, *Achromobacter*, *Flavobacterium*, *Nocardia*, *Bdellovibrio*, *Mycobacterium* etc, and the two most common nitrifying bacteria, *Nitrosomonas* and *Nitrobacter* (Higgins and Burns, 1975). Additionally, various filamentous forms, such as *Sphaerotilus*, *Beggiatoa*, *Thiothrix*, and *Geotrichum* etc, may also be present (Higgins and Burns, 1975).

Metcalf and Eddy (2003) have defined the microorganisms by structure and functions. In principle, the groups of organisms found in surface water and wastewater can be classified as *Eucaryotes*, *Eubacteria*, and *Archaeobacteria*, More details are shown in Table 2-2.

Table 2-2 Classification of Microorganisms by Structure and Function.

Group	Cell structure	Characterization	Representative members
Eucaryotes	Contain true nucleus	Multicellular with extensive differentiation of cells and tissue. Unicellular of coenocytic or, mycelial; little or no tissue differentiation	Plants (seed plants ferns, mosses). Animals (Vertebrates, invertebrates). Protists (algae, fungi, protozoa)
Eubacteria	Contain no nuclear membrane	Cell chemistry similar to eucaryotes	Most bacteria
Archaeobacteria	Contain no nuclear membrane	Distinctive cell chemistry	Methanogens, halophiles, thermoacidophiles

In nature, the key role of bacteria is to stabilize organic materials and at the same time, to act as food for predators at higher tropic levels. In the activated-sludge process, bacteria are the most important microorganisms because of their role of decomposing organics in the wastewater. A portion of the organic waste is used by aerobic and facultative bacteria to obtain energy for cell synthesis and the remainder into new cell tissue. Two sources of cell carbon for microorganisms are organic matter and carbon dioxide. The microorganisms can be classified by source of energy and carbon adapted. Organisms that make use of organic carbon are called *heterotrophs*; Organisms that make use of carbon dioxide as the carbon sources are called *autotrophs*. The conversion of carbon dioxide to organic cell tissues is a reductive process that requires a net input of energy. Autotrophic organisms must therefore spend more of their energy for synthesis than heterotrophs *do*, resulting in lower growth rates among the *autotrophs*. The energy needed for cell synthesis may be supplied by light or by a chemical oxidation reaction. Those organisms that are able to use light as an energy source are called *phototrophs*. Phototrophic organisms may be either *heterotrophic* (*sulfur bacteria*) or *autotrophic* (*algae* and *photosynthetic bacteria*). Organisms that derive their energy from chemical reactions are known as *chemotrophs*. As the *phototrophs*, *chemotrophs* may be either *heterotrophic* (*protozoa*, *fungi*, and most *bacteria*) or *autotrophic* (*nitrifying bacteria*). *Chemoautotrophs* obtain energy from the oxidation of reduced inorganic compounds such as ammonia, nitrate, and sulfide. *Chemoheterotrophs* usually derive their energy from the oxidation of organic compounds. In accomplishing biological treatment

processes, the *chemoheterotrophic* organisms are of primary importance because of their requirement for organic compounds in addition to both carbon and energy source. Details are listed in Table 2-3.

Table 2-3 General Classification of Microorganisms by Sources of Energy and Carbon

Classification	Energy source	Carbon source (substrate)
<i>Autotrophic:</i>		
<i>Photoautotrophic</i>	Light	CO ₂
<i>Chemoautotrophic</i>	Inorganic oxidation-reduction reaction	CO ₂
<i>Heterotrophic</i>		
<i>Chemoheterotrophic</i>	Oxidation-reduction reactions	Organic carbon
<i>Photoheterotrophic</i>	Light	Organic carbon

Organism growth also requires nutrients for cell synthesis. Nutrients, rather than carbon may at times be the limiting material. The principal inorganic nutrients required by microorganisms are N, S, P, K, Mg, Ca, Fe, Na, and Cl.

While the bacteria are the microorganisms that actually degrade the organic waste in the influent, the metabolic activities of other microorganisms are also important in the activated sludge system. For example, protozoa and rotifers act as effluent polishers. Protozoa consume dispersed bacteria that have not flocculated, and rotifers consume small biological floc particles that have not settled.

Although it is important that bacteria decompose the organic waste as quickly as possible, it is also imperative that they form a settleable floc, which is a prerequisite for effective separation of the biological solids in the clarifier. It has been observed that as the mean cell residence time of the cells in the system increases, the settling characteristics of the biological floc are enhanced. For an industrial wastewater plant, a mean cell residence time of about 10 to 15 days is required to achieve effective settling. Even though excellent floc formation was obtained, the effluent from the system could still be high in biological solids as a result of poor design of the

secondary settling unit, poor operation of the aeration units, or the presence of filamentous microorganisms such as *Sphaerotilus*, *E.coli*, and *fungi* (Higgins and Burns, 1975; Jenkins et al., 1986).

In the reactor, the bacterial culture or activated sludge carries out the conversion according to the stoichiometry shown in the following equations:

Oxidation and Synthesis:

Endogenous respiration:

In these equations, COHNS represents the organic matter in wastewater. It is shown that in aerobic processes, food (organic material), activated biomass, nutrients, and oxygen are four main elements for the reaction.

Nevertheless, only a portion of the original waste is actually oxidized to low-energy compounds such as NO_3^{2-} , SO_4^{2-} and CO_2 ; whereas the remainder is synthesized into cellular material. Also many intermediate products are formed before the end products.

From a chemical standpoint, the activated sludge consists mainly of several types of biochemical compounds including carbohydrates, proteins, lipids, and nucleic acids, synthesized by all living cells. These biochemical compounds contain mainly carbon, which the cells obtain from the compounds in the waste. Some of these compounds also contain nitrogen, phosphorous and many other elements in smaller amounts. Naturally all of the elements needed to synthesize the biochemical compounds must be present in the wastewater. When the needed compounds are lacking, those in short supply must be provided.

Usually, the chemical composition of the sludge is not of major interest in the activated sludge process but microbial growth is normally assessed as an increase in

the mass of sludge in the system regardless of its composition. It should be emphasized that when comparing the balanced growth with activity of the sludge, the latter one must be preferred and monitored. However, it is a prerequisite to maintain the reactor biomass' ability to remove substrate.

Oxygen is supplied to an activated sludge reactor in order to provide the microorganisms with the means to oxidize a portion of the organic compounds in the waste material (i.e. the oxygen is the electron acceptor). A portion of the energy released during the oxidation process is converted into chemical energy (i.e. Adenosine Triphosphate), which permits the organisms to use the remaining organic carbon as elements to synthesize the particular compounds (carbohydrates, proteins, lipids and nucleic acids) needed for their structure and function. The amount of oxygen used during the process of obtaining energy and extracting organic carbon from the wastewater for growth is quantified by the biochemical oxygen demand (BOD) exerted during the metabolic purification of the wastewater. Thus, the exertion of BOD and the growth of microorganisms, that is sludge production, take place concurrently and are interrelated. After the organic carbon has been either oxidized or taken up by the microorganisms in the growth process, oxygen uptake will still occur because the newly synthesized population begins to undergo auto digestion or endogenous respiration.

Overall, in order to continue to reproduce and keep function properly, the organism must have 1) a source of energy, 2) carbon for the synthesis of new cellular material, and 3) inorganic elements (nutrients) such as nitrogen, phosphorus, sulfur, potassium, calcium, and magnesium. Organic nutrients (growth factors) may also be required for cell synthesis. Biological treatment is the degradation of organic waste by the action of microorganisms. Degradation alters the molecular structure of organic compounds and the degree of alteration determines whether biotransformation or mineralization has occurred. Biotransformation refers to the simplification of an organic compound to a daughter compound, which is partial degradation. Mineralization is the complete breakdown of organic materials into cellular mass, carbon dioxide, water and inert inorganic residuals, which is complete degradation.

To make sure the bacteria in reactors biodegrade the soluble organic material to some degree, some other factors effecting biological treatment need to be observed prudently. These factors are summarized under the following categories:

- Enzymatic processes
- Substrate biodegradability
- Inhibition and toxicity
- Microbial community

Enzymatic process

Waste constituents can occur in a size as small as a single molecule or as large as a droplet. For degradation to occur, the substrate must first be exposed to a bacterial cell's outermost coating. The action initiates a series of metabolic steps in the degradation of organic waste as depicted in Figure 2-1.

Substrate biodegradability

Experience and research showed that most synthetic organics were biodegradable, making biological treatment a technically feasible alternative. Attempts to correlate degradability with various structural parameters indicate that the following conditions, either individually or in combination, were frequently associated with recalcitrant or persistent compounds:

- 1) Halogenations
- 2) Large number of halogens
- 3) Highly branched
- 4) Low solubility in water
- 5) Atomic charge difference

Figure 2-1 Metabolic Steps in Degradation of Waste Organic

Inhibition and toxicity

Organic and inorganic waste materials move through a progression of effects as the concentration increases. An organic substance that is biodegradable at one concentration becomes persistent at higher concentrations by inhibiting the growth of the new cells. At even higher concentrations, the substance can become toxic to the bacteria. These effects derive presumably from the degree to which the substance overwhelms the enzymatic systems that normally degrade it. Many of the inorganic nutrients necessary for the synthesis of cellular mass are toxic to the same organisms at higher concentration.

Basic to the design of a biological treatment process or the selection of the type of process to be used is an understanding of the biochemical activities of the important microorganisms.

2.4 Fundamental Microbial Kinetics

Bacteria can be reproduced by binary fission, by a sexual mode, or by budding, with binary fission as the most common way. The time required for each fission, which is termed the generation time, can vary from days to less than 20 min. For single population of microorganism, the general growth pattern of bacteria in a batch culture has four, more or less, distinct phases. They are the induction phase, the log-growth phase, maturity phase, and the decline phase. However, most biological treatment processes are comprised of complex, interrelated, mixed biological population, with each particular microorganism in the system having its own growth curve. The position and shape of a particular growth curve in the system, on a time scale, depend on the food and nutrients available and on environmental factors such as temperature, pH, dissolved oxygen, and so on (Metcalf and Eddy, 2003).

The kinetics of biological growth is based on three fundamental relationships, which are the bacterial growth rate, the relationship between substrate concentration and growth rate, and the growth yield. The rate of growth of bacterial cells can be defined by the following relationship:

$$r_g = \mu X \quad (2.3)$$

Where r_g = rate of bacterial growth, mg/L. hr

μ = specific growth rate, h^{-1}

X = concentration of microorganism, mg/L

In biological treatment systems, the biomass decay phase occurs at the same time as bacterial growth. As a result, the net growth rate of microorganisms must be adjusted for such conditions as death and endogenous respiration or predation by other cells. To include these affects, an endogenous decay term is used to modify the general growth equation as the following expression:

$$r'_g = (\mu - d)X \quad (2.4)$$

Where r'_g = net rate of bacterial growth, mg/L. hr

d = endogenous decay coefficient, h^{-1}

To evaluate the microorganism concentration, the two most commonly used methods are: the use of volatile solids concentration and the elemental cellular constituents of

solids such as carbon, nitrogen, and phosphorus, as a measure of the bacterial concentration. These methods, however, do not distinguish between living and dead bacterial cells. Other methods that can be used for bacterial evaluation include the use of deoxyribonucleic acid (DNA) and adenosine triphosphate (ATP).

To describe the relationship between the rate of bacterial growth and substrate concentration, the most widely accepted model that was proposed by Monod (1949):

$$\mu = \frac{\mu_m S}{K_m + S} \quad (2.5)$$

Where μ_m = maximum specific growth rate, h^{-1}

K_m = half velocity coefficient; equal to substrate concentration at one-half the maximum growth rate, mg/L .

S = concentration of growth-limiting substrate, mg/L .

The Monod equation has been widely used in biological process models for both aerobic and anaerobic waste treatment systems. The specific growth rate of biomass is limited by the substrate concentration. Thus, when the substrate concentration is changed, the growth rate and product formation rate will be affected.

As mentioned in section 2.3, in a biological process system, a portion of the substrate is used by microorganisms for cell growth, and another portion is oxidized to end products. A constant relationship was found by Monod (1949) between the rate of bacterial growth and the rate of substrate utilization:

$$r_g = -Y_x r_{su} \quad (2.6)$$

Where r_{su} = rate of substrate utilization, $\text{mg/L} \cdot \text{h}$

Y_x = maximum yield coefficient, mg/mg (defined as the ratio of the mass of cells formed to the mass of substrate consumed)

2.5 Major Biological Treatment Process

Through proper analysis and environmental control, almost all wastewaters can be treated biologically (Metcalf and Eddy, 2003). The objectives of the biological

treatment of wastewater are to coagulate and remove the non-settleable colloidal solids and to stabilize the organic materials. For industrial wastewater, the objective is to remove or reduce the concentration of organic and inorganic compounds. The principle methods now used for the treatment of wastewater and sludge are varied based on the contaminants to be treated. For example, nutrients (nitrogen and phosphorus) removal in the wastewater can be done by biological treatment. For better illustration, the major biological processes applied in wastewater treatment are summarized in Table 2-4.

Table 2-4 Major Biological Treatment Processes Used for Wastewater Treatment

Type	Common name	Used	
Aerobic processes:			
Suspended-growth	Activated-sludge process	Carbonaceous BOD removal (nitrification)	
	Conventional (plug-flow)		
	Complex-mix		
	Step aeration		
	Pure oxygen		
	Sequencing batch reactor		
	Contact stabilization		
	Extended aeration		
	Oxidation ditch		
	Deep tank		
	Deep shaft		
	Suspended-growth nitrification		Nitrification
	Aerated lagoons		Carbonaceous BOD removal (nitrification)
	Aerobic digestion		Stabilization, carbonaceous BOD removal
Attached-growth	Conventional air	Carbonaceous BOD removal (nitrification)	
	Pure oxygen		
	Trickling filters		Carbonaceous BOD removal, nitrification
	Roughing filters		Carbonaceous BOD removal
	Rotating biological contactors		Carbonaceous BOD removal (nitrification)
Combined suspended- and attached-growth processes	Packed-bed reactors	Carbonaceous BOD removal (nitrification)	
	Activated biofilter process, trickling-filter solids-contact process, biofilter activated sludge process, series trickling-filter activated-sludge process	Carbonaceous BOD removal (nitrification)	
	Anoxic processes:		
	Suspended-growth	Suspended-growth	Denitrification
Attached-growth	Fixed-film denitrification	Denitrification	
Anaerobic processes:			
Suspended-growth	Anaerobic digestion	Stabilization, carbonaceous BOD removal	
	standard rate, single stage		
	High-rate, single-stage		Stabilization, carbonaceous BOD removal
	two- stage		Stabilization, carbonaceous BOD removal
	Anaerobic contact process		Carbonaceous BOD removal
	up-flow anaerobic		Carbonaceous BOD removal
Attached-growth	Sludge-blanket	Carbonaceous BOD removal, waste	
	Anaerobic filter process		Stabilization (denitrification)
	Expanded bed		Stabilization, carbonaceous BOD removal
Combined aerobic, anoxic, and anaerobic processes:			
Suspended-growth	Single or multi-stage	Carbonaceous BOD removal, nitrification, denitrification,	
	Processes, various proprietary		
Combined suspended and attached-growth	Processes phosphorous removal	Carbonaceous BOD removal, nitrification, denitrification, phosphorous removal	
	Single or multi-stage processes		
Pond processes	Aerobic ponds	Carbonaceous BOD removal	
	Maturation (tertiary) ponds	Carbonaceous BOD removal (nitrification)	
	Facultative ponds	Carbonaceous BOD removal	
	Anaerobic-ponds	Carbonaceous BOD removal	

2.6 Advanced Suspended Culture Processes

Suspended culture processes are developed based on the principle of the activity of suspended microorganisms. Essentially, these processes use a settling tank designed to separate the phases and recycle a part of the biomass.

The latest processes have solved these problems using more compact space-saving bioreactor which design is based on two principles: 1) increasing the height of reactors and 2) ensuring biomass retention with a membrane. Lazarova and Manem (1994) summarize there are two main groups of huge reactors corresponding to the processes-*Biotower Biology* and *Deep-Shaft* and multi-reactor technology bioreactors

Biotower Biology, the most important technical device in these reactors is the design of the air injection system for the tall reactors. The result of operating the first industrial installations showed higher removal rates (up to 2 to 3 times) than in conventional processes combined with up to 20% reduction in excess sludge production (Fouhy, 1992).

Deep-Shaft and multi-reactor technology bioreactors, the development of Deep-Shaft reactors is based on two technological principles: First air-lift aeration, which produces very high liquid circulation rates ($1.2-1.5 \text{ m s}^{-1}$) in very deep, complete mixing reactors. Second is the liquid percolation through a series of aerated chambers (multireactor) in 20 to 60 m reactors (Engwirda, 1986). These very deep installations will achieve high oxygen efficiency of over 60-75% in tower bioreactors (Diesterweg et al., 1980; Pascik and Mann, 1984) and 85-90% in deep-shaft reactors (Fields, 1992). Thus, energy consumption is reduced by more than 50% (Fouhy, 1992) compared with that of conventional activated sludge tanks. The gas and odor emission is 5 - 10 times lower (Pascik and Mann, 1984).

Biomass separation is integrated in the biological reactor. It is performed by sedimentation or floatation (multireactor). The main problem of these systems is the poor sludge settling properties. The considerable difference in pressure at the surface and bottom of the reactors may affect biomass activity and sludge flake integrity. Overall, the most important figures of the two groups of huge reactors suspended

culture processes above mentioned are the high oxygen use rate, stable biological operation with high load fluctuations and higher treatment capacity stimulated by high biomass concentrations, although costly economic investment is required for these processes.

2.7 Aerobic Attached-Growth Treatment Process

Aerobic attached-growth biological treatment processes are usually used to remove organic matter in wastewater. The attached-growth processes include the trickling filter, roughing filter, rotating biological contactor, and fixed/moving-bed film reactors. The use of attached growth is a mean of obtaining very high concentrations and various types of bacteria. When treating wastewater, high concentrations of bacteria make it possible to increase the loading applied (e.g., kg of COD or BOD₅ m⁻³ d⁻¹) and reduce the sizes of treatment process.

2.7.1 Fixed Bed Bioreactors

Fixed-bed biofilm reactors, such as the trickling filter and bio-filters, have been widely used by environmental engineers to treat wastewater and gases. The processes are developed using inorganic, porous filling materials like expanded schist (density approximately 1.5 gram/cm³; diameter 2-6 mm). Lazaroval and Manem (1994) described several examples of industrial fixed bed which may work as down or up flow processes. The main advantage of fixed beds is that they can operate simultaneously as biological reactors and filters, which means that secondary settling is not required. Specific energy consumption is similar to that in activated sludge tanks (approximately 1.0 ~ 1.4 KW per kg COD removed) but the loading rates are much higher (5-10 kg COD m⁻³ d⁻¹) at a mean flow rate of 2.0 - 2.5 m³ h⁻¹. Such installation cost is from 20-30% higher than conventional plants, excluding land cost. These reactors are economically competitive if land is limited and if tertiary treatment is required (Pujol et al., 1992). However, as the biomass grows over time, bed clogging and increasing pressure-drop are among the most challenging problems faced by long-term operation of fixed-bed biofilm reactors (Weber and Hartmans, 1996; Sorial et al., 1998). New continuous back-washing reactors are developed to overcome this problem (Koopman et al., 1990).

2.7.2 Mobile Bed Bioreactors

The biofilm surface can be fixed, where the carriers are in constant motion caused by the liquid and/or gas flows (Yu et al., 2001). These cover all biofilm processes with continuously moving media (stirred, expanded, fluidized and/or circulating) maintained by air agitation and/or water velocity or by mechanical means (Table 2-5). This mode of operation has some effects as follows:

- 1) Improving mass transfer;
- 2) Reducing biofilm diffusion limitations;
- 3) Accelerating biochemical reactions by increasing biofilm/liquid transfer area and
- 4) Using very porous granular material to increase the specific surface area available for bacterial growth.

These advantages explain the better performances of mobile bed reactors described by several authors (Heijnen et al., 1989). The main disadvantage of fluidized bed is in their sophisticated construction related to the scale-up of aeration devices, flow distribution etc. (Sutton and Mishra, 1990). Furthermore, the physical properties of the medium (density of the virgin media and media with biofilm growth) and the filling rate of the reactors considerably affect hydrodynamic process performance.

Table 2-5 Overview Mobile Bed Bioreactors

Type	Medium	Volumetric loads (kg m ⁻³ d ⁻¹)	Biomass (kg SS m ⁻³)
2-phase aerobic fluidized bed	Sand/GAC	0.6-1.3 (NH ₄ ⁺ -N) 0.6-0.72 (BOD)	5.5~22
3-phase aerobic fluidized bed	Anthracite 0.8 mm; Clay; plastics	6.4~15 (COD)	2~3
Inverse fluidized bed	PE 2~5 mm; Expanded polyethylene	12-35 (COD)	5~20
Air lifts	Basalt 0.2 mm; Sand 0.2 mm	1.5~4.2 (NH ₄ ⁺ -N)	25~40
Turbulent bed	Plastic	0.5~0.9 (COD)	2.88~4.22
Stirred bed	Patent 2~4 mm	15~20 (COD)	7.0~16

2.7.2.1 Fluidized Bed Bioreactors

The fluidized bed process differs from other mobile beds due to homogeneous expansion of the medium, maintained by the liquid velocity. The first fluidized bed reactor developed for water treatment in 1970 is patented in the USA by Ecolotrol (Cooper, 1981; Sutton and Mishra, 1990). Since then, considerable attention is devoted to biological carrier based fluidized bed technology which combines the best features of the activated sludge process and the trickling filter (Stathis, 1980). A large number of laboratory and pilot tests perform particularly on two-phase aerobic, anoxic and anaerobic fluidized beds. Two-phase fluidized beds are recommended as an attractive, competitive process in the following treatments:

- a) Aerobic or anoxic treatment of industrial water with low levels of organic pollutants (Sutton and Mishra, 1990)
- b) Tertiary treatment with nitrification (Cooper and Williams, 1990)
- c) Methanisation of food industry effluents.

Despite the major advantages of two-phase fluidized bed design, scale-up and industrial development are limited by numerous problems and technical constraints, the most important of which are the control of bed expansion and biofilm thickness, influent distribution device and oxygen saturation system. To solve these problems, the three-phase fluidized reactor is developed.

2.7.2.2 Three-phase Fluidized Bed Reactor

Increasing volumes of stream of wastewater together with spatial constraints and the tightening of effluent quality standards have driven the development of new intensive biotechnologies for wastewater treatment. Through some studies and practices, the three-phase fluidized biofilm reactor becomes a developed aerobic wastewater treatment technology, which has great potential application due to its flexibility and efficiency (Mulder and Eikelboom, 1993). The three-phase fluidized bed process is sometimes preferred to an activated sludge process for the following reasons:

- a) The reactor has large specific biofilm surface areas;

- b) Oxygen is supplied from the gas phase to the liquid phase simultaneously with oxygen consumption by bio-oxidation;
- c) Large area for construction is not required; and clogging problems are prevented and rapid transfer of substrates between the liquid and biomass is promoted.

A three-phase fluidized bed process has also the advantages of lower hydraulic retention time (HRT), higher concentration of biomass, good performance in chemical oxygen demand (COD) and ammonium removal, ability to resist shock loads and high mass transfer rate (Fan et al., 1987; Cheng and Chen, 1994; Tavares et al., 1995).

Three-phase fluidized bed reactors/processes partly solve the problems by using simultaneous gas and liquid injection. The three phases comprise the solid medium, which contain the biofilm; the liquid, which is the wastewater to be treated; and a gas, such as air used for oxygen supply. This improves liquid/solid mass transfer and induces high shear stress that can controll biofilm thickness (Trinet et al., 1991). The three-phase fluidized bed reactors gains popularity in water and wastewater treatment (Lazarova and Manem, 1994; Sutton and Mishra, 1990; Shieh and Kennan, 1986). Three phase fluidized bed reactor/process were developed in Scandinavia in the late 1980's to provide a compact and robust solution for nitrogen removal, (Rusten et al., 1994c). Three-phase fluidized bed reactors/processes can be divided into process groups according to the medium used and the driving force applied for fluidization (Figure 2-2).

Figure 2-2 Classification of Three-Phase Fluidized Bed Reactors

The operation and performance results from the pilot plant studies on three-phase fluidized bed reactors (TPFBRs) are reported in detail elsewhere (Sutton et al.,

1985; Hare et al., 1988), and the operation of a number of both small and large scale biological TPFBR pilot plants results in the derivation of process and component information for the design of large scale commercial facilities (Sutton and Mishra, 1990). The TPFBRs utilize small, fluidized media for cell attachment and grow (Atkinson and Davies 1972; Atkinson and Rahman 1979; Atkinson et al., 1984; Andrews 1986; Bryers 1987; Kolot 1981; Scott 1987; Switzenbaum 1985). The formation of biofilm on the fluidized media yielded a high volume of biomass results in suitable F/M ratio, which ensures good process efficiency and stability without cell washout problems (Atkinson and Davies, 1972; Bull et al., 1983; Chen et al., 1985a, 1985b; Cooper 1981; Shieh and Keenan, 1986). Due to the higher volume of biomass in the reactor, a larger volumetric load can be handled.

TPFBRs are proven to be effective for the treatment of many kinds of wastewater. These include wastewater originates from coke plants (Nutt et al., 1984), domestic wastewater (Collivignarelli et al. 1991; Forster et al. 1986; Oppelt et al., 1978; Ryhiner et al., 1988; Scheible and Grey 1988; Sutton and Mishra 1990), contaminated surface and groundwater (Sutton, 1987), industrial wastewater (Sutton et al., 1979), and wastewaters containing chlorinated compounds (Holst et al., 1991; Livingston, 1991), phenolic wastewater (Holladay et al., 1978; Lin and Weber 1991; Worden and Donaldson, 1987), nitrogen contaminant wastewater (Cooper and Williams 1990; Jeris et al., 1977; Hirata et al., 1988, 1990; Hirata and Hosaka, 1989a), ammonia-nitrogen containing wastewater (Hirata et al., 1989) washed drum wastewater (Hirata et al., 1992), and kitchen wastewater (Hirata *et al.*, 1991). The application of the technology is developed further in the UK (Siviter, 1997) and elsewhere in Europe for both new treatment plants and for plant upgrades. In principle, at high BOD concentration, the biological reaction obeys the zero order reaction; while at lower one, the biological reaction obeys the first order reaction. Based on characteristics of the TPFBR, which is applied to the high COD/BOD loads and the activated sludge reactors is applied to lower ones, so that wastewater is treated most efficiently and most economically in the combination of the three-phase fluidized reactor and activated sludge tank.

2.7.2.3 Kaldnes Carrier reactor

High strength industrial wastewater is difficult to treat in conventional activated sludge system without having very large tank and long hydraulic retention time. The three-phase fluidized reactor, having a large surface area for biomass to grow on, is able to reduce the large reactor volume and long hydraulic retention time required. However, in order to solve the problems that biofilm can not be protected and grown well on the surfaces of the carrier and the specific surface is not big enough, it led to the development of the Kaldnes carrier. The process with Kaldnes carriers is developed by Kaldnes Miljøteknologi in Norway, in cooperation with the SINTEF research organization (Rusten et al., 1999). The process uses the specially developed Kaldnes media which acts as a biofilm carrier. It is used both alone and as a roughing stage followed by activated sludge in many wastewater plants. The TPFBR is a continuously operating, non-cloggable biofilm reactor with low head loss, high specific biofilm surface area and does not require backwashing. This is achieved by having the biofilm (or bio-mass) grown on small carrier elements that move along with water in the reactor. The movement is caused by aeration in the aerobic version of the reactor. The carrier elements are made of polyethylene (density 0.96 g cm^{-3}) and shaped like small cylinders (about 10 mm in diameter and 7 mm in height) with a cross inside the cylinder and longitudinal fins on the outside. In order to keep the biofilm carriers in the reactor, a screen of perforated plates (with 5x25 mm slots) is placed at the outlet of the reactor. The agitation is arranged so that the carrier elements are constantly being moved upwards over the surface of the screen (See Figure 2-3). This creates a scrubbing action that prevents clogging.

Depending on the treatment required and strength of a given wastewater, the filling of carrier elements in a reactor can be decided for each case giving considerable flexibility in the specific biofilm surface area. A maximum filling of 67% (volumetric filling of carrier material in empty reactor), has a potential specific growth area of biofilm at about $500 \text{ m}^2 \text{ m}^{-3}$. Because the growth is much less on the outside of the cylindrical carrier than on the sheltered inside area, the maximum practical specific growth area is expected to be about $350 \text{ m}^2 \text{ m}^{-3}$. There is no dead space or unused space in the reactor; therefore, the wastewater is completely mixed in the reactor. In the Kaldnes TPFBR, however, the major part of the biomass grown on the protected

surfaces within the carrier elements and this is one of the reasons why it was selected for the pilot study.

The Kaldnes carrier process is used at both pilot and full-scale facilities for municipal and industrial wastewater treatment (Rusten et al., 1992; Hem et al., 1994; Rusten et al., 1994b; 1995; 1996a) as well as for food industry wastewater. For instance, in the potato wastewater application it is shown to remove 95.3% and 97.5% total COD at loading of $2 \text{ kg COD m}^{-3} \text{ d}^{-1}$ and $4 \text{ kg COD m}^{-3} \text{ d}^{-1}$ respectively (Rusten et al., 1996b). In the pulp and paper application, it is shown the removal of 65~70% total COD and 75~80% soluble COD at loading of $10\sim50 \text{ kg COD m}^{-3} \text{ d}^{-1}$ (Rusten et al., 1994a; Dalentoft and Thulin 1997). The Kaldnes-carrier three-phase fluidized bed reactor is not only used in removal of carbonaceous materials but also can be particularly implemented to remove nitrogen in municipal wastewater treatment plant (Rusten et al 1997). Further details are summarized in Appendix I.

The application of Kaldnes carrier three-phase fluidized bed reactor in the process as a roughing stage followed by the activated sludge process is similar to the first stage in IWWT, which provides an effective and simple means of reducing high influent carbonaceous materials. For example, at an organic loading of up to $53 \text{ g BOD}_5 \text{ m}^{-2} \text{ d}^{-1}$, 60 to 80% of the easily biodegradable BOD_5 fraction is removed. At organic loads of $10 \text{ to } 20 \text{ g BOD}_5 \text{ m}^{-2} \text{ d}^{-1}$ slowly biodegradable organic matter is also metabolized, sometimes removing more than 95% BOD_5 . After polishing in an activated sludge unit, the final effluent has an average concentration of 3.4 mg/L filtered BOD_5 (Rusten, 1992).

In the first stage of the process, Kaldnes carrier three-phase fluidized reactor consistently performs even under shock loads and is not liable to activated sludge bulking (Sunner et al. 1999). Therefore, it is also applied in upgrading chemical wastewater process, such as Exxon in Louisiana, USA (Rusten et al., 1999).

Figure 2-3 Kaldnes Carrier-Based Fluidized Reactor

2.7.2.4 Organic load in three-phase fluidized bed reactor

In the TPFBR, wastewater is treated by both biofilm and suspended bacteria. The biological removal rate is greatly affected by the specific surface area of biofilm (Hirata et al., 1988; Cecen and Gonenc, 1994; Hem et al., 1994). A number of empirical and rational parameters are proposed for the design and control of the fluidized reactor. The most commonly used parameter is the food-to-microorganism ratio:

$$(2.7) \quad F/M = \frac{Q^0 S^0}{VX}$$

In conventional activated sludge process, where F/M is the food-to-microorganism ratio [d^{-1}], V , the volume of the aeration tank [m^3], Q^0 is the influent wastewater flow rate [$\text{m}^3 \text{d}^{-1}$] and X , the concentration of total bacteria in the aeration tank [g m^{-3}].

In a three-phase fluidized bed bioreactor, X represents the concentration of the bacteria of both on the carrier-attached biofilm and the MLSS. Normally the F/M ratio ranges from 0.5 to 2 in the attached-growth treatment process (Metcalf & Eddy, 2003).

The concept behind biofilm reactor is that bacteria attach naturally to solid surfaces and/or are entrapped inside attachment matrixes so that the majority of the bacteria are immobilized on effective surface areas (Yu et al., 2001). As individual media particles are in suspension, they become completely coated with biomass under some certain conditions (Bignami et al. 1991; Kargi and Park 1982; Scheible and Grey, 1988). The average volatile solid concentration in an aerobic fluidized bed reactor can

be more than an order of magnitude higher than that of the activated sludge process (Jeris et al., 1977). As the concentration of bacteria in the reactor can be maintained at a high level, the F/M ratio will be lower compared to the similar reactor used with only suspended sludge, which is same to allow the reactor to handle higher organic load.

Most of the aerobic TPFBRs make use of various brands of suspended carriers, on which the biofilm attaches and grows. In recent years, there are dramatic proliferations of researches on the carriers for biological wastewater treatment process, such as activated carbon PAC, cement ball, Toyoura sand, quartz sand motioned by Hosaka (1985), and others fibrous carrier, gel beads, biolox rings, bio-flow rings, and Kaldnes carriers etc. Much work is done by using PVA as a matrix for biofilm attachment and growth. PVA immobilized systems is used in various process including biocatalysts, nitrification and denitrification (Hashimoto and Furukawa, 1987). The carriers in the three-phase fluidized reactor have a variety of shapes and physical properties, which can affect the performance of the process. Therefore, other parameters must be taken into account while selecting the carriers to ensure a successful process start-up.

2.8 Factors of Affecting Performance of TPFBR

The organic removal efficiency of the reactors is determined by the amount of biomass and the interfacial area between biofilm and bulk liquid. Physical properties of carriers, such as size, shape, material and density, changed dramatically as biomass accumulates on the carrier surfaces. These changes directly affect the hydrodynamic behavior of the carriers in a biological fluidized bed reactor and, consequently, reactor performance. These factors might also have a direct influence on the enzyme activities and growth rate or indirectly through the biomass/biofilm structures, the diffusion rates, the solubility of oxygen, etc. (Anette et al., 1998). The balance between growth and detachment of carrier-attached biofilm can influence reactor start-up. Reactor start-up can be very slow, especially when slow-growing microorganisms (e.g. nitrifiers) are involved.

In order to achieve the anticipated performance of the reactor with the right type of carrier, the properties such as porosity, homogeneity, particle dimensions, density, as well as mechanical, chemical and biological stability needed to be considered. They are crucial for maximum treatment yield, trouble free plant performance and maximum service life of the carrier material (Morper et al., 1990). A proper choice of carrier type may considerably enhance reactor start-up, while a wrong choice may cause delay or even start-up failure.

Differences in the macroscopic biofilm structure and properties in technical systems are also observed to be influenced by several factors such as shear stress, feeding pattern, substrate type and load, etc. (Loosdrecht et al., 1995).

2.8.1 Biofilm

Biofilm formation and growth are important factors for successful operation of the carriers fluidized bed reactor. Christensen and Characklis (1990) state the theory of biofilm forming on the carriers, of which it is said that the biofilm is composed of two major components: microbial cells and products of metabolism, specifically exopolymers, which may assist in binding microbial cells to surface. The microbial extracellular and cell surface polymers are important in biofilm phenomena during the initial interaction between a bacterial cell and the substrate. Most microorganisms are able to grow on the surface of a solid when organic compounds, mineral salts and oxygen are available. They are anchored by means of an exopolymer-based gelatinous material produced by the bacteria, inside which the bacteria can, to some extent, move about. The colonization of the solid matter begins in selected areas, whence the biofilm develops continuously until the entire surface of the support is covered with a monocellular layer. After which, growth is continued by the production of new cells covering the first layer. The oxygen and nutrients are carried in the water to be diffused throughout the biofilm until the deepest cellular accumulations are no longer affected by the oxygen and nutrients. After some time, stratification occurs, with an aerobic layer, where the oxygen is diffused, on top of a deeper anaerobic layer in which there is no oxygen. The thickness of these two layers varies according to the type of reactor and support; more details are shown in Fig 2-4. Trinet et al. (1991) also confirms that microbial adhesion is promoted by the bonding

action of exopolymers. Consequently, microbial exopolymer plays a key role in biofilm formation and growth.

The use of biofilm processes for treating wastewater shows that the rate at which the substrate is utilized stabilizes at a constant value when the biofilm is deep enough for oxygen to become a limiting factor in the deepest layers, the “active” depth may be about 200 μm . The growth of cells within the biofilm can be described by Monod kinetics (Characklis, 1990). Maximum growth rates are found close to or identical to those found in suspension for both some aerobic bacteria and some sulfate reducing bacteria (Characklis, 1990; Okabe et al., 1995). The degradation of a soluble organic material in an activated sludge system is thought to be performed by a specific population of the microbial community, referred to as the competent biomass, which possesses the genetic capability to metabolize that soluble organic compounds and utilize them for growth. Microbial conversions in biofilm are controlled by growth kinetics and mass transport processes. Mass transport through the diffusion boundary layer and within the biofilm is assumed to be only molecular diffusion perpendicular to the substratum in the existing biofilm models (Rittmann and Manem, 1992; Wanner and Gujer, 1986; Wanner and Reichert, 1996). Factors affecting the biofilm formation and growth include substrate characteristics and COD concentration of the wastewater, the type of support media, hydrodynamics, operating conditions and nutrient availability, etc. inside the biofilm, there is a constantly changing population mix with increasing depth. At the surface, there is an active multiplication of cells because of the presence of high substrate concentrations. Towards the attachment surface, substrate may become limiting and endogenous decay may result. However, Okabe et al., (1998) describes biofilm structures, which is very porous and consisted of intertwined hairy biomass, which holds many microcolonies. Presence of the macropores with mean diameter of 20~200 μm and significantly facilitated particulate transport into the biofilm is found. The biofilm structure seemed to be well designed to maximize the transport of substrates and products and the resistance to external shear force due to water flow in. Biofilm mass may be lost by erosion of the biofilm surface due to shearing by the liquid flow, or by detachment of the biofilm from the attachment surface due to sloughing. Wanner and Gujer (1984) predicted theoretically that fast growing microorganisms will tend to predominate near the

surface, while slow growers will be deeper inside the film, scavenging substrate from the fast growers. Paul (1997) finds that the populations of heterotrophic, facultative and autotrophic microorganisms varied with depth in biofilm. It is also found the ratio of living cells to total biomass decreases from about 72-91% in the top biofilm layers to 31-39% in the bottom layers. Essentially all the actively metabolizing aerobic microorganisms are on the top 100µm of the biofilm (Zhang et al., 1994). In an aerobic biofilm reactor, the wastewater is treated by both biofilm and suspended sludge and the biological removal rate is greatly affected by the specific surface area of biofilm has been approved (Hirata et al., 1988; Cecen and Gonenc, 1994; Hem et al., 1994). Thus, the BOD is mainly removed by the bacteria attached to the surface of packed materials in the bioreactor (Lim and Huang, 2001).

Figure 2-4 Specific Sections of Biofilm

2.8.2 Carrier Abrasion and Collision

Biofilm development is determined by a balance between the growth and detachment. Spielman (1978) reported that the collision frequency depended on the particle concentration, particle diameter and the power input into systems. Several factors can be envisioned to cause detachment of biomass from suspended particles (carriers) such as collision of particles with one another as well as with reactor walls, liquid shear force in turbulent eddies and also in wakes of rising gas bubbles. These collisions cause an on-going abrasion of the biofilm carriers, leading to a reduction in

biofilm volume. Experiments in lab-scale airlift reactors, in which biofilm carriers and bare carrier particles are mixed, shows that inter-particle collision is the main cause of biofilm detachment (Gjaltema et al., 1995). When the carrier solid occupation is up to 30% to the reactor volume, the abrasion rate is linear with both the concentration of biofilm carriers and the bare carrier particles.

Particle collision is found to dominate the detachment. The general principles from particle collision theory can be applied to describe and quantify detachment in particulate biofilm systems regardless of the breakage of carriers. The total damage caused by collisions is quantified by the abrasion rate A [g h^{-1}], the product of the collision frequency N [h^{-1}] and the damage caused by a single collision, known as the collision impact I [g]:

$$A = I \times N \quad (2.8)$$

In a biofilm pellet-bare carrier system, the total abrasion rate is given by:

$$A_{\text{total}} = A + A_{bc} = 0.5I_{bb} \times N_{bb} + I_{bc} \times N_{bc} \quad (2.9)$$

in which subscripts bb denoted biofilm-biofilm and bc , biofilm-carrier collisions. (Note N_{bb} needed to be multiplied by a factor 0.5 to avoid double counting of biofilm-biofilm collisions).

However, the particle size influences both the collision frequency and the collision impact because the larger particles are contacted more easily and are more massive. As a result, the theoretical abrasion rate per particle increases considerably with increasing particle size. Abrasion due to interparticle collisions is presumed to be the key mechanism for biofilm detachment in liquid fluidized beds of particles (carriers) covered by thin, compact biofilm (Gjaltema, 1997). The numbers of collisions increase very rapidly as the particles become larger and heavier. As a result, the abrasion rate per particle increases drastically with increasing particle size (Gjaltema, 1997). Large and heavy particles also require greater power input to initiate the suspension and circulation of carrier particles. Therefore, carrier particles should be restricted from large size and weight.

2.8.3 Hydrodynamic Condition

The hydrodynamic condition is an important factor for the biofilm accumulation on the carriers in a TPFBR. Characklis (1981) expressed that biofilm dry density increases with increasing turbulence and substrate loading rate. Lazarova et al. (1993) found that shear stress was the determining factor for the contents of living cells and the composition of the microbial community within the biofilm. In cases where the turbulence is too low, shearing of the biofilm is inadequate and more biomass than wanted may established itself within the voids of the carrier, thus restricting the free passage of water and substrates to the biofilm. On the other hand, excessive turbulence may inhibit microbial growth, possibly by damaging cell membranes (Toma et al., 1991). When the turbulence is adequate, the biofilm is thin. However, the high thickness of the biofilm can not be achieved, possibly due to N_2 gas accumulation in the film when the thick biofilm become diffusion limited with subsequent gas release. Other metabolic products such as CO_2 , N_2 and CH_4 can accumulate in biofilm and decrease the bulk biofilm density. A loose biofilm layer is easily peeled off by the effects of turbulence. Cheng (1997) mentioned that biofilm formation was significantly affected by the mean liquid velocity. While the mean liquid velocity increased from 444 to 563 m/h, the biomass attached on to the GAC decrease from 30.4 to 15.6 mg VSS/g GAC due to hydraulic sloughing. High velocity is shown to exert a profound influence on the amount of attached biomass; it is caused by the abrupt intensification of shear stress and frictional forces acting on the particle surface.

2.8.4 Oxygen Transfer and Aeration Efficiency

Like any other biodegradation system, oxygen concentration is an important factor affecting microbial activities of the biofilm attached on the surface of carriers and thus the volatile organic compounds (VOC) removal efficiency (Zhou and Bishop, 1997). There are two ways for oxygen to be transferred. The first is for oxygen to be added and dissolved into wastewater by an external, pressurized oxygenator prior to fluidize reactor treatment (Shieh and Keenan, 1986; Sutton, 1980; Sutton et al., 1981). The second is by direct air injection into an aerated carrier-based fluidized reactor through an internal draft tube to promote oxygenation and mixing (Fan et al., 1987;

Forster et al., 1986). Fluidization of carriers in an aerated fluidized bioreactor is maintained by gas agitation and liquid circulation. The air flow is limited, as pointed out by Trinet et al (1991) that the specific detachment rate for biofilm would increase by increasing the superficial gas velocity. Generally the oxygen penetration depth in biofilm ranges from 100 to 200 μm (Van Loosdrecht and Heijnen, 1993). Yu (2001) reported that the higher concentration the biomass was in the carriers, the greater the oxygen was limited in the biofilm. It is well known that high specific oxygen absorption can be achieved with shallow tanks, high diffuser densities and low specific air flow rate. High aeration efficiencies can be obtained by high volumetric oxygen transfer rates and appropriate selection of the blowers used at the wastewater treatment plant (Martin et al., 1998). Tavares et al. (1995) also reported that biofilm characteristics were significantly affected by superficial gas velocity. The biofilm accumulation decreases when superficial gas velocity increases in the range of 0-20 m h^{-1} and the superficial liquid velocity is maintained at 98.6 m h^{-1} (Cheng et al., 1997).

2.8.5 Carrier Surface Roughness

Carrier roughness is one of the factors that can affect the collision impact; Zhang (1994) expressed that an increase in surface roughness appeared to decrease the average thickness of the dissolved oxygen (DO) boundary layers as well as the resulting mass transferring resistance. Ohashi and Harada (1994) reported that at the early stage of biofilm formation the relative roughness exhibited somewhat high values even though low values of the absolute roughness. This implies that the increment in roughness is not simply related to the increase in thickness, but also will be significantly affected by detachment. Very rough and edgy carrier particles like ground basalt are shown to enhance biofilm detachment, which may prevent or delay biofilm development. Nevertheless, the surface irregularities can offer protection from liquid shear and turbulence as well as particle collisions. In this way, rough carriers can provide better opportunities for biofilm formation than smooth carriers (Characklis, 1990). Therefore, the ideal carrier particles should be rough but not be very edgy.

CHAPTER THREE

PILOT STUDY

3.1 Innovative Approaches for IWWT

With expansion of customers, it was expected that more wastewater would be received and treated in IWWT. Thus, the TPFBRs in IWWT must be upgraded and would be able to handle the increasing organic load in line with the design capacity. In general, upgrading of TPFBR in IWWT to increase the organic removal efficiency involves three acts as follows:

- The existing process may be optimized with respect to the biological activities. However many means had been carrying out at IWWT before pilot study started, but all the efforts failed.
- The biological activities may be increased by changing to a process with a higher capacity. As the land is restricted on site; there was no space for additional reactors to set up.
- To upgrade existing reactors with a right type of carrier, this might improve the reactor's treatment efficiency.

Consequently, the strategy of selection and optimization right type of carrier becomes increasingly important. By this, it is targeted to increase the treatment efficiency in the three-phase fluidized reactor and eventually achieve the design capacity.

3.2 Pilot Plant Description

In order to obtain suitable type of carrier, a pilot study was carried out to evaluate and select carrier from a total three types. Four duplicated runs were fabricated in same sizes according to the design of IWWT in a relevant scale, which were made of PVC and operated in parallel, namely run 1, 2, 3 and 4.

The schematic diagram of the runs is illustrated in Figures 3-1 & 3-2. Technical drawings of the pilot systems are shown in the Appendix II.

Figure 3-1 Four Integrated Pilot Study Runs

* TPFBR stand for Three-Phase Fluidized Reactor

**Activated sludge tank

Figure 3-2 Schematic Diagram of Pilot Study Run

The influent was taken from the feed line from TK001 to the online TOC analyzer and introduced to each run at a constant predetermined flowrate by controlling Masterflex variable speed pump (Cole-Parmer instrument Company USA, Serial No J99001033, Model No 7521- 47). The effluent of each TPFBR was overflowed to the downstream activated sludge reactor, subsequently to the clarifier and finally discharged. In the clarifier, the sludge settled down to the bottom and the supernatant flowed over some v-notch weirs on a continuous basis. The total hydraulic retention time, was set, similar to IWWT, at approximately 22 hours, of which 10 hours for TPFBR, 10 hrs for activated sludge process and 2 hrs in clarifier. The actual wastewater used as feeding to each run was set at about 15 L h^{-1} by controlling Masterflex variable speed pump (Cole-Parmer Instrument Company USA, Serial No

J99001033, Model No 7521- 47). The expected dissolved oxygen concentrations of 4 mg/L for TPFBR and about 2 mg/L for the activated sludge reactor were maintained in each run throughout the study. And mixed liquor suspended solids (MLSS) ranged from 3000 - 4000 mg/L in activated sludge reactor by wasting sludge from the clarifier was expected.

In order to compare the performance of different carriers selected for the study in each TPFBR, the organic load and hydraulic load correspondingly equivalent to 100% to 110% and 100% of the IWWT design capacity were sustained all the time. As a cautious approach, the performances of selected carrier were closely observed under the conditions as mentioned in next section.

3.3 Sampling and Analysis Program

The pH, temperature in both stage reactors, influent TOC, TPRFB effluent TOC, final effluent TOC and TSS were checked up daily; the COD and BOD₅ in influent and TPRFB effluent were analyzed weekly; the MLSS in each reactor was examined twice a week and the weight of biomass on each carrier surface was checked weekly in first two months. The details of analysis program are summarized in Table 3-1.

Table 3-1 Program of Sampling Analysis

Test parameters	Influent	TPFBRs	A/S	Effluent
DO, mg O ₂ /L	Daily	Daily	Daily	
pH	Daily	Daily	Daily	Daily
Temperature C°	Daily	Daily	Daily	
Filtered TOC, mg/L	Daily	Daily	Daily	Daily
Filtered COD, mg/L	Weekly	Weekly		Weekly
Settled BOD, mg/L	Weekly	Weekly		Weekly
Biomass		Weekly		
MLSS/MLVSS, mg/L	Twice per week	Twice per week	Twice per week	
NH ₄ ⁺ -N, mg/L				Twice per week
NO ₃ ⁻ -N, mg/L				Twice per week
PO ₄ ³⁻ -P, mg/L				Twice per week

TPFBRs stand for Three-Phase Fluidized Reactors;

A/S stands for activated sludge tanks.

3. 4 Experimental and Methodology

3.4.1 Tested Carriers

In total, three types of carrier were employed for this study: the existing carrier made of polyvinyl alcohol (PVA) coated with powdered activated carbon (PAC) was referred to as type I carrier (Figure 3-3), the Bio Carrier Plastic (BCP) was referred to as type II carrier (Figure 3-4), and the Kaldnes carrier was labeled as type III carrier (Figure 3-5). The physical characteristics and the costs are summarized in Table 3-2. The media fillings in reactors and the corresponding displaced water volumes are elaborated in Table 3-3.

Figure 3-3 Type I Carrier- Existing Carrier

Figure 3-4 Type II Carrier Bio-Carrier Plastic (BCP)

Figure 3-5 Type III -Kaldnes Carrier

Table 3-2 Media Properties and Costs

Physical Characteristics	Type I carrier	Type II carrier	Type III carrier
Total surface area (m ² m ⁻³)	600	750	500 m ² m ⁻³ (Protected surface area 300m ²)
Density	1.1 g cm ⁻³	0.98 ~ 1.0 g cm ⁻³	0.92 ~ 0.96 g cm ⁻³
Diameter	2 ~ 6 mm	4x4 mm	7x10 mm
Filling (reactor volume)	10 ~ 30%	10 ~ 30%	35% ~ 65%
Material	PVA & carbon	Plastic	Polyethylene
Cost	1500 USD m ⁻³	1300 USD m ⁻³	1000 USD m ⁻³

Table 3-3 Media Filling Equal to Corresponding Displaced Water Volume

Type I Carrier					
Carrier filling	10%	15%	20%	30%	40%
Displaced water volume	5%	7.5%	10%	15%	20%
Type II Carrier					
Carrier filling	20%	25%	30%	35%	40%
Displaced water volume	11.5%	14.5%	16.5%	19%	21.5%
Type III Carrier					
Carrier filling	42%	50%	60%	65%	70%
Displaced water volume	8.5%	9.2%	10.8%	12.7%	13.6%

3.4.2 Processes Start-up

The period of pilot study was split into two stages according to where the returned sludge went. The first stage was from 28th of Mar to 29th of April 2000, during which 100% of return sludge was being pumped back to TPFBRs and approximately 12 days of sludge retention time was maintained; the second stage started from 30th of April to 23rd of June 2000, during which 100% of return sludge was being pumped back to activated sludge reactors and the sludge retention time was same as that in phase I.

The TPFBR in run 1 was seeded with 22.5 liters of virgin type I carriers, which took 15% of reactor volume and equivalent to 7.5% of water-displaced volume (See Table 3-3). With an intention of assessing performance of the reactor with higher filling of existing carriers, 45 liters of used type I carrier which were retrieved from IWWT, were seeded in run 2 and the filling occupied 30% of TPFBR volume and equaled to 15% of water-displaced volume (See Table 3-3). As recommended, the run 3 was packed with 30 liters of type II carriers that occupied 20% of TPFBR volume, which equal to 11.5% of displaced-water volume (See Table 3-3). 90 liters of type III

carriers were seeded in run 4 that filling stood 65% of TPFBR volume, which equal to 12.7% of the displaced-water volume (See Table 3-3). The air supplied to the reactors was tapped off from the existing air pipe. And the seeding sludge was also obtained from activated sludge process at IWWT. 80 and 60 liters of sludge were dumped into TPFBR and activated reactor for each run respectively.

Because of the lack of nutrients in the wastewater coming from fine chemical plants, a solution of mixed phosphoric acid and urea was dosed into the runs at flow rate of 0.12 L h⁻¹ controlled by same variable speed pump as mentioned before. The nutrient solution containing 4000 ppm N and 800 ppm P was prepared in a 200-liter drum and the dosing rate was based on the equations specified in Table 3-4. The value of TOC for feeding water was measured by the online TOC analyzer (SHIMADZU – 5000A, Japan). To expedite biofilm growing on carriers, the settled sludge was sucked from bottom of clarifier and pumped back to each TPFBR at approximate flow rate of 7.5 L h⁻¹. Four weeks later, the point of returned sludge was shifted to the activated sludge process and kept there thereafter.

Table 3-4 Nutrient Addition (According to IWWT Designer’s Instruction)

Name	Urea	Phosphoric acid
Equation	$US = N/COD \times 1/A \times 1/\theta \times K \times B \times Q$	$PS = P/BOD \times 1/C \times 1/\theta \times K \times B \times Q$
Denote	US: Amount of 40% urea solution N/COD = 5/100 A; Urea concentration 40 wt % = 0.4 θ ; specific gravity = 1.1; K; (NH ₂) ₂ CO/N ₂ = 2.14 B; Inlet wastewater COD concentration (g/L)	PS; Amount of 75 wt% phosphoric acid Solution,P/COD =1/100 C; Phosphoric concentration 75 wt% = 0.75 θ ; specific gravity = 1.58 K; H ₃ PO ₄ /P = 3.16 B; Inlet waste water COD concentration (g/L)

Table 3-5 Experimental Parameters

Runs	TPFBR	AT	CV	Carrier	Filling	DWV	HRT	N,P	MLSS
Unit	Liter	Liter	Liter				hrs	ml/min	g L ⁻¹
Run 1	150	150	60	Type I	15%	92.5%	22	2	3.0-4.0
Run 2	150	150	60	Type I*	30%	85%	22	2	3.0-4.0
Run 3	150	150	60	Type II	20%	78.5%	22	2	3.0-4.0
Run 4	150	150	60	Type III	60%	89.2%	22	2	3.0-4.0

AT stands for aeration tank volume;

CV stands for clarifier volume

Filling stands for the carriers occupied volume of TPFDB reactors;

DWV stands for the displaced water volume in TPFDB reactors;

HRT stands for the hydraulic retention time in whole run;

*Type I carriers with biofilm were retrieved from the IWWT clarifier.

3.4.3 Test Methods

For this study, most of the lab test methods were in line with the “Standard Method for the Examination of Water and Wastewater” as published by Americana Public Heathen Association (APHA, 1998). For instance, the method of testing COD was applied according to chemical oxygen demand high range by reactor digestion method; APHA 5220 D. Method of testing BOD₅ was according to APHA 5210 B. Method of the measuring SOUR was according to APHA 2710 B; Oxygen-Consumption Rate. The methods used for analyzing the total and volatile suspended solids (MLSS/MLVSS) are described in Standard Methods (APHA, 1998) section 2540 D and 2540 E.

Method of testing P was adopted according to Hach method 8178- Phosphorous, reactive (also known as orthophosphate) amino acid method. Hach method 10020, Chromo tropic acid method was applied for testing nitrogen nitrate. (HACH internal testing method)

3.4.3.1 Weighing Biofilm

- Filling with 200 ml clean water in a 400 ml beaker;
- Taking 10 pieces of carriers and put into the beaker;
- Putting the beaker into Sonicator (Misonix Incorporated) for two hours and getting the solution.
- The rest of the steps will follow the methods of analyzing MLSS/ MLVESS as mentioned above.

3.4.3.2 Method of Testing pH (744 pH Meter)

Maintaining an optimum system pH is crucial during the sensitive start-up period. The pH determinations were made using a pH meter (744 pH Meter, Made by Metrohm Ltd, Switzerland) equipped with a glass electrode. Normal range of

accuracy was 0.01 pH unit. Sample pH was measured immediately to minimize increase by escape of dissolved carbon dioxide.

3.4.3.3 Numbers of Carriers in Each Reactor

With the aim of obtaining well-defined relations between carrier-filling and the correlative displaced water volume in each TPFBR, a test using cylinders to determine displaced water volume was conducted. The results are summarized in Table 3-3. Since the weight of each type of carrier could be measured by weighing balance (AB204 Weighing Balance, S/N 1116111090 Mettler Toledo, Switzerland), added each carrier’s specific gravity and the corresponding displaced water volumes were known, consequently, the number of carriers in each reactor could be computed out. The results have been summarized in Table 3-6.

Table 3-6 Carrier Numbers and Densities in Reactors

The number and density of carriers in each run				
Run	Run 1	Run 2	Run 3	Run 4
Number of carriers	35,120	70,250	7.23×10^5	1.0×10^5
Density (carriers L ⁻¹)	253	550	6140	747

3.4.3.4 Measure Type I Carrier Diameter and Projected Area

Quantimet 500 image analyzer, Leica Cambridge Instruments was applied in counting, measuring, and classifying for the type I carriers. An object was considered to be any contiguous group of pixels that shared a specified range of intensity values. With the count/size command, the sizes of carriers could be identified, and number of carriers could be counted, and measured. The procedures are described as follows:

- Perform manual grey scale threshold of carriers.
- Count the grains in an image and measure each carrier project area.
- Arrange clustered carriers.
- Classify the measurement data.
- Color-code the carriers by class.
- Store the measurement results to an Exel™ worksheet.
- Create a customized report using Image-Pro Plus and the Image-Pro-Report generator.

3.5 Results and Discussion

The pilot study was carried on for nearly three months, of which it was separated into two phases according to where the returned sludge was pumped to. The phase I started from 28th Mar to 29th April 2000 and phase II started from 30th April to 23rd June 2000.

3.5.1. Result for Phase 1

3.5.1.1Temperature

During phase 1, the temperatures of the influent, TPFBRs and the activated sludge reactors were daily monitored. Table 3-7 summarizes values of temperature in each TPFBR for phase 1.

Table 3-7 Temperature in Reactors

Temperature												
Influent	30.1-30.8(°C)											
Runs	Run 1			Run 2			Run 3			Run 4		
(°C)	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
TPFBR	32.3	29.6	30.3	31.4	29.1	29.4	31.1	29.4	30.3	32.3	29.4	30.2
ASR*	32.6	30.1	30.5	32.4	29.5	29.8	31.6	29.6	30.4	31.4	29.8	30.5

*ASR stands for activated sludge reactor

3.5.1.2 pH

The pH of the four runs was closely monitored on site. Details are summarized in Table 3-8.

Table 3-8 pH Values in Each Run

pH values during the phase 1 period												
Runs	Run 1			Run 2			Run 3			Run 4		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
TPFBR	8.27	7.38	8.14	8.45	7.30	7.92	8.68	7.35	8.08	8.68	7.37	8.18
ASP	8.86	7.65	8.35	8.67	7.56	8.01	9.18	7.64	8.01	8.80	7.88	8.05

3.5.1.3. Concentration of MLSS, Weight of Biofilm and Sludge Volume Index (SVI) in Each Clarifier

The wastewater was treated by both biofilm and mixed liquid suspended solids in TPFBRs during the period of phase 1. In order to monitor concentrations of MLSS in TPFBR and the biomass on carriers, they were measured weekly. The relevant results are summarized in Table 3-9 & 3-10, and the details of MLSS and total amount of biomass in the TPFBRs are shown in Figures 3-6 & 3-7. (Note: the structure of surface of type I virgin carrier was too sophisticated to measure the biofilm. Hence, the thickness of biofilm 0.3 mm was adopted that was recommended by vendor). Further more, the values of SVI in clarifier for each train have demonstrated in Figure 3-8.

Table 3-9 Concentration of MLSS & ratios of MLVSS vs Attached biomass in TPFBRs for Phase 1

Runs	MLSS(mg/L) Min~Max	MLVSS(mg/L) Min~Max	AVE (MLSS) (mg/L)	AVE (MLVSS) (mg/L)	MLVSS/ Carriers biofilm
Run 1	3020~4360	2100~3052	3615±403	2632±282	Invalid
Run 2	1800~4700	1260~3290	3337±834	2530±583	15
Run 3	1420~3970	995~2780	2967±713	2080±490	1.2
Run 4	2320~4670	1630~3270	3388±480	2371±384	0.32

Table 3-10 Weight of Biomass on Each Piece of Carrier

Week		1	2	3	4
Unit		(mg)	(mg)	(mg)	(mg)
Type I (In run 2)	Biofilm	0.563	0.610	0.496	0.527
	Volatile Biofilm	0.361	0.332	0. 313	0.303
Type II	biofilm	0.072	0.357	0.335	0.437
	Volatile Biofilm	0.051	0.233	0.239	0.324
Type III	biofilm	5.926	11.717	12.642	13.240
	Volatile Biofilm	3.713	8.922	9.831	9.813

Figure 3-6 Concentrations of MLSS in TPFBRs

Figure 3-7 Total Biomass in Each TPFBR

Figure 3-8 Values of SVI in Each Clarifier for Phase 1

3.5.1.4 Contents of Micronutrition

The elements of nitrogen and phosphorus are essential to the growth of microorganisms. They are the nutrient and biostimulants. Thus, both contents were measured two times per week. Details of result are summarized in Table 3-11.

Table 3-11 Concentrations of Total Nitrate and Phosphoate in Final Effluents

Runs	Total N (mg/L) Min ~ Max	Phosphoate (mg/L) Min ~ Max	AVE (TN) (mg/L)	AVE (P) (mg/L)
Run 1	1.2~11.6	0.25~11.7	4±3.1	5±3.0
Run 2	0.4~19.9	0.2~13	5±3.6	5±3.6
Run 3	1.0~18.8	0.2~13	7±5.3	6±3.3
Run 4	1.1~24.7	0.75~12.5	6±6.1	5±3.3

3.5.1.5 Process Start up and Biofilm Formation

Biofilm occurred in virtually any system where microorganisms are present. For this reason scientists in many different fields are studying biofilm growth. This combined effort has led to a fairly good description of conversion of soluble substrates by biofilm and reasonable insight in the population distribution in biofilm systems (Characklis and Marshall, 1989). Both features can be predicted well provides the biofilm structure is known. As mentioned in section 3.4.1, the carriers were put into each TPFBR, after 7 days of operation, the biomass could be detected on surfaces of type I carrier in run 1; a little of bacterial colony was observed in dented cavities on type II carriers; only patchy biofilm attached on inner surfaces of type III carriers. As the rough surfaces in cavities or protected surfaces are subjected to lower shear stresses and can avoid abrasion forces among carriers, they are more conducive for biofilm developing than smooth surfaces exposed to bulk liquid. In the meantime, the corresponding values of TOC were 73, 260, 703 and 85 mg/L in run1, run 2, run3 and run 4 respectively. After 14 days, the biofilm on the carriers could be clearly observed, especially at the inner surface of type III carrier, where bacterial colonies in brown were fully covered; and the surfaces of type II carrier were covered with thin white brown biofilm and some large flocs of biomass dotted on the type I surfaces (See

Figure 3-10 & Table 3-10), the corresponding values of TOC were 86 , 235, 473 and 83 mg/L in run 1 , run 2 , run 3 and run 4 respectively.

Yet the structure of biofilm will be affected by the load of substrate on biofilm surfaces, the hydrodynamic conditions, including shear stress on biofilm, how the biofilm grows on the carriers' surfaces, and how many kinds of organisms and physiological groups there are. These factors are beyond the scope of this study. As described in study objective, the main purpose for the pilot study is to ascertain which carrier's performance is the best on organic removal. In order to individually compare the performance of three types of carrier, the returned sludge was pumped back from TPFBRs to activated sludge process on the day 30 onwards.

3.5.1.6 TPFBRs' Performance on TOC

Even the biomass on the type I virgin carrier was hard to be measured, but based on the performance of TPFBR, especially at the first two weeks, more bacterial colony should have attached on the carriers in run 1 as the organic removal was superior to TPFBR in the other run. During the same period, the performance of TPFBR in run 4 appeared better than that in run 2 or run 3. As can be seen in Figure 3-11 and 3-12, comparing the performance between the reactors in run 2 and run 3, the performance seemed to be the worse in run 2.

As anticipated, it was observed that the final effluent became in black in run 1. The same phenomenon had also occurred in IWWT while the process just started. It came from the activated carbon powder (ACP) which peeled off as the result of intense abrasions occurred in the TPFBR. With the removal of ACP from carrier's surfaces, lesser biofilm left on carriers, thus the performance for run 1 gradually fell behind on the organic removal. However, after the day 14, the biofilm attachment on the surfaces of carrier in run 1, run 3 and run 4 could be clearly brought into being. With acceleration of biofilm on the carriers, the ranks of performance on organic removal were varied slowly. As can be seen, from day 14 to day 30, the average concentrations of TOC in effluent of each TPFBR were 86, 235, 473 and 83 mg/L in run 1, run 2, run 3 and run 4 respectively. From Figure 3-11, it was found the performance of TPFBR in run 4 appeared better than that in run 1. It eventually

became the most significant on organic removal from the previous second position. The minimum value of TPFBR TOC was 39 mg/L, compared with that in run 1, the minimum value was 89 mg/L. Unexpected, the performance of TPFBR in run 2 became the poorest among the runs, even the carriers were retrieved from IWWT and some biomass had attached on the surfaces of carriers initially, while there was no any biofilm on the other carriers at the beginning. As the length of time for the study was not sufficient by then, it was somewhat difficult to explain why the performance of TPFBR in run 3 was better than that in run 2 at the beginning. Overall, during the phase 1 period , the average values of TPFBR TOC were 173, 380, 388 and 156 mg/L in run 1, run 2, run 3 and run 4 respectively. Details are expressed in Table 3-12.

Figure 3-9 Biomass on Carriers

Figure 3-10 Concentrations of TOC for TPFBRs In & Out

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Figure 3-11 TOC Removal Efficiencies in TPFBRs

Table 3-12 TOC Removal Efficiencies in Each TPFBR

TOC removal efficiencies in each run				
Days	Run 1	Run 2	Run 3	Run 4
28-Mar	0.73	0.52	0.61	0.55
29-Mar	0.96	0.44	0.86	0.79
30-Mar	0.95	0.47	0.59	0.73
31-Mar	0.92	0.58	0.65	0.88
1-Apr	0.93	0.77	0.57	0.92
2-Apr	0.92	0.75	0.53	0.84
3-Apr	0.93	0.71	0.80	0.92
4-Apr	0.93	0.87	0.64	0.93
5-Apr	0.91	0.86	0.57	0.92
6-Apr	0.93	0.81	0.61	0.93
7-Apr	0.92	0.72	0.78	0.95
8-Apr	0.91	0.60	0.85	0.95
9-Apr	0.95	0.74	0.90	0.96
10-Apr	0.89	0.74	0.84	0.92
11-Apr	0.93	0.76	0.77	0.96
12-Apr	0.74	0.55	0.51	0.74
13-Apr	0.83	0.53	0.55	0.94
14-Apr	0.86	0.62	0.53	0.89
15-Apr	0.78	0.80	0.82	0.86
16-Apr	0.73	0.82	0.71	0.81
17-Apr	0.78	0.75	0.72	0.85

3.5.1.7 TPFBRs Performance on COD & BOD₅

Figure 3-12 indicates the values of COD in each TPFBR for phase 1. With the time elapsed, the COD of TPFBR in run 1 was changed from beginning 229 to 1244 mg/L. Generally, the performance of the reactor should rely on the bacterial density. Since the value of COD was increased, this meant that the quantity of biomass in the reactor for run 1 was reduced. Opposed to run 1, the concentrations of TPFBR COD in run 4 decreased and ranged form 716 to 244 mg/L. At same time, the concentrations of COD ranged from 975 to 881 mg/L and 540 to 1036 mg/L in run 2 and run 3 respectively. The TPFBR performance in terms of COD removal in run 3 was better than that in run 2.

Figure 3-12 Concentration of COD in TPFBRs

Even with the identical input organic load to each run and under the almost same operating conditions, the growing of biofilm on the carriers varied significantly in each run. In terms of concentrations of TPFBR BOD₅, that was also varied. For instance, the value of TPFBR BOD₅ increased form 36 to 298 mg/L in run 1; in reverse, the value of TPFBR BOD₅ reduced from 316 to 170 mg/L and the performance became the best in run 4. However, the BOD₅ of TPRBR in run 1 was still better than that in run 3, which was in turn better that in run 2. The details are plotted in Figure 3-13.

Figure 3-13 Concentration of BOD₅ in TPFBRs

3.5.1.8 Final Effluent TOC

One day after the four runs being put into operation, the analyses of TOC for the final effluent were implemented. The results are depicted in Figure 3-14. As can be seen, the values of TOC were the lowest within the first 14 days and the average TOC was 34.9 mg/L in run 1. At the same time, the performance on TOC in run 4 seemed to be improved and the average values of TOC was 46.4 mg/L; the performance of run 2 was the worst and the average values of TOC was 134 mg/L, which was much higher than 97.4 mg/L in run 3. With the development of biofilm attached on the carriers, the values of final TOC for run 4 declined. After the day 15, the values turned lower than that in run 1 and the performance became the best onwards. Then the performance on TOC for run 1 lagged into second position. Furthermore, from day 17 to day 18, the values of TOC for run 3 also appeared better than that for run 1. Subsequently, from day 19 to day 23, the values of TOC in run 3 were higher than those in run 1. And in the following days, from day 24 to day 28; the values were lower than those in run 1 again. Overall, the average concentrations of final TOC were 58.4 mg/L, 146 mg/L, 91.2 mg/L and 34.5 mg/L in run 1, run 2, run 3 and run 4 respectively for the phase 1 period.

Figure 3-14 Final Effluent TOC

3.5.1.9 Final Effluent COD & BOD₅

The analyses of COD and BOD₅ were implemented after the study was conducted for two days. The details have been graphically presented in Figure 3-15 and Figure 3-16. Both values of final COD and BOD₅ for run 1 and run 4 were the lowest and second lowest from day 2 to day 9 are shown. However, on day 17 onwards, the values of both COD & BOD₅ for run 4 were lower than those for run 1. On day 23, somehow the values of COD and BOD₅ for run 3 were lower than those for run 1. The average concentrations of the COD & BOD₅ for the runs are summarized in the Table 3-13. As mentioned previously, during phase 1, since the feeding substrate was biodegraded by both biofilm and mixed liquid suspended solids in TPFBRs, many factors could affect the performance of the processes, at the that time, it was hard to explicate which carrier performed the best. With the aim of directly comparing the performance with each type of carrier, the point of the returned sludge was shifted from the TPFBR to activated sludge reactor instead.

Table 3-13 Average Values of COD & BOD₅ in Final Effluent for Phase 1

Runs	Run 1	Run 2	Run 3	Run 4
COD (mg/L)	273	697	390	105
BOD ₅ (mg/L)	40	218	47	12
TSS (mg/L)	113	172	178	32

Figure 3-15 Final Effluent COD

Figure 3-16 Final Effluent BOD₅

3.5.2 Result for Phase 2

3.5.2.1 Temperature

During the period of phase 2, the temperatures of influent, TPFBRs and the activated sludge process were also monitored daily. The results are summarized in Table 3-14.

Table 3-14 Temperature in Each System

Temperature												
Influent	30.3 ~ 31.2 (°C)											
Runs	Run 1			Run 2			Run 3			Run 4		
(°C)	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
TPFBR	32.0	30.3	30.3	31.8	29.1	29.4	31.2	30.4	30.2	32.3	29.3	30.5
ASR*	32.5	30.6	30.8	32.3	30.5	30.8	31.7	30.6	30.6	32.5	30.4	30.8

*ASR stands for activated sludge reactor

3.5.2.2 pH

The pH was also daily monitored on site. Details are summarized in Table 3-15.

Table 3-15 pH Values in Phase 2

pH												
Runs	Run 1			Run 2			Run 3			Run 4		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
TPFBR	8.6	7.7	8.1	8.6	7.1	8.0	8.5	7.3	8.3	8.6	7.7	8.3
ASP	8.7	7.8	8.2	8.8	7.3	8.1	8.7	7.6	8.4	8.8	7.8	8.5

3.5.2.3 Concentration of MLSS, Weights of Biofilm and Sludge Volume Index (SVI) in Each Clarifier

During the period of phase 2, the essential operating conditions, such as pH, temperatures and contents of dissolved oxygen were kept approximately same as phase 1. As the returned sludge was shifted into activated sludge basin, the previous steady states were destroyed and another steady state would be set up under the condition of biofilm to biodegrade organic alone. As can be seen from Figure 3-17, the concentration of MLSS in each TPFBR was sharply reduced. On day 32, the

concentrations were 2520, 2840, 2740 and 2880 mg/L in run 1, run 2, run 3 and run 4 respectively. However, until day 53, the corresponding concentrations of MLSS were reduced to the minimum values, which were 640, 220, 700 and 780 mg/L in run 1, run 2, run 3 and run 4 respectively. The day after, the concentration of MLSS in each reactor was constantly increased till the day 60; another steady state was probably reached as the values of the MLSS did not vary significantly in each run. As known, the feeding substrate was treated by biofilm and the detached biofilm which was suspended in reactors. In order to understand the development of biofilm on carriers, the weight of biomass on the carriers for run 2, run 3 and run 4 were examined weekly and the results are summarized in Table 3-16 & 3-17. (Note: as the features of type I virgin carrier surfaces were too sophisticated that the biofilm was difficult to measure. Thus, a 300µm thickness of biofilm on the carriers in run 1 was assumed according to the vendor suggestion). However, during the period of phase 2, the substrate was mainly biodegraded by the biofilm on the carriers in the reactor. The details of weight of the biofilm in each TPFBR are presented in Figure 3-18. In addition, the SVI values in each clarifier for phase 2 have been shown in Figure 3-19

Table 3-16 Concentration of MLSS & ratios of MLVSS vs Attached biomass in TPFBRs for Phase 2

Runs	MLSS (mg/L) Min ~ Max	MLVSS (mg/L) Min ~ Max	AVE (MLSS) (mg/L)	AVE (MLVSS) (mg/L)	MLVSS/ Carriers biomass
Run 1	620~2520	200~1960	1081±460	727±391	Invalid
Run 2	220~2840	100~2140	1115±528	787±419	4.8
Run 3	640~2740	540~2020	1144±463	835±359	0.39
Run 4	340~2880	280~2140	1251±539	887±387	0.11

Table 3-17 Weight of Biofilm on Each Piece of Carrier

Week		5	6	7	8
Unit		(mg)	(mg)	(mg)	(mg)
Type I *	Biofilm	0.422	0.491	0.542	0.567
	Volatile Biofilm	0.290	0.281	0.312	0.283
Type II	biofilm	0.441	0.572	0.551	0.491
	Volatile Biofilm	0.343	0.358	0.361	0.336
Type III	biofilm	14.254	14.931	14.893	14.762
	Volatile Biofilm	10.510	10.802	11.664	10.676

Figure 3-17 Concentration of MLSS in Each TPFBR for Phase 2

Figure 3-18 Total Biomass in Each TPFBR for Phase 2

Figure 3-19 Values of SVI in Each Clarifier for Phase 2

3.5.2.4 Contents of Micronutrition

As nitrogen and phosphorus are essential to the growth of microorganisms, both elements of contents were continuously monitored. Table 3-18 summarizes the details for phase 2 period.

Table 3-18 Contents of Total Nitrate and Phosphate in Final Effluents

Runs	Total N (mg/L) Min ~ Max	Phosphate (mg/L) Min ~ Max	AVE (TN) (mg/L)	AVE (P) (mg/L)
Run 1	1.5~9.6	0.65~8.7	5±3.3	4±3.3
Run 2	0.8~15.9	0.6~11.3	5±3.1	5±3.2
Run 3	1.0~12.5	0.5~16	7±5.6	6±3.4
Run 4	1.1~22.7	0.85~15.5	6±5.6	5±3.6

3.5.2.5. TPFBRs Performance on TOC

During the period of phase 2, the probably same hydraulic and organic loads to each run were maintained. Looking at Figure 3-21, the trends of TOC in each TPFBR effluent are indicated. From the day 31 to 36, the values of TOC in each reactor seemed to rise; simultaneously the concentrations of MLSS in the TPFBRs decreased significantly. For instance, within the same period, the values of TOC rose up form

253, 372, 424 and 171 mg/L to 740, 795, 581 and 422 mg/L in run 1, run 2, run 3 and run 4 respectively. Thereafter, the performance of TPFBR in run 4 became the best in terms to TOC. However, from the day 38, the performance of TPFBR in run 3 also exceeded that in run 1 till the completion of the study except a few days. Apparently, the performance in run 2 seemed not to be improved and remained the worst during the whole period of phase 2.

Figure 3-20 Carriers of Activated Carbon Powder Peeled off

An interesting phenomenon was observed on day 57 and day 72 separately, the systems faced two times of shocks loading, which are plotted in the Figure 3-21. However, the process in run 4 was least affected and recovered quickly; the corresponding values of TOC were 422 mg/L and 390 mg/L for the day 57 and day 72 respectively. The removal efficiency was recovered to above 80% within three days (Figure 3-22). On the contrast, the values of TOC in other runs sharply increased up to 853, 1009 and 841 mg/L for the day 58; 572, 534 and 488 mg/L for the day 72 in run 1, run 2 and run 3 respectively.

On day 78 to day 81, the performance of TPFBR in run 1 were better than the that in run 3 and the average values of TOC were individually 257 mg/L, 306 mg/L respectively.

Anyway, during the period of phase 2, the average of the values of TOC in TPFBR were 370, 454, 293 and 170 mg/L in run 1, run 2, run 3 and run 4 respectively.

3.5.2.6 TPFBRs Performance on COD & BOD₅

After the place of the returned sludge shifted, each TPFBR worked independently onwards. The values of COD and BOD₅ were still regularly analyzed and the results are described in Figures 3-23 & 3-24. On day 38, the values of the COD and BOD₅ were 678, 356, 880, 430 mg/L ; 429, 210, 316 and 127 mg/L in run 1, run 2, run 3 and run 4 respectively. On day 57, when the shock loading happened, the values of COD & BOD₅ in the TPFBR changed significantly, which were 832 mg/L, 543 mg/L in run 1; 789 mg/L, 463 mg/L in run 2; 674 mg/L, 302 mg/L in run 3 and 487 mg/L, 210 mg/L in run 4.

Figure 3-21 Values of TOC in TPFBRs' Effluent for Phase 2

Figure 3-22 TOC Removal Efficiencies in TPFBRs for Phase 2

Figure 3-23 Concentrations of COD in TPFBRs' Effluent for Phase 2

Figure 3-24 Concentrations of BOD₅ in TPFBRs' Effluent for Phase 2

3.5.2.7 Final Effluent TOC

Since the point of returned sludge shifted, the operating conditions were changed and the existing steady balance on biofilm changed and a new steady state would be set up. On day 31, the concentrations of TOC for final effluent were 125, 166, 195 and 35 mg/L in run 1, run 2, run 3 and run 4 respectively, which were higher than those in the later period of phase 1. However, on day 36, the concentration of TOC for run 4 was reduced to 22 mg/L. In the meantime, the values for the other runs also decreased and the corresponding values reached to 101, 114 and 123 mg/L in run 1, run 2 and run 3 respectively. The similar condition was maintained till the day 56. On day 57, a key customer discharged high concentration of wastewater that caused a higher organic loading to all four runs and made all processes upset. At that time, the concentrations of TOC reached up to 270, 366, 134 and 43 mg/L in run 1, run 2, run 3 and run 4 respectively. Unexpectedly, the process for run 4 was not completely deteriorated and improved to 23 mg/L in three days. The processes were fully deteriorated in the other runs and the recovering time was required at least 5 days or even longer. On day 72, another shock load occurred, and a similar phenomenon happened again. The performance in run 4 was not fully damaged and recovered quickly as well. Figure 3-21 has demonstrated values of TOC for each run for phase 2

period, it is clearly indicated the concentrations of final TOC for run 4 was always the lowest, the second was in the run 3 and the worst was in run 2 throughout the period of phase 2.

Figure 3-25 Concentration of TOC in Each Final Effluent for Phase 2

3.5.2.8 Final COD and BOD₅

Looking at the Figures 3-26 & 3-27, the different performances among all runs are exhibited. One week after the returned sludge point shifted, the parameters of COD and BOD₅ were continuously analyzed. On the day 38, the values of COD and BOD₅ were 393, 620, 150 and 87 mg/L; 66, 146, 45 and 25 mg/L in run 1, run 2, run 3 and run 4 respectively. Overall, the ranks of performance in each run had no significant changes from day 38 to the end of the study and the average values of COD and BOD₅ are summarized in the Table 3-19.

Compare the performance of TPFBR in each run between phase 1 and phase 2, the ability of the organic removal was changed when the point of returned sludge shifted to different reactors. Details, in terms of values of TOC and the removal efficiencies are summarized in Table 3-20.

Table 3 -19 Values of COD & BOD₅ in Each Final Effluent

Runs		Run 1		Run 2		Run 3		Run 4	
Phase 2	Criteria	Min-Max	Ave	Min-Max	Ave	Min-Max	Ave	Min-Max	Ave
	COD(mg/L)	84~510	273	236~955	697	200~565	390	37~86	71
	BOD ₅ (mg/L)	10~107	40	47~478	219	10~123	47	5~18	12

Table 3 - 20 Comparison of Performance between Phase 1 and Phase 2

TOC removal efficiencies and average values in each run				
Runs	Run 1	Run 2	Run 3	Run 4
Phase 1 TOC removal efficiency	88%	71%	66%	84%
Average TOC (mg/L)	73	154	99	30
Phase 2 TOC removal efficiency	68%	59%	74%	83%
Average TOC (mg/L)	85	187	64	24

Figure 3-26 Concentrations of COD in Each Final Effluent for Phase 2

Figure 3-27 Concentration of BOD₅ in Each Final Effluent for Phase 2

3.6 Discussion

In order to compare the performance of TPFBR in each system, during the whole period of pilot study, a steady constant input organic loading and a hydraulic loading, equivalent to 100% and 100 ~110% of design capacity for IWWT respectively, were maintained. From the results obtained from phase 1, the values of TOC, COD and BOD₅ varied dramatically in each TPFBR.

3.6.1 Effect of Biofilm Growth

As known, bacteria colonize the carrier surface at specific sites, such as cavities or inner protected areas, in the form of micro colonies first, and then gradually develop into a full biofilm. The process from a bare carrier to a full biofilm particle is achieved by bacterial activities that include (Kao, 1989; Applegate and Bryers, 1990):

- Transport: cells move from the bulk liquid to the carrier surface;
- Adsorption : cells begin to colonize the substratum ;
- Multiplication : bacteria multiply on the substratum;
- Desorption: adsorbed cells reenter the liquid;

- Erosion: shear stresses induce cell loss on the substratum.

Among the above activities, the first three have positive influences on biofilm formation, and the last two have negative effects. Moreover, over this study, another activity should be well thought-out, it is the abrasion occurred among the carriers, which, when the particle sizes are large to a certain level, are fluidized by turbulence. Based on the bacterial activities, the development of biofilm can be classified into three stages in terms of extending of coverage through the formation history, namely, bare carrier, intermediately covered carrier, and biofilm particle (Tijhuis et al., 1994). For an individual carrier, the biofilm growth should follow the bacterial growth theory and can be divided into four phases as shown in Figure 3-28.

Figure 3-28 Typical Bacterial Growth Curve (Mark, 1999)

Induction phase: It is a process from bare carrier to visible patchy biofilm, i.e. intermediately covered carrier. After feeding of wastewater, the bare carriers were kept fluidized in reactors, dispersed bacteria would have a chance to adhere or attach onto the carriers. In this phase, the initial attachment of bacteria should be by adsorption onto the cavities in the type I & II carriers and inner surfaces of type III carrier. The type I virgin carriers with rough surfaces and cavities in run 1 had an advantage at this stage, as shear stress within the cavities could be considerably lower than that experienced at the smooth surfaces. This process can be completed within a relatively short duration. The ability to degrade toxic and recalcitrant compounds will

depend primarily on the presence of appropriate microorganism and introducing time. Introducing time can vary from hours to weeks depending on the microorganism population and organic compound. Melcer et al. (1994) found that a period of 3 weeks was required before complete removal of dichlorobenzene (DCB) occurred in a municipal activated sludge plant. Based on the performance on TPFBR (See Figure 3-10), the induction period might be probably fourteen days as the performance gradually increased within the first two weeks. During the induction phase, it was difficult to determine how the biofilm performed, in consequence, the organic removal in each TPFBR varied significantly and the corresponding parameters in each final effluent fluctuated drastically.

Log-growth phase: This is a development phase where intermediately covered carriers become completely covered. The process is very much influenced by the liquid shear and abrasions present in the system (Tijhuis et al., 1994). For this pilot study, assumed that the liquid shear was constant as the organic and hydraulic loadings were more or less unchanging, thus, the log-growth phase would mainly be affected by abrasions. As the type I carriers are bigger than 4 mm in diameters, added the density of type I carrier was heavier than that of water, indeed it resulted in serious abrasions. Consequently, the ACP was peeled off resulted in the black effluent at the initial stage of the pilot study. However, type II carriers with a less density than water seemed to stick to the theory of bacterial growth, a thin layer of gray color biofilm covered on the type II carriers was observed during the phase 1 period. Once sufficient bacteria were developed onto the particles and multiplied, the biofilm formed. After the returned sludge shifted, as can be seen from Table 3-17, much more biofilm grown on the type II carriers and formed a elastic layer on the carrier surfaces, the impact of particle-particle interaction might become lesser that resulted in the better performance in run 3 and the results has been shown in Figures 3-21 to 3-24. Compared with the other carriers, more biofilm developed on the type III carriers (See Table 3-10 & 3-17 & Figure 3-9), as it grew at the areas protected by the out frame. As the result, this reactor performed the best during the study.

Maturity phase: biofilm accumulation will be very much governed by the microorganism growth and the loss of biomass due to detachment and biomass decay.

When bacteria growth, detachment and decay reached a relative balance, the biofilm growth rate will decrease to zero. In this phase, substrates and / or oxygen transfer will become the limiting factor for a biofilm system. As a result, biofilm with a certain thickness will enter into a mature stage. In a matured biofilm particle, anoxic or anaerobic conditions can be developed in the inner layer of the biofilm due to oxygen deficiency as shown in Figure 3-29 (Hao and Nieuwstade, 1994):

Figure 3-29 Schematic Cross Section of a Biofilm Particle

Decline phase: as biofilm developed, its thickness become thicker and thicker. The outer heterotrophic layer will be continuously detached due to shear stress and replaced by the newly grown biofilm. However, the nitrifiers in the inner layer will be aged without constant renewal. In addition, the inner layer may also experience oxygen and substrate deficiencies. The nitrifier layer may therefore be subject to decay and weaken the adherent force on the carriers. At the same time, denitrification process can occur in the inner layer, i.e. anoxic layer. This is because denitrifiers can use the residual carbon source and NO_2/NO_3 and thus lead to the release of nitrogen gas. The nitrogen gas released can in turn lead to: 1) cracks occurred through the biofilm and 2) a large fragment of biofilm will detach off when the cracks become big enough. Detachment can be divided into three distinctly different processes (Rittmann,1989) namely, (i) grazing or predator harvesting due to protozoa or metozoa feeding on the outer surface of a bacterial biofilm; (ii) erosion resulting from the continuous removal of small particles from the surface of the biofilm, primarily caused by the shear stress induced by water flowing past the biofilm; and (iii) abrasion resulting from the collision and / or rubbing of carriers covered with biofilm. The similar phenomenon mentioned above might occur in run 3, because the biomass on the carriers did not vary significantly from the later of phase 1 to the end of the

study and the corresponding performance was better than that in run 1 all the time, except the date from day 78 to day 81.

3.6.2 Organic Biodegraded by Biofilm

During the phase 1 period, actually the wastewater was treated in combined process that consisted of the biofilm on the surfaces of carrier and suspended bacteria. Based on Hirata (1998) statement, the volumetric biological removal rate (R_{all}/V) can be calculated from the volumetric biological removal rate with biofilm (R_B/V) and that with suspended sludge (R_{ss}/V) which is shown in Eq.3.1. Overall, biological removal efficiency (η_{all}) in each reactor can be calculated from the biological removal efficiencies with biofilm (η_B) and that with suspended sludge (η_{ss}) as shown in Eq.3.2.

$$\frac{R_{all}}{V} = \frac{R_B}{V} + \frac{R_{ss}}{V} \quad (3.1)$$

$$\eta_{all} = \eta_B + \eta_{ss} \quad (3.2)$$

As known, the reactor's performance should depend on the total amount of the biological community. Look at the Figure 3-19, eventually the total biomass of TPFBR in run 4 was the most. With the equal input organic loading to each run and the same operating conditions, the highest biomass gave run 4 a better performance.

Comparing the concentrations of MLSS in each TPFBR, it was found that the divergences of the average concentrations of MLSS in four reactors were not large and the biggest difference was approximately 648 mg/L (See Table 3-9) in phase 1. The variety of concentration of the MLSS in TPFBRs was not significant in phase 2 either and the biggest difference was about 336 mg/L (See Table 3-19). For this study, the comparison of the performance in each TPFBR therefore was the comparison of the biofilm performance, or in other words, the performance of each TPFBR was determined by the biofilm on the carriers.

3.6.3 Functions of Powder Activated Carbon

Based on IWWT designer's expectation, the merit of PAC was anticipated to carry out for cultivating biofilm growing. As known, the activated carbon is the most versatile adsorbent due to its constitutional ability to adsorb substances from both gaseous and aqueous phases. The term of activated carbon in its broadest sense

includes a wide range of amorphous carbon-based materials prepared to exhibit a high degree of porosity and an extended inter-particulate surface area. The extremely large surface is an important attribute of the activated carbon. The specific surface area typically ranges from 500 to 1400 m²/g, with an upper limit of approximately 2500 m²/g. Subject to the carries applied in the biological processes for wastewater treatment, the more surfaces for the biomass growing, the more biofilm will occur in reactor. According to the design, a thick layer of biofilm was estimated to accumulate in the voids of the PAC and a thickness of 300µm biofilm was expected. With the aim of better understanding the type I carrier and ascertain the thickness of activity carbon on the carrier's surface, an independent analysis was conducted (Ong, 2001) and the results are described as below:

“The activated carbon layers ranged from 60 to 120 µm on individual carrier and the interstitial spaces ranged from 40 to 130 µm in length. Intertwined strands of polyester threads were observed protruding from the surface of carrier particles. When the carrier was emerged in water for 2 hours and then dissected, the particles exuded substantial amounts of water, demonstrating the ability to retain water in interstitial void spaces; when the particle was dissected, the internal surface structure appeared similar to the outer surface structure.”

In addition to medium of type I carrier, Khoo and Ting (2001) reported that PVA was more resistant to mechanical abrasion and more stable over a wide pH range. If the advantages of the PAC and PVA as mentioned above had been fulfilled well, the type I carrier could have had a good performance in run 1.

Figures 3-10 to 3-11 show the performance of TPFBR in run 1 was well initially. This is because as the virgin carrier was applied in run 1, the CAP layer was still adhered well after a short time and enhanced the biomass attached on it, thus the concentrations of TPFBR & final effluent TOC at beginning were the lowest.

As the TPFBR is completely mixed reactor, shrinkage of type I carriers in run 1 was observed. During the phase 1 period, the TPFBR effluent in run 1 was always in black, a similar phenomenon had occurred in IWWT. In order to further ascertain figures of type I carrier in run 1, on day 30, some type I carriers were taken out and

analyzed under image analyzer (Quantimet 500 image analyzer). It was found only lesser biofilm subsisted in the cavities and ACP was hardly observed on the surfaces eventually (See Figure 3-20). Comparison of diameters between the used and virgin type I carriers is graphically illustrated in Figure 3-32; the state of changes for the carrier's projected areas is shown in Figure 3-33. The details have also been summarized in Appendix III. For the reasons above, the performance in run 1 gradually fell behind. With the time consuming, most of APC was peeled off resulted in the performance of the reactor in run 1 therefore become worse than that in run 3 (See Figures 3-21 to 3-24).

3.6.4 Effects of Organic Loadings

During the phase 1 period, as the returned sludge was pumped to the TPFBR, consequently, the corresponding hydraulic retention times were 6.17 hours, 5.67 hours, 5.90 hours and 5.94 hours in run 1, in run 2, in run 3 and in run 4 respectively. Since the carriers' physical properties were diverse, this resulted in the dissimilarities on space in the reactors, which were 138.75 liters, 127.5 liters, 132.75 liters and 133.8 liters in run 1, in run 2, in run 3 and in run 4 respectively. And since the input organic loading to each reactor was same, the volumetric loads had slight differences. The details have been listed in Table 3-22. As can be seen, the quality of being distinguishable on volumetric loading and hydraulic retention time among the systems were not large, the relevant differences were only 0.28 g TOC L⁻¹ .day and 0.8 hour respectively. Nevertheless, the performances of the reactors varied significantly (See Figure 3-24). Thereby the volumetric loading could not determine the performance of TPFBR. It is accepted that the performance of a biofilm reactor is primarily dependent upon the biofilm growth area in the TPFBR.

Table 3-21 Volumetric Loads in Each TPFBR (kg TOC m⁻³ d⁻¹)

Runs	Max	Min	Average
Run 1	3.75	2.53	3.00
Run 2	4.07	2.75	3.28
Run 3	3.89	2.64	3.14
Run 4	3.85	2,60	3.10

Figure 3-30 Value of TOC versus TOC Volumetric Load for Each TPFBR

The different physical properties of carriers' results in different surface areas for biofilm growth in each TPFBR, the number of carriers can be reckoned, and as a result, the surface area loading can be calculated. So as to compare the area loading to each reactor, a few assumptions have been used: 1) the organic concentration at the surface of the biofilm equals the bulk liquid concentration; 2) the biofilm density is uniform; 3) The carrier's surface is fully covered with the biofilm and the thickness on each carrier is neglected; and 4) as described, the shape of type I carrier is regarded as a ball (6 mm in diameter), the type II carrier is considered as cylinder (4 mm in length and 4 mm in diameter), the type III is supposed to hollow cylinders (about 10 mm in diameter and 7 mm in height). Thus, the carrier's surface area loading to each run can be expressed as below:

Surface Area Loading on Type I Carrier in Run 1

- Average influent TOC loading to each run was 417 g d^{-1} ;
- Diameter of the Type I carrier $\Phi = 6(\text{mm})$;
- Surface area of a ball $A = 4\pi R^2 = 113.04 (\text{mm}^2)$;
- Number of the carriers = 35120;
- Surface area load $\omega_1 = 417 / (113.04 \times 35120) = 105 (\text{g TOC m}^{-2} \text{ d}^{-1})$

Surface Area Loading on Type I Carrier in Run 2

- Average influent TOC loading to each run was 417 g d^{-1} .
- Surface area of a ball $A = 4\pi R^2 = 113.04 \text{ (mm}^2\text{)}$;
- Number of the carriers in Run 2 = 70250
- The surface area load $\omega_2 = \omega_1/2 = 52.5 \text{ (g TOC m}^{-2} \text{ d}^{-1}\text{)}$

Surface Area Loading on Type II Carrier in Run 3

- Average influent TOC loading to each run was 417 g d^{-1} ;
- One carrier's surface area = 75.36 mm^2 ;
- Number of the carriers in Run 3 = 723750;
- Surface area load $\omega_3 = 417 / (75.36 \times 723750) = 7.6 \text{ (g TOC m}^{-2} \text{ d}^{-1}\text{)}$.

Surface Area Loading on Type III Carrier in Run 4

- Average influent TOC loading to each run is 417 g d^{-1} .
- One carrier's surface area = 499.8 mm^2
- Number of the carriers in Run 4 = 100000
- 6) Surface area load $\omega_4 = 417 / (499.8 \times 100000) = 8.3 \text{ (g TOC m}^{-2} \text{ d}^{-1}\text{)}$

The biological removal rate is greatly affected by the specific surface area of biofilm (Hem et al., 1994). As the surface area loading was the least on type II carrier, the second least was on type III carrier and largest on type I carriers. If based on the surface area loading calculated above, the best performance of TPFBR should be in run 3, second should be in run 4 and the worst should be run 1. Actually, the performance in run 4 was the best and the second was in run 3, the last one in run 2 (See Figures 3-21 to 3-24). This is because the biofilm attached on the type III carriers' inner surfaces, which were protected from abrasions and collisions by the outside frame (See Figure 3-31). As so, some attached bacteria, which normally grow very slow under a relevant short retention time, could grow better in the reactor at the extended retention time. This was also conducive for bacteria to progressively grow and form denser biofilm layer, thus more biofilm (biomass) could be maintained in the reactor in run 4. The amount of the biofilm was measured and above 10 mg of volatile biomass from one piece of type III carrier was obtained, (See Table 3-17), which was much more than those on both type I and type II carriers. Due to existing of multi-brand bacteria on carriers, the reactor probably could handle the fluctuation of the feeding loads, which is why while the systems faced the shock loadings during

the pilot study, the processes in run 4 did not deteriorate as much as the other runs did, and only three days were needed for the process to fully recover.

Figure 3-31 Biofilm Growth Inside of Kaldnes Carrier

On the contrary, the biofilm attached on the surfaces of type II carrier was affected by the abrasions while the carriers were fluidized in the reactor, because the surface was not sheltered and biofilm could not develop well on (see Table 3-17), therefore, the performance was not good as run 4. In addition, as can be seen in Figure 3-7 and 3-18, the SVI in Run 4 became much better with the time consuming compared with the other Runs.

3.6.5 Effects by Particle Size and Density

As mentioned earlier, the carriers applied in run 2 were retrieved from an existing reactor. Since the carriers had been put in the IWWT for several months, most of activated carbon had been peeled off, which is critical parts for biofilm growth. Gjaltema et al., (1997) has reported that particles collisions are found to dominate the biofilm detachment, and the particle size influences both collision frequency and the collision impact, larger particles clash each other more easily and frequently. As the size of the type I carrier is quite large and the carriers had been used for several months in IWWT, only little PAC left on PVA cores. As a result, lesser biofilm attached on the carriers in spite of the carrier quantity was higher than that in run 1. On the other hand, more carriers would occupy more space in the reactor. The more carriers used, the more volume the carriers would take, consequently the lesser space for the bulk of wastewater to be treated. During the phase 2 period, since the flow rate to each run was equal, the HRT in run 2 was only 8.5 hours. Comparing with others, 9.25 hrs in run 1, 8.85 hrs in run 3 and 8.92 hrs in run 4, it was still the shortest. As mentioned, the density of the carrier was higher than that in run 1 which induced

more frequency of the collisions and resulted in lesser biofilm attached on the surfaces. As a whole, the reactor performance in run 2 was the worst throughout the whole pilot study.

As can be seen from Figures 3-21 & 3-24, the performance of TPFBR in run 1 was worse than that in run 4. Relay on the IWWT process design, the amount of biofilm on type I carriers equivalent to the concentration of MLSS should be nearly 30,000 mg/L while the carriers filling was at about 15% of reactor volume; while in the conventional activated sludge process, normally the concentration is about 2,500 – 4,000 mg/L. In addition, the specific gravity of the Type I carrier is 1.1 g cm^{-3} , which is heavier than that of wastewater. With the purpose of keeping the carriers constantly fluidized in reactor, more air must be provided, which would cause serious abrasions among the carriers in run 1. As the filling was 30% in run 2 which was double that in run 1, thus much more air flowrate would be required resulting in much more biofilm detachment. Therefore, the biofilm could not be developed well in run 1 and run 2 (See Figure 3-31). As mentioned previously, the total biomass on carriers is the key factor of TPFBR for organic matters biodegraded. The lesser biomass/biofilm would contribute to higher organic loading. Therefore, the performance in run 1 and run 2 could not reach the expected.

Figure 3-32 Comparison of Diameter for Type I Carriers

Figure 3-33 Comparison of Projected Areas between Used and Virgin Type I Carriers

3.7 Conclusions

From the comparison of the three types of carrier, performed under the same operation conditions, it can be summarized as follows:

1. As known, the performance of TPFBR is related to the surface area loadings and the total biomass in the reactor. Comparing with the other runs, the specific surface area loading was the least in run 4, which was only $8.3 \text{ g TOC m}^{-2} \text{ d}^{-1}$. In addition, the reactor had most biomass resulted in the lower food to microorganism (F/M) ratio, therefore the Kaldnes carrier was successful in pilot study operation by removing TOC from 66% to 96% of the input organic loadings, and the effluent TOC values ranged from 10 to 28 mg /L, well within the regulatory limit of 30 mg /L. In order to improve the treatment capacity of IWWT, the Kaldnes carrier could be the right type of carrier for replacement existing carriers.
2. The defect of the existing carrier was pointed out. The large size in diameter and heavier density caused the fierce abrasions among the fluidized carriers. This resulted in the PAC peeled off and little biofilm attached on carrier surfaces. Therefore the type I carrier was unable to achieve IWWT design capacity.

Overall, the results obtained in this study suggested the Kaldnes carrier could be the right type carrier in the future applied in IWWT in order to increase the capacity of the wastewater treatment. The Kaldnes carriers would be applied in IWWT soon.

CHAPTER FOUR

FULL SCALE PLANT PERFORMANCE TEST

4.1 Introduction

As positive results were gained from the pilot study, the carrier in IWWT was decided to replace with the type III carriers. However, before this full-scale application, the trial of Kaldnes carrier TPFBR had not been applied in a centralized wastewater treatment plant similar to IWWT that treated multiple streams of chemical wastewater. Due to lack of the references, the further full-scale performance test must be carried out with the insights gained in the previous pilot study.

4.2 Methodology

As mentioned in Chapter One, a total of three rounds of full-scale performance test with type I carriers had been conducted at IWWT, but the results were unsatisfactory. All the tests were based on same testing procedure, identical testing parameters and same analytical methods. The same procedure, testing parameters and analytical methods were also adopted in the Kaldnes carrier reactor for the full-scale performance test.

4.2.1 Test procedures

The flow is controlled at less than $110 \text{ m}^3 \text{ h}^{-1}$ by either incoming wastewater or through partial recycling of treated effluent and the organic load is controlled at about $317 \text{ kg COD h}^{-1}$ – full design capacity. The performance test can start when the plant received at least 75% organic loading. If the loading is low, normal butanol which is easily biodegradable might be added directly to the process.

Both hydraulic and organic loadings to the process should be controlled without sudden change and shock. In the full-scale performance test, on the hydraulic loading, a fluctuation/change of 10% - 20% of the design capacity in a day is allowed, following by a three-day steady run, with the organic loading being controlled around 100% (within 5% fluctuation).

4.2.2 Test parameters

During the period of the full-scale performance test, the test parameters will be analyzed according to the specifications summarized in Table 4-4. The analytical methods are based on the procedures specified in “Standard Methods for the Examination of Water and Wastewater”.

Table 4-1 Testing Parameters for Full-Scale Performance

Tested parameters during the full scale performance test			
pH	6-9	12 hours	StM, pH meter
TSS	50 mg/L	12 hours	StM, filter, dry and weigh
TOC	30 mg/L	12 hours	Shimadzu TOC analyzer
COD	100 mg/L	12 hours	StM, Hach Closed Reflux/Colorimetry
BOD ₅	50 mg/L	24 hours	StM, 25 °C incubation for 5 days

StM: Standard Methods for the Examination of Water and Wastewater by APHA, AWWA, & WEF, 20th Ed.

4.2.3 Kaldnes Carrier Replacement with Different Filling

Positive results gained from the pilot study confirmed the treatability of wastewater by Kaldnes carrier reactor. The act of carriers’ replacement was carried out at IWWT. The implementation of carrier’s replacement was started on 26 April, 2001, and completed by 27 July, 2001. In total 12 reactor chambers of carrier-based TPFBR with each volume of 100 m³ in the first stage were retrofitted, tagged as in Table 4-2, R-101 A to F in Train A and G to L in Train B. In the meantime, in order to improve oxygen uptake ratio, the dish air diffuser aeration system was also replaced by pipes with thin slots for the coarse aerobic bubbles to agitate carriers fluidized in reactor. Sieve assemblies were also retrofitted at the outlet of each reactor to keep Kaldnes carriers in the reactors. With the purpose of assessing the impact of different carrier filling, the carrier fillings in reactors R-101 D, E, F, J, K, L were kept at 50%; and other reactors R-101 A, B, C, G, H, I the fillings were controlled at 60% of reactor’s volume (carriers occupying empty reactor volume).

Table 4-2 Media Filling in Train A and B

Train A	R-101A	R-101B	R-101C	R-101D	R-101E	R-101F
Train B	R-101G	R-101H	R-101I	R-101J	R-101K	R-101L
Filling	60% of the empty reactor volume			50% of the empty reactor volume		

During the period of carrier’s replacement, the daily operation was maintained because customer’s wastewaters were still received and had to be treated. In order to keep the plant at normal working conditions, only two chambers (A & G, B & H, C & I, D & J, E & K, and F & L) were changed on every occasion. In addition to ensure effluent parameters encounter limits of ENV regulations, the bulk of wastewater, equivalent to the two chambers’ treated, was diverted into municipal wastewater treatment plant which located near to IWWT. The water left in reactors was firstly pumped out and then the aerobic diffuser systems were changed, followed by pouring Kaldnes-carriers. The whole effort of replacement was completed within three months.

4.3 Process Start up

The new Kaldnes carrier reactors were started-up two by two from the beginning of May 2001. When raw wastewater was added with nutrients solution of N & P and the return activated sludge to the reactors, the effluent in turn by gravity, overflowed to the corresponding aeration basins A & B.

In order to expedite biofilm growing on carriers and compare the performance of the reactor with different filling ratio, the means of shifting returned sludge applied in the pilot study was intended to be duplicated in IWWT. But when the shifting of the returned sludge was carried out, the concentrations of MLSS in TPFBR sharply reduced and the corresponding concentration of TOC in effluent increased were observed, which might be attributed to shortage of biomass. To avoid process upset, the returned sludge was shifted back to the Kaldnes Carrier Reactor (KCR) and maintained.

The temperature of mixed wastewater was about 36 - 38°C, after the cooler, it was cooled to about 32 °C prior to be fed to the KCRs. The KCRs and the following activated sludge reactors were all made of concrete with the coating of epoxy resin inside. The cooled wastewater was fed to the distributors from where it was equally distributed to each KCR. Simultaneously, a combined flowrate consisted of urea, phosphoric acid and returned sludge was pumped into the distributor together with the feeding wastewater. In which the urea (NH_2CONH_2) flowrate was 70 liters/hr with the concentration at 40%, the phosphoric acid (H_3PO_4) flowrate was 15 liters/hr with concentration at 85% and the returned sludge flowrate was $50 \text{ m}^3 \text{ h}^{-1}$ with the sludge concentration at 11000 mg/L respectively.

The composite samples were collected at the outlet of R-101A & D, activated tank A & B and final discharge point. Three of four air root blowers (Model ARJ2502, UNOZAWA-GUMI IRON WORKS, LTD, Tokyo Japan) with each capacity $4600 \text{ m}^3/\text{hr}$, blew air into processes and maintained the 3 to 4 mg/L and 2 mg/L of the DO in KCRs and activated sludge reactors respectively. The air diffusers in KCRs were pipes with 3 mm fine slots and Cellpole discs (Cellpole industries, Co., Ltd. Japan) in the activated sludge tank. The flowrate of waste sludge was approximately kept at $10 \text{ m}^3 \text{ h}^{-1}$, subsequently the sludge retention time was maintained at 11 days. (The process diagram was shown in Figure 1-1.)

4.4 Results and Discussions

4.4.1 Comparison of Performance with Different Filling

After the act of the replacement of Kaldnes carrier in IWWT, the input organic loading to IWWT was kept at 85% of design capacity; in the meantime, the corresponding specific area organic loadings were $7.5 \text{ g TOC m}^{-2} \text{ d}^{-1}$ and $8.9 \text{ g TOC m}^{-2} \text{ d}^{-1}$ in reactors with the filling at 60% and 50% respectively. The occasion for process commissioning lasted over 10 months after the carriers' replacement in all reactors, and it was found that the removal efficiency of filling at 50% of reactor volume lower than that at 60%. Overall, the average removal efficiencies of the corresponding COD, TOC and BOD_5 were 96.8%, 98.8%, 96.4% for the filling at 60% and 94.3%, 98.5%, 95.5% for the filling at 50% respectively. More details are

expressed in Figures 4-1 to 4-3. With the aim of comparing the biofilm growth at differential specific area loading, some carriers in chambers 101A and 101D were collected and analyzed periodically and the results are summarized in Table 4-3. Concurrently, the biomass activities were also checked by measuring the oxygen uptake ratios. The results showed that the biofilm had more activities in the train with filling at 50% than that with the filling at 60%. The results are summarized in the Table 4-4.

To the end of July 2001, the reactors with the filling at 50% were wholly topped up to 60%. However, the process was upset for a few times after the carrier replacement until the performance test. The reason was more wastewater with phenol was sent to the IWWT due to one customer expanded the process. As known, phenol would be toxic to aerobic bacteria when the concentration increasing up to certain level (Clair N, 1994). The other twice upsets were caused by wastewater with high organic loadings due to customers' bad control. As the more energy released while the oxidation took place in the aerobic reactors, the energy generated heated water and caused the temperatures rising in the KCRs resulted in inhibitory effect on bacteria activity. Eventually, the full-scale performance test was conducted on 11th Sep 2002 and lasted over 3 weeks until 5th Oct 2002.

Table 4 - 3 Weight of Biomass per Carrier

Reactor	Ten days		Two months		Three months	
	Biofilm (mg)	Volatile biofilm (mg)	Biofilm (mg)	Volatile biofilm (mg)	Biofilm (mg)	Volatile biofilm. (mg)
A	4.9	3.8	19.3	10.4	19.1	10.6
D	6.2	3.9	17.8	10.8	18.3	11.1

Table 4 - 4 Results of SOUR for Biofilm in Different Chambers

Chamber		Two week	Four week	Six week
A	OUR (mg O ₂ /L. hr)	37	19	63
	SOUR(mgO ₂ /gVSS.hr)	5	7	19
D	OUR(mg O ₂ /L. hr)	41	39	67
	SOUR(mgO ₂ /gVSS.hr)	6	9	20

Figure 4-1 Comparing Reactor TOC with Differential Filling

Figure 4-2 Comparing Reactor COD with Differential Filling

Figure 4-3 Comparing Reactor BOD_5 with Differential Filling

4.4.2 Full Scale Performance Test Results

With the purpose of making sure the full-scale performance test will succeed, the influent temperature was strictly controlled, the values ranged from 31.2 ~ 32.6 °C; the concentrations of DO in both KCR and the activated sludge reactors, were all the time above 2 mg/L.

Based on the procedures earlier mentioned, the full-scale performance test was carried out. Initially the feeding flowrate maintained at 85 m³ h⁻¹ with concentration of TOC at about 1400 mg/L was fed to the KCRs from TK001, which was approximately equivalent to 100% and 77% of the organic and hydraulic loadings of design capacity respectively. Looking at the Figure 4-4, on 11th of Sep, the process performed well and the final effluent parameters of TOC, COD, BOD₅ and TSS were 8, 36, 10 and 5 mg/L respectively. However, after the two days to 14th of Sep under the same conditions, the final parameters were increased and the values of TOC, COD, BOD₅ and TSS rose to 25, 78, 16 and 40 mg/L respectively. Interestingly, in the following days, the final parameters gradually decreased. Till to 16th of Sep, the parameters of TOC, COD, BOD₅ and TSS were 10, 50, 16 and 18 mg/L respectively. Afterwards to the 22nd of Sep with the same organic and hydraulic loadings, the process performed well and all the final effluent parameters were within the ENV limitations. By then, the results of full-scale performance test were satisfied with 100% of design organic loading.

As the process in IWWT performed well at 100% of design organic loading, so the hydraulic load was gradually increased due to more wastewater produced from the customers. On 23rd of Sep, the hydraulic loading was increased up to 86% of designed loading, the final effluent parameters were good and the values of TOC, COD, BOD₅ and TSS were 7, 32, 9 and 6 mg/L respectively. On 24th and 25th of Sep, the hydraulic load was increased up to 91% of the design loading and maintained with the good final effluent parameters. On 26th of Sep, the hydraulic loading was increased up to 95 % of the design; the final parameters were still satisfied. As can be seen from the Figure 4-4, with the hydraulic loading increased, the organic loadings were also raised and ranged from the 105% to 107%.

Eventually, on 27th of Sep, the hydraulic loading reached to 100% of the design capacity and maintained onwards.

During the period of the pilot study, the KCR was able to handle higher organic loading. As the final parameters were ideal, in addition, with a new process started from one customer, more organic waste generated, therefore the organic load was slowly increased again. On day 28th of Sep, the organic load was increased up to 109% of design and the corresponding final parameters of TOC, COD, BOD5 and TSS were 11, 49, 14 and 12 mg/L respectively. And on 30th of Sep, eventually the organic loading reached 115% of design; in the meantime, the relevant final effluent parameters monitored were very encouraging and had little changes. Surprisingly, that the final parameters didn't rise up but appeared to be reduced with the increased organic loading. Overall, the average concentrations of the TOC, COD, BOD5 and TSS in the final effluent were 9, 55, 15 and 16 mg/L respectively for the date from 27th of Sep to 5th of Oct. More details have been summarized in Table 4-5. Organic loading in excess of 115% of design were not tested due to exhaustion of the additional waste organic resource. According to the final effluent parameters, it was conceivable that much higher organic loading could be treated in the IWWT.

Table 4-5 Parameters in Final Effluent for Full-scale Performance Test

The parameters in the final effluent of the full scale performance test						
Date	Organic load	Hydraulic load	Final TOC (mg/L)	Final COD (mg/L)	Final BOD ₅ (mg/L)	Final TSS (mg/L)
11-Sep	100%	77%	7	36	10	5
12-Sep	100%	77%	6	58	16	9
13-Sep	99%	77%	8	54	15	8
14-Sep	101%	77%	10	43	12	7
15-Sep	103%	77%	10	69	19	18
16-Sep	101%	77%	12	57	16	16
17-Sep	105%	77%	7	56	16	21
18-Sep	101%	77%	14	78	22	40
19-Sep	101%	77%	9	66	18	29
20-Sep	104%	77%	7	50	14	18
21-Sep	100%	86%	10	46	13	8
22-Sep	100%	91%	10	39	11	7
23-Sep	105%	91%	6	32	9	6
24-Sep	106%	95%	7	49	14	1
25-Sep	107%	100%	8	45	13	2
26-Sep	105%	100%	7	38	11	4
27-Sep	106%	100%	8	50	14	15
28-Sep	109%	100%	10	49	14	12
29-Sep	111%	100%	12	56	16	15
30-Sep	113%	100%	11	54	15	5
1-Oct	111%	100%	11	53	15	8
2-Oct	112%	100%	11	66	18	13
3-Oct	111%	100%	11	46	13	23
4-Oct	111%	100%	15	66	18	10
5-Oct	113%	100%	10	45	13	12

Figure 4-4 Result of Full-scale Performance Test

4.4.3 Discussions

In the biological process, the F/M ratio, as known, is one of the decisive elements that will determine the reactor's performance. The F/M ratio under the input organic loading at 100% of design capacity in IWWT can be estimated and calculated.

F/M ratio: since the carrier's filling is 60% of the reactor volume, based on the Table 3-3, the corresponding displaced water volume in IWWT was 10.8% of the reactor volume that equaled 129.6 m^3 . In terms of the weight of the carrier, it equals 123.12 tons (specific gravity = 0.95). As the weight of each carrier was 0.10 g, the total number of the carriers in the IWWT TPFBRs should be $123.12 / 0.15 \times 10^{-6} = 820.8 \times 10^6$ pieces approximately. Based on the results in Table 4-2, the total weight of biofilm in IWWT was 8947.6 (820.8×10.9) kg; added the MLSS in the reactor was about 4200 mg/L, so the F/M ratio was about 0.36 kg BOD₅/ kg biomass. d. However, the normal F/M ratio for the attached bioprocess ranges from 0.5 to 2.0 kg BOD₅/ kg biomass. d (Metcalf Eddy 2003). Therefore even of the organic loading increased from 85% up to 100% of the design capacity or even higher; all the final effluents were still at very low levels which were well within ENV limitations.

It is noticeable from the Figure 4-4, two days after the full-scale performance test started that the values of final effluent parameter were increased. A few days later these values fell to normal level. That can be probably explained that the previous steady state was broken down in biofilm as the KCRs did not face such higher organic loading. Which forced the process moved into a new stabilized state, before the new steady condition achieved, the performance of the reactor might be fluctuated. As known, the full design treatment capacity was 7608 kg COD/d, the corresponding COD volumetric loading and specific surface area loading were $6.34 \text{ kg COD m}^{-3} \text{ d}^{-1}$ and $8.4 \text{ g TOC m}^{-2} \text{ d}^{-1}$ respectively. Comparing with organic loading, before the performance test conducted, which was about 80% of the design capacity and equivalent to the volumetric and specific surface area loadings at $5.3 \text{ kg COD m}^{-3} \text{ d}^{-1}$ and $7.0 \text{ g TOC m}^{-2} \text{ d}^{-1}$ respectively. As the loading increased, the sludge settleability became poor and the fine particles in the final effluent occurred, which would contribute to some concentrations of TOC, COD and BOD₅. Finally when the biofilm

& suspected bacteria acclimatized to the high organic loading and reached a new stabilized stage, sludge settlement improved and resulted in low turbidity and good final effluent quality.

Figure 4-5 indicates the historical trends of incoming organic loadings and effluent COD in IWWT before and after the carriers replacement. As can be seen, the final values of COD decreased with the organic loading increased. For instance, the average organic loadings were 70%, 75% and 97% of the design capacity for July, August and September in 2002 respectively, but the corresponding average values of COD in final effluent were 71, 55 and 51 mg/L respectively. This can be probably explained that Kaldnes carrier's reactors could perform well with the increase of organic loadings in IWWT.

Figure 4-5 Overview of IWWT Performance

4.5. Conclusions and Recommendations

4.5.1 Conclusions

The process of IWWT had been operating below design expectations since its start-up. Investigations revealed that the main reason for the underperformance could be attributed to the first stage TPFBRs bad performance due to the lesser biofilm attached on type I carriers than expectation. Therefore the plant was not able to reach its design target and maintained the final parameters under regulatory discharge limit.

Based on the pilot study results, the Kaldnes carrier was selected and put into reactors in IWWT. In order to ascertain the performance of the Kaldnes carrier in IWWT, a full-scale performance test was then implemented and got successfully, from which some conclusions are drawn and summarized as follows:

1. Through comparing the different specific area loadings in IWWT, it indicated if even using the same carriers but with the different filling ratio (specific area loadings), the performance also would be different. In other words, the lower specific area loading will result in good effluent quality. Overall, the filling ratio is kept at 60% of reactor volume in IWWT; the process could perform well and match the plant design target.
2. Compared with the type I carriers and Kaldnes carrier, the Kaldnes carrier has the advantages with its ideal configurations so that more biofilm grows in the protected surface area. Moreover, after the carriers replacement in the existing reactors for IWWT, the full scale performance test further proved that replacement with the Kaldnes carrier is the right method of the innovation for IWWT process and the average TOC, COD and BOD₅ removal efficiency could reach up to 99.3%, 98.4% and 99.8% respectively.
3. The performance of Kaldnes carrier with the filling ratio at 60% of the empty reactor in existing plant is much better than that of the former carriers. In contrast with the previous three rounds of full-scale performance tests, the performance of the process after replacement with Kaldnes carriers, the organic treatment capacity could increase upward to 100% or even higher, but the final effluent

parameters were good and all within qualities ENV limitations. This confirmed the pilot study result was correct and the replacement of Kaldnes carrier was the right method of innovation for IWWT.

4.5.2 Recommendations

1. The priority of current project was to find out the right type of carrier with good performance under constant organic and hydraulic loads, it was not studied the impact of various feeding loads to the different Kaldnes carrier filling ratios and air flow rate to biofilm growth on the Kaldnes carriers. In future research, attention should be paid on the air flow rate vs different filling ratio of Kaldnes carrier in different time period. It may find a correlation trend between different air flow rate and carrier-filling ratio, under which the biofilm grows fast.

2. To develop kinetic model

Even though the good performance of Kaldnes carrier in existing wastewater treatment plant has been known, there is still a gap on how to develop a kinetic model to guild future application of Kaldnes carrier in other wastewater treatment plants. Future research is required to develop such a model.

CHAPTER FIVE

SUMMARY

The Integrated Wastewater Treatment (IWWT) plant is SUT Sakra Pte Ltd's second industrial biological wastewater treatment plant on Jurong Island in Singapore. The facility was designed to treat an influent at a flow rate of $110 \text{ m}^3 \text{ h}^{-1}$ with chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5) concentrations at 2878 mg/L and 1870 mg/L respectively. The influent is made up of seven chemical wastewater streams from several chemical manufacturing plants. The treatment system is a two-stage biological process, with the first stage of a three-phase fluidized bed aerobic reactor (TPFBR), and the second of a conventional activated sludge process.

During commissioning, the plant was found to be able to perform up to only 80% of the design capacity of $317 \text{ kg COD h}^{-1}$, provided that the final effluent COD and BOD_5 was less than 100 mg/L and 50 mg/L respectively. The cause for the underperformance was identified as inadequate biofilm attachment to the carriers in the fluidized bed reactors.

In total four runs of pilot plant were set up simulating the two-stage process in IWWT. A comparing study was conducted to select a carrier with the best performance of COD and BOD_5 removal efficiencies. Altogether, there were three types of carrier studied; i.e. type I - the existing carrier made of Polyvinyl Alcohol (PVA) coated with layers of powder activated carbon (PAC), which was the original carrier used in the real plant; type II - a Bio-carrier Plastic (BCP) made of plastic and type III - Kaldnes carrier made of polyethylene. And in the additional run, the used type I carriers retrieved from the IWWT plant were filled into the reactor. In order to compare each performance of the three types of the carrier, actual industrial wastewater, equivalent to 100% of the IWWT design hydraulic load and 100 ~ 110% of organic load, was fed to each run throughout the study.

Results gained from the pilot study indicated that the three- phase fluidized bed reactor (TPFBR) seeded with the Kaldnes carrier could furnish the most effective treatment among the three types of carrier. The average removal efficiencies of COD & BOD₅ were 86% & 88.9% respectively, with final effluent average COD & BOD₅ concentrations of 71 mg/L and 10 mg/L respectively, well within the local regulatory limit of 100 mg/L and 50mg/L. At the same time, type II carrier only achieved 74% removal efficiency. And the original type I carrier bore the worst performance of 68% organic removal, this value even continued dropping as the activated carbon peeled off from the PVA core under the heavy abrasions. It was also noticed that the type III carrier had the best resistance to shock loading. As a result, the Kaldnes carrier was considered as the most likely to meet the performance requirements of the full-scale plant.

Based on the positive pilot study results, all the Type I carriers in the first stage process in IWWT were replaced with the Kaldnes carriers by August 2001. In order to further verify and prove the success of the carrier replacement project, a full scale performance test was conducted in September 2002. Results obtained from the full-scale performance test showed, after the carriers' replacement, the organic removal efficiency for IWWT was increased by 20-30% and reached up to the design capacity or even more; the corresponding average COD and BOD₅ for the final effluent were 51 mg /L, and 14 mg/L respectively, which matched the stringent effluent discharge limits. With the Kaldnes carriers, the plant was finally able to achieve its original design capacity. Currently, the plant is still running with great satisfaction. The biomass grew well on the Kaldnes carrier and the final effluent complied with state discharge limits.

As the object of this study was to find the right type of carrier, during the period of the study, the input organic loading and hydraulic loading to each run almost did not change, in addition, thus the results of performance of TPFBR with Kaldnes carrier under various input organic loading did not investigate in this study. Hopefully in the future, the similar study can involve such items and get more information on that aspect.

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Appendix I References of Kaldnes Carrier Application

Appendix 1 References of Kaldnes Carrier Application

Application in industrial

Facility & Location	Year	Organic load to plant		Reactor volume		Industry & Objective
Opoland Chips Norway	1992	1,400	3,086	210 (m3)	7,415(ft3)	Potato Industry,
		kg COD/day	lb COD/day			Complete organic removal
Sande Paper Mill Norway	1993	60,000	132,276	1,700	60,027	Paper board mill,
		kg COD/day	lb COD/day			Complete organic removal
Stora Papyrus Grycksbo Sweden	1993	700	1,543	135	4,767	Fine paper mill,
		kg BOD7/day	lb BOD7/day			Complete organic removal
Meieriet Sor Norway	1993	210	463	65	2,295	Dairy,
		kg BOD7/day	lb BOD7/day			Complete organic removal
Gjovik Potetindustri Norway	1994	1,000	2,205	34	1,201	Potato industry,
		kg COD/day	lb COD/day			Complete organic removal
Lom & Skjak Norway	1994	250	551	100	3,531	Dairy,
		kg BOD7/day	lb BOD7/day			Complete organic removal
Laga Mill Sweden	1994	4,000	8,818	200	7,062	Recycle paper mill
		kg COD/day	lb COD/day			Post treatment from Trickling Filter
Hilleshog Sweden	1994			2	70	Seeds
						Degradation of Specific substance
Wargons Bruk Sweden	1994	49,000	108,025	2,000	70,620	Sulphite pulp, Goundwood
		kg COD/day	lb COD/day			Complete organic removal

Shoalhaven Mill	1995	5,000	11,023	576	20,339	Paper mill, Pre-treatment prior to AS
Australia						
SCA Hygiene Paper	1995	8,900	19,621	380	13,418	Paper mill, Pre-treatment prior to AS
Germany						
Borgeskogen	1995	200	441	40	1,412	Tank washing facility, Complete organic removal
Norway						
Rockhammers Bruk	1995	20,000	44,092	150	5,300	Bleached CTMP mill Pre-treatment prior to AS
Sweden						
Utansjo Bruk	1995	70,000	154,322	550	19,420	Sulphite pulp mill Pre-treatment prior to AS
Sweden						
Intercell SA	1995	22,000	48,501	550	19,420	Kraft, NSSC, recycle fiber, kraft paper Pre-treatment prior to AS
Poland						
Alhier	1996	15,000	33,069	600	21,186	Paper Mill COD removal Pre-treatment prior to AS
Spain						
Ostlandsmeieriet	1996	50	110	17	600	Dairy, Complete organic removal
Norway						
IVEX	1996	460	1,014	166	5,861	Recycle Paper Mill, Complete organic removal
Chagrin Falls, Ohio USA						

Backhammers Bruk	1996	7,000	15,432	1,500	52,965	Unbleached Kraft & Paper
Sweden		kg COD/day	lb COD/day			Complete organic removal
Edet Bruk	1996	8,000	17,636	1,700	60,027	Tissue from recycled fiber mill
Sweden		kg COD/day	lb COD/day			Complete organic removal
Nyboholms Bruk	1996	2,000	4,409	500	17,655	Tissue from recycled fiber mill
Sweden		kg COD/day	lb COD/day			Complete organic removal
Prior Elverum, Norway	1997	840	1,852	150	5,297	Chicken processing
		kg BOD7/day	lb BOD7/day			Complete organic removal
Campri/Sacessav Italy	1997	228	503	120	4,237	Distillery,
		kg BOD5/day	lb BOD5/day			Complete organic removal
Werra Papier Germany	1997	565	1,246	130	4,590	Paper Mill,
		kg BOD/day	lb BOD/day			Pre-treatment prior to AS
Asahimatu Food Japan	1997	70	154	42	1,483	Soya Been Steaming,
		kg BOD5/day	lb BOD5/day			Complete organic removal
Hoogoven Kwidzyn, Poland	1997	600	4			Nitrification of ground water
		m3/hr	MGD			
Katrinefors Bruk	1997	8,000	17,637	1,500	52,965	Tissue from recycled fiber
Sweden		kg COD/day	lb COD/day			Complete organic removal
Astra AB	1997	1,200	2,645	1,800	63,558	Pharmaceuticals
Sweden		kg TOC/day	lb TOC/day			Complete organic removal
Tasman P&P	1997	15,000	33,069	1,500	52,965	TMP mill

	New Zealand		kg COD/day	lb COD/day			Pre-treatment prior to aerated lagoon	
	McWhorter	1997	100	220	90	3,178	Chemicals	
	Sweden		kg COD/day	lb COD/day			Pre-treatment prior to municipal plant	
	Munkedals AB	1997			200	7,062	Printing Paper	
	Sweden						Post-treatment to trickling filter	
	SCA Ostrand	Graphic 1997	10,000	22,046	500	17,655	TCF kraft pulp mill	
	Sweden		kg COD/day	lb COD/day			Anaerobic/aerobic condensate treatment	
	ARLA	1997			100	3,531	Cheese	
	Sweden						Denitrification	
	Laga Mill	1997	4,000	8,818	200	7,062	Board from recycled fiber	
	Sweden		kg COD/day	lb COD/day			Extension of existing treatment plant	
	Morinaga Co. Ltd.	1998	158	348	60	2,119	BOD-removal	
	Japan		kg BOD/day	lb BOD/day			Polishing anaerobic	
	Nippon Light Metal	1998	40	88	117	4,131	Metal Finishing	
	Japan		kg COD/day	lb COD/day			COD removal afterAS process	
	Exxon Chemical	1998	17,700	39,021	1,670	58,968	Chemical Facility,	
	Baton Rouge, LA		kg BOD5/day	lb BOD5/day			Pre-treatment prior to AS	
	USA							
	Valley Pride Pack	1998	1,337	2,948	266	9,392	Slaughter House,	

Norwalk, WI	USA		kg BOD5/day	lb BOD5/day				Pre-treatment prior to AS
Phillips Petroleum	1998	5,454		12,024	1,927	68,042		Refinery/chemicals,
Borger, TX	USA	kg BOD5/day	lb BOD5/day					Pre-treatment prior to AS
Norsk Hydro	1998	230		507	85	3,001		
Rafnes, Norway		kg BOD7/day	lb BOD7/day					Complete organic removal
Maggi Kempthal	1996	150		331	280	9,887		
Switzerland		kg TN/day	lb TN/day					Nitrification
Maggi Kempthal	1998	1,000		2,205	600	21,186		
Switzerland		kg BOD5/day	lb BOD5/day					BOD-removal + pre denit
Thurpapier, Weinfel	1998	1,998		4,405	4,760	168,076		Paper Mill
Switzerland		kg COD/day	lb COD/day					Pre-treatment prior to AS
Fiskeby Board	1998	10,000		22,046	255	9,004		Recycle Paper Mill,
Sweden		kg COD/day	lb COD/day					Pre-treatment prior to AS
Nordsjo	1998				12	424		Chemicals
Sweden								Pre-treatment prior to municipal plant
Haindl Paper	1998	20,000		44,092	1,800	63,558		Newsprint from recycled fiber
Germany		kg COD/day	lb COD/day					Pre-treatment prior to AS
Boras Energi	1998	4,000		8,818	1,500	52,965		Energy from biofuel
Sweden		kg COD/day	lb COD/day					Detoxification of condensate
Enso Pankakoski	1998	5,000		11,023	540	19,067		Board from recycled fiber
Finland		kg COD/day	lb COD/day					Complete organic removal

AssiDoman Packaging France	1998	1,500	3,307	350	12,359	Board, liner, fluting from recycled fiber
		kg COD/day	1b COD/day			Post-treatment after anaerobic fluidized bed
Schonfelder Paper Germany	1999	2,600	5,732	270	9,534	Paper Mill, Complete organic removal
		kg COD/day	1b COD/day			
Piper Impact I New Albany, MS USA	1999	185	408	153	5,402	Metal Finishing, Complete organic removal
		kg BOD5/day	1b BOD5/day			
Piper Impact II New Albany, MS USA	1999	123	271	284	10,028	Metal Finishing, Complete organic removal
		kg BOD5/day	1b BOD5/day			
Bartow Ethanol Bartow, FL USA	1999	3,319	7,317	855	30,175	Alcohol Production, Complete organic removal
		kg BOD5/day	1b BOD5/day			
Lewis County Dairy Lowville, NY USA	1999	644	1,420	113	3,990	Kosher Dairy, Complete organic removal
		kg BOD5/day	1b BOD5/day			
Dresden Paper	1999		1,400	3,086	240	8,474
Paper Mill, Heidenau, Germany			kg BOD5/day	1b BOD5/day		
Pre-treatment prior to AS						
DENSO Co. Ltd. Kouda Factory, Japan	1999		1,686	0	853	30,119
			m3/day	MGD		

BOD & Nitrogen removal	Sountry Co.	1999	1,200	0	756	26,694
	Japan		m3/day	MGD		
BOD & Nitrogen removal	Unipac Optotoel electronic s Corp.	1999	400	0	400	14,124
	Taiwan		m3/day	MGD		
Electronics Complete removal	Sapporo Brewerie s Ltd.	1999	8,000	2	1,200	42,372
	Japan		m3/day	MGD		
Beverage Complete removal	Steinbeis Temming	1999	4,000	1	420	14,830
	from Germany		kg COD/day	lb COD/day		
Paper recycled fiber Pre-treatment prior to AS	UPB	1999	9,000	2	900	31,779
	from Malaysia		kg COD/day	lb COD/day		
Paper recycled fiber Pre-treatment prior to AS	Cargill Foods	1999			100	3,531
	seed Austrailia					
Oil extraction Complete removal						

removal		1999		1,000		0	2,400	84,744	
	Nordic Synthesis								
Chemicals	Sweden			kg Nitrogen/day		lb Nitrogen/day			
Denitrification									
Pharmaceuticals	Astra AB Sweden	1999		1,200 kg TOC/day		2,645 lb TOC/day	1,800	63,558	
Extension of existing plant									
	AE Staley Loudon, TN USA	2000		10,909 kg BOD5/day		24,050 lb BOD5/day	675	23,834	
Beverage									
Pre-treatment prior to AS									
	Coca-Cola Apizaco, Mexico	2000		4,197 kg BOD5/day		9,253 lb BOD5/day	251	8,880	
Beverage									
Pre-treatment prior to AS									
	Frito-Lay	2000		3,950 kg BOD5/day		8,700 lb BOD5/day	286	10,092	
Potato Industry	Beloit, WI USA			kg BOD5/day		lb BOD5/day			

Appendix II Schematic Diagram of Pilot Study Systems

Schematic diagram of a pilot train
(Plan view)

Appendix III Dimensions Changed for Type I Carriers

Appendix III Schematic Diagram of the Pilot Study Systems

Carriers with Sludge Attached					
No of carriers	Area	Diameter (max)	Diameter (min)	Diameter (mean)	Roundness
1	40.5706	9.6078739	5.6995363	7.054611	1.6386738
2	30.1197	8.9733305	4.0662012	6.3463359	1.9025048
3	5.30004	3.1480589	2.1955953	2.5508695	1.2444551
4	1.80308	1.8289753	1.0243801	1.4840355	1.2507682
5	14.230206	5.2553592	3.34654	4.2380252	1.3764811
6	39.1484	9.4174891	4.2659793	7.3658104	1.5317359
7	13.9239	7.5791054	1.9157447	4.5278082	2.9589424
8	82.1213	13.644701	8.3209829	10.190538	1.6693231
9	32.3888	6.6964617	5.9802408	6.350925	1.1942292
10	18.0468	7.3168111	3.0779033	4.9684029	1.7896941
11	34.7858	9.1356974	4.5651512	7.0776434	1.6918732
12	64.4421	10.864578	7.4074326	9.1390009	1.2800106
13	86.1589	14.14592	8.177146	10.444734	1.7559795
14	8.41348	3.877439	2.4452384	3.3222878	1.8638008
15	46.9972	9.1884584	7.00220967	7.8050861	1.4051417
16	9.24977	4.4084425	2.4793105	3.513665	1.2827759
17	13.8174	4.5064335	3.7189658	4.0818896	1.430827
18	33.6459	9.3036785	4.5217733	6.9635568	2.0420783
19	0.14915	0.41607317	0.33044937	0.37112617	1.0790596
20	45.5697	9.0183315	6.8131704	7.676229	1.245882
21	28.8865	8.8223209	4.465766	5.9243546	1.5539684
22	27.3019	8.3893576	3.7375393	6.2758732	1.7296764
23	12.6508	4.9203382	2.7483125	4.0414724	1.9099411
24	8.38418	3.8429415	2.4233565	3.2704573	1.7703015
25	14.8134	6.0051293	2.6641681	4.485991	3.7723975
26	33.2358	8.5152416	4.5085011	6.6711121	1.4335346
27	47.1091	9.4181967	6.917141	7.7426243	1.3692958
28	45.6922	8.6505346	6.8287892	7.6113639	1.2239748
29	45.8413	8.5739965	6.9700732	7.5502334	1.2082163
30	9.31369	4.5344195	2.4012754	3.3369401	1.2980502
31	61.161	7.8106585	5.1509376	6.1795459	1.3140517
32	27.728	8.773292	4.4385471	6.1797199	1.6324077
33	27.0169	8.749568	3.4209208	5.7494669	1.7258633
34	11.8838	4.2609816	3.0934396	3.7882843	1.6129717
35	72.0965	10.153444	8.6892424	9.5664225	1.2393903
36	10.4823	6.2980123	1.61966871	3.8819859	1.9162551
37	37.3107	10.034313	3.6051466	7.4593258	1.5659326
38	22.2921	6.1003933	4.6124539	5.2719617	1.1933937
39	39.3854	8.9559498	5.6798763	7.3525586	1.305866
40	17.4449	5.8898177	3.7846301	4.564075	2.3901517
41	0.04261	0.30968118	0.17496376	0.24232247	1
42	42.5601	8.9470243	5.7142367	7.4509077	1.5100029
43	7.82222	4.2359056	2.2406225	3.060356	1.3679367
44	69.9579	12.409973	5.9404721	9.4764156	1.4658641
45	30.695	7.4859376	4.78504499	6.0983686	1.3604943
46	7.09779	3.4310269	2.4095793	2.9144051	1.2909251
47	17.3197	5.5130749	3.6393368	4.632726	1.9174824

Appendix III Schematic Diagram of the Pilot Study Systems

48	10.8158	5.0617485	2.788717	3.7123814	2.4003053
49	20.0176	5.2123599	4.6792402	4.9801874	1.1897675
50	64.4874	10.532234	6.8546762	9.024766	1.3101135
51	41.7771	10.015848	5.9884744	7.5845871	1.4930561
52	38.4905	8.7975311	5.256793	7.0390058	1.6281502
53	50.0388	9.1040115	6.9061584	7.9601607	1.280849
54	10.2485	4.092968	2.793488	3.5521286	1.3302358
55	30.0691	7.4345288	4.9524403	6.0211825	1.3948956
56	30.9826	8.5441246	4.5616498	6.3795805	1.6429296
57	16.0067	5.338573	3.4096134	4.4683452	1.5230941
58	17.9908	6.598582	3.3548861	4.7081561	1.4326943
59	38.8128	11.646962	3.6323779	7.3572488	1.80441633
60	71.4653	10.579542	7.2552176	9.5710211	1.3104043
61	18.1586	5.0827518	4.3168697	4.7607732	1.2308052
62	85.0137	12.358466	8.7583914	10.377802	1.266845
63	77.6656	12.23708	6.0106702	9.8493376	1.6591436
64	70.1576	10.414623	8.6369781	9.3378553	1.3436806
65	58.6973	13.445717	5.027431	9.1874014	1.6504219
66	3.42771	2.7541208	1.2310315	2.196995	1.3808231
67	27.5682	9.8359394	3.7570844	6.3534332	2.1048298
68	66.0507	11.72854	7.6915989	9.1169491	1.4710423
69	29.4512	8.3817348	4.2734642	5.9791036	1.4088235
70	79.9054	12.295377	7.4750786	10.055809	1.3352388
71	74.0834	11.156898	8.0748873	9.6486883	1.2678546
72	33.9149	7.4638472	5.5306797	6.4875307	1.2402092
73	40.6425	8.0031605	6.1657491	7.2312837	1.250388
74	59.9304	9.4890499	7.9255781	8.6845436	1.2012504
75	66.8125	10.465263	8.1069813	9.0628437	1.756575
76	48.0333	10.735481	6.2657995	7.9142237	1.5799929
77	19.0082	5.6504936	3.699939	4.8602285	1.3045132
78	31.8029	8.654852	4.8175006	6.2408218	2.319523
79	12.1109	4.8480868	3.023778	3.9331596	1.2511812
80	52.6595	10.437741	6.4986553	8.3420229	1.3043681
81	78.8001	12.293427	5.9706583	10.054086	1.676186
82	61.1902	9.572468	7.9255781	8.8041019	1.2178234
83	65.6912	10.371058	8.1064892	9.0267296	1.7328417
84	3.70736	2.8941653	1.4236569	2.3085685	1.3399124
Min	0.04261	0.30968118	0.17496376	0.24232247	1
Max	86.1589	14.14592	8.7583914	10.444734	3.7723975
Mean	35.9984	7.89159646	4.799598255	6.290772545	1.544616271
	24.0395	3.067061205	2.148175692	2.461455586	0.410852443

Appendix III Schematic Diagram of the Pilot Study Systems

Virgin Carriers					
No of carriers	Aera	Diameter (max)	Diameter (min)	Diameter (mean)	Roundness
1	91.333794	12.98255	8.5425644	10.646285	1.5127112
2	81.591316	12.916426	7.9338074	10.059671	1.3956047
3	47.09045	10.140452	6.2402439	7.796772	1.5378458
4	71.667725	12.022671	5.9543543	9.5589209	1.6844198
5	93.640244	13.684949	8.5519133	10.771775	1.4737442
6	127.88809	14.554511	10.939943	13.009922	1.4284439
7	55.099106	9.0102062	7.5910439	8.2814255	1.4558558
8	78.624359	14.23395	7.4572425	9.7881956	1.8595538
9	23.144394	7.7816205	3.9991667	5.5013339	1.980918
10	61.248749	11.379079	6.5484638	8.8309431	1.5558566
11	19.25326	6.2657995	4.1942024	4.8918276	1.4369936
12	38.682301	9.9934874	4.2005482	7.6746941	1.6985407
13	75.771919	12.130512	7.1169748	9.7715139	1.4994904
14	24.750385	7.5601058	4.1443768	5.4621224	1.438687
15	13.670906	5.377593	3.0056677	4.172645	1.6958106
16	38.128326	8.7314386	5.1299543	7.1009484	1.6702325
17	61.792068	11.176455	7.3424282	8.8387976	1.3804091
18	45.519085	9.1176052	6.0837803	8.6364975	1.4321274
19	54.345379	13.015024	4.1224689	8.6364975	2.3814499
20	28.148804	6.5944638	5.4484444	5.9230247	1.2279749
21	60.614876	10.97191	6.5419531	8.8597031	1.4890468
22	37.489124	7.4316626	6.0857501	6.9158945	1.2846987
23	26.236528	7.5769968	3.9184351	5.6281123	1.5476491
24	37.007061	11.451406	3.8873861	8.2225409	2.1900005
25	13.625629	5.4946866	2.9339228	4.0916839	2.2402296
26	31.097116	7.7376871	5.1977768	6.317522	1.6057264
27	49.604641	10.229882	6.1696358	7.9876809	1.3892175
28	31.76951	7.7706604	4.8315778	6.367979	1.6308212
29	27.648096	7.6520228	4.0639081	5.7712097	1.4686346
30	44.60556	8.7251825	6.3730593	7.5405483	1.3382131
31	43.516254	8.4788818	5.6777658	7.3013844	1.6631078
32	98.159927	13.895751	8.424839	11.0100305	1.5843359
33	96.604538	14.201449	8.424839	10.984052	1.6019547
34	13.103616	5.4725881	2.6959682	4.3329139	1.8011504
35	20.51568	6.2995009	3.0356455	5.0436859	1.4737884
36	15.471321	5.5910268	3.7389643	4.3952446	1.40408
37	6.6583409	3.6217306	2.1895218	2.8520131	1.4000427
38	14.661667	5.0756726	3.5278566	4.3098817	1.2194836
39	83.144035	11.381418	9.2186985	10.186378	1.4316138
40	42.653332	8.3068876	5.5222464	7.45398	1.7747047
41	53.056324	10.878543	6.0697556	8.273428	1.5120735
42	42.512177	10.16249	5.5537467	7.5309124	1.5862523
43	86.915321	12.194782	9.1041574	10.397511	1.3055161
44	23.149721	5.8841629	4.611588	5.3543544	1.301356
45	74.416283	11.946221	6.6715574	9.5245819	1.9190065
46	44.403145	9.9522266	4.783937	7.8658066	1.5774753
47	16.41148	6.1415124	3.091717	4.5375948	1.5164732

Appendix III Schematic Diagram of the Pilot Study Systems

48	82.659309	15.918056	4.9524403	11.940993	2.3175335
49	34.868401	8.4134512	5.4391489	6.9535789	1.3281436
50	21.106941	6.1672611	4.1597714	5.079114	1.5325788
51	48.334229	9.679266	6.280447	7.8427887	1.4252315
52	16.960127	7.3159013	2.3789892	5.0759683	1.8062953
53	98.463547	13.880408	9.8076019	11.057166	1.546692
54	42.855747	8.6941442	6.1210961	7.4262195	1.4913462
55	43.100773	8.570734	6.1778326	7.481133	1.5103842
56	61.325985	13.600223	6.0124426	8.9020166	2.1706879
57	34.255833	7.8844748	5.1465406	6.686899	1.5348524
58	47.364777	12.060382	5.242928	8.2740641	1.8566055
59	62.298103	9.9622583	8.0116425	8.8359308	1.3107033
Min	6.6583409	3.6217306	2.1895218	2.8520131	1.2194836
Max	127.88809	15.918056	10.939943	13.009922	2.3814499
Mean	48.475182	9.582074576	5.705503042	7.626547668	1.590413161