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Design Criteria for Aerobic Treatment of Grease Waste by Filamentous Microorganisms in Activated Sludge

Christian Edward Seal Mery
University of Tennessee - Knoxville

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To the Graduate Council:

I am submitting herewith a dissertation written by Christian Edward Seal Mery entitled "Design Criteria for Aerobic Treatment of Grease Waste by Filamentous Microorganisms in Activated Sludge." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Gregory D. Reed, Major Professor

We have read this dissertation and recommend its acceptance:

Bruce R. Robinson, Chris D. Cox, Paul D. Frymier

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Gregory D. Reed
Major Professor

We have read this dissertation
and recommend its acceptance:

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Bruce R. Robinson

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Chris D. Cox

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Paul D. Frymier

Accepted for the Council:
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Linda Painter
Interim Dean of Graduates Studies

(Original signatures are on file with the official student records)

**Design Criteria for Aerobic Treatment of Grease Waste
by Filamentous Microorganisms in Activated Sludge**

A Dissertation Presented for
the Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Christian Edward Seal Mery
December 2006

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Abstract

The focus of this investigation was the determination of design and operational criteria for the aerobic biological treatment of grease waste. The aerobic biological treatment is intended promote filamentous organisms, which are capable of degrading oil and grease. Significant amounts of grease waste are generated by different industries. These wastes are recovered in grease traps, oil/water separators and flotation systems. Current practice consists of the recollection of the waste and disposal in a landfill or by incineration. The collected waste has to be disposed of either placing it in a landfill or by incineration. Additionally a change in landfill legislation is anticipated that will make it necessary to treat grease-trap waste. Therefore it is necessary to develop alternative methods for treating these grease-trap wastes.

The design criteria established by this research are:

The treated waste has a density lighter than water; additionally filamentous microorganisms tend to trap fine bubbles therefore floating. In order to maintain thorough contact between the media and substrate, down draft vortex mixing is required. The biological kinetics for the aerobic treatment of grease-trap waste (maximum growth rate, maximum specific rate of substrate utilization, true yield of cell synthesis and the concentration giving one-half the maximum rate). A predictive model for the biological treatment was developed. The research determined that the traditional method of sedimentation was not adequate for the separating the biomass from the liquid phase. In

contrast the dissolve air flotation experiments showed that it was possible to reach the treatment goal (300 mg/ l SS). In order to reach this treatment goal it was determined that the air pressure should be 45-70 psi and that the recycle rate should be 30-35%. A economic analysis of the process using the proposed treatment method resulted in an estimated cost of 4570 per 1000 gallons of grease waste.

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Chapter 1

Introduction

1.1. Introduction

The focus of this investigation was the determination of design criteria for the aerobic biological treatment of grease waste. The aerobic biological treatment is accomplished by filamentous organisms, which are capable of degrading oil and grease (Jung *et al.* 2002, Nielsen *et al.* 2002, Cammarota *et al.* 2001, Lefebvre *et al.* 1998, and Wakelin & Foster 1997 and 1998). It has been recorded that wastewater which contains a high concentration of oil/grease has been associated with filamentous bulking during wastewater treatment (Goddard and Foster 1987 and 1991, Hong *et al.* 1996, Nielsen *et al.* 2002, and Bendt *et al.* 2002) and produces clogging and operational problems in anaerobic treatment units (Cammarota *et al.* 2001).

Significant amounts of grease waste are generated by different industries. These wastes are recovered in grease traps, oil/water separators and flotation systems. The collected waste has to be disposed of either by placing it in a landfill or by incineration (Lefebvre *et al.* 1998). The traditional solutions of transporting this waste to a dumpsite or incineration facility are associated with high cost and time consumption (Keenan & Sabelnikov 2000). For this reason it is desirable to develop a more competitive method for treating these wastes.

The length of treatment time for fat, oil, and grease is expected to be long, due to the low solubility of the waste. This suggests that waste with a high concentration of greases and oils would have lengthy periods of treatment (Tano-Debrah *et al* 1999). This will cause high MCRT, which could promote filamentous microorganisms.

The treatment of wastewater that contains high concentrations of oil and grease has been known to cause interference with the microbiological processes at wastewater treatment plants and leads to a decrease in the efficiency or even to the complete failure of the treatment (Mendoza & Stephenson 1996 and Keenan & Sabelnikov 2000). This drop in the efficiency of the treatment is associated with filamentous organisms that are related with foaming problems. Nocardioforms and *M. parvicella* possess a poorly wet-table (hydrophobic) cell surface. When present in sufficient numbers in activated sludge they render the flocs hydrophobic and amenable to attachment of air bubbles. When the filamentous organisms grow to certain levels, they render the flocs hydrophobic and permit the attachment to air bubbles that attach to the surface of the sludge (Jenkins *et al* 2003).

The treatment of grease-trap waste in traditional activated sludge treatment facilities may produce filamentous bulking, oxygen transfer problems, and reduced efficiency of the process effectiveness due to settling problems. Because of these possible problems, the treatment of waste that contains a high concentration of oil and grease in traditional activated sludge has not been recommended.

Industries that generate grease wastes that are collected in grease traps, oil/water separators and flotation systems, have the need to dispose of these wastes. Conventional methods of disposing of grease waste consist of discarding into landfills or by incineration. In addition, in recent years French legislation has prohibited the dumping of lipidic residues in landfills. This prohibition is due to the high fermentative level of the lipidic residues (Lefebvre *et al* 1998). Therefore, the landfill option might not be available long term.

An alternative method for treating the grease waste is physical-chemical treatment or biological treatment. Physico-chemical treatment has shown that it can only remove part of the organic load. This process does not have a high efficiency and is expensive (Karpati *et al* 1990)

The effluents of food related industries contain significant quantities of fats and proteins. The fats, grease, and proteins present in these effluents have a low biodegradability coefficient. In addition, these wastes tend to solidify at lower temperature, producing damage, clogging and bad odors. These wastes represent a serious problem for the anaerobic biological process (Masse *et al* 2001, Cammarota *et al* 2001, and Vidal *et al* 2000). It has been observed that a high concentration of wastewaters containing long-chain fatty acids (LCFA) produces inhibition in anaerobic treatment (Hwu *et al* 1996).

Studies have shown that several microorganisms that are capable of degrading fats and greases are filamentous organism that can produce filamentous foaming (Nielsen *et al*

2002, Wakelin & Forster 1997, and Chua *et al* 1996). Long chain fatty acids and low temperature facilitate the appearance of *M. parvicella*, which is responsible for filamentous bulking (Mamais *et al* 1998). The down side of the presence of these microorganisms is the filamentous foaming which produces compaction and settling interference (Jenkins *et al* 2003).

Conventional treatment of high concentrations of FOG have been shown to generate operational and treatment problems. Therefore there is reason to develop alternative treatment methods. Additionally, physical-chemical methods have been shown to be an inefficient method and expensive for treating grease waste, and anaerobic treatment produces clogging problems in the equipment. For these reasons it is desirable to investigate design criteria for aerobic biological treatment and to perform a comparative economic analysis with the existing alternatives.

1.2. Thesis Statement

The focus of this research was on the determination of operation and design criteria for the aerobic degradation of grease waste by filamentous microorganisms in activated sludge as an alternative method for treatment.

1.3. Key Words

Fat, oil, and, grease (FOG), biodegradation, filamentous microorganism, water pollution control, settling properties, batch reactor design, dissolve air flotation (DAF)

1.4. Objectives

The research objectives were the determination of the operational and design criteria for filamentous organism in activated for the aerobic treatment of fats, oils and grease. The specific objectives of the study were:

1. Analyze the performance of the aerobic sequential batch reactor treatment for grease wastes. Determine the biological model coefficients for the batch reactor ($\mu_{\max}$, Y , q , and K).
2. Determine the type of mixing necessary for the biological process.
3. Determine the solid-liquid separation properties of the biomass. The objective was to determine the degree that the biomass can be separated by air flotation and/or sedimentation.
4. Develop a statistical model for predicting the efficiency of the treatment process.

5. Provide an economic analysis of the process by looking at the cost of the proposed biological removal of fat and grease waste in comparison to other existing removal technologies or disposing systems.

Chapter 2

Literature Review

2.1. Introduction

Several different types of reactors are utilized in environmental engineering. These reactors are generally designed to promote the generation of suspended growth or biofilms. In order to select the optimum reactors or series of reactors for a given waste treatment problem and location, it is necessary to understand the kinetics of substrate removal by different microorganisms and the fundamental properties of different reactor types.

The factors that influence the choice between the different reactors include physical and chemical characteristics of the waste to be treated, the concentration of the pollutants treated, the presence or absence of oxygen, the efficiency and reliability of the treatment, the climatic conditions under which the reactor operates, the number of biological processes, operator's experience and skills, operational costs, construction costs and times, and different possibilities of operations of the reactor (Rittman & McCarty, 2001).

2.2. Physical and Chemical Characteristics of Grease Waste

Oleaginous material such as fats, animal grease, and vegetable oils are found in wastewater from industries, restaurants, and kitchens (Sugimori et al., 2002). These

oleaginous materials are captured in grease traps, oil/water separators, and flotation systems.

Fats, oils, and grease are basically triglycerides, which consist of straight chain fatty acids linked, as esters, to glycerol (Figure 2.1). These components can vary in chain length, number of carbon atoms, and if they're saturated or unsaturated (Wakelin & Foster, 1997). The glycerides of fatty acids that are liquid at ordinary temperature are called oils, and those that are solids are called grease (or fats) (Metcalf & Eddy, 2003).

The low solubility of fats and oils reduces their rate of microbial degradation. Mineral acids attack them, resulting in the formation of glycerin and fatty acid. In the presence of alkalies, such as sodium hydroxide, glycerin is liberated, and alkali salts of fatty acids are formed. These alkali salts are known as soap. Common soaps are made by saponification of fats with sodium hydroxide. They are soluble in water but in the presence of hardness constituents, the sodium salts are changed to calcium and magnesium salts of the fatty acids, or so-called mineral soaps. These are insoluble and are precipitated (Metcalf & Eddy, 2003).

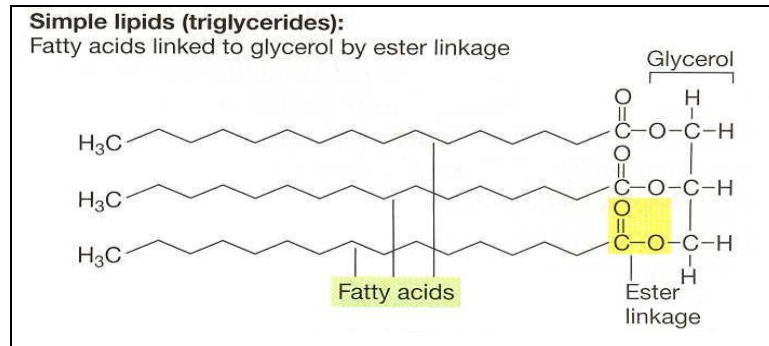


Figure 2.1 Simple lipids

Source: Brock Biology of Microorganism, 2002

2.3. Biological Process of Grease and Oil Removal

2.3.1. Degradation Pathway

The initial process of biological degradation of fats consists of microorganisms that initially hydrolyze the ester bond, using an extra-cellular enzyme (lipases). The reaction results in the formation of glycerol and free fatty acids (Figure 2.2). This enzyme attacks fatty acids with different chain lengths. The last lipase can be either highly specific or non-specific, which results in the decomposition of specific triglycerides containing specific fatty acids or breakdown triglycerides containing different fatty acids. The results of lipase action are the release of free fatty acids and glycerol. Various chemoorganotrophic microorganisms can degrade these substances anaerobically as well as aerobically (Brock Biology of Microorganism, 2002).

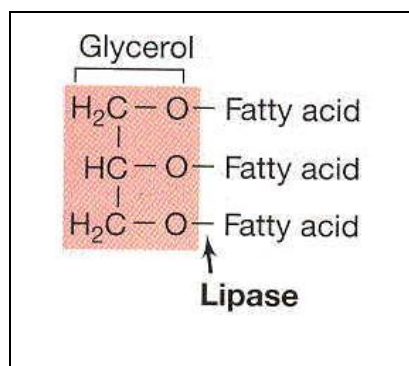


Figure 2.2 Actions of Lipids on Fat

Source: Brock Biology of Microorganism, 2002

2.3.2. Microorganisms that Degrade Grease and Oil

The studies of the types of microorganisms that are capable of degrading fat, grease, and oil have shown that several microorganisms are capable of degrading these wastes (Jung et al., 2002, Nielsen et al., 2002, Cammarota et al., 2001, Lefebvre et al., 1998, and Wakelin & Foster, 1997-1998). The degradation of wastewater that contains a high concentration of grease and oil has been associated with the appearance of filamentous organisms (*Spahareotilus natans*, *Thiothrix*, *Beggiatoa*, *Nocardia* and *Microthrix* *genuses*), a phenomenon known as filamentous bulking (Jung et al., 2002).

The presence of *M. parvicella* has been associated with the consumption of long chain fatty acids. This microorganism is suspected to be a specialized lipid consumer that can out-compete other bacteria under alternating anaerobic-aerobic conditions. Due to the significant amount of lipids and long chain fatty acids present in many wastewater

streams, a significant biomass production can be supported in a treatment plant (Nielsen et al., 2002).

Filamentous microorganisms generate a stable mousse on the surface of the aeration tank. This hinders the flocculation and sedimentation of the biomass and blocks gas transfer that is needed for the biological degradation. Also, these microorganisms generate “agglomerates” or “pellets” inside the secondary sludge flocs, hindering sedimentation and reducing station efficiency for standard aeration waste treatment (Jung et al., 2002). The impact that filamentous organisms have on the sedimentation and agglomeration properties of the flocs requires the implementation of different methods for removing the biomass from the treated wastewater. Also, it may be possible to determine the conditions that promote filamentous growth, so that the occurrence of filamentous microorganisms can be promoted.

2.4. Physical Properties of the Floc

Activated sludge floc consists of a wide range and variety of particle sizes. These particles can range from a single particle (0.5 to 5 μm) to large aggregates, which can reach sizes up to 1mm (1000 μm). These flocs are made up of biological microorganisms, inorganic and organic particles. The microorganisms that form the floc have a wide range of organism types that vary from prokaryotes to eukaryotes (Jenkins et al., 2003).

The activated sludge process consists of two basic processes: the biological conversion of pollutants in the reactor and the separation of the solids. The biological conversion consists of providing an environment for the degradation of soluble and particle organics that are found in the wastewater. Additionally, for removal it is necessary to have mixing and a variable consortium of microorganisms and macro-organisms, designated as activated sludge, for degrading the waste. The separation of the solid phase is usually performed in a gravity clarifier. This process consists of providing a quiescent environment that allows the activated sludge to flocculate and then separate from the treated wastewater (Jenkins et al., 2003). Any problem that affects the activated sludge consortium or/and the activated sludge solid separation implies a decrease in the overall efficiency of the process. Liquid-solid separation is the most common cause of failure in wastewater treatment plants (Rittmann & McCarty, 2001)

The problems that affect the activated sludge settling properties are divided into exocellular polymer bridging and filamentous organism networks. The exocellular polymer bridging produces dispersed growth, viscous bulking, and pin floc. Filamentous problems can produce filamentous bulking and foam or scum problems. Given the nature of this study, exocellular problems are not going to be considered.

2.4.1. Filamentous Bulking

Filamentous bulking is a common problem of poor activated sludge compaction and settling properties (Eckenfelder, 1998). This problem is caused by an excess of

filamentous microorganisms in activated sludge (Figure 2.3). These interferences are a result of a diffused floc structure or the growth beyond the boundaries of the flocs into the bulk solution and bridging between them (Jenkins et al., 2003).

2.4.2. Foam/Scum

The foam/scum problem in activated sludge is associated with the presence of filamentous organisms. These foam/scum-related organisms correspond to the nocardioforms, *M parvicella* and to a lesser degree with type 1863. Another cause of foam/scum problems can be because of nutrient deficiency or denitrification. (Jenkins et al., 2003)

Nocardioforms and *M. parvicella* possess poorly wettable cell surfaces. When these microorganisms are present in sufficient high numbers in the activated sludge, they render the flocs hydrophobic and amenable to the attachment of air bubbles. This causes the activated sludge floc to float into the surfaces, generating the foam/scum. (Jenkins et al., 2003)

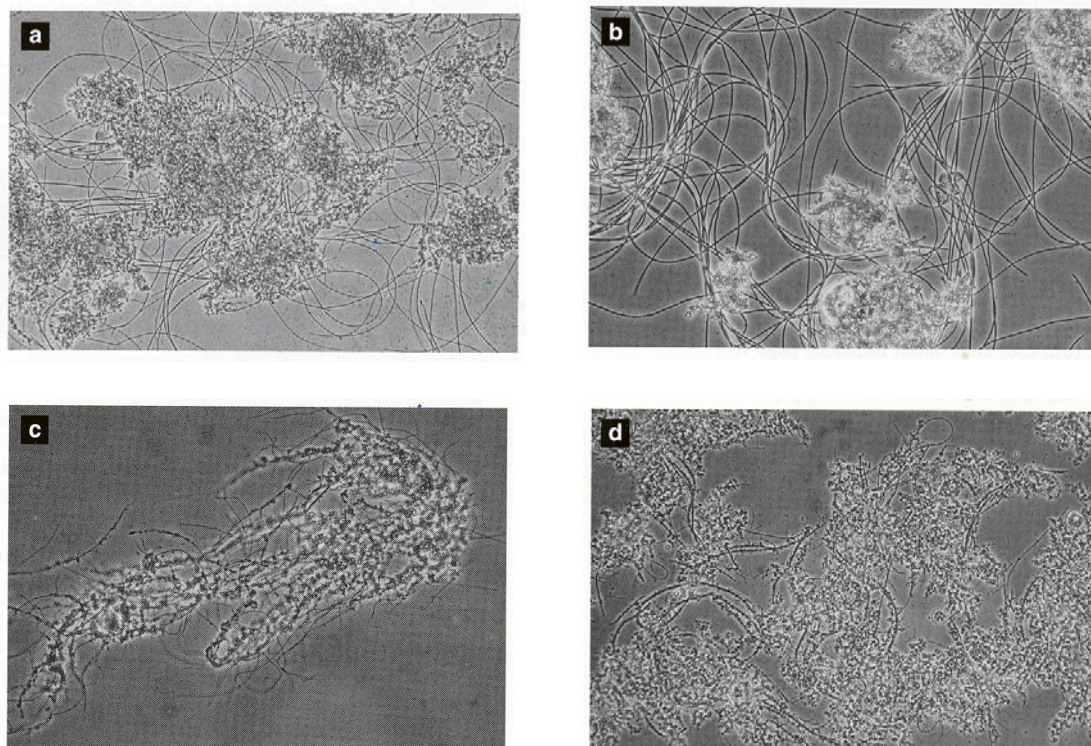


Figure 2.3 Phase Contrast Micrographs of Effects of Filamentous Organisms on Floc Morphology and Settleability: (A) and (B) Inter-Floc Bridging; (C) and (D) Diffused Floc Structure

Source: Jenkins et al., 2003

2.4.3. Effects of Filament on Sludge Settling Properties

The effect that filament organisms have on settling properties has been shown to be described by a correlation between the total extended filament length (TEFL) and the activated sludge settling properties (Jenkins et al., 2003). Studies performed by Palm et al., showed that for values of TEFL above 10^7 $\mu\text{m}/\text{mL}$ the SVI increased rapidly, with values exceeding 150 mL/g (Figure 2.4). In addition, studies performed by Sezgin et al. (1980), showed that this relationship was valid for several full-scale plants (Figure 2.5). Comparative studies performed by Lee et al. (1983) showed that the closest correlation between filament length and settling properties could be measured between TEFL and Diluted Sludge Volume Index (DSVI).

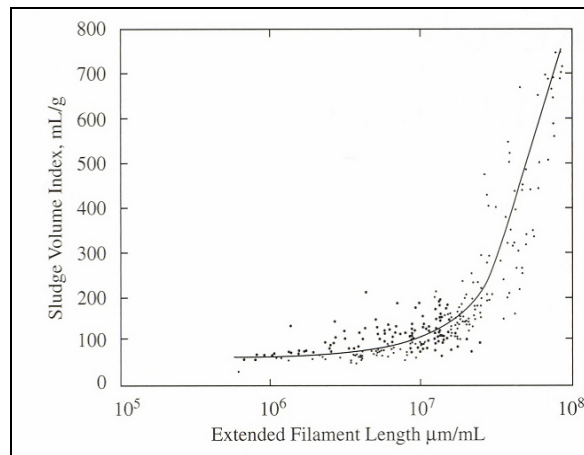


Figure 2.4 Effects of extended filament length on SVI.

Source: Jenkins et al., 2003

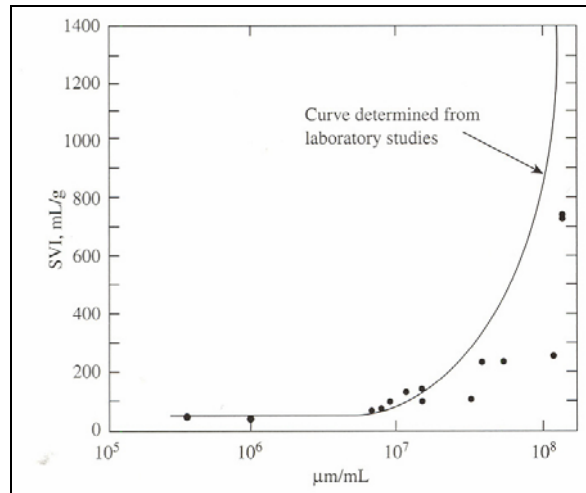


Figure 2.5 Validation of SVI with filament length for 14 full-scale California wastewater treatment plants.

Source: Jenkins et al., 2003

The settling properties of an activated sludge can be related to the TEFL. For this purpose Lee et al. (1983) performed studies that evaluated different settleability indices with the TEFL. From this study it was possible to observe a correlation between the TEFL and the diluted sludge volume index. The relation between DSVI and TEFL is shown in Figure 2.6.

The relation between SVI and TEFL proposed by Lee et al., (1983) used the simplest function that provided a reasonable fit to the data (Equation 2.1). The power function fitted to the data is shown in Table 2.1.

$$Y = a \cdot X^b \quad (2.1)$$

Table 2.1 Correlation of Settleability Indices with TEFL

Index	Least squares regression +		Visual line of best fit			Sample size
	a	b	r	S_{e+}^{2+}	S_{e+}^{2+}	
DSVI	56.0	0.343	0.85	10,480	5920	97
SVI _{1.5}	53.8	0.393	0.82	14,080	8590	82
SVI _{2.5}	63.1	0.334	0.81	4680	4440	64
Stirred						
SVI _{2.5}	52.7	0.361	0.82	3940	3270	57
SVI _{3.5}	81.3	0.248	0.82	2020	2250	35

⁺ Y = SVI (ml g⁻¹); X = TEFL (km g⁻¹)

⁺ Calculated from $\frac{\sum(Y - \bar{Y})^2}{n - 2}$. Where $\bar{Y}$ = SVI estimated using regression equation or visual line of best fit.

Source: Lee et al. (1983)

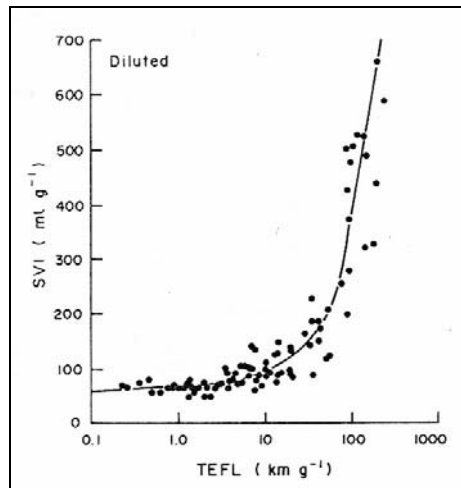


Figure 2.6 Relationship of DSVI to TEFL

Source: Jenkins et al., 2003

2.5. Reactor Selection and Operation

The reactor selected for this project was a sequential batch reactor (SBR). This reactor was selected for its flexibility and simplicity. The main advantage of using this type of reactor for the project is that it allows the management of variable retention times. The use of SBR is necessary because of the uncertainty of treatment times. The SBR is a self contained system that may not require a liquid/solid separation unit, because the liquid/solid separation can be performed in the same reactor tank. In addition, this type of reactor permits changes in the operation that don't require additional construction.

The design of SBR not only considers the equipment design, but also the design of the operation (Rippin, 1983). A SBR is an activated sludge process. This process can be designed using a single tank or multiple tanks in parallel. The SBR process can normally be described or divided into five phases for a single treatment cycle (Fig 2.7): fill, react, settle, draw, and idle.

The principal components of a SBR are tank, inlet, outlet, mixing and aeration systems, and controllers. Most designers find that a three-tank system is a good compromise, unless some unusual condition exists. The geometry of SBR tanks tends to be relatively deep and the width to length ratio is unimportant.

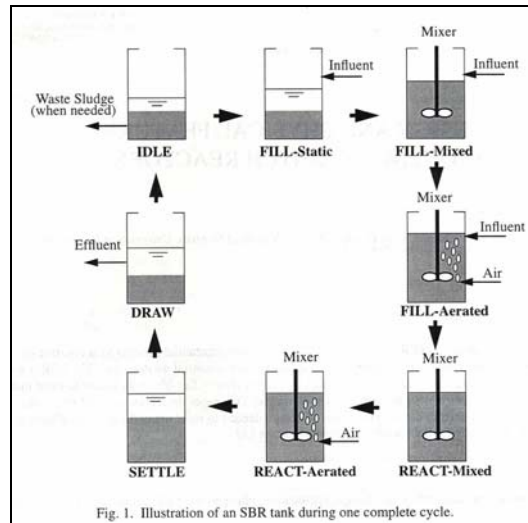


Figure 2.7 Illustration of an SBR Tank During one Complete Cycle

Source: Ketchum, 1997

The fill phase provides for the addition of influent and may be static, mixed, or aerated, depending on the treatment objectives. Static Fill results in minimum energy input and high substrate concentration at the end of the fill. Mixed Fill results in denitrification if nitrates are present, a subsequent reduction of oxygen demand and energy input, and the anoxic or anaerobic condition required for phosphorus removal. Aerated Fill results in the beginning of aerobic reactions, a reduction of cycle time, and holds substrate concentrations low, which may be important if biodegradable constituents exist that are toxic at high concentrations (Ketchum, 1997).

Mixed Fill for a short period has been found to select organisms that settle better and limit the formation of filamentous organisms (Irvine et al., 1985). Continuous aeration during Mixed Fill was used to limit the substrate concentration toxic levels when treating

toxic organics, which needed a short period of mixed fill to avoid the development of filamentous bacteria and poor settling sludge.

A substantial increase in the initial substrate concentration produces a preferable floc for forming over filamentous organisms. From Figure 2.8, it can be seen that filamentous organisms are discouraged in systems that have high growth rates (i.e., at elevated substrate concentrations) and prolonged starvation periods (Irvine et al., 1997)

Settling rates under conventional batch reactor design are based on subsidence of the sludge blanket layer. It is common to consider for design a rate greater than one meter in 10 minutes, for a concentration of the biomass of 2000 mg/l of mixed liquor (Ketchum, 1997).

2.6. Reactor Operation Parameters

2.6.1. pH

Every microorganism has a well-defined optimum pH range where it is possible for those organisms to grow. A good number of the microorganisms can grow at a range of 2 to 3 units from the optimum pH. Most of the natural environments have a pH between 5 and 9, and most microorganisms can develop in this range.

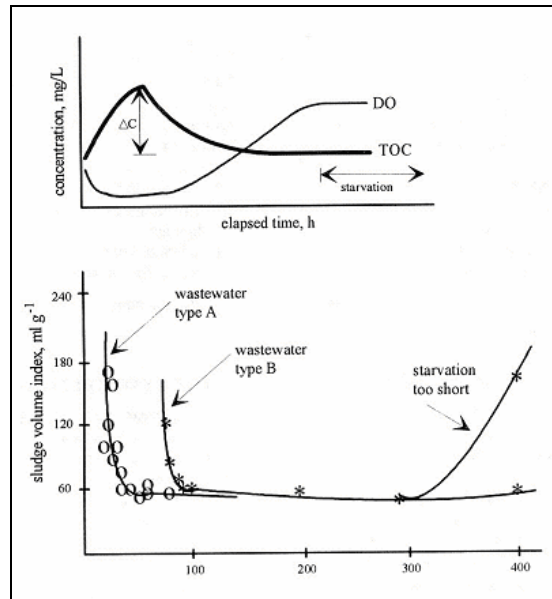


Figure 2.8 Effect of increase of initial substrate concentration (during the fill phase), and of the duration of the final starvation phase, on sludge settleability, expressed in terms of Sludge Volume Index (SVI).

Source: Irvine et al, 1997

Studies performed by Tano-Debrah et al. observed that oil-rich wastewaters are generally quite acidic, with pH around 4.2. Due to the high acidity of the wastewater, it might be necessary to adjust the pH prior to the inoculation to facilitate rapid growth. Experimental data suggest that with an adequate nutrient level in the wastewater effluent, the pH adjustment may not be a critical factor (Tano-Debrah, 1999). However, Tyagi noted that it is necessary to maintain a pH range between 6.5 and 8.0 in biological systems (Tyagi 1991).

It was observed that the strain SOD-1, which is capable of degrading salad oil, has a range of pH between 7 and 9 (Figure 2.9). The optimal pH for this microorganism was determined to be at a pH of 8. (Sugimori et al., 2002).

A study performed by Tano-Debrah isolated 15 different types of microorganisms that could degrade fats and oils. From this experiment it was observed that most of the microorganisms grew best at neutral pH, and few of them could live at pH below 5 and could grow well up to a pH of 9.2. The microbial inoculum, which was composed of 15 different microorganisms, had a better performance in the alkaline pH range (Figure 2.10). It was observed that during the experiment there was a change in the pH. This change had an increase in the pH for acid pH range and a decrease in the pH for the alkaline pH range (Figure 2.11), hence they self-regulate (Tano-Debrah et al., 1999).

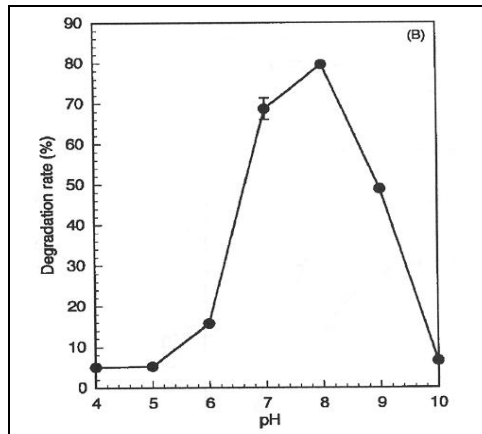


Figure 2.9 Effects of pH on Salad Oil Degradation By Strain SOD-1. The Cultures were Inoculated in the Basal Medium Containing 3000-ppm Salad Oil for 24 H with Shaking at 20°C.

Source: Sugimori et al., 2002

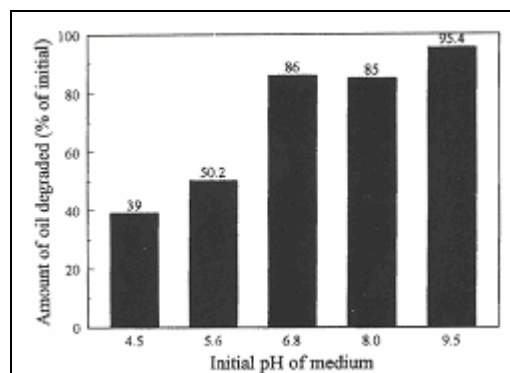


Figure 2.10 Effects of Initial Medium pH on the Degradation of Fats/Oil

Source: Tano-Debrah et al., 1999

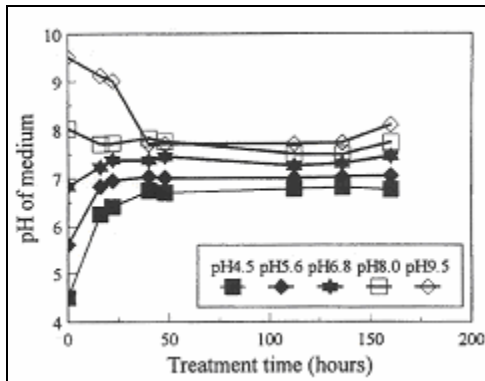


Figure 2.11 Changes in the pH of Media during Fat/Oil Biodegradation in Cultures with Different Initial pH

Source: Tano-Debrah et al., 1999

From the previous experiment it was observed that an initial adjustment in the pH can facilitate the growth of the microorganisms. It was observed that the microorganisms adjust the initial pH (Figure 2.11), and if an adequate level of nutrient is present in the wastewater, adjustment of the pH might not be a critical issue.

pH adjustment has been shown to enhance the performance of the biological treatment, and it is necessary to maintain a pH range for adequate treatment. For this reason it has been suggested to study the performance with and without pH adjustment and perform an economic analysis.

2.6.2. Temperature

Temperature is one of the most important environmental factors that can affect the growth and survival of microorganisms. The minimum and maximum temperature that a specific microorganism can tolerate varies greatly between microorganisms.

Temperature can affect the microbial growth of an organism in two ways. Initially, an increase of the temperature will result in the increase of the chemical and enzymatic reaction rate and therefore in a faster growth. If the increase of temperature passes a certain threshold (optimum temperature), the growth decreases until the microorganism can no longer grow or survive. This decrease happens because enzymes are damaged; this damage can be irreversible.

A comparative study performed by Tano-Debrah showed that the optimal degradation temperature for degrading salad oil with the JAT inoculum was between 20 to 25 °C. The removal efficiency obtained at this interval was 73% in a period of 48 hours. At a higher temperature of 30 °C the removal efficiency was 60%, at 42°C it was 35% and at 15°C the removal efficiency was 45%. (Tano-Debrah et al., 1999)

Similar results were obtained during a study performed by Sugimori. His study showed that the optimal temperature was approximately 35°C and a pH of 8. The efficiency obtained at this point by the strain SOD-1 was 83% for the initial 3000-ppm of salad oil in suspension in 24 hours (Figure 2.12). It was also observed that a further increase in the temperature would denaturalize the enzyme with the consequent decrease in the efficiency of the process.

The optimum growth temperature for *M. parvicella* in activated sludge has been reported to be below 12 to 15°C and sludge loading rates below 0.1 kg/kg-d. For temperatures above 20°C in activated sludge filamentous microorganisms do not multiply and fall apart (Knoop and Kunst, 1998).

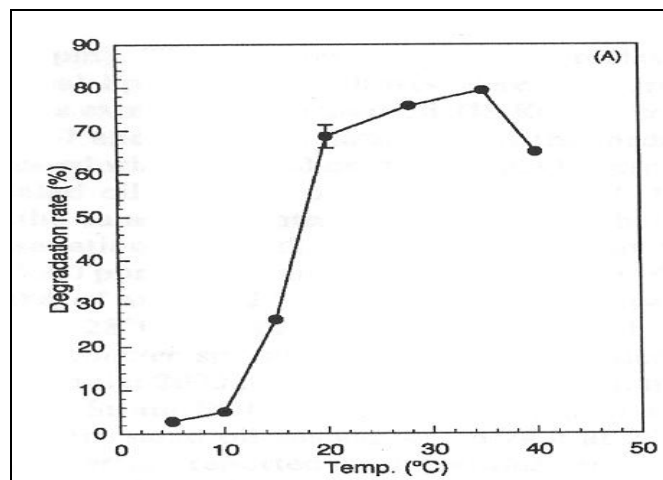


Figure 2.12 Temperature Effect on Salad Degradation by Strain SOD-1 for 24 Hours

Source: Sugimori et al., 2002

Seasonal temperature changes will affect the population of microorganism in the activated sludge. These changes will have an effect on the floc properties and consequently with the solids separation properties. The seasonal changes will create periods of transition. Therefore it is expected that there is going to be a population shift due to seasonal changes, with a possible change in the liquid-solids separation properties. The optimum growth temperature for *M. parvicella* in activated sludge has been reported to be below 12 to 15°C and sludge loading rates below 0.1 kg/kg-d. For temperatures above 20°C in activated sludge filamentous microorganisms do not multiply and fall apart (Knoop and Kunst, 1998).

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2.6.3. Retention Time

The study performed by Tano-Debrah (1999) showed that high concentrations of FOG in grease trap wastewater require longer retention times (See Figure 2.13).

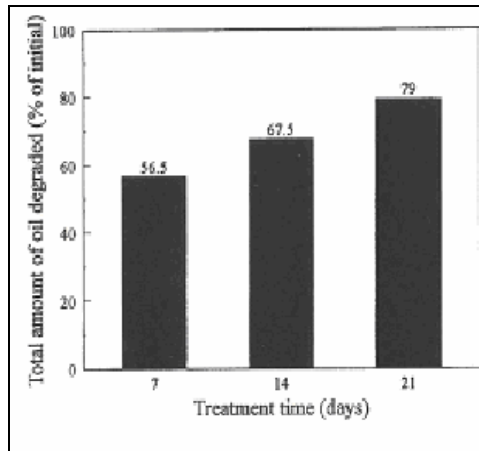


Figure 2.13 Effects of Treatment Time on the Amount of Fat/Oil Degraded. The Fat Extracted From the Grease-Trap Wastewater Samples was used, for a Grease Concentration of 20-g/ 100 ml of Fat.

Source: Tano-Debrah et al., 1999

The treatment time of grease trap wastewater can be reduced if the microorganisms in the activated sludge are acclimatized to the waste. The acclimatizing of the microorganisms would imply that the microorganism selected by the acclimatization process lipase producer had been selected. Studies performed by Wakelin and Forster have shown that an activated sludge that had been acclimatized to grease waste didn't exhibit a lag phase (Wakelin and Forster, 1996).

2.6.4. Phosphate Concentration

Sugimori analyzed the phosphate concentration (Sugimori et al., 2002). From this experiment it was possible to observe the influence of the phosphate concentration

(Figure 2.14 and 2.15). From Figure 2.14, it is possible to observe a decrease in the efficiency of the degradation rate, due to an increase of $(\text{NH}_4)_2\text{HPO}_4$. The reduction of the degradation rate can be related to the pH decline (data not shown). As mentioned before, a change in the pH will impact the degradation rate.

2.7. Biodegradation Using Different Types of Fat, Grease and Oils.

In a comparative biodegradation test performed by Tano-Debrah et al, the inoculum was used to determine the biodegradability of different fats and oils. All the samples analyzed presented some degree of biodegradation. The results of degradation showed that olive oil had the highest percentage of degradation, and that shea fat had the lowest percentage of degradation (Figure 2.16). The main reason for this difference is the chemical composition of these fats and oils, and because certain fatty acid esters exert antimicrobial activities against some bacteria. (Tano-Debrah et al 1999)

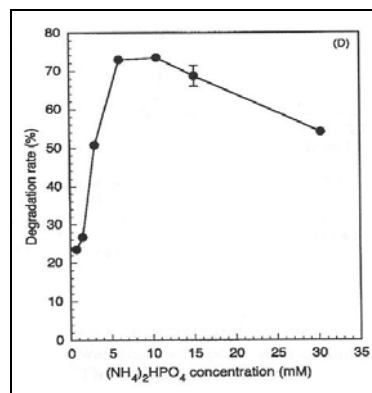


Figure 2.14 Effect under the presence of 2 g/l (11.5 mM) K_2HPO_4 and 1 g/l (8.33 mM)

NaH_2PO_4 on Salad oil degradation by Strain SOD-1.

Source: Sugimori et al., 2002

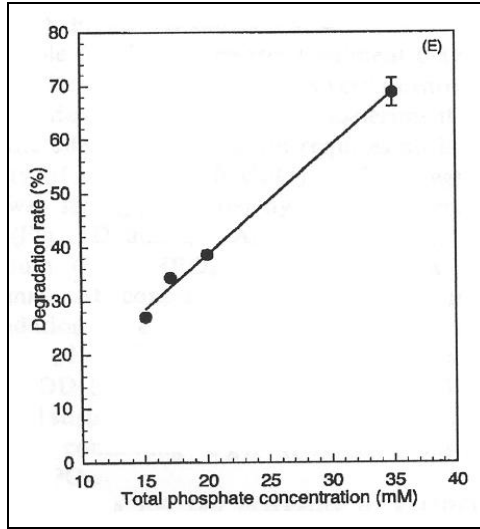


Figure 2.15 Effect under the change of K_2HPO_4 and NaH_2PO_4 to a ratio of 1:1.38 (NaH_2PO_4/ K_2HPO_4) at 15.1mM $(NH_4)_2HPO_4$ on Salad oil degradation by Strain SOD-1.

Source: Sugimori et al., 2002

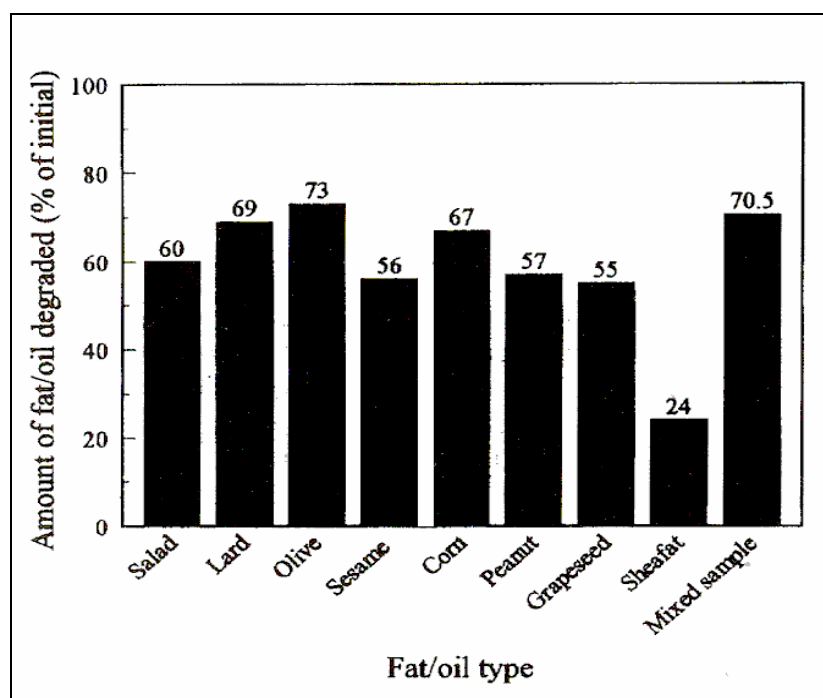


Figure 2.16 Degradation of different fats/oils using the JAT inoculum. Fat/oils was added to a basal medium ($\text{pH } 7.0 \pm 1$) at 10 % rate (w/v) prior to autoclaving. The inoculum (about $4.8 \cdot 10^8$ cell/ml) was added at 2% and the culture incubated with shaking at room temperature (about 30°C) for 7 days.

Source: Tano-Debrah et al., 1999

Wakelin and Forster performed a comparative study of pure cultures, using different types of fats, oils, and grease (Figure 2.17 and Table 2.2). From this figure and table, it is possible to observe that for filamentous organisms the removal rates were generally poor, ranging from 17.5% for *R. rubra* / olive oil to 38.1% for *G. amarae* / coconut oil. The exception was *M. parvicella*, which removed 83.8% of the fast food restaurant grease (FFRG). (Wakelin and Forster, 1997)

In addition to the last, Wakelin and Forster (1997) compared the performance between mixed cultures: MC1, AS and AAS on different FOG substrates (Figure 2.18 and Table 2.3). The experimental results obtained from Table 2.3 showed that activated sludge and acclimatized activated sludge had better efficiencies than the MC1. Acclimatized activated sludge showed a better performance and the general pattern of growth, but the removal of FOG was similar to un-acclimatized activated sludge.

The results for biodegradation of grease waste obtained in both experiments confirm that aerobic biodegradation can be used to degrade grease-trap waste. The composition of lard contains fatty acids that are commonly found in urban wastewater (Mendoza-Espinosa et al., 1996).

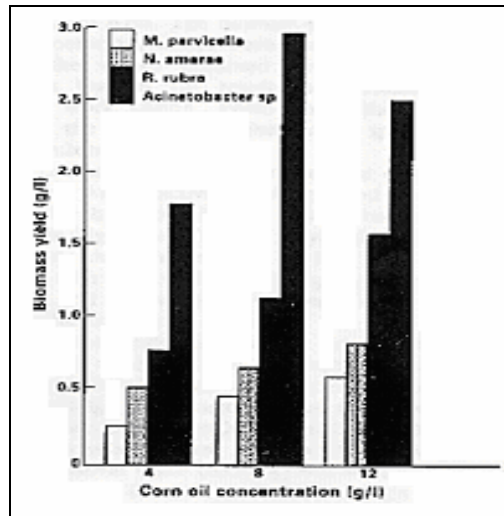


Figure 2.17 Comparison of the biomass yields produced with different FOG substrates

Source: Wakelin and Forster, 1997

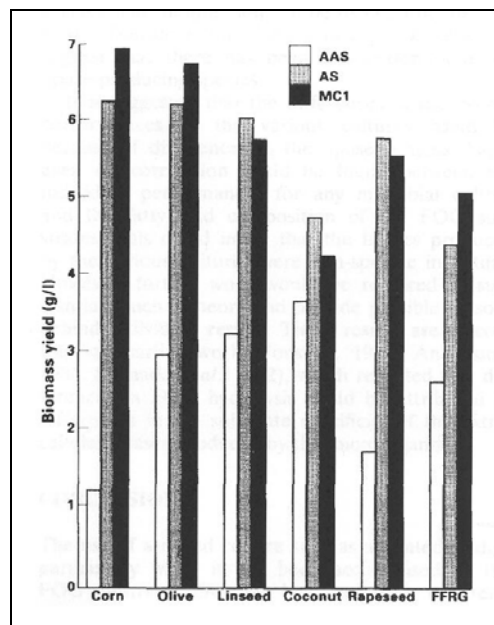


Figure 2.18 Comparison of the biomass yields produced by mixed cultures with different FOG substrates.

Source: Wakelin and Forster, 1997

Table 2.2 Comparison of the performances of pure cultures with different fat, oil and grease (FOG) substrates.

	FOG removal (%)				Yield coefficient (g/g)			
	Acinet.	G. am.	M. par.	R. rub.	Acinet.	N. am.	M. par.	R. rub.
Corn	63.8	35.0	26.9	24.4	0.6	0.23	0.19	0.52
Olive	50.9	19.4	25.5	17.5	0.61	0.58	0.28	0.96
Linseed	67.5	28.3	27.4	33.1	0.51	0.48	0.18	0.28
Coconut	60.6	38.1	25.0	31.3	0.67	0.46	0.15	0.45
Rape	64.4	37.5	28.8	23.8	0.67	0.52	0.22	0.62
FFRG	65.0	26.3	83.8	22.5	0.41	0.36	0.35	0.26

Source: Wakelin and Forster, 1997

Where:

Acinet: *Acinetobacter* sp.

N. am: *Gordona amarae* (Formerly known as *Nocardia amarae*)

M. par: *Microthrix parvicella*

R. rub: *Rhodococcus rubra*

Table 2.3 Comparison of the performance of mixed cultures with different FOG
substrates

	FOG removal (%)			Yield coefficient (g/g)		
	MC1	AS	AAS	MC1	AS	AAS
Corn	35.0	97.5	97.0	0.44	0.80	0.90
Olive	53.8	96.9	95.4	0.69	0.80	0.88
Linseed	66.3	97.9	98.5	0.61	0.77	0.73
Coconut	71.9	87.4	95.5	0.64	0.68	0.55
Rape	28.8	96.0	97.3	0.75	0.75	0.71
FFRG	72.5	98.0	95.6	0.47	0.57	0.66
Sunflower	58.8	97.5	99.6	0.69	0.78	0.86
Castor	48.8	65.4	52.4	0.58	0.69	0.51
Lard	61.8	95.8	93.6	0.39	0.57	0.64

Source: Wakelin and Forster, 1997

Where:

AS: Activated sludge

AAS: Acclimatized activated sludge

Other studies have shown that the degradation efficiencies of grease waste have reached up to 83.0% for salad oil (Sugimori et al., 2000), 50% for an oil (Bentham et al., 1997) and 92% with bio-additives for lard and 86% for activated sludge (Mendoza-Espinosa et al., 1996).

The results obtained by Wakelin and Forster (1997) for the *M. parvicella* in the degradation of FFRG suggest that this microorganism can have an important role in the degradation of grease-trap waste. The fact that *M. parvicella* generates filaments implies that a separation mechanism from the effluent has to be considered.

The removal efficiencies that have been reached in previous studies aren't high enough to comply with the existing final discharge standards, therefore the proposed treatment will be considered an intermediate treatment with post-treatment in a conventional treatment process.

Chapter 3

Material and Methods

3.1. Introduction

The experimental procedure utilized the operation of a Sequential Batch Reactor (SBR) to determine the operational characteristics and biological kinetics for the aerobic degradation of the grease waste. Additionally tests were performed using a dissolve air flotation unit (DAF) and column test for determining the liquid-solid separation properties.

The SBR configuration was selected because of the ability to vary control of the retention time of the process. The necessity for variable control of the aeration time of the treatment is due to the nature of the grease-trap waste. Biodegradation of grease-trap waste is known to require long treatment times therefore this configuration will permit the operation of the process to adapt to the necessary treatment length. Additionally, SBR is a self-contained unit, which permits a high degree of operational flexibility and easy control of the reactor.

The SBR operational conditions were set to promote filamentous organisms in the activated sludge process. Several studies have observed that filamentous organisms have the ability to uptake and to store oleic acid, long chain fatty acids in aerobic and

anaerobic conditions (Nielsen et al., 2002; Tandoi et al., 1998; Mamais et al., 1998). In pure culture studies it has been shown that *M. parvicella* utilizes long chain fatty acids as carbon and energy sources. The hydrophobic nature of the filament offers an advantage in the competition for water-insoluble fats and lipids. (Nielsen et al., 2002)

The objective of determining the liquid-solid separation properties are as result of the nature of the grease-trap waste and the promotion of filamentous organisms. Grease-trap wastes have a high component of FOG that has a lower density than water, tending to float. Filamentous microorganisms are known to hinder floc-settling properties. For the purpose of separating the biomass from the effluent it was proposed to use air flotation and compare it to gravity settling.

3.2. Methodology

The major factors that are critical for designing a treatment process are described in this section. An adequate design that is developed with an understanding of various design factors can tolerate changing conditions without exceeding process design objectives (WEF 1998).

To determine the design criteria for biological degradation of grease waste, it was necessary to determine the following factors; Dynamic Factors and Liquid Solid Separation.

Dynamic Factors; the determination of design criteria for designing a system that is capable of treating high concentrations of grease depends in part, on the understanding of the dynamics of the process. Therefore it is necessary to determine the equilibrium or steady state conditions for the process. Reaching the steady state is needed for the estimation of the biological kinetic parameters. There is a considerable variability in the literature concerning the determination of the kinetic parameters for growth and substrate removal in batch reactors (Stasinakis *et al.*, 2003). This study used an analysis and comparison of the most two common methods; Oxygen Uptake Rate (OUR) and Volatile Suspended Solids.

Liquid-Solid Separation; the biological treatment of wastewater generates sludges which have to undergo a liquid-solid separation process. Traditionally sedimentation has been employed, but because of the tendency of the waste to float and the presence of filamentous organism it was necessary to determine a mechanism for separating solid from liquid. Therefore the liquid solid separation solid flux and the flotation capacity of the sludge were determined.

3.3. Known Operational Parameters

pH: lab scale tests have shown that the optimal pH for degrading grease and oil is located in the alkaline range (Sugimori *et al*, 2002 & Tano-Debrah *et al*, 1999). The optimal pH is located in the range of 7 to 8.5.

- Nutrient: an inadequate level of C: N: P might produce viscous bulking.
- Dissolved Oxygen: Studies have shown that low DO promotes the growth of *M. Parvicella* (Jenkins *et al* 2003). It is considered that a low DO concentration corresponds to $< 2-1.5 \text{ mg O}_2/\text{l}$.
- Low F/M: Studies have shown that at $F/M \leq 0.1 \text{ kg BOD}_5/\text{kg MLSS d}$ *M. parvicella* was found. An increase on the ($F/M > 0.2 \text{ kg BOD}_5/\text{kg MLSS d}$) slowly decreases the specie concentration (Knoop & Knust, 1998).
- Low temperature: The optimum temperature for the growth of *M. parvicella* is between 12 to 15 C° (Knoop and Kunst, 1998)

3.4. Unknown Operational Parameters

To study the steady state properties of the biological treatment it is necessary to determine the biological kinetics. The maximum specific growth rate ($\hat{\mu}$), maximum

specific rate of substrate utilization ($\hat{q}$), true yield of cell synthesis (Y) and the concentration giving one-half the maximum rate (K) were determined.

3.5. Determination of the Potential Liquid/Solid Separation:

Determination of sludge settling properties: The objective was to identify the limiting solids handling capacity. This study employed a transparent column between 100 to 150 cm tall and 7 to 10 cm in diameter with stirring mechanism or mixing mechanism and measures the height and time of the interface. From this test it was possible to obtain the solids flux (AEEP 1988).

- Different predetermined concentrations of sludge are blended with supernatant liquid and thickened sludge.
- From a well-mixed sample, obtain an aliquot of sludge for suspended solids analysis.
- The height versus time of the interface was measured until the interface diminished considerably.

Determination of the flotation capacity of the sludge. The objective was to determine the potential of the biomass to be separated from the waste mixture. The study will employ a Dissolve Air Flotation unit (DAF), and the foam potential test and the dispersed solids.

Dispersed solids after air flotation: measurements from the clear supernatant were taken and suspended solids were measured. This information estimated the effluent biomass concentration.

Dissolve air flotation: the procedure used in obtaining the rate-of-separation data was to observe the solids-liquid interface and to record its movement with time. In the tests using dissolved-air flotation the rate of rise of the major portion of the solids was recorded. At times, the solids-liquid interface may be vague and good judgment had to be exercised in following this interface.

The objective of the research can be summarize on the following table (Table 3.1)

Table 3.1 Outline of Criteria Determination Approach

Criteria Determination	Question	Necessary Actions
Dynamic Factor	Understand the steady state or equilibrium condition.	Determination of the biological kinetics parameters. Tests: BOD ₅ , COD, Oil and Grease, Oxygen Uptake, pH, MLSS, T
Liquid Solid Separation	Determine the degree of separation of the biomass	Settling properties: Solid Flux, dissolve SVI (DSVI). Flotation Capacity: Dissolve air flotation, dispersed solid after air flotation, Foam high

3.6. Methods and Materials

The sampling and analytical procedure was based on Eckenfelder's approach (Eckenfelder 1995).

O₂ uptake rate (OUR): This test measures the uptake of oxygen by the biomass. This analysis was performed daily. The oxygen uptake rate was employed for determining the $\mu_{\max}$. The measurements were taken with YSI 52 dissolved oxygen meter and a YSI 5905 BOD probe. The method used corresponded to Standard Methods 2710 B Oxygen-Consumption Rate.

The determination of the maximum growth rate was determined by the procedure developed by Kappeler and Gujer (1992).

Comparison analysis was performed between previously mechanically shredded grease-trap wastes versus non-shredded sample. To determine if there was a significant improvement in the biological kinetics by mechanically reducing the particle size of the grease-waste, a comparative analysis was performed. The analysis performed consisted of running in parallel a bench scale reactor which the previous mechanically disaggregate grease-trap waste was and, a 1 m³ reactor in which the waste was not previously treated. The use of a bench scale reactor was to use a smaller volume of grease-trap waste that required mechanical desegregation. The statistical analysis that was performed consisted

of an exact style test. This test compared both the mean of the μ_{max} rate and determined if there was a significant difference between both samples.

Biochemical Oxygen Demand: The BOD was performed according to the Standard Method 5210 B. 5-Day BOD Test. The measurements were taken every 2 days.

Chemical Oxygen Demand: The COD was performed according to the Standard Method 5200 D Close Reflux, Colorimetric Method. The vials employed corresponded to HACH Digestion Solution for COD 0-1500 ppm. Range and analyzed by a Hilton Ray Spectronic 20D. The measurements were taken every 2 days.

Total Suspended Solids: The analyses were performed according to the Standard Methods 2450 D Total Suspended Solids Dried at 103-105°C. The measurements were taken daily.

Temperature: This parameter is basically a control parameter; these measurements were performed according to the Standard Methods 2550 Temperature.

Sludge volume indexes (SVI): The analyses were performed according to the Standard Methods 2710 D Sludge Volume Index. The SVI was measured at the following times: 0, 5, 10, 15, 30 and 60 minutes. With this information a SVI vs. Time curve were constructed.

Dissolved air flotation: This test was performed according to the Operation Manual for the Diffused Air - Dissolved Air Flotation Test Apparatus (DADAFTA) published by OFITE, Inc.

Oil and grease: The analysis was performed according to the EPA Method 1664 A: N-Hexane Extractable Material (HEM; Oil and Grease) and Silica Gel Treated N-Hexane Extractable Material (SGT-HEM; Non-polar Material) by Extraction and Gravimetry. The results from this test were used for determining the biological kinetics; estimate maximum specific rate of substrate utilization (q), true yield of cell synthesis (Y) and the concentration giving one-half the maximum rate (K). Fitting the Monod kinetic to a non-linear model using the statistical package JMP 6 was used for the determination of the biological kinetics. The samples were taken every two days.

3.7. Biological Reactor Design

The biological reactor configuration used corresponded to a batch reactor. This configuration was selected due to its flexibility for treatment and operation. The initial preliminary experimental and data collection part was performed with the use of a full-scale reactor. This reactor corresponds to an aeration tank located inside of the Kuwahee Waste Treatment Plant, located in Knoxville Tennessee. The dimensions of the reactor are 20 ft high, 20 ft wide and 30 ft long. Three lines of diffusers provide the aeration and the mixing.

The experimental phase was performed with the use of a medium scale reactor (1 m³) with mixing by a Lightning mixer and aerator (Model ND-1A) and a diffuser provided the aeration. This reactor was constructed by KUB from a 1m³ polymer tank with a top rig for installing the mixer and diffuser.

The use of a bench scale reactor (30 gallons) was employed for comparative analysis between disaggregated grease-trap wastes. A Maxima Hightorque Fisher Scientific and Dyna-Mix Fisher Scientific provided the mixing for the bench scale reactor. A diffuser provided the aeration for the bench scale reactor.

3.8. Samples and Schedule

The sampling schedule considered the seasonal shift that the microorganism community was expected to experience. The schedule was divided into three periods: cold weather, transition period between cold weather and warm weather, and warm weather. By dividing the intended schedule into three, the seasonal effect will be considered for the statistical determination and analysis of the operation parameters. The following tests were performed (Table 3.2 Frequency of Test):

Table 3.2 Frequency of Test

Parameter	Frequency	Operational Parameter
Oil and Grease	Every Two Days	Degradation rates and kinetics
pH	Daily	Degradation rates and kinetics
BOD	Every Two Days	Degradation rates and kinetics
COD	Every Two Days	Degradation rates and kinetics
O ₂ uptake rate	Daily	Degradation rates and kinetics
Total Suspended Solids	Every Two Days	Degradation rates and kinetics
Temperature	Daily	Degradation rates and kinetics
Sludge volume indexes	At the end of the process	Liquid solid separation
Solid Flux	At the end of the process	Liquid solid separation
Air Flotation	At the end of the process	Liquid solid separation

Chapter 4

Preliminary Experiment and Results

4.1. Introduction

The preliminary experimental phase is divided into two sections. The initial part consisted of the experiments performed using a full-scale reactor. The initial experimental phase showed that the biomass adapted to the grease-trap waste, but there were evidence of mixing problems. The second phase was performed in a medium scale reactor. The medium scale reactor was used for determining what type of mixing was necessary for assuring a complete contact between the biomass and the FOG, additionally the method for determining the biological kinetics was defined.

4.2. Large Scale Reactor

The initial experimental phase consisted of the use of a large-scale reactor. This reactor corresponds to an aeration tank located inside of the Kuwahee Waste Treatment Plant, located in Knoxville Tennessee. The dimensions of the reactor are 6.1 m high, 6.1m wide and 9.1m long and, a total volume of 340 m³ (Figure 4.1 and Figure 4.2). Three lines of diffusers provide the aeration and the mixing.



Figure 4.1 Full Scale Reactor

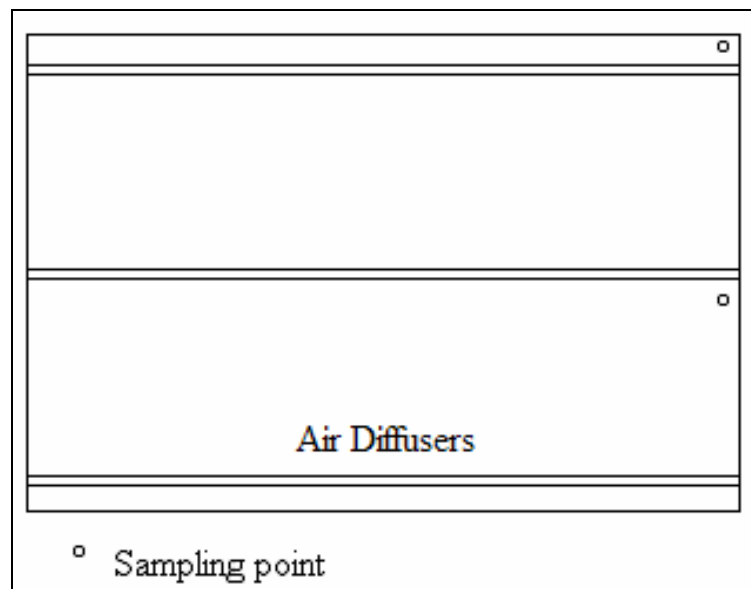


Figure 4.2 Diagram of Air Diffusers and Sampling points

The reactor operation consisted in the filling and operational phase. The reactor was filled with grease-trap waste (114 m³ approx.) by using trucks. After the initial substrate was introduced to the reactor, the biomass (activated sludge) was added. The amount of activated sludge that was used corresponded to 76 m³ with a concentration of approximately 3,000 mg/l.

The full scale reactor filling process took 3 days. The long period of time that was necessary for the filling of the reactor was caused by the grease-trap waste being frozen and it had to be removed by using pressured water (Figure 4.3).

4.2.1. Experimental Results

The full scale reactor was operated during the period of January 25 to March 11 of 2005. The initial experimental results showed that there was a mixing problem and additionally that biomass was acclimatization to the substrate. The mixing problem was observed in the oil and grease, BOD and suspended solids results. Additionally it was visually observed that there was a surface layer of grease-trap waste.



Figure 4.3 Grease Trap

The analysis that measured the substrate during the experimental phase corresponded to BOD₅ and oil and grease by solid phase extraction. These results were measured by the Knoxville Utility Board Water Quality Laboratory.

4.2.1.1 Mixing Problems

The initial results obtained for BOD, Oil and Grease and Suspended Solids showed a wide dispersion between analyses (Figures 4.4, 4.5 and 4.6). Additionally it was observed that there was a surface layer of scum that was not incorporated into the total volume of the reactor. The surface scum layer can be observed in Figure 4.1.

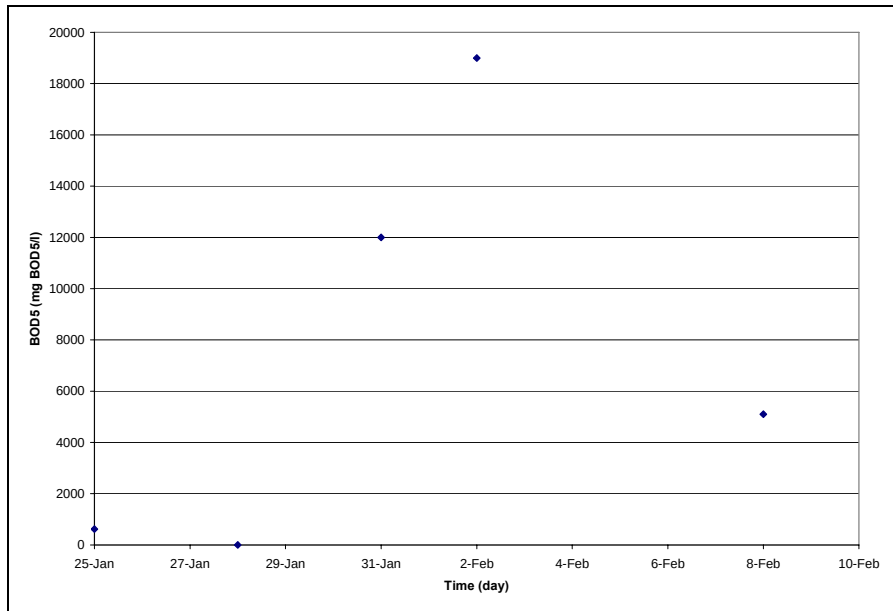


Figure 4.4 BOD₅ vs. Time

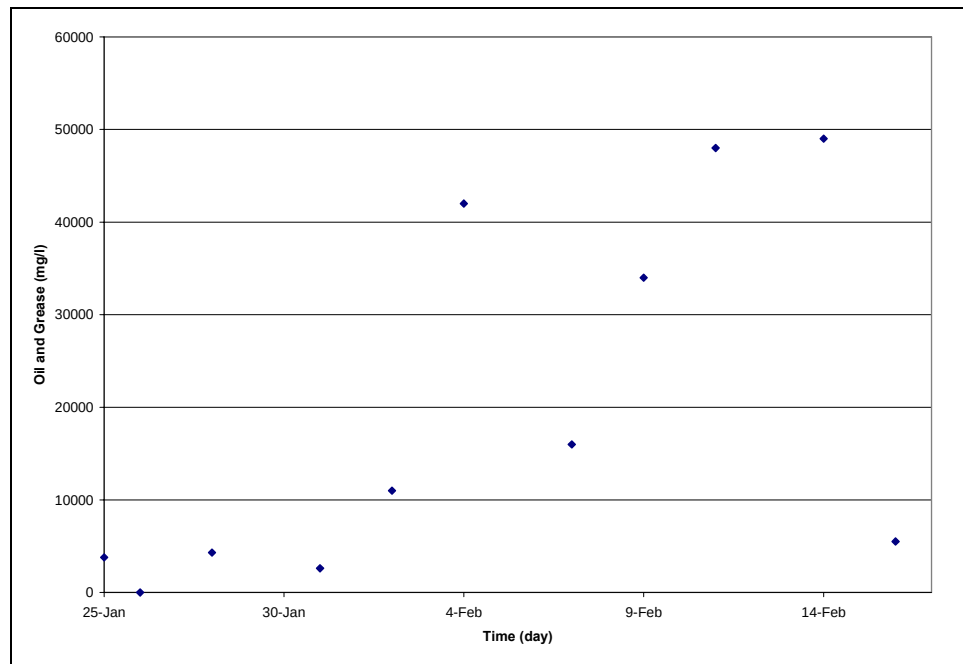


Figure 4.5 Oil & Grease vs. Time

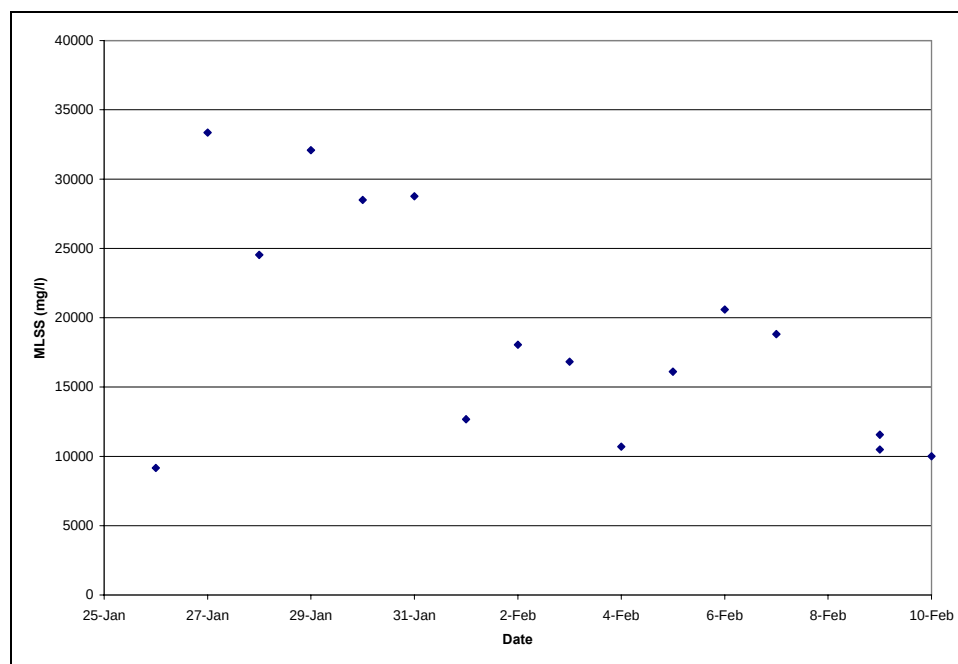


Figure 4.6 Suspended Solids vs. Time

The variability from the results for Oil and Grease can be explained due to difficulties of obtaining a representative sample of the waste. During the reactor operation it was observed that there was a surface layer of grease in the reactor (Figure 4.3). This grease layer was not possible to quantify and therefore produced problems for the measurements of Oil and Grease. This occurs since the grease and oil tend to float and, in addition, the bubbling from the diffusers help to lift the grease to the surface. This produced a complication in obtaining a representative sample of the mix liquor.

The surface layer of grease significantly affected the efficiency of the process, instead of having the whole volume of the reactor degrading the grease waste only the area that was in contact with the grease degraded the waste.

4.2.2. Reactors Performance

4.2.2.1 pH

During the experimental phase it was observed that the reactor pH tended to increase (Figure 4.7). The adjustment on the pH by the microbial population has been previously observed (Tano-Debrah et al., 1999) and pH adjustment does not appear necessary.

4.2.2.2 Liquid Solid Separation Properties

Solid liquid separation is usually the last stage of the treatment process. In this stage it is necessary to separate the biomass or the solids from the liquid phase. Depending on the degree of separation it is possible to determine the success of the process. The experiments performed to determine the efficiency of two different methods of separating the solids from the liquid are sedimentation and air flotation.

4.2.2.3 Sedimentation:

From Figures 4.8, 4.9, and 4.10 and Table 4.1 and 4.2, is possible to observe that the sedimentation properties of the sludge are hindered over time. The main reason of this reduction in the sedimentation properties of the sludge corresponds to the growth of filamentous bacteria. Comparing the results that were obtained for the SVI with the

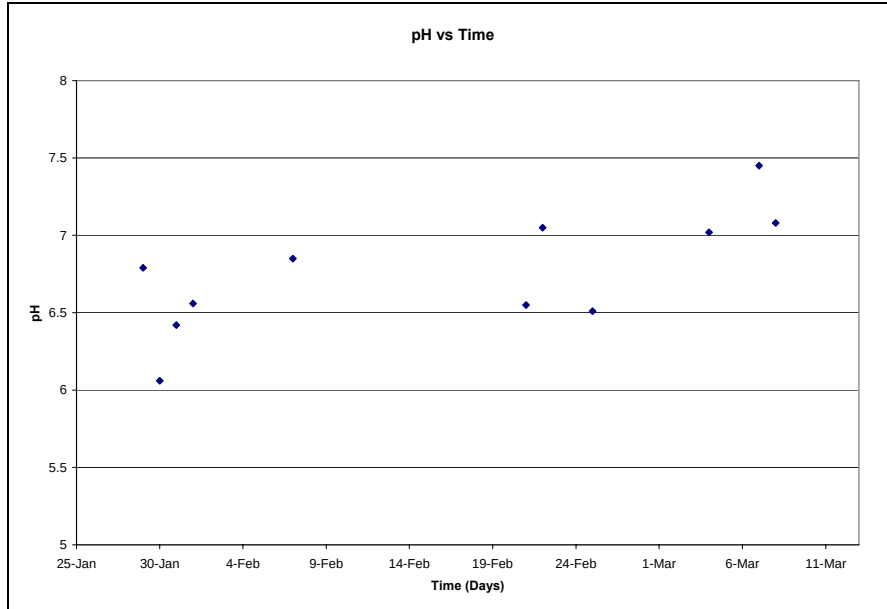


Figure 4.7 pH vs. Time

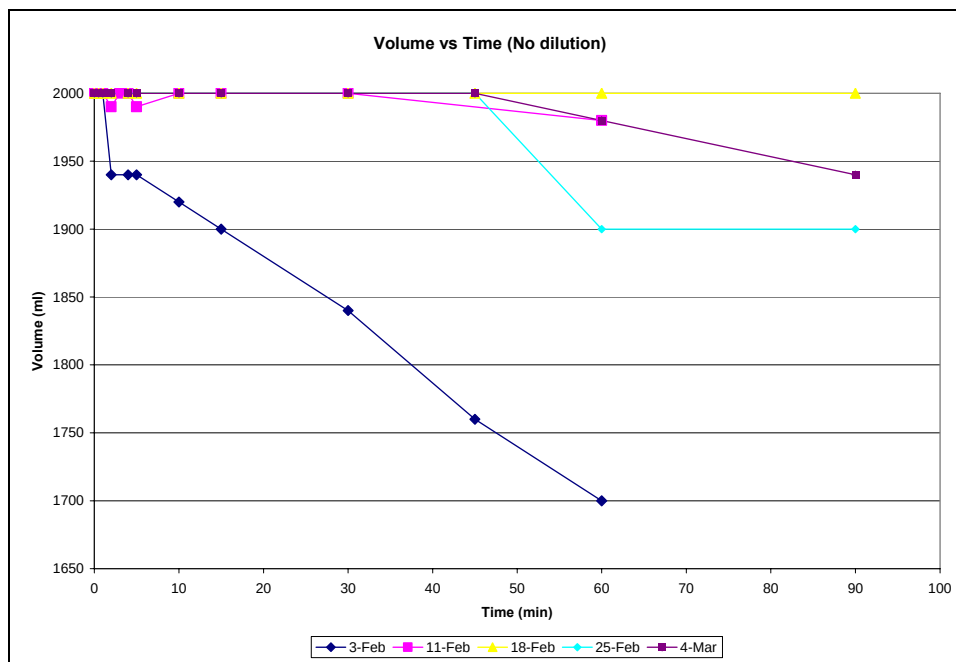


Figure 4.8 Volume Sediment vs. Time

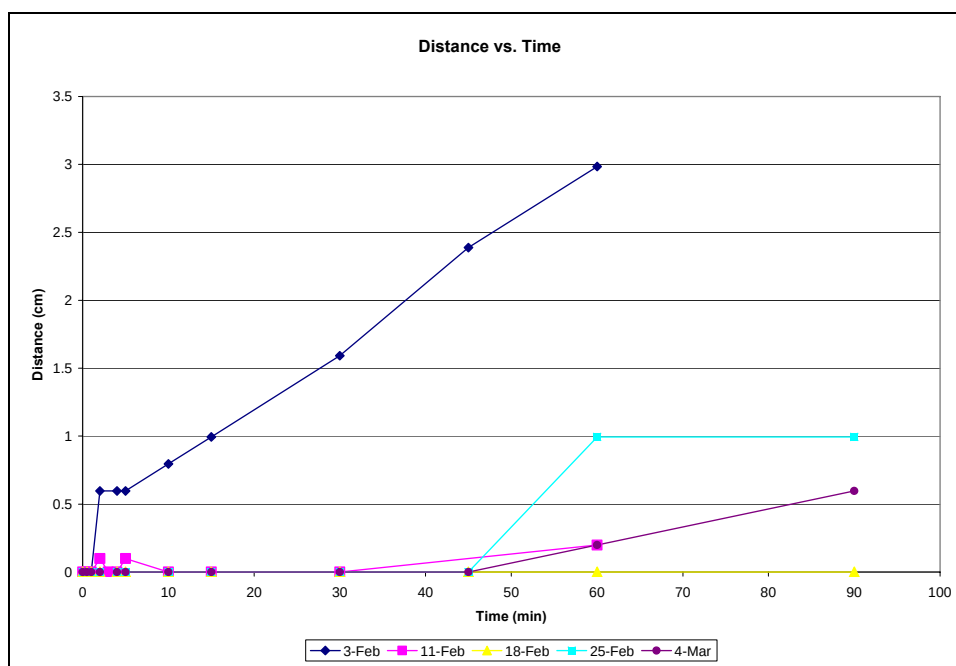


Figure 4.9 Cumulative Sediment Distances vs. Time

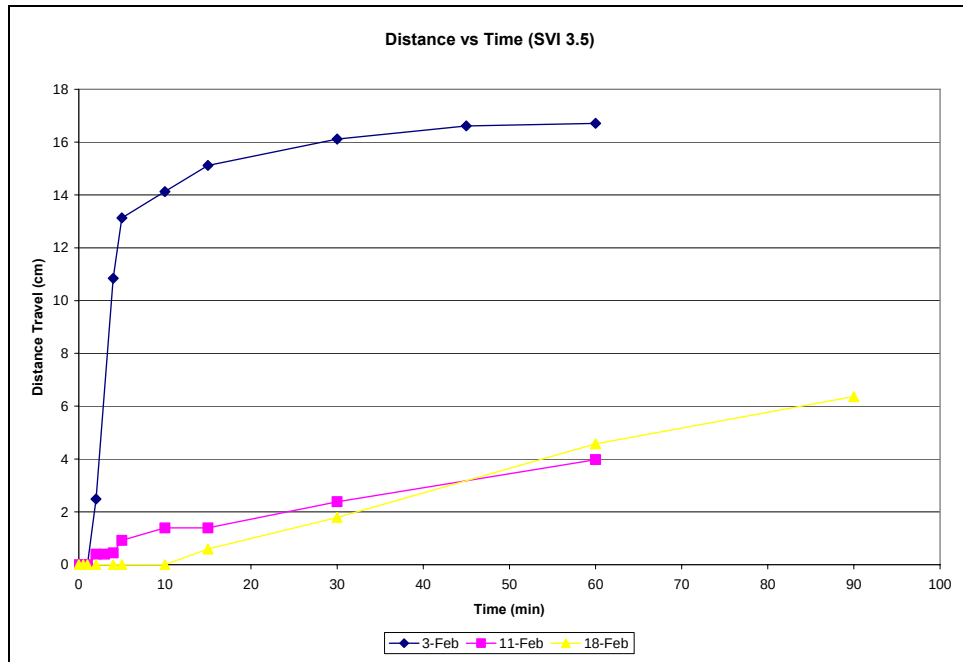


Figure 4.10 SVI_{3.5} Distances vs. Time

Table 4.1 SVI and SVI 3.5

Date	SVI	SVI 3.5
3-Feb	130	54
11-Feb	142	251
18-Feb	142	260
25-Feb	142	
4-Mar	142	

Table 4.2 Solid Flux Column Removal Efficiency Results

Date	Initial SS	Final SS	Removal
3-Feb	658	198	
3-Feb	980	301	
3-Feb	758	235	
Average	799	245	0.69
11-Feb	1135	890	
11-Feb	895	872	
11-Feb	808	889	
Average	946	884	0.07
18-Feb	7240	7100	
18-Feb	7230	7159	
18-Feb	7520	7231	
Average	7330	7163	0.02
25-Feb	7140	6890	
25-Feb	7140	6823	
25-Feb	6630	6875	
Average	6970	6863	0.02
4-Mar	6400	6377	0.00

correlations obtained by Palm et al (1980) and Sezgin, et al. (1980) it is possible to observe that the filament length for February 18 to March 4 between 10^6 and 10^7 $\mu\text{m}/\text{ml}$. These values were obtained by using Figures 2.4 and 2.5

The results obtained from $\text{SVI}_{3.5}$ analysis it is possible to observe a decrease in the sedimentation properties of the sludge.

The results obtained for the sedimentation properties during the experimental phase decrease during time. The decrease in the sedimentation properties can be associated with an increase of the filamentous length.

The analysis performed for determining the sedimentation properties corresponded to the solid flux column method. The following results were obtained:

4.2.3. Dissolve Air Flotation (DAF)

The objective of this experiment was to determine the best operation conditions for the dissolved air flotation system for separation of grease waste treatment effluent. The operation pressure, recycle rate, air to solid ratio and raise rate for the DAF unit were determined. The statistical model for predicting the performances for the DAF unit was developed by correlating the experimental results with the control variables of the process.

4.2.3.1 Experiment Analysis

Response variables:

- a. Y_1 : Total solid in supernatant, USS (mg/l) after the flotation is completed; a sample of waste treated was collected under the solid-water interface by using a 25 ml pipette.
- b. Y_2 : Percentage of Solid Recovery, %R. This corresponds to the following relationship: $\%R = C_k \times (C_0 - C_F) / C_0 \times (C_k - C_F) \times 100$

Where:

%R: Percentage of solid recovery

C_k : Total solid in the concentrated sludge (float, floating solid cake)

C_0 : Total solids in the raw sludge influent (sludge sample prior to using DAF)

C_F : Total solid in supernatant (Y_1)

- c. Y_3 : Air to solid ratio, A/S (mg/l). This corresponds to the following relationship: $A/S = 1.3 s_a \times (f \times P - 1) / S_a$

Where:

A/S: Air to solids ratio, mg/l

s_a : Air solubility (From Table)

f: Fraction of air dissolved at pressure P, usually $P = 0.5$

P: Equipment operation Pressure, atm.

S_a : Initial suspended solids, mg/l

- d. Y_4 : Rise Rate, GPM/ft². Corresponds to the average slope by adding the highest gain obtained between intervals and the lowest gain between lowest gain intervals, and then divided by 2. Converting the average slope to Rise Rate: $Y_4 = (\text{Average Slope} / 3725) / 0.06705 \text{ GPM/ft}^2$

Factors under Study:

- a. X_1 : Equipment operation pressure, psi (high 75-80, medium 60 and low 40 psi)
- b. X_2 : Recycle rate, amount of clarified liquid that is recycle into the equipment, in percentage (high 80, medium 50-60, low 20%)
- c. X_3 : Initial suspended solids, mg/l. The suspended solid corresponded to the concentration found in the reactor. Samples taken 3, 9 and 37 days since the beginning of the treatment of the grease waste (Jan 25, 2005)
- d. X_4 : Corresponded to if there was an adequate biomass separation from the liquid treated liquid ("0" yes and "1" no)

Background Variables

- a. Room temperature: The room temperature was set to 20 to 25°C. This was achieved by using the heating system that is in the room.
- b. PH: The pH of the sample was not altered; the pH of the reactor did not have considerable variation during the test.
- c. Dissolved oxygen of the sample: The dissolved oxygen of the sample was maintained by means of constant aeration before the analysis. The objective of this was to avoid anaerobic conditions.

4.2.3.2 Replication

The experiment consisted in a 3 by 3 factorial, therefore nine possible combinations where possible. The replication consisted in creating complete randomize blocks (blocking by day).

4.2.3.3 Method of Randomization

The randomization method consisted of creating an excel file with all nine possible combinations and assigning a random order to each combination in each run. The design matrix can be seen in Appendix Design Matrix.

4.2.3.4 Planned Method of Statistical Analysis

- a. A second order model for each of the response variables was fitted.
- b. Determination of the significant estimated parameters.
- c. Use of a contour profiler for determining the optimal pressure and recycle rate.

4.2.3.5 Statistical Analysis

The initial correlation between control variables and response variables indicated that the total solids in the supernatant (Y_1) had a variance that was proportional to μ^2 , therefore it was decided to transform the variable as $\text{Log}(Y_1)$ to obtain a linear model.

The experimental analysis consisted of initially performing a linear fit to determine the variables of influence for the linear model for each response variable (Using an $\alpha = 0.05$). The initial linear fit was performed using JMP 6.0 and the linear fit results can be seen in Appendix Initial Linear Fit.

From the previous analysis it is possible to observe that the effluent suspended solid concentration (Y_1) will depend on the recycling rate (X_2) and the initial suspended solids concentration and their interaction. The initial suspended solids concentration is hard to control, therefore the effluent quality will depend mainly from the recycling rate. The same analysis was performed for the other response variables: The percentage of solid recovery (Y_2) depends on X_2 , X_1X_2 , X_2X_2 , X_2X_3 and X_3X_3 . The air to solid ratio (Y_3) depends on X_1 , X_2 , X_1X_2 , X_1X_3 and X_2X_3 . The rise rate (Y_4) depends mainly on X_1 and X_2 .

The terms that are not significant for any of the responses are: X_1X_1 , X_4 and X_3 . The parameter X_3 was added to conserve the hierarchy in the model.

It was observed from the experimental data that the effluent suspended solids (Y_1), cannot reach levels that comply with the final discharge standards (30 mg/l). The final effluent quality was expected to not comply with the standards and the system was expected to be a pretreatment before treating the effluent in a conventional activated sludge plant. For these reason the effluent quality was set at a maximum of 300 mg/l (5.7 in Ln scale)

The percentage of Solid Recovery (Y_2) should be maximizes to at least 99%. In other words that 99 percent of the solids should be removed.

The air to solid ratio (Y_3) should be minimized. The objective of minimizing was to reduce the amount of air used; in this way it is possible to minimize cost.

The rise velocity of the solid – air mixture (Y_4) vary from 1 to 5 in per min. converting this range into GPM/ft², the target range will be set between 0.623 to 3.11 GPM/ft².

In this experimental phase, it was observed that for the condition of 40 psi and 20 % recycle rate there was not an adequate separation ($X_4 = 1$). Therefore this condition should be avoided and this parameter should be included in the analysis.

Using JMP 6.0 a contour profiler plot was constructed to showing graphically the areas where the previous operational conditions occur (Figure 4.11). The white area in Figure

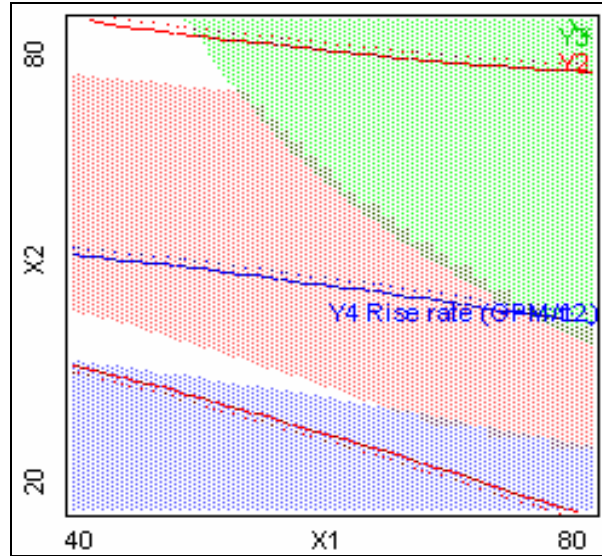


Figure 4.11 Operational Areas for DAF

4.10 represents the region where all the operational conditions are satisfied. The colored areas correspond to a condition that doesn't comply with the boundary conditions.

From the analysis it was observed that there are two regions where the operational conditions are satisfied. The first area corresponded to low pressure (40-60 psi) and medium recycling rate (40%). The second area corresponds to low pressures (45-50) psi and high recycling rate (80%).

4.2.3.6 Conclusions

The results from this analysis reveal two possible areas for complying with the optimization of the DAF unit. The area that defines the region of low pressure and

medium recycling percentage corresponds to the best solution. This area was selected as the best solution because lower operational pressures result in smaller volumes to compress, which leads to a savings of energy. The other area uses a higher recycling volume that would require more energy for compressing the air and that would increase the operational cost and the construction cost for the DAF unit.

For future experimentation it was decided that the optimal pressure was between 40 and 60 psi. This was used in the future experimental design, which concentrated the experimental zone in this area. This increased the precision of the analysis.

4.2.4. Microscope Population Observation

During the preliminary experimental phase the variation of the population of the microorganism was determined using an electronic microscope and the following pictures were taken for the days: January 26, February 16 and 23 (Figure 4.12, 4.13 and, 4.14). For this period of time it was observed that there was an increase in the number of filamentous organisms, which was consistent with the sedimentation properties.

4.2.5. Conclusions

The results for the initial preliminary experimental phase showed an inadequate mixing, which led to non-homogenous samples and a poor substrate contact with the biomass,

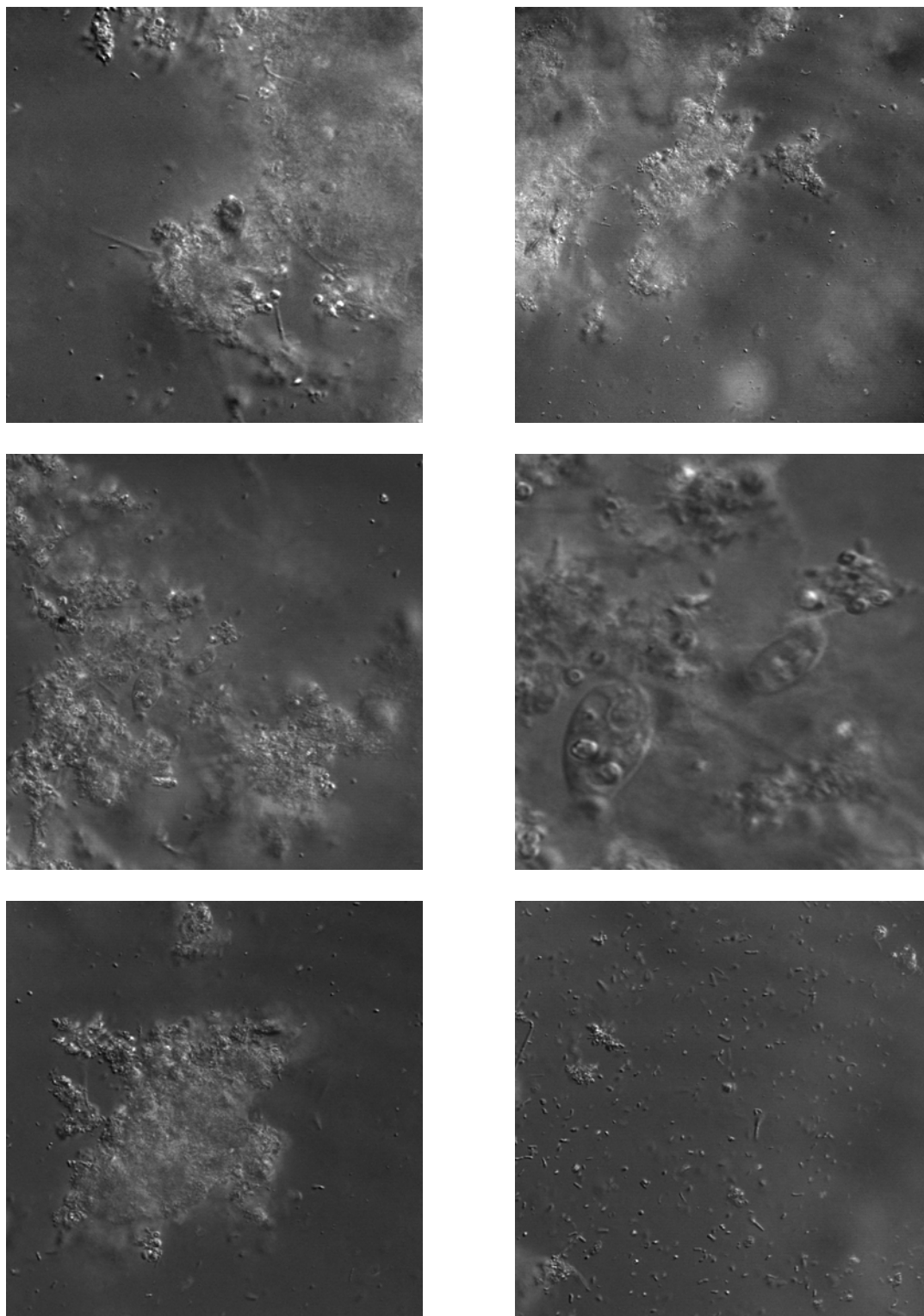


Figure 4.12 Day Jan 26 2005

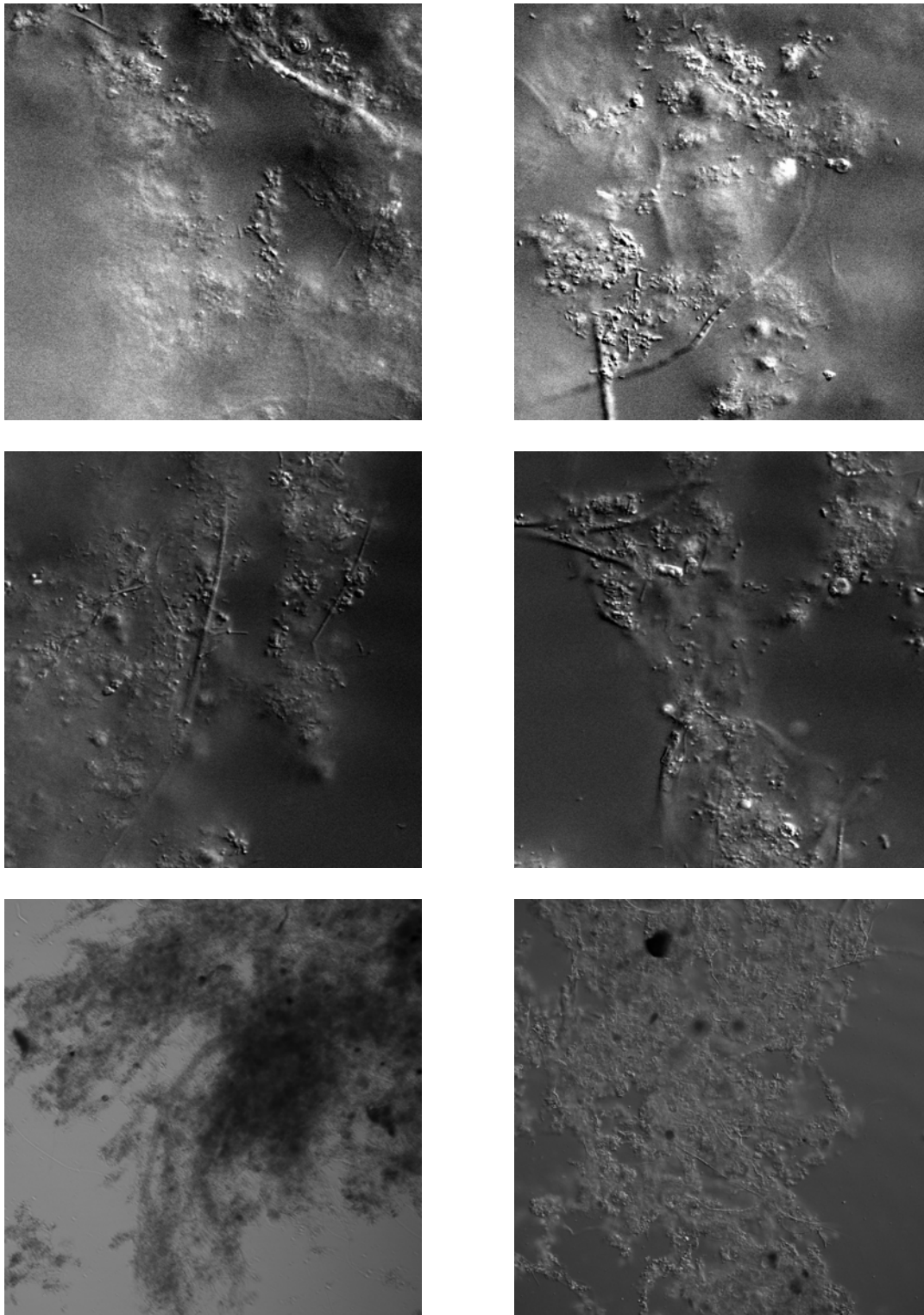


Figure 4.13 Feb 16 2005

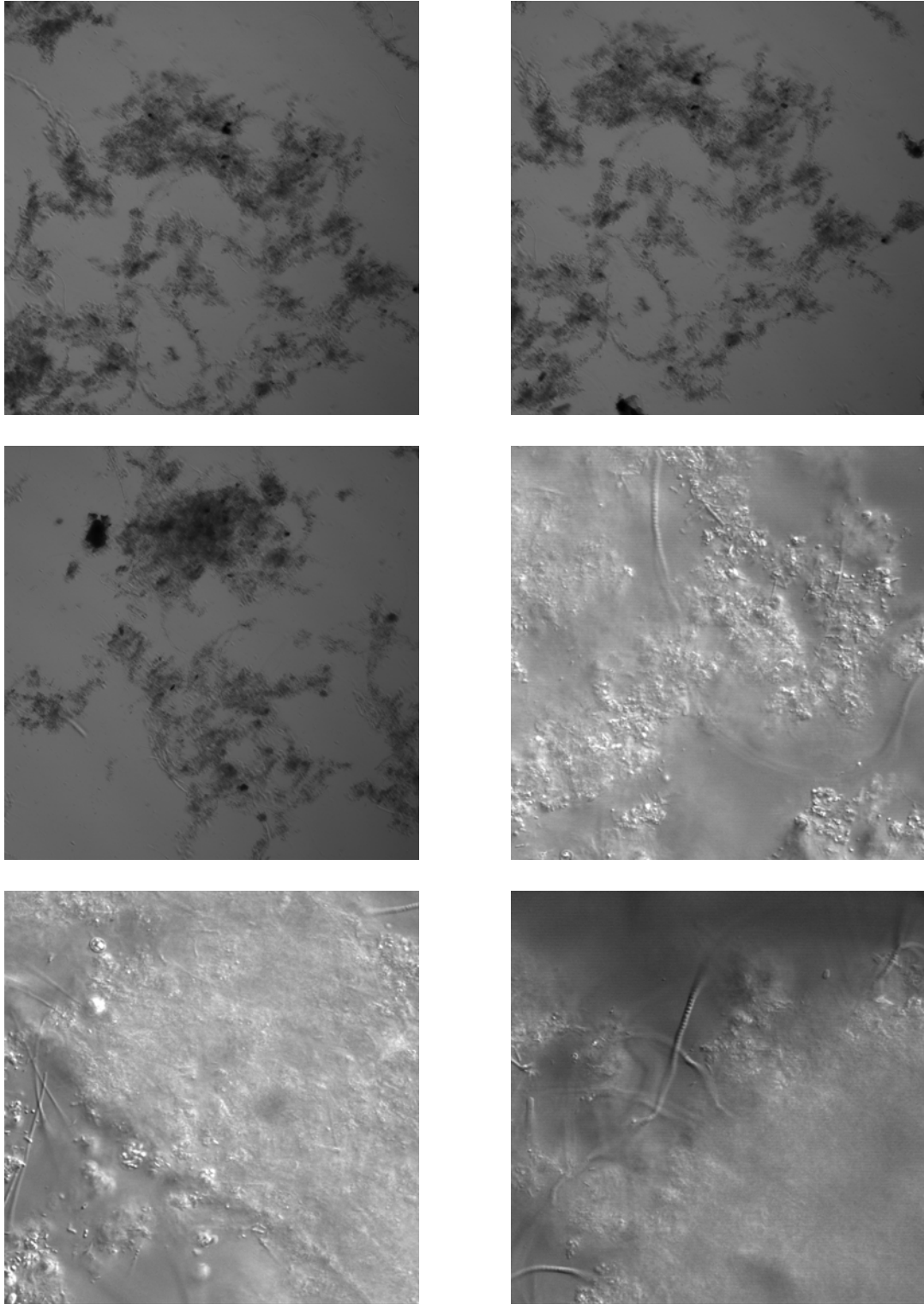


Figure 4.14 Feb 23 2005

slowing the process. Additionally a decrease in the sedimentation properties was observed that was caused by an increase in the filamentous organisms of the population.

During the experimental phase it was observed that biomass acclimatized to the substrate. This adaptation was observed in the increase of the OUR. Additionally it was observed that the initial low pH of the waste did not have a negative impact on the process, which changed during the process to a neutral pH.

4.3. Medium Scale Reactor (1m³)

The second phase of the preliminary experimental stage was conducted in a medium scale reactor. The reactor had a volume of one cubic meter, with an upper rigged structure that permitted the support of mixing equipment and the aeration system (Figure 4.15). The aeration system consisted of a shaft with a diffuser system located at the end, which was connected to a compressor by an air line. The degree of aeration was controlled by the use of a valve. Two mixers provided the mixing for the 1m³ reactor.

The reactor is located at Kuwahee Waste Treatment Plant, inside the DAF unit building. The reactor was constructed by the KUB from a 1m³ polymer tank and a upper rigging structure was installed for supporting the mixing motors and aeration system.



Figure 4.15 Reactor and Detail of Air System and Mixer

4.3.1. Verification of Degree of Mixing

The initial experimental phase had problems with non-representative samples due to incomplete mixing. It was necessary to initially verify if there was an adequate degree of mixing in the medium scale reactor. The suspended solids of the surface water layer were compared to the suspended solid concentration at a depth of approximately 40 cm.

The experimental procedure consisted of feeding the reactor with grease waste and then turning both mixing units on. A time lag of 10 minutes was permitted for ensuring an adequate mixing between the grease waste and the activated sludge.

After the time lag, six grab samples were collected. These samples were divided between 3 surface samples and 3 depth samples, and each sample was divided into 3 replicates. The order in which the samples were taken was random. For each grab samples, total suspended solids were determined.

4.3.1.1 Analysis

The following analysis was performed to determine if there was complete mixing, One-way analysis between the suspended solids of the depth. The purpose of this analysis was to determine if there was a significant difference between the suspended solids of surface layer and the solids taken at 40 cm (Table 4.3).

Comparisons for each pair using Student's t (Figure 4.16); the test statistic corresponds to $t_0 = -2.11991$ and the t statistic for an $\alpha = 0.05$ corresponds to $-t_{0.025, 18} = -2.101$. Because $t_0 > -t_{0.025, 18}$, we can conclude that the mean of the suspended solids are not different and that the reactor has an adequate mixing. Additionally a power analysis was performed to the database (Appendix Power Analysis).

4.3.2. Operation of the Reactor

The reactor was run as continues batch reactor. The loading phase was performed according to the experimental procedure (Chapter 3). The volume of grease trap waste

Table 4.3 Determination of the Degree of Mixing

Depth	Sample	Replicate	Suspended Solids
0	1	1	13360
0	1	2	17420
0	1	3	19750
0	2	1	15590
0	2	2	11790
0	2	3	13650
0	3	1	12940
0	3	2	13120
0	3	3	12870
1	1	1	15170
1	1	2	15680
1	1	3	13060
1	2	1	13640
1	2	2	13570
1	2	3	11970
1	3	1	12430
1	3	2	11610
1	3	3	13440

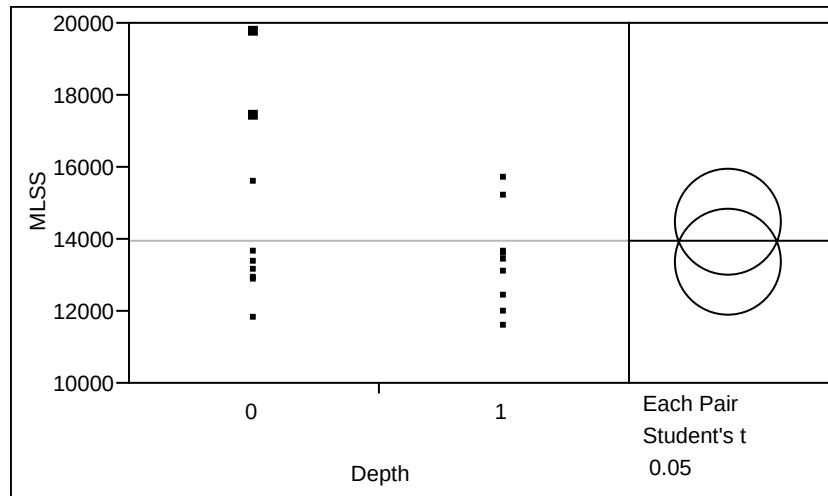


Figure 4.16 One-way Analysis of Total Suspended Solids by Depth

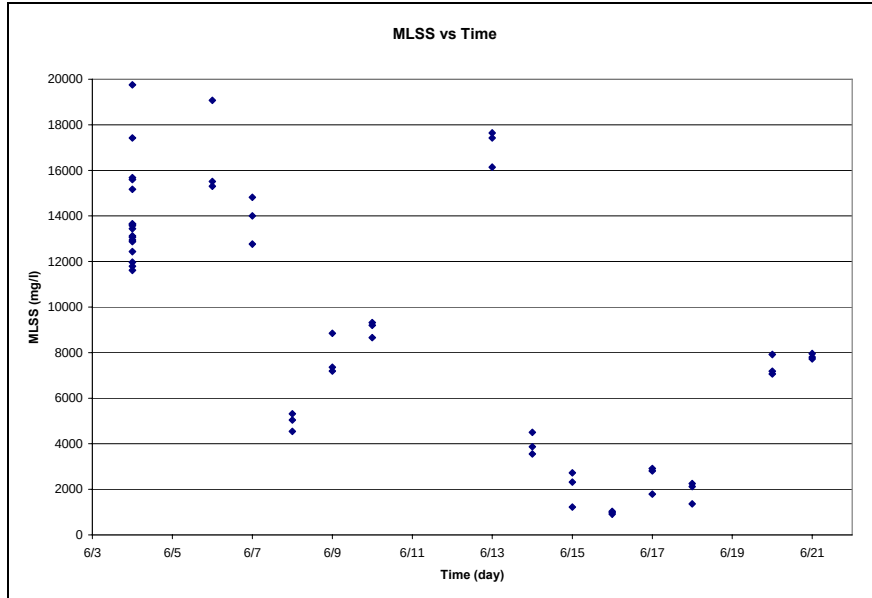


Figure 4.17 Initial Sampling Variations 6/4-6/21

that was loaded to the reactor was approximately 40 to 50 liters. Each batch of grease trap waste was run between 1 and 2 weeks.

4.3.2.1 MLSS results

The initial samples had a high variation between the data (Figure 4.17). This variation can be explained due to the high volume of solids of the samples. The high amount of solids tended to clog quickly (5 ml or less) the filters that were use (47 mm). This problem was solved by increasing the size of the filter (142 mm) and pressure filtration was used instead of vacuum filtration.

Analysis of Variance for the MLSS during 6/28 – 7/21

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4584407	4584407	10.9580
Error	50	20918026	418361	Prob > F
C. Total	51	25502433		0.0017

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t	Lower 95%	Upper 95%
Intercept	7899.7592	176.6319	44.72	<.0001	7544.9836	8254.5348
Date	34.238588	10.34307	3.31	0.0017	13.463914	55.013261

The analysis indicated that there was an increase in the Total Suspended Solids (Figure 4.18). But this increase it is on the order of less than 1%, which does not have a major impact on the process.

Analysis of Variance for the MLSS during 8/2 – 8/8

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4247102	4247102	8.3081
Error	19	9712854	511203	Prob > F
C. Total	20	13959956		0.0095

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t	Lower 95%	Upper 95%
Intercept	4545.3333	348.8767	13.03	<.0001	3815.126	5275.5407
Date	224.85714	78.01121	2.88	0.0095	61.577813	388.13647

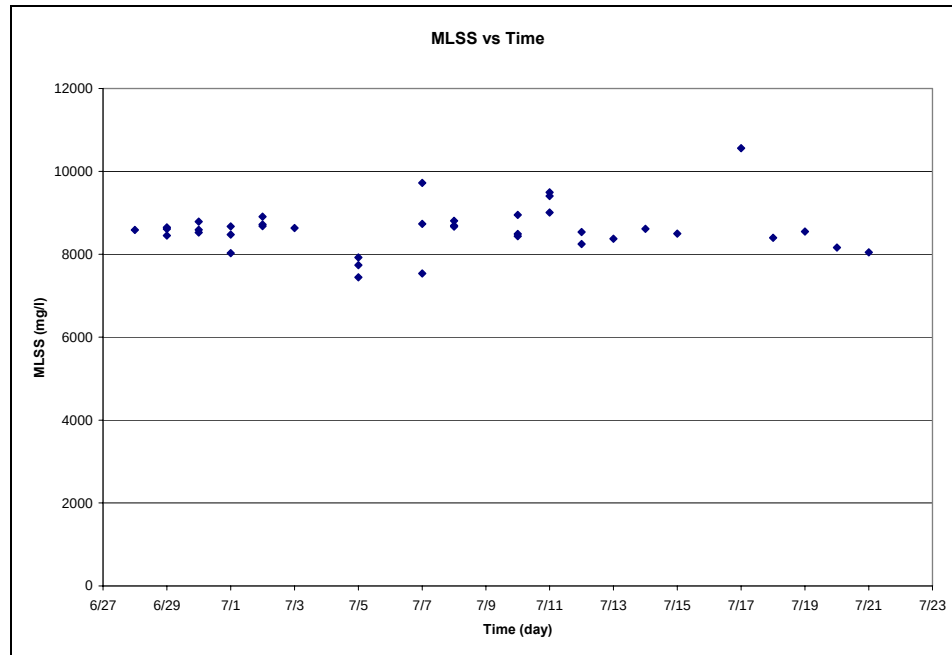


Figure 4.18 Total Suspended Solids vs. Time 6/28 – 7/21

The analysis indicated that there was an increase on the Total Suspended Solids for the period of time 8/2 – 8/8 (Figure 4.19). The increased observed corresponds to 5%.

Analysis of Variance for the MLSS during 8/16 – 8/21

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4718188	4718188	4.3935
Error	12	12886759	1073897	Prob > F
C. Total	13	17604947		0.0579

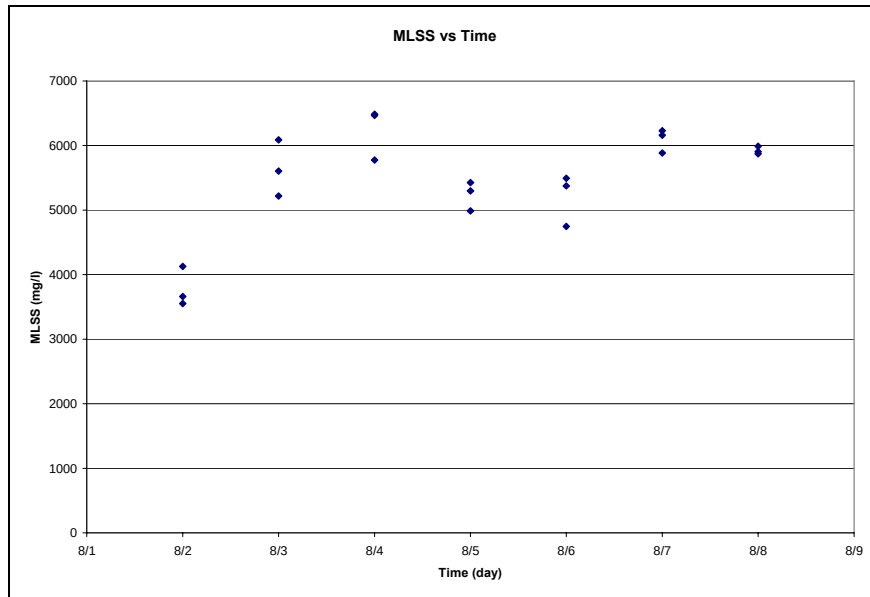


Figure 4.19 MLSS vs. Time 8/2 – 8/8

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t	Lower 95%	Upper 95%
Intercept	5053.0798	583.4352	8.66	<.0001	3781.8836	6324.2759
Date	367.53374	175.344	2.10	0.0579	-14.50794	749.57542

From the experimental result it was possible to observe that there was a no significant increase on the TSS concentration (Figure 4.20).

The experimental results showed that there was no important increase on the Total Suspended solids on the reactor. In a couple of cases it was observed that the statistics indicated an increase, but these increases were small relative to the Total Suspended Solids and won't have an impact in the process or calculations

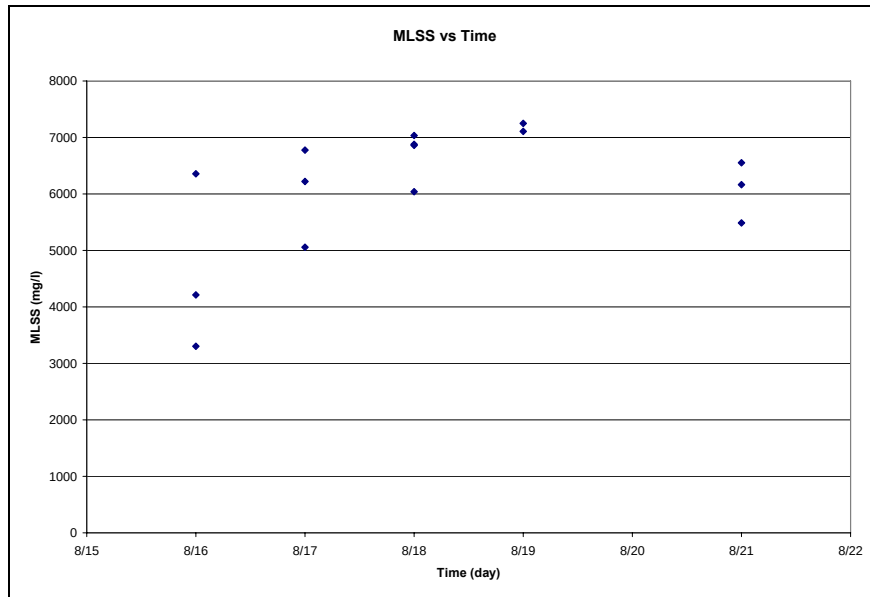


Figure 4.20 MLSS vs. Time 8/16 – 8/21

4.3.2.2 COD

The Chemical Oxygen Demand was performed according to the Standard Method. The following results were obtained during the experimental phase (Figure 4.21, 4.22 and, 4.23):

It was possible to observe an initial increase on the Total COD (Figures 4.21, 4.22 and 4.23). Additionally this increase was observed on the Filtered COD. The Total COD should not change significantly during time. This is because the total COD measures microorganism as well as substrate.

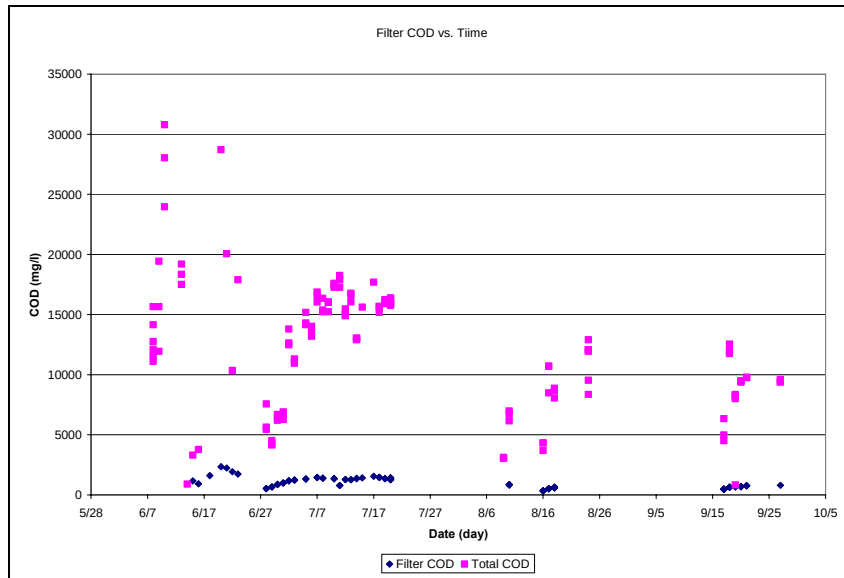


Figure 4.21 Total and Filter COD vs. Time 6/7-9/21

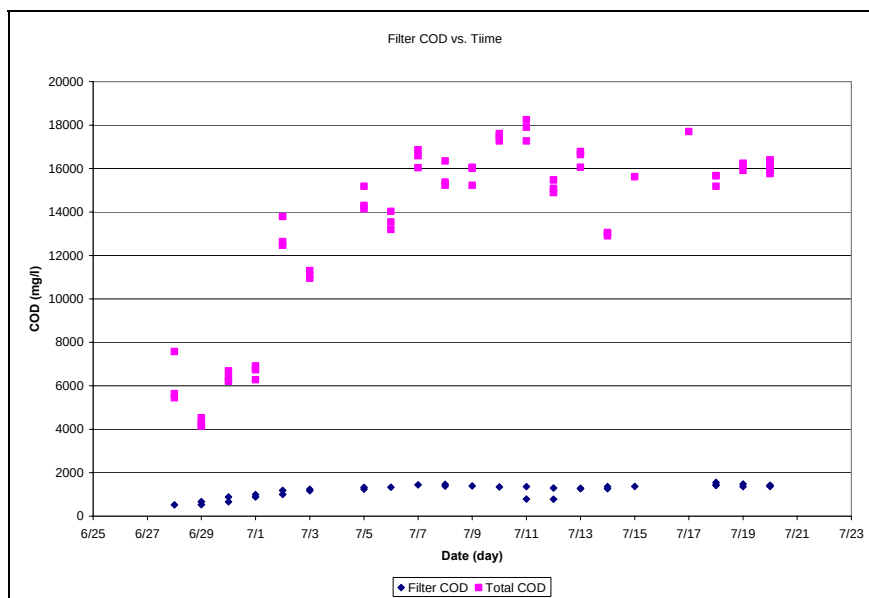


Figure 4. 22 Total and Filter COD vs. Time 6/28 – 7/20

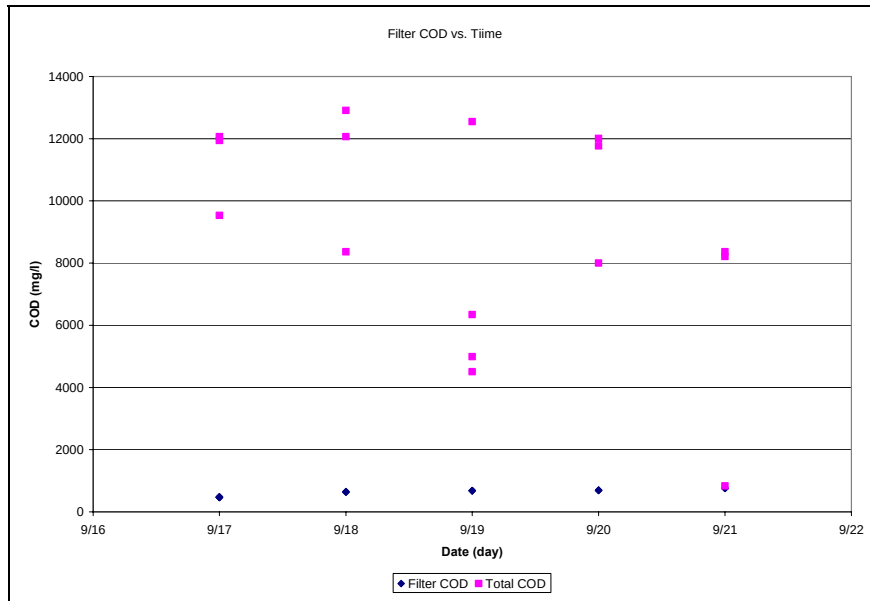


Figure 4. 23 Total and Filter COD vs. Time 9/17-9/21

4.3.2.3 Oil and Grease

The Oil and Grease measurements were performed according to the Hexane Extraction Method. The following results were obtained during the experimental phase:

From Table 4.4 and, Figure 4.24 it was possible to have an estimation of the total mass of grease that was at the beginning of the experiment, which was estimated to be 18.9 kg. The reactor was fed approximately 40 liters of Grease Trap Waste.

The experimental results show that the oil and grease content was significantly reduced the first 5 days. The grease waste was reduced approximately 86%.

Table 4.4 Oil and Grease Estimation

Date	Oil and Grease (g/l)
8/1	21
8/3	13
8/5	3
8/8	4
8/10	5

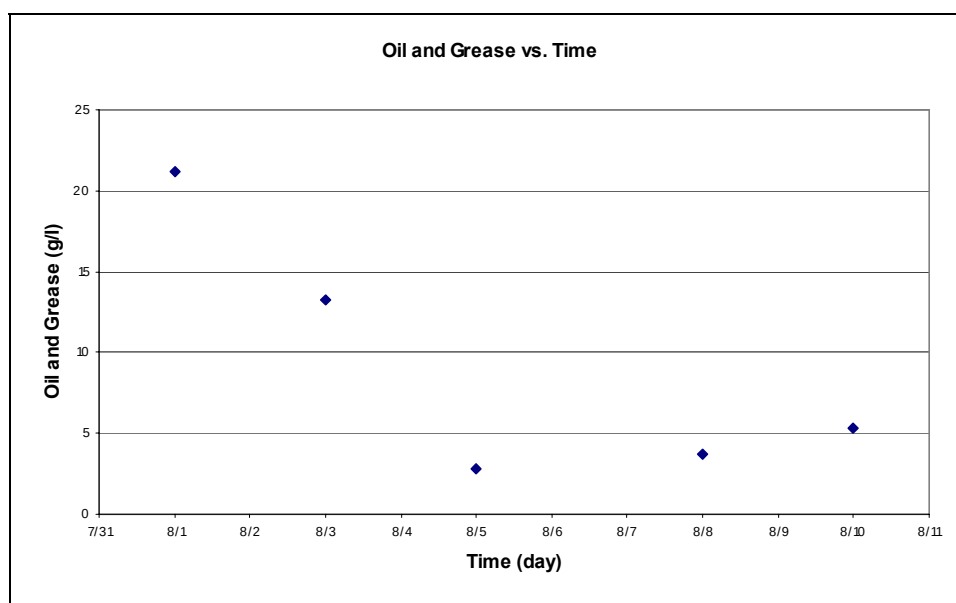


Figure 4.24 Oil and Grease COD vs. Time

Transformed Fit Log

$$\text{Log (O\&G (mg/l))} = 3.1481878 - 0.2646102 \text{ Day}$$

Summary of Fit

RSquare	0.721187
RSquare Adj	0.58178
Root Mean Square Error	0.601709
Mean of Response	2.023595
Observations (or Sum Wgts)	4

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1.8729957	1.87300	5.1733
Error	2	0.7241068	0.36205	Prob > F
C. Total	3	2.5971025		0.1508

From the previous analysis it was possible to observe that the reactor had an exponential behavior. From the previous analysis it was possible to estimate the μ_m .

$$(\mu_m - b_H) = 0.265 \text{ day}^{-1}$$

4.3.2.4 Oxygen Uptake Rate Results

The results obtained for the OUR indicated an initial increase in the first 4 days and then the OUR decreased or leveled during the rest of the experimental phase (Figure 4.25).

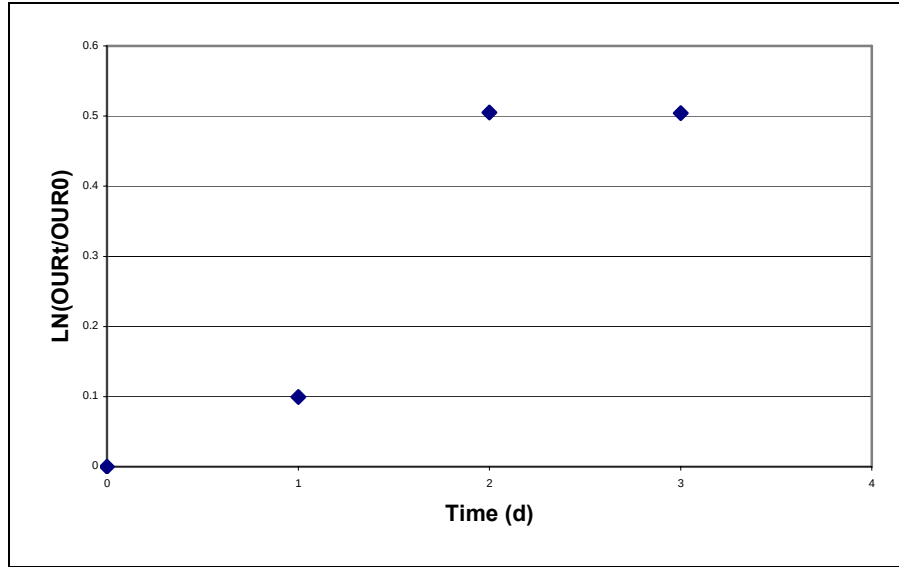


Figure 4.25 Determination of the Specific Growth Rate

The μ_m was estimated using the first 4 days, where the most of the degradation occurs (Figure 4.25). The results obtained correspond:

$$(\mu_m - b_H) = 0.1873 \text{ day}^{-1}$$

4.3.3. Comparison μ_m between Oil and Grease and OUR

Comparing the results obtained between the two methods, it was observed that both were in the same range (Table 4.5). When the values obtained for the experiment are compared with other experiments, it was observed that these are much smaller than in the literature review (Table 4.6). The main differences with these results are that in the previous research the grease-waste was readily available, which is not the case for this experiment.

Table 4.5 Comparison of $\mu_{\max}$

Method	μ_m (day ⁻¹)	μ_m (h ⁻¹)
Oil and Grease	0.2646	0.0110
OUR	0.1873	0.0078

Table 4.6 Literature results for $\mu_{\max}$

Author	Microorganism	Substrate	μ_m (h ⁻¹)
Lefbvre et al	Acclimatize activated sludge	Saponified Grease	0.36
Keenan and Sabelnikov	Rhodococcus	Waste oil	0.6
Keenan and Sabelnikov	Caseobacter	Waste oil	0.6
Keenan and Sabelnikov	Acinetobacter sp	Waste oil	0.5

The grease-waste that was used for the experimental work was solid and had to undergo a change of phases. The conversion was from solid, which is not bio-available to the microorganism, into liquid phase. This change of phases limits the efficiency of the biological process.

Chapter 5

Experimental Results

5.1. Introduction

The experimental phase consisted of experiments for determining the biological kinetics, liquid solid separation and the operational criteria. Two different reactors were used; medium scale reactor (1 m³) and bench scale reactor (30 gallons). The objective of using two different types of reactors was to determine if there were significant differences in the biological kinetics by pre-treating the grease-trap waste by a hydraulic shear. The use of a household blender was used to provide the hydraulic shear for reduce particle size (Figure 5.1).

The medium scale reactor was employed for determining the non-rended operational conditions. Meanwhile the bench scale reactor was employed for determining the grease-trap rended conditions. The reason for using a bench scale reactor for the rended condition was an equipment size limitation given the volume of grease-trap waste to be hydraulically sheared by using a household blender. The use of bench scale reactor required a smaller volume of substrate, permitting the use of a conventional household blender.



Figure 5.1 Bench Scale Reactor

5.2. Experimental Results

5.2.1. Determination of Kinetics

The biological kinetics that defines the biological process were obtained by means of oxygen uptake (OUR), oil and grease (O&G), and suspended solids (SS). The biological kinetics that were determined corresponded to: maximum growth rate ($\mu_{\max}$) maximum specific rate of substrate utilization (q), true yield of cell synthesis (Y) and the concentration giving one-half the maximum rate (K).

The $\mu_{\max}$ was determined by correlating the oxygen uptake vs. time (Kappeler and Gujer, 1992). The Y and the K were estimated by correlating the Monod kinetics with the initial

condition and the results obtained for oil and grease. The true yield of cell synthesis was correlated between $\mu_{\max}$ and Y .

5.2.2. Determination of $\mu_{\max}$

The initial operation conditions for the batch reactor were set to have an excess of substrate and oxygen. By having an excess of substrate and oxygen, the system behaves as an unrestricted heterotrophic growth.

The relationship derived by Monod, relates the specific growth rate of the growing microorganism to the concentration of a rate limiting substrate, Equation 5.1:

$$\mu_{\text{synthesis}} = \left(\frac{1}{X_a} \cdot \frac{dX_a}{dt} \right)_{\text{synthesis}} = \mu_{\max} \frac{S}{K + S} \quad (5.1)$$

The endogenous decay corresponds to the energy needed to sustain the microorganism.

The rate of endogenous decay can be expressed as:

$$\mu_{\text{decay}} = \left(\frac{1}{X_a} \frac{dX_a}{dt} \right)_{\text{decay}} = -b \quad (5.2)$$

Using the relationships derived by Monod (Monod equations), Equations 5.3 and 5.4 are derived. The net specific growth rate of the active biomass (μ) is the sum of the specific growth rate due to synthesis ($\mu_{\text{synthesis}}$) and the specific growth rate due to decay (μ_{decay}),

$$\mu = \mu_{\text{synthesis}} + \mu_{\text{decay}} \quad (5.3)$$

$$\text{Or: } \mu = \frac{1}{X_a} \cdot \frac{dX_a}{dt} = \mu_{\text{synthesis}} + \mu_{\text{decay}} = \mu_{\text{max}} \frac{S}{K + S} - b \quad (5.4)$$

Simplifying Equation 5.4:

$$\frac{dX_a}{X_a dt} = \mu_{\text{max}} \frac{S}{K + S} - b \quad (5.5)$$

Integrating equation 5.5 the following is obtained:

$$\ln \left[\frac{X_a(t)}{X_a(t=0)} \right] = \left(\mu_{\text{max}} \frac{S}{K + S} - b \right) \cdot t \quad (5.6)$$

For the operation conditions of the reactor it is possible to correlate the $X_a(t) / X_a(t=0)$ with $\text{OUR}(t) / \text{OUR}(t=0)$ (Kappeler and Gujer, 1992). Considering the initial conditions for the batch reactor where the S corresponds to S_0 and that $S_0 \gg K$, it is possible to simplify Equation 5.6. Therefore the μ_{max} can be calculated using the following equation:

$$\ln \left[\frac{OUR(t)}{OUR(t=0)} \right] = (\mu_{\max} - b) \cdot t \quad (5.7)$$

The previous equation represents a straight line, where the slope equals the $(\mu_{\max} - b)$. The endogenous decay coefficient (b) is much smaller than $\mu_{\max}$ and can be replaced by the following equation (Kappeler and Gujer 1992):

$$\mu_{\max - \text{calculated}} = 1.05 \cdot \mu_{\max} \quad (5.8)$$

5.2.3. Experimental Results:

5.2.3.1 Medium scale reactor

The experimental results for the determination of the $\mu_{\max}$ can be seen on Table 5.1 and Figure 5.2.

Table 5.1 Determination of $\mu_{\max}$ (Medium Scale 1m³)

Data Set	$\mu_{\max} \text{ (day}^{-1}\text{)}$
1	0.4342
2	0.8213
3	0.7191
Average	0.6582

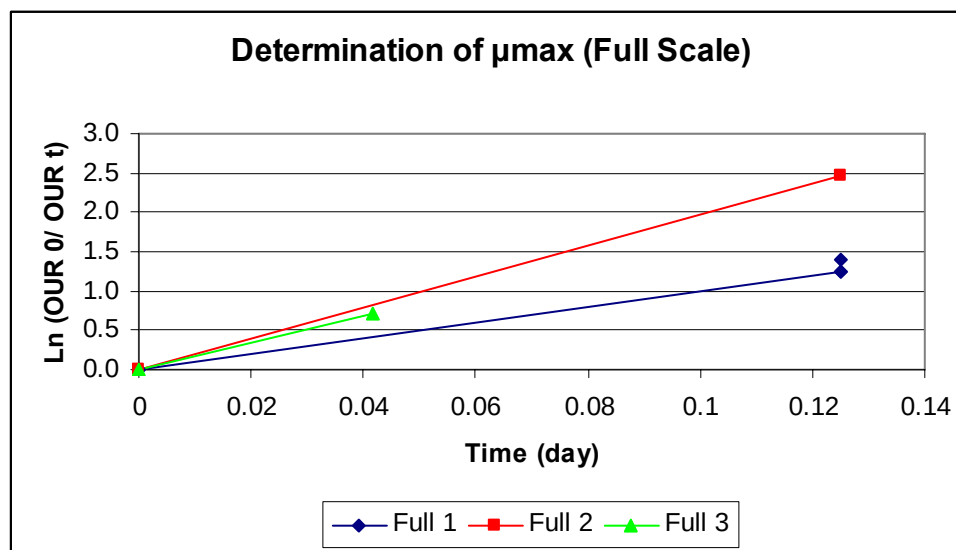


Figure 5.2 Determination of $\mu_{\max}$ (Medium Scale 1m^3)

5.2.3.2 Bench scale reactor

The experimental results for the determination of the $\mu_{\max}$ can be seen on Table 5.2 and Figure 5.3.

5.2.4. Analysis of $\mu_{\max}$

The analysis for $\mu_{\max}$ was divided into two parts. The first part of the analysis consisted of the comparison between the experimental results obtained for the mechanically disaggregated and the non-disaggregated $\mu_{\max}$. The second part consists of the comparison between the experimental results and literature values.

Table 5.2 Determination of $\mu_{\max}$ (Bench Scale)

Data Set	$\mu_{\max}$ (day ⁻¹)
1	0.6931
2	0.9163
3	0.7340
4	0.4055
Average	0.6872

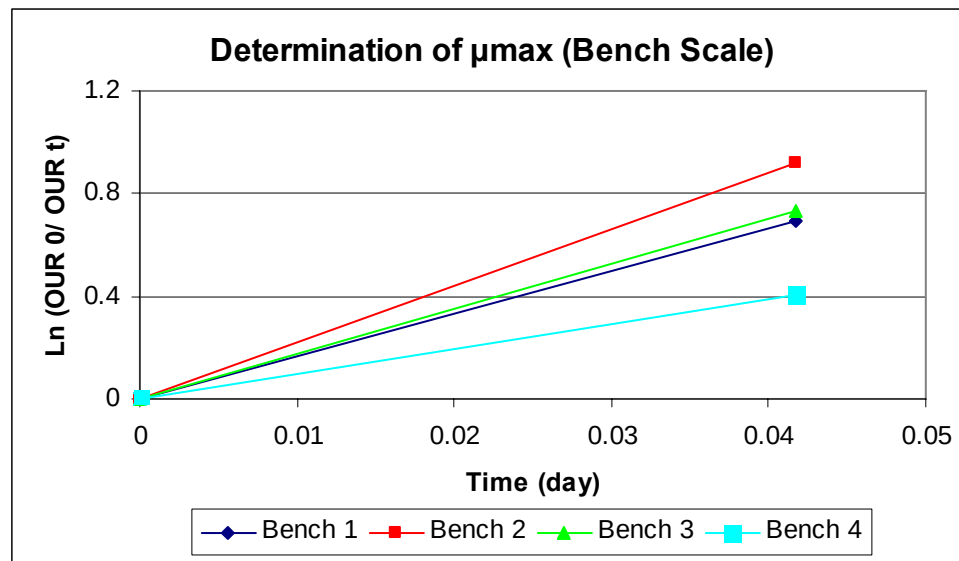


Figure 5.3 Determination of $\mu_{\max}$ (Bench Scale)

The following analyses determined if there were improvements in the treatment process by using a hydraulic shear to pre-treat the grease-trap waste. The necessity for determining whether to pre-treat or not the waste was because the grease-trap waste was in a solid state. By applying a hydraulic shear for the reduction of particle size of the waste, it might be possible to improve the process enlarging the contact surface for the activated sludge to interact. To analyze these results, the exact rank-sum test was employed. This test was selected due to the small number of data taken. The exact rank-sum test (Table 5.3) is appropriate for comparing group samples if size 10 or smaller per group.

Variables:

x_i ; Medium scale reactor (1m^3) (non-treated waste)

y_j ; Bench scale reactor (pre-treated waste)

The exact test statistic:

W_{rs} ; sum of ranks for the group having the smaller sample size, $= \sum R_i \quad I = 1, n$

Decision Rule

H_0 ; maximum growth rate 1m^3 reactor = maximum growth rate Bench scale

H_1 ; maximum growth rate 1m^3 reactor $\neq$ maximum growth rate Bench scale

Reject H_0 if $W_{rs} \leq x_{\alpha/2, n, m}^*$ or $W_{rs} \geq x_{\alpha/2, n, m}$

Table 5.3 Exact Version of the Rank-Sum test

1m ³ reactor		Bench Scale	
x_i	R_k	y_i	R_k
0.4342	2	0.4055	1
0.7191	4	0.6931	3
0.8213	6	0.7540	5
		0.9163	7

Analysis

The sum rank obtained for the smaller sample corresponds: $W_{rs} = 12$

From Table B4 Quantiles (p-values) for the rank-sum test statistic W_{rs} $p = \text{Prob} [W_{rs} \geq x] = \text{Prob} [W_{rs} \leq x^*]$ we obtained (Helsel and Hirsch 1991):

$x_{0.029, 3, 4}^* = 6$ and $x_{0.029, 3, 4} = 18$, therefore we accept H_0 .

With the rank-sum test analysis it is possible to conclude that there is no significant difference (using $\alpha = 0.052$) between pre-treating and non-treated grease-trap waste. Therefore it is possible to conclude that there is no significant increase in efficiency by previously applying a hydraulic shear to the grease-trap waste for reducing the particle size of the waste. The statistical analysis showed that there was no significant difference between both of the samples. Therefore both samples were considered for estimating the $\mu_{\max}$. Average $\mu_{\max} = 0.678 \text{ day}^{-1}$.

The results obtained for the average maximum growth rate compared with previous investigation have a smaller value than the literature values (Table 4.3 Literature results for $\mu_{\max}$). This difference is most likely because the previous research was performed with a single type of grease waste. The grease-trap wastes used in this research consisted of different types of FOG, which would complicate the degradation process and consequently reducing the efficiency. An additional factor that decreased the $\mu_{\max}$ was that the grease was in a solid state, in contrast with the previous research.

5.2.5. Determination of Maximum Specific Rate of Substrate Utilization, True Yield of Cell Synthesis and the Concentration Giving one-Half the Maximum Rate

The estimation of the remaining biological kinetics was obtained by employing JMP 6. A non-linear model was used to estimate maximum specific rate of substrate utilization (q), true yield of cell synthesis (Y) and the concentration giving one-half the maximum rate (K).

5.2.5.1 Experiment Variables

Response variables:

- a. Y_1 : Maximum specific growth rate, $\hat{\mu}$ (d^{-1}) this value was estimated using the OUR method used by Stasinakis (Stasinakis et al. 2003)
- b. Y_2 : Concentration given one-half the maximum rate, K (mg O&G/L) this value was estimated using the non-linear model.
- c. Y_3 : Maximum specific rate of substrate utilization, $\hat{q}$ (mg O&G/ mg TSSa -d) this value was estimated using the non-linear model.
- d. Y_4 : True yield for cell synthesis, Y (mg TSSa / mg O&G) this value was estimated using the non-linear model.

Where:

mg O&G: mg of oil and grease measured by hexane extraction.

mg TSS: mg of total suspended solids.

Factors under Study:

- a. X_1 : Initial concentration of active biomass X_a^0 (mg TSSa) at time 0.
- b. X_2 : Initial concentration of oil and grease S^0 (mg O&G / L) at time 0
- c. X_3 : Concentration of oil and grease S (mg O&G / L)
- d. X_4 : Time T day

Background variables:

- a. Reactor Temperature:
- b. PH: The pH of the sample was not altered; the pH of the reactor did not have considerable variation during the test.
- c. Dissolve oxygen of the sample: The dissolve oxygen of the sample was maintained by means of constant aeration before the analysis. The objective of this was to avoid anaerobic conditions.

Planned Method of Statistical Analysis

- a. Determine the maximum growth rate was by using OUR method (Stasinakis et al. 2003)
- b. Estimation of the microbial kinetics was by using a non-linear model.

5.2.5.2 Statistical Analysis

The rate substrate utilization is assumed to follow a Monod kinetic:

$$\frac{dS}{dt} = -\frac{\hat{q} \cdot S}{K + S} X_a \quad 5.9$$

Assuming the absence of decay, the organism concentration at any given time equals the initial concentration, X_a , plus the concentration resulting from the consumption during that period time, $Y \Delta S$, or:

$$X_a = X_a^0 + Y \cdot \Delta S \quad 5.10$$

Or

$$X_a = X_a^0 + Y \cdot (S^0 - S) \quad 5.11$$

By substituting Equation 5.11 into 5.9 it is obtained:

$$\frac{dS}{dt} = -\frac{\hat{q} \cdot S}{K + S} \cdot [X_a^0 + Y \cdot (S^0 - S)] \quad 5.12$$

Considering the initial boundary conditions:

$$X_a(0) = X_a^0 \quad S(0) = S^0 \quad 5.13$$

Integrating equation 5.12 and using the boundary conditions:

$$t = \frac{1}{\hat{q}} \cdot \left[\left(\frac{K}{X_a^0 + Y \cdot S^0} + \frac{1}{Y} \right) \cdot \ln(X_a^0 + Y \cdot S^0 - Y \cdot S) - \left(\frac{K}{X_a^0 + Y \cdot S^0} \right) \cdot \ln \frac{S \cdot X_a^0}{S^0} - \frac{1}{Y} \ln X_a^0 \right] \quad 5.14$$

The substrate utilization growth is correlated to the following expressing

$$\mu = \hat{q} \cdot Y \quad 5.15$$

Substituting Equation 5.15 into 5.14 it is possible to simplify the non-linear model into:

$$t = \frac{Y}{\mu} \cdot \left[\left(\frac{K}{X_a^0 + Y \cdot S^0} + \frac{1}{Y} \right) \cdot \ln(X_a^0 + Y \cdot S^0 - Y \cdot S) - \left(\frac{K}{X_a^0 + Y \cdot S^0} \right) \cdot \ln \frac{S \cdot X_a^0}{S^0} - \frac{1}{Y} \ln X_a^0 \right] \quad 5.16$$

5.2.5.3 Analysis

The sample population for the model consisted in four variables for the data set (Appendix Experimental Data for Non-Linear Model). The data set by run number (RN), experimental day (Day), experimental average of $\mu_{\max}$, Oil and Grease concentration (O&G), suspended solids (S Solids) and, initial Oil and Grease concentration (S_0). Table 5.4 shows the percentage of removal for Oil and Grease for each data set. The values for O&G can be seen in Appendix O&G.

The response variable for the model corresponded to Day and the predictor equation corresponded to Equation 5.6. By using the non-linear platform of JMP 6, the following results were obtained for the non-linear model:

Table 5.4 Percentage of Removal for Oil and Grease by Run

Run	Treatment Time (day)	Initial O&G (g/l)	Final O&G (g/l)	% Removed
1	19	2.705	0.604	78
2	11	1.378	0.44	68
3	34	21.151	0.42	98
4	10	7.465	1.583	79

Solution

The output results for the non-linear fit are located in the Appendix Non-Linear Fit for Determining the Biological Kinetics. The estimated biological kinetics values obtained for the non-linear models correspond to:

$$K = 41 \text{ g O\&G / l}$$

$$Y = 0.10 \text{ g VSS / g O\&G}$$

$$\text{From Equation 5.7; } q = 6.6 \text{ g O\&G / g VSS-d}$$

Comparing the results obtained for the experimental data with literature values, it was observed that the results are smaller than aerobic, heterotrophic organisms. The laboratory results for the biological kinetics were expected to be lower than conventional activated sludge because of the nature of the waste. The non-homogeneous nature of grease-trap waste makes it difficult to biologically degrade. Additional variation in the experimental results is a result of the method selected to determine the biological kinetics.

The resulting model for the biological kinetics where compared to the experimental data. The residuals between the experimental data and model where calculated (Appendix: Analysis Between Experimental Data and Model). From the residual analysis it is possible to observe that residuals do not follow any pattern and that the variance is constant. Additionally it was observed that the discrepancy between estimated oil and grease concentration differ due to the errors in laboratory analysis (Appendix: Oil and Grease Laboratory vs. Model).

Conclusions

The experimental results confirmed that it is possible to biologically degrade grease-trap waste aerobically. The process requires longer retention time that traditional activated sludge. The lengthy treatment time is due to the resilience of the substrate to be degraded. Additionally it was observed that there was no significant improvement in treatment by performing a previous reduction of the particle size of the waste.

5.3. Prediction Model

The prediction model was based on the Monod Kinetics (Equation 5.6), the previously determined biological kinetics, and literature design parameters for batch reactor.

Analysis

The value of the initial concentration of the grease-trap concentration must be known to determine the length of the treatment. The estimation of the grease-trap concentration per unit of volume was estimated by the following method. The reactor volume was 1m^3 as well as the volume of grease-trap waste added (Table 5.5) to the reactor. After the grease-trap waste was added, the O&G concentration inside the reactor was estimated. By determining the total mass of grease inside the reactor and divided by the volume of grease-trap waste added to the reactor it was possible to estimate the concentration of O&G of the grease-trap waste per unit of volume (Table 5.5).

The average concentration of Oil and Grease for KUB grease-trap waste was 244.2 g/l and the standard deviation was 172 g/l. For purpose of modeling the degradation of grease-trap waste, the average of the concentration of grease-trap waste was employed. The final Oil and Grease concentration for the process will be considered 300 mg/l.

Table 5.5 Estimation of the Grease-trap waste concentration

Reactor Concentration O&G (g/l)	Reactors Volume (liter)	Total Concentration (gr.)	Volume added of Grease-Trap waste (liter)	Concentration of Grease-Trap waste (g/l)
1.378	800	1102	18.9	58.2
2.705	800	2164	18.9	114.3
7.465	800	5972	37.9	157.8
21.000	800	16800	37.9	443.8
21.151	800	16921	37.9	447.0

The initial Oil and Grease concentration for the reactor corresponds to the following equation:

$$S^0 = \frac{V_{Grease-trap} \cdot C_{Grease-trap}}{V_{Reactor}} \quad 5.17$$

Where:

$V_{Grease-trap}$ = Volume of grease-trap to be treated (l)

$C_{Grease-trap}$ = Average grease-trap waste concentration (O&G g/l)

$V_{Reactor}$ = Volume of the biological reactor (l)

The typical reactor concentration of suspended solids for batch reactor corresponds to 2,000 – 4,000 mg/l. For purpose of modeling the typical range of suspended solids was employed.

The prediction model was constructed using Equations 5.16 and 5.17. The previously determined biological kinetics and oil and grease concentration for the grease-trap waste were employed as constants. Using JMP 6.0, contour plots were constructed for time vs. reactor volume, initial biomass and volume of grease-trap waste to be treated.

$$t = \frac{Y}{\mu_{max}} \cdot \left[\left(\frac{K}{X_a^0 + Y \cdot S^0} + \frac{1}{Y} \right) \cdot \ln(X_a^0 + Y \cdot S^0 - Y \cdot S) - \left(\frac{K}{X_a^0 + Y \cdot S^0} \right) \cdot \ln\left(\frac{S \cdot X_a^0}{S^0}\right) - \frac{1}{Y} \cdot \ln(X_a^0) \right] \quad 5.18$$

Where:

$$Y = 0.10 \text{ g VSS/ g O\&G}$$

$$\mu_{\max} = 0.6748 \text{ d}^{-1}$$

$$K = 41 \text{ g O\&G / l}$$

$$X_a^0 = \text{initial biomass and variegate between } 2.0 - 4.0 \text{ g VSS / l}$$

$$S^0 = \frac{V_{\text{Grease-trap}} \cdot 244.2 \text{ g/l}}{V_{\text{Reactor}}}$$

$$S = \text{final oil and grease concentration } 0.3 \text{ g O\&G / l}$$

5.4. Solids-Liquid Separation

The solid-liquid separation analysis was divided in two steps. The first one, focused on the analysis of the settling characteristics of the activated sludge, and the second one, focused on the analysis of the statistical model developed to determine the optimal ranges of the controlling parameters to perform the solid-liquid separation in a DAF unit. With this information it was possible to perform a comparative study between the two separation methods (Cartajen, 2006)

5.4.1. Settling Characteristics

Once the biological reactor treatment phase had ended a sample was taken from the batch reactor and a Sludge Volume Index (SVI) test was performed (Table 5.6). As is mentioned in Chapter 2, it is known that there is a strong correlation between the TELF and SVI. The SVI values for each batch are shown below:

As it can be seen, values of SVI are all above 200 (mL/g). These values show that settling properties of the activated sludge are poor, resulting in an inefficient performance. Values for TELF had been associated with TELP between $10^7 - 10^8$ $\mu\text{m/mL}$ (Sezgin et. al, 1978).

5.4.2. Additional Investigation

With the preliminary ranges for the operational parameters defined, an expanded DAF test program was performed (Cartajena, 2006). Results are shown in Table 5.7. Performing the same analysis, significant parameters were determined.

Table 5.6 Sludge Volume Index (SVI)

Sample	Settled Sludge Volume (mL/L)	SVI (mL/g)
1	980	233
2	960	208
3	980	196
4	950	221

Cartajena, 2006

Table 5.7 Data set used in the Statistical Analysis

Data Set	Pressure	Recycle	Initial TS	SS Subnatant	%R	A/S	Rise Rate	Log (SS Subnatant)
1	40	30	11960	140	98.80	0.5147	0.3	4.94164242
1	40	40	11960	415	96.50	0.6862	0.62	6.02827852
1	40	50	11960	280	97.70	0.8578	0.56	5.6347896
1	50	30	11960	124	99.00	0.7181	0.23	4.82028157
1	50	40	11960	480	96.00	0.9575	0.62	6.1737861
1	50	50	11960	306	97.40	1.1968	1.5	5.7235851
1	60	30	11960	80	99.30	0.9215	0.24	4.38202663
1	60	40	11960	423	96.50	1.2287	0.76	6.04737218
1	60	50	11960	358	97.00	1.5358	1.5	5.88053299
2	40	30	8740	340	96.10	0.7043	0.42	5.82894562
2	40	40	8740	489	94.40	0.939	0.51	6.19236249
2	40	50	8740	407	95.30	1.17378	0.52	6.00881319
2	50	30	8740	256	97.10	0.9826	0.37	5.54517744
2	50	40	8740	604	93.10	1.3102	0.54	6.4035742
2	50	50	8740	494	94.30	1.6377	1.03	6.20253552
2	60	30	8740	200	97.70	1.261	0.35	5.29831737
2	60	40	8740	546	93.80	1.6813	0.69	6.30261898
2	60	50	8740	578	93.40	2.1017	1.23	6.35957387
3	40	30	9120	258	97.20	0.6749	0.27	5.55295958
3	40	40	9120	412	95.50	0.8999	0.27	6.02102335
3	40	50	9120	305	96.70	1.1249	0.27	5.72031178
3	50	30	9120	195	97.90	0.9417	0.35	5.27299956
3	50	40	9120	498	94.50	1.2556	0.52	6.21060008

Table 5.7 (Continue)

Data Set	Pressure	Recycle	Initial TS	SS Subnatant	%R	A/S	Rise Rate	Log (SS Subnatant)
3	50	50	9120	367	96.00	1.5695	0.47	5.90536185
3	60	30	9120	168	98.20	1.2085	0.33	5.12396398
3	60	40	9120	447	95.10	1.6113	0.4	6.10255859
3	60	50	9120	406	95.50	2.0141	0.71	6.00635316
4	40	30	8250	284	96.60	0.6439	0.4	5.64897424
4	40	40	8250	312	96.20	0.8585	0.49	5.74300319
4	40	50	8250	285	96.50	1.0731	0.43	5.65248918
4	50	30	8250	260	96.80	0.8983	0.36	5.56068163
4	50	40	8250	343	95.80	1.1978	0.58	5.83773045
4	50	50	8250	387	95.30	1.4972	0.67	5.95842469
4	60	30	8250	245	97.00	1.1528	0.35	5.50125821
4	60	40	8250	398	95.20	1.5371	0.9	5.98645201
4	60	50	8250	446	94.60	1.9214	1.23	6.10031895

As can be seen in Appendix Determination for the Linear Fit for Determining Variables for Final DAF model, suspended solid concentration in the supernatant (Y1) depends mainly on the recycle ratio (X2), as well as in its interaction with air pressure (X1) and the initial total solids concentration (X3). In the same way, percentage of recovery (Y2) relies on recycle ratio (X2), and its interaction with air pressure (X1). Since %R depends on suspended solid concentration in the supernatant (X3), this dependency with recycle ratio is correct. Air to solid ratio (Y3) depends on the interaction of air pressure (X1) and recycle ratio (X2) with the initial total solids (X3).

Rise Rate (Y4) depends on recycle rate (X2), initial total solids (X3), and the interaction between each other. Having the significant parameters identified, a new analysis of the data was performed. In this run, parameters that were insignificant were not included in the model.

The second analysis of the data used a contour profiler (Figure 5.4). The use of the contour profiler included the boundary previously defined to determine the area of successful treatment. In this second analysis, the area of successful treatment corresponded to the white area of Figure 5.4. The values of operation for the air pressure (X1) ranged between 45-70 psi. For recycle rate (X2), values ranged between 30-35 %.

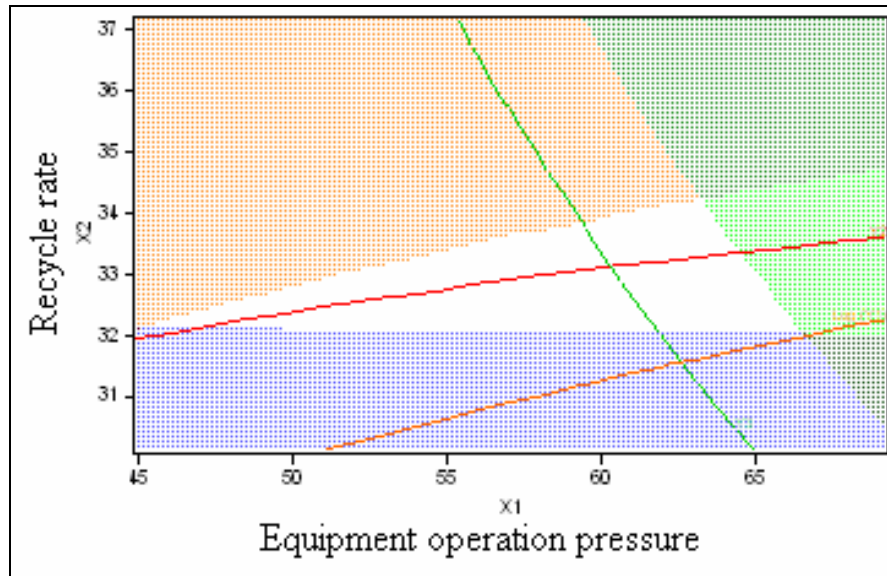


Figure 5.4 Contour Profiler Current Investigation

As it can be observed, if both contour profilers are compared (Determination of DAF Chapter 4 vs. Cartajena 2006), that values for air pressure were confirmed. Just a little variation was obtained with the second analysis. However, for the recycle rate values are now located in a lower range.

With a lower range for the recycle ratio, an important minimization of the costs can be obtained. The lower the recycle rate the lower the cost of the treatment.

In addition, from the contour profiler results it can be observed that the parameter defining the lower limit of the recycle ratio (X2) is the rise rate (Y4). While the upper limit of the recycle ratio and the complete range for the air pressure (X1) is defined by the suspended solid concentration (Y1) of the subnatant and the air to solid ratio (Y3).

Percentage of recovery (Y2) resulted in being a non-defining parameter of the system. This can be concluded from the fact that our main goal was to obtain a final concentration of the suspended solids in the supernatant lower than or equal to 300 (mg/L), without the influence of the effectiveness of the system.

5.5. Economic Model

From the biological prediction model for the system, it is possible to obtain an estimate of the cost of the treatment. The cost estimate was performed by determining the construction cost (Batch reactor volume and the DAF unit cost) and the operational cost (treatment time) for the estimated treatment cost of grease-trap waste.

5.5.1. Batch Reactor Cost

The batch reactor cost was estimated by using cost estimates performed by EPA. These costs estimates can be found in Wastewater Technology Fact Sheet Sequential Batch Reactors. The technology fact sheet corresponds to the year 1999, therefore the cost where updated using a future value equation and the rate inflation of 2000 to 2006 (Table 5.8). The future value equation corresponds to:

Table 5.8 Inflation Rate per Year

Year	Inflation Rate
1998	1.6
1999	2.2
2000	3.4
2001	2.8
2002	1.6
2003	2.3
2004	2.7
2005	3.4
2006*	4

Source: Federal Reserve Bank of Minneapolis

<http://woodrow.mpls.frb.fed.us/Research/data/us/calc/hist1913.cfm>

$$FV = PV \cdot (1 + r) \quad 5.19$$

Where:

FV = Future value

PV = Present value

r = interest rate or inflation rate

Estimating that the useful life of the project is 10 years, it is possible to determine the daily cost per unit of volume (Table 5.9 and 5.10). Additionally a second order fit was constructed of the cost vs. batch reactor volume using JMP 6.0. The resulting model corresponds to Equation 5.20.

Table 5.9 Estimation of the Future Value per Design Flow Rate

Design Flow Rate (m ³ /d)	Budget Level Equipment Cost (\$) 2006
45	117216
57	170836
3785	422725
5299	505025
5526	505025
7570	703295
16086	1458962

Table 5.10 Daily Reactor Cost per Unit of Volume

Design Flow Rate (m ³ /d)	Daily Cost of Reactor (\$ / 10 year based)
45	32
57	47
3785	116
5299	138
5526	138
7570	193
16086	400

$$Cost_{Reactor} = \left(29.787 + 0.02088 \cdot RVolume + 3.04 \cdot 10^{-7} \cdot (RVolume - 5481)^2 \right) \cdot Time \quad (5.20)$$

Where:

Cost_{Reactor} = Batch reactor cost per batch (\$)

R-Volume = Batch reactor volume (m³)

Time = Reactor batch time (day)

5.5.2. Mixing Cost

The experimental results indicated that it was necessary to have mechanical mixing, and that fine bubble was not effective alone for mixing. Therefore a mechanical system was be selected for the mixing. From literature results the following relationship was selected: that 1.30 hp are needed for every 1000ft³ of reactor volume. Additionally the national average electricity cost for the industrial sector corresponded to 1.77 cents per kilowatt-hour (Energy Information Administration, 2005).

<http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html>

The mixing cost per unit of volume was obtained from the previous relationships: For every 1m³ of reactor, 0.034248 kilowatt-hours are required and therefore for every 1m³ of reactor it will cost 0.014549 per day. Therefore the reactors mixing cost corresponds to:

$$Cost_{Mixing} = 0.014549 \cdot RVolume \cdot Time \quad (5.21)$$

Where:

Cost_{Mixing} = Daily mixing cost (\$)

R-Volume = Batch reactor volume (m³)

Time = Reactor batch time (day)

5.5.3. Dissolve Air Flotation

The estimation of the cost for the DAF unit was based on the flotation-thickening unit. This cost is similar to a dissolve air flotation-thickening unit; however, it uses digester gas instead of air (Emerging Technologies for Biosolids Management, EPA 2006). The approximate Capital Cost: 7.50 per dry lb (at 6-8% solids, or 1.90 per gallon) processed per day. Approximate O&M Cost: 8.00 per dry ton of biosolids processed for polymer. The DAF cost will be considered per batch cost; as a result the following cost curve was obtained:

$$Cost_{DAF} = 0.01653 \cdot Y \cdot O \& G_{mass} + Y \cdot O \& G_{mass} \cdot 0.00008 \quad (5.22)$$

Where

Cost_{DAF} = Liquid/solid separation cost (\$)

O&G_{mass} = Mass of Oil and Grease to be treated (g O&G)

$$Y = 0.102 \text{ (g VSS/ g O\&G)}$$

Therefore the total cost curve corresponds to the summation of the Reactor cost plus Mixing cost and DAF cost (Equation 5.23).

$$Cost_{Total} = Cost_{Reactor} + Cost_{Mixing} + Cost_{DAF} \quad 5.23$$

5.5.4. Alternative Cost (Landfill disposal)

The traditional treatment that is employed corresponds to the disposal of grease-trap waste in a landfill. The estimated cost for extraction from grease trap, the transportation and final disposal into a landfill was estimated to be 93 dollars per 1000 gallons (3785 l). Using the statistical model the following results were obtained for the treatment of 1000 gallons of grease-trap waste.

From Figure 5.5 and Table 5.11 and 5.12 it is possible to observe that for a higher initial concentration of active biomass (Suspended Solids) the treatment time is reduced with a subsequent reduction in the treatment time. For the

Table 5.11 Percentage Cost Distribution

Initial SS (g/l)	Reactor Volume (m3)	Batch Reactor Cost	Mixing Cost	Liquid / solid separation cost	Total Cost
4	10	1885	1120	1566	4571
Percentage Cost (%)		41 %	25 %	34 %	100 %

Table 5.12 Total Cost for Treating 1000 Gallons of Grease-Trap Waste

Initial SS (g/l)	Reactor Volume (m3)	Time	Batch Reactor Cost	Mixing Cost	Liquid / solid separation cost	Total Cost
2	10	12.6	3081	1831	1566	6478
2.2	10	11.8	2880	1712	1566	6158
2.4	10	11.1	2709	1610	1566	5885
2.6	10	10.5	2560	1521	1566	5647
2.8	10	9.9	2429	1444	1566	5439
3	10	9.5	2313	1375	1566	5255
3.2	10	9.0	2210	1313	1566	5090
3.4	10	8.6	2117	1258	1566	4941
3.6	10	8.3	2032	1208	1566	4806
3.8	10	8.0	1955	1162	1566	4683
4	10	7.7	1885	1120	1566	4571

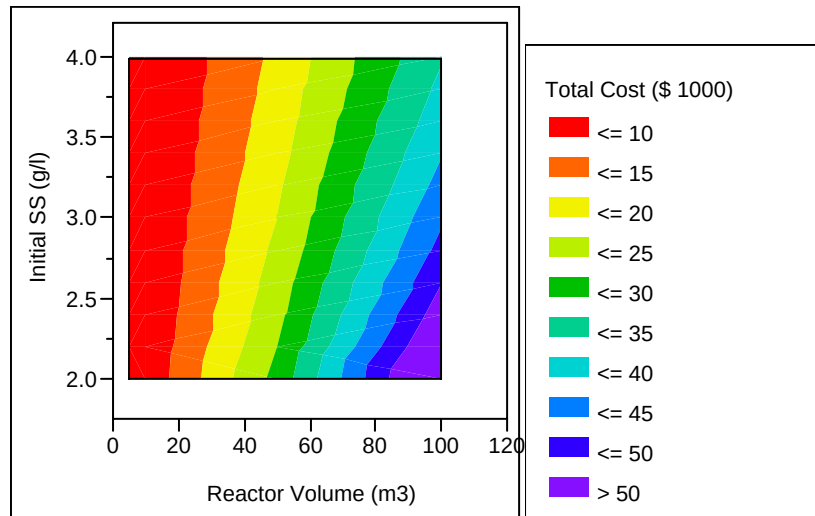


Figure 5.5 Total Cost for Biological Treatment of Grease-Trap Waste

Treating 1000 gallons of grease trap waste by the proposed method would cost 4570 dollars compared to 93 dollars. This estimation was performed using the Equation 5.23 and 5.18 using an initial suspended solid concentration of 4,000 mg/l and a reactor volume of 10 m³.

From Table 5.11 it is possible to observe that the highest cost for proposed treatment corresponds to construction cost for the reactor. The energy cost for treatment of the waste only corresponds to 25% of the total cost.

5.6. Problems observed

During the operation of the reactor, an increase of the viscosity of the activated sludge resulted in a slime type sludge. The change in appearance and viscosity of the sludge

produced difficulties in the dewatering of the waste, which were observed during column settling test and DAF.

The results obtained for the dewatering test showed difficulties in dewatering the sludge. The difficulties of dewatering the sludge can be resumed as: no settling, no interface (DAF), bubbles trapped (Table 5.13).

The estimated SVI for the high viscosity batch corresponds: $SVI = 269$

The increase in the viscosity and slime type activated sludge can be explained by a low food to biomass ratio (F/M) of the activated sludge. This unbalance growth results in the generation of exopolymers.

Table 5.13 Settling Distance for Column Test Exopolymers Batch

Surface Interface (cm)	Time (min)
0	0
0	0.5
0	1
0	2
0	3
0	4
0	5
1	10
1	15
1	30
1	60

The presence of exopolymers results in the molecular interaction of substances with the water, leading to enmeshing of the particles. This interaction produced a high viscosity and reduction in the specific gravity, which is a major cause in the dewatering of the activated sludge (Nelson et al. 1988).

Grease-trap waste has a low solubility and it is difficult to degrade, therefore it may generate conditions where low F/M ratios cause operational problems. This low F/M ratio can generate conditions where the excretion of exopolymers by the biomass occurs. The presence of exopolymers could severely hinder the biological process.

Chapter 6

Conclusion

The experimental results confirmed that it is feasible aerobically treat grease-trap waste by filamentous bacteria. The research produced a better understanding of the biological process and determined design criteria for the process. This new information was divided into; mixing, kinetics estimation, solids-liquid separation requirements, cost analysis and operation problems.

6.1. Mixing

A fine bubble diffuser provided the mixing for the large-scale reactor. The resulting mixing did not adequately incorporate the grease-trap waste and the filamentous rich microorganism population. The fine bubble aeration generated a surface layer of grease-trap waste and biomass, which stayed on top of the reactor. In order to incorporate the surface layer into the treatment volume, it was necessary to change the mixing method. The selected method was mechanical mixing with down draft set to produce a vortex.

The fine bubble mixing resulted in an inadequate incorporation of the surface grease layer and filamentous population into the reactors volume. As a result of changing the type of mixing to a down draft vortex mechanical mixer it was observed an improvement in the degree of mixing. Down vortex mixing permitted the incorporation of the grease-

trap waste and the biomass, and therefore use the entirety of the volume of the reactor. Setting the mechanical mixer to a level that produced a vortex ensured that there was no accumulation of grease-trap waste in the surface. Therefore for an adequate design of a grease-trap waste system it is necessary to consider mechanical down draft mixing.

The results obtained for the comparative study between mechanically reduced particles size versus non-disaggregated grease-trap waste showed that there were no significant differences between the two experiments. Therefore it is possible to conclude that there is no significant increase in efficiency by mechanically reducing the particle size of the sample. The mixing mechanism was set to ensure a vortex that would incorporate the grease-trap waste into the volume of the reactor. This vortex action generates a sufficient shear to reduce the particle size.

6.2. Biological Kinetics Estimation and Model

The biological kinetics estimated for the treatment of grease-trap waste had lower values than other studies of FOG. The main reason for this difference in efficiency in the degradation process is due to the type of waste treated. The resulting biological kinetics was lower due to the nature of the waste. The previous studies used single-component FOG compositions. The grease-trap waste used for this study was not a homogenous waste. The heterogeneous composition of the waste is due to that is a recompilation of all the FOG that was discarded into the sewage system.

The high variability of the grease-trap waste created a complication to the population that requires adaptation to the waste. The degradation process for the grease trap waste follows the principle of degrading the most bio-available energy form and once depleted continues with the next most easily available energy source. Therefore the biomass has to adapt to the new energy source, which implies a time to adapt.

The resulting model can help in the design of future treatments for grease-trap waste or wastes that contain a high diversity of FOG. This consideration is necessary because the model was calibrated for a non-homogenous waste. In the case of using an industrial or single-origin FOG waste, it would be necessary to recalculate all the biological kinetics. This is necessary because the FOG waste composition could imply in longer or shorter periods of time. Therefore it is necessary to perform a study of the biological kinetics for the waste.

6.3. Solids-Liquid Separation

The experimental results that showed that there was a decrease in the sedimentation properties of the activated sludge, with increase in the filamentous population. This decrease was correlated to an increase in the filamentous population (Pictures Population Observation, Chapter 4), and also in the increase in the SVI. In contrast the results obtained for the DAF experiment showed that it was possible to reach the treatment goal

(300 mg/l SS). To reach this treatment goal it was determined that a treatment condition corresponding to 45-70 psi air pressure, and 30-35% of recycle rate of influent. This condition was selected for minimizing the equipment cost and for complying with the treatment goal.

The experimental results showed that to separate the biomass from the liquid phase it was necessary the use of a DAF unit that was more effective than sedimentation. This was due to the decrease in the sedimentation properties as a result the increase in the filamentous population, which are known to have poor separation properties.

6.4. Cost Analysis

From the cost analysis it was observed that the proposed treatment method has a higher cost than disposing of the grease-trap waste in a landfill. Currently European legislation is requiring that lipidic waste be treated. Therefore it is expected in a future that grease waste will have to be treated. For this reason it is necessary to develop alternatives for the treatment of lipidic waste.

6.5. Future work

Treatment time for grease-trap waste is longer than regular activated sludge. The extended treatment time has an economic impact on the treatment. The higher cost

implies the necessity for improvement of the efficiency of the process. The following alternatives should be studied; increase the solubility of the grease-trap waste by additives, and determine the conditions for unbalance growth in the process.

An alternative to long periods of treatment time corresponds to the use of additives. The additive will depend on the nature of the product. Some possible additives that can be used correspond to degreasers, enzymes and, solvents. As a result it is possible to perform comparative studies for the use of these products. The comparative studies should compare the increase in the biological kinetics versus the reduction of cost.

The unbalance growth corresponds to the condition of the microorganisms due to the lack or insufficient quantities of energy source that causes a generation of exopolymers. The resulting effect corresponds to an increase in the viscosity of the activated sludge. This increase generates problems in liquid/solid separation, for that reason it is necessary to develop a better understanding of this condition. Therefore, a study that produces the occurrence of unbalance growth could help define a treatment zone and help avoid the generation of exopolymers.

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Appendix

Power Analysis

Using JMP 6.0 the following analyses were performed: Power Analysis and, Least Significant Number. The purpose of these analyses was to determine the possibility of making a Type II error. From the analysis it was observe that an increase in the sample population could help avoid committing a Type II error.

Power Analysis

α	σ	δ	Number	Power
0.0500	2134.803	552.8604	17	0.1702
0.1000	2134.803	552.8604	17	0.2698

Least Significant Number

α	σ	δ	Number(LSN)
0.0500	2134.803	552.8604	59.75426
0.1000	2134.803	552.8604	42.26177

OUR Data

Medium Scale Reactor (1m³)

Determination of OUR Curves Data Set 1 (1m³)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.02	28.8	28.8	0.000
0	0.02	28.8	28.8	0.000
0	0.03	43.2	28.8	0.000
3	0.07	100.8	28.8	1.253
3	0.08	115.2	28.8	1.386
3	0.07	100.8	28.8	1.253
6	0.12	172.8	28.8	1.792
6	0.09	129.6	28.8	1.504
6	0.1	144	28.8	1.609
12	0.14	201.6	28.8	1.946
12	0.12	172.8	28.8	1.792
12	0.12	172.8	28.8	1.792
24	0.34	489.6	28.8	2.833
24	0.34	489.6	28.8	2.833
24	0.31	446.4	28.8	2.741

Determination of OUR Curves Data Set 2 (1m³)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.008	11.52	11.52	0.000
3	0.094	135.36	11.52	2.464
6	0.036	51.84	11.52	1.504
12	0.0725	104.4	11.52	2.204
24	0.066	95.04	11.52	2.110
48	0.074	106.56	11.52	2.225
72	0.0725	104.4	11.52	2.204
96	0.084	120.96	11.52	2.351
120	0.098	141.12	11.52	2.506

Determination of OUR Curves Data Set 3 (1m³)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.04	60.8	60.8	0.000
1	0.09	124.8	60.8	0.719
3	0.09	127.54	60.8	0.741
6	0.08	108	60.8	0.575
9	0.08	109.44	60.8	0.588
20	0.07	106.56	60.8	0.561

Bench Scale Reactor 30 Gallons

Determination of OUR Curves Data Set 1 (Bench)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.004	5.76	5.76	0.000
1	0.008	11.52	5.76	0.693
3	0.012	17.28	5.76	1.099
6	0.023	32.40	5.76	1.727
12	0.024	35.20	5.76	1.810
24	0.022	31.68	5.76	1.705

Determination of OUR Curves Data Set 2 (Bench)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.004	5.76	5.76	0
1	0.01	14.4	5.76	0.916
3	0.014	20.16	5.76	1.253
9	0.024	34.56	5.76	1.792
18	0.064	92.16	5.76	2.773

Determination of OUR Curves Data Set 3 (Bench)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.006	8.64	8.64	0
1	0.0125	18	8.64	0.733969175
3	0.016	23.04	8.64	0.980829253

Determination of OUR Curves Data Set 4 (Bench)

Time	OUR	OUR (d)	C ₀	LN(OUR-d / C ₀)
0	0.012	17.28	17.28	0
1	0.02	28.8	17.28	0.510825624

Design Matrix for Dissolve Air Flotation Experiment

Design Matrix for DAF Experiment

Run	Day	Pressure (psi)	Recycle Rate (%)
1	3	75	20
2	3	60	80
3	3	40	40
4	3	60	40
5	3	60	20
6	3	40	80
7	3	75	80
8	3	75	40
9	3	40	20
10	9	40	40
11	9	60	80
12	9	80	80
13	9	80	20
14	9	40	20
15	9	60	20
16	9	40	80
17	9	60	40
18	9	80	40
19	37	60	20
20	37	40	50
21	37	80	80
22	37	60	80
23	37	40	80
24	37	60	50
25	37	40	20
26	37	80	50
27	37	80	20

Initial Linear Fit for Determining Variables for DAF Model

Summary of Fit for Log (Y_1)

RSquare	0.890978
RSquare Adj	0.822838
Root Mean Square Error	0.199332
Mean of Response	5.630242
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	5.1954551	0.519546	13.0759
Error	16	0.6357302	0.039733	Prob > F
C. Total	26	5.8311853		<.0001

Parameter Estimates

Term	Estimate	Std Error	t	Prob> t
			Ratio	
Intercept	4.7315742	1.277813	3.70	0.0019
X1&RS	-0.00147	0.031745	-0.05	0.9636
X2&RS	0.0271781	0.015457	1.76	0.0978
X3&RS	-0.000033	0.000045	-0.73	0.4776
X1*X1	0.0001193	0.000229	0.52	0.6095
X1*X2	-0.000143	0.000118	-1.21	0.2444
X2*X2	-0.000131	0.000105	-1.24	0.2312
X1*X3	-2.614e-7	3.866e-7	-0.68	0.5086
X2*X3	-6.699e-7	2.332e-7	-2.87	0.0110
X3*X3	4.1925e-9	1.125e-9	3.73	0.0018
X4	0.0567013	0.235497	0.24	0.8128

Summary of Fit for Y₂

RSquare	0.880874
RSquare Adj	0.80642
Root Mean Square Error	0.233786
Mean of Response	98.89481
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	6.4663819	0.646638	11.8311
Error	16	0.8744922	0.054656	Prob > F
C. Total	26	7.3408741		<.0001

Parameter Estimates

Term	Estimate	Std Error	t	Prob> t
Intercept	102.516	1.49868	68.40	<.0001
X1&RS	-0.049575	0.037232	-1.33	0.2017
X2&RS	-0.113697	0.018129	-6.27	<.0001
X3&RS	0.0000961	0.000053	1.82	0.0874
X1*X1	0.0001377	0.000269	0.51	0.6153
X1*X2	0.0003983	0.000139	2.87	0.0111
X2*X2	0.0006173	0.000123	5.01	0.0001
X1*X3	4.6325e-7	4.534e-7	1.02	0.3221
X2*X3	0.0000015	2.735e-7	5.47	<.0001
X3*X3	-5.873e-9	1.32e-9	-4.45	0.0004
X4	0.0588074	0.276202	0.21	0.8341

Summary of Fit for Y₃

RSquare	0.983501
RSquare Adj	0.97319
Root Mean Square Error	0.217929
Mean of Response	1.40232
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	45.298159	4.52982	95.3784
Error	16	0.759890	0.04749	Prob > F
C. Total	26	46.058049		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-2.908098	1.397032	-2.08	0.0538
X1&RS	0.0741062	0.034706	2.14	0.0486
X2&RS	0.0435785	0.016899	2.58	0.0202
X3&RS	-0.000024	0.000049	-0.48	0.6367
X1*X1	-0.000199	0.00025	-0.80	0.4381
X1*X2	0.0005249	0.000129	4.06	0.0009
X2*X2	-0.000085	0.000115	-0.74	0.4711
X1*X3	-0.000003	4.226e-7	-6.14	<.0001
X2*X3	-0.000002	2.549e-7	-8.63	<.0001
X3*X3	5.9218e-9	1.23e-9	4.81	0.0002
X4	0.4804604	0.257468	1.87	0.0805

Summary of Fit for Y₄

RSquare	0.969194
RSquare Adj	0.94994
Root Mean Square Error	0.146296
Mean of Response	0.983704
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	10.773588	1.07736	50.3377
Error	16	0.342442	0.02140	Prob > F
C. Total	26	11.116030		<.0001

Parameter Estimates

Term	Estimate	Std Error	t	Prob> t
Intercept	-3.0054	0.93783	-3.20	0.0055
X1&RS	0.0634292	0.023298	2.72	0.0151
X2&RS	0.0448367	0.011344	3.95	0.0011
X3&RS	0.0000304	0.000033	0.92	0.3705
X1*X1	-0.000346	0.000168	-2.06	0.0561
X1*X2	-0.000165	0.000087	-1.90	0.0755
X2*X2	-0.000069	0.000077	-0.90	0.3840
X1*X3	-5.296e-7	2.837e-7	-1.87	0.0804
X2*X3	-1.189e-7	1.711e-7	-0.69	0.4973
X3*X3	4.427e-10	8.26e-10	0.54	0.5993
X4	0.2877035	0.172839	1.66	0.1155

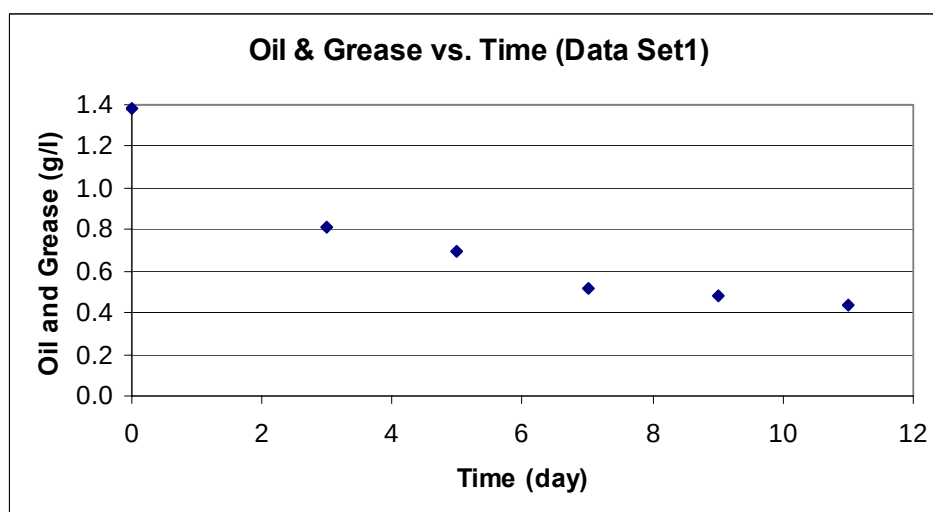
Oil and Grease vs. Time

Oil and Grease vs. Time Set 1

Date	Initial W	Final W	Volume (ml)	Flask I	Flask F	Mass (mg)	Concen (g/l)
0	173.28	222.77	49.49	118.31	118.38	0.0682	1.378
3	171.98	220.77	48.79	115.62	115.66	0.0395	0.810
5	172.53	217.28	44.75	78.42	78.45	0.0312	0.697
7	171.87	220.75	48.88	119.72	119.75	0.0251	0.514
9	168.29	214.87	46.58	115.66	115.68	0.0226	0.485
11	167.18	211.5	44.32	110.98	111.00	0.0195	0.440
Blank	154.34	254.36	100.02	93.46	93.46	-0.0005	-0.005
QC1	169.44	218.12	48.68	78.49	78.51	0.0162	0.333
QC1+ Spike	173.31	222.64	49.33	115.37	115.41	0.0342	0.693

Spike 200 mg/l

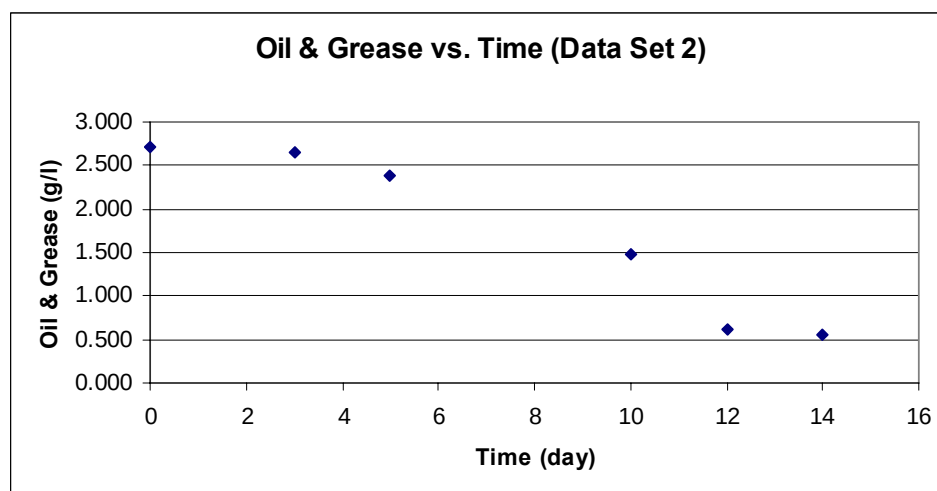
EQ 2 Method 1664 = 90.1 %



Oil and Grease Data Set 1

Oil and Grease vs. Time Set 2

Date	Initial W	Final W	Volume (ml)	Flask I	Flask F	Mass (mg)	Concen (g/l)
0	167.29	214.87	47.58	119.72	119.85	0.1287	2.705
3	168.72	221.91	53.19	115.62	115.76	0.1412	2.655
5	167.45	213.69	46.24	118.32	118.43	0.1103	2.385
10	154.11	199.91	45.8	122.42	122.49	0.0674	1.472
12	167.61	215.84	48.23	78.49	78.52	0.0302	0.626
14	153.84	219.1	65.26	115.61	115.64	0.0360	0.551
Blank	170.82	271.01	100.19	88.84	88.84	0.0001	0.001
QC1	168.52	188.536	20.01	66.72	66.74	0.0181	0.904
QC1+ Spike	167.73	187.99	20.26	115.37	115.39	0.0202	0.997



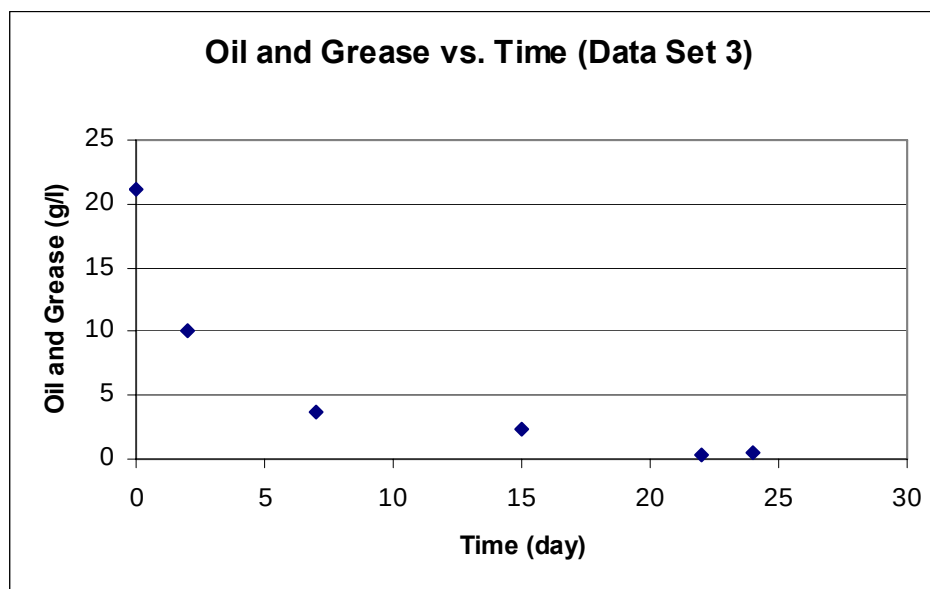
Oil and Grease Data set 2

Oil and Grease vs. Time Set 3

Date	Initial W	Final W	Volume (ml)	Flask I	Flask F	Mass (mg)	Concen (g/l)
0	172.29	204.09	31.8	106.93	107.61	0.6726	21.151
2	168.52	207.68	39.2	120.1	120.49	0.3972	10.144
7	167.73	196.95	29.2	66.719	66.826	0.1072	3.669
15	171.88	201.74	29.9	110.95	111.02	0.0704	2.358
22	169	221.28	52.3	93.483	93.499	0.0158	0.302
24	167.57	260.47	92.9	92.888	92.927	0.039	0.420
Blank	171.89	272.99	101.1	88.8421	88.842	0.0001	0.001
QC1	154.27	175.63	21.4	86.8300	86.877	0.0467	2.186
QC1+ Spike	173.30	198.72	25.4	78.423	78.49	0.0665	2.616

Spike 200.00 mg/l

EQ 2 Method 1664 = 107.4 %



Oil and Grease Data set 3

Oil and Grease vs. Time Set 4

Date	Initial W	Final W	Volume (ml)	Flask I	Flask F	Mass (mg)	Concen (g/l)
0	168	240.86	72.86	78.2417	78.7856	0.5439	7.465
2	167.34	217.45	50.11	86.8302	87.0491	0.2189	4.368
4	169.49	219.66	50.17	86.5782	86.7658	0.1876	3.739
6	166.62	216.6	49.98	88.8066	88.9574	0.1508	3.017
8	167.51	218.21	50.7	88.4222	88.545	0.1228	2.422
10	167.9578	191.3985	23.4	78.183	78.2201	0.0371	1.583

Experimental Data for Non-linear Model

Day	$\mu_{\max}$ (d ⁻¹)	O&G (g/l)	S Solids (g/l)	S ₀ (g/l)	RN
1	0.6748	2.705	0.61	2.705	1
3	0.6748	2.655	0.61	2.705	1
6	0.6748	2.645	0.61	2.705	1
10	0.6748	1.908	0.61	2.705	1
12	0.6748	0.626	0.61	2.705	1
14	0.6748	0.551	0.61	2.705	1
16	0.6748	0.475	0.61	2.705	1
19	0.6748	0.604	0.61	2.705	1
0	0.6748	1.378	0.653	1.378	2
3	0.6748	0.81	0.653	1.378	2
5	0.6748	0.697	0.653	1.378	2
7	0.6748	0.514	0.653	1.378	2
9	0.6748	0.485	0.653	1.378	2
11	0.6748	0.44	0.653	1.378	2
0	0.6748	21.151	1.38	21.151	3
2	0.6748	10.144	1.38	21.151	3
7	0.6748	3.669	1.38	21.151	3
15	0.6748	2.358	1.38	21.151	3
22	0.6748	0.302	1.38	21.151	3
24	0.6748	0.42	1.38	21.151	3
0	0.6748	7.465	0.305	7.465	4
2	0.6748	4.368	0.305	7.465	4
4	0.6748	3.739	0.305	7.465	4
6	0.6748	3.017	0.305	7.465	4
8	0.6748	2.422	0.305	7.465	4
10	0.6748	1.583	0.305	7.465	4

Non-Linear Fit for Determining the Biological Kinetics

JMP 6.0 Output for non-linear fit for the determination of the biological kinetics values for data Table 5.4 using equation 5.6.

Nonlinear Fit

Response: Day, Predictor: Model, Group: Data Set

Control Panel

Criterion	Current	Stop Limit
Iteration	2	60
Obj Change	1.449229e-13	1e-15
Relative Gradient	2.0060766e-7	0.000001
Gradient	4.6673428e-7	0.000001

Parameter	Current Value	Lock	
K	41.344424038	☒	SSE 727.56770071
Y	0.1020171628	☒	N 26

Edit Alpha 0.050

Convergence Criterion 0.00001

Goal SSE for CL 856.701184

Solution

	SSE	DFE	MSE	RMSE
	727.56770071	24	30.315321	5.5059351

Parameter	Estimate	ApproxStdErr	Lower CL	Upper CL
K	41.344424038	33.2397931	30.5434383	52.1454098
Y	0.1020171628	0.10283235	.	0.13760558

Solved By: Analytic NR

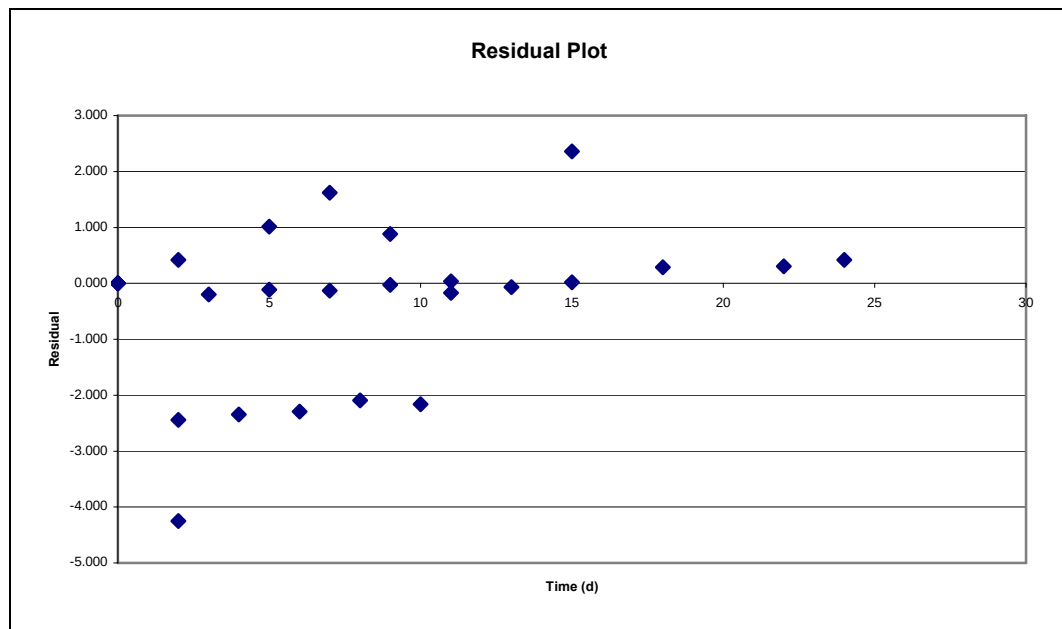
JMP 6.0 Analysis for Non-Linear Fit

Analysis Between Experimental Data and Model

Experimental data vs. Model

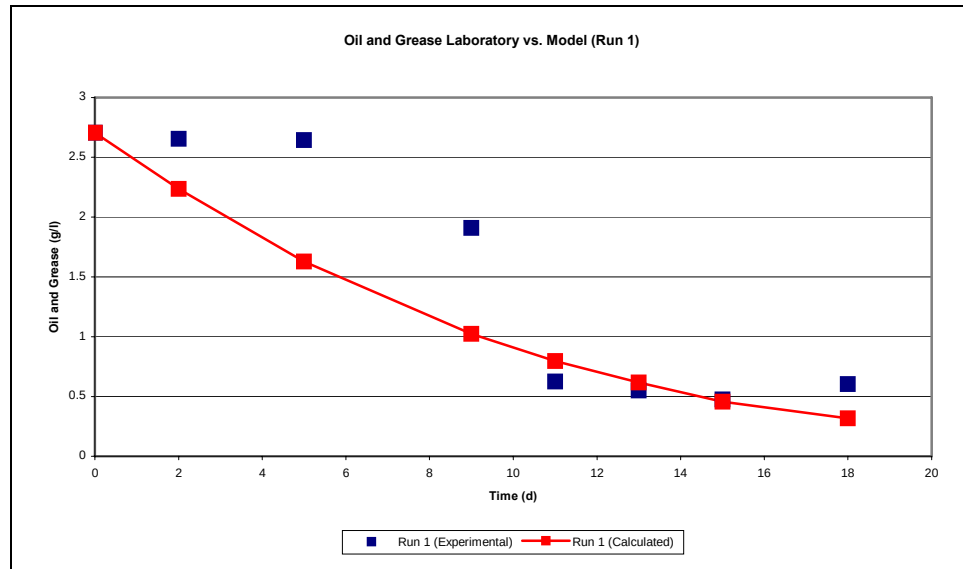
Run	Time (d)	O&G Experiment (g/l)	O&G Model (g/l)	Residual
1	0	2.705	2.705	0.000
1	2	2.655	2.234	0.421
1	5	2.645	1.629	1.016
1	9	1.908	1.023	0.885
1	11	0.626	0.798	-0.172
1	13	0.551	0.618	-0.067
1	15	0.475	0.456	0.019
1	18	0.604	0.318	0.286
2	0	1.378	1.378	0.000
2	3	0.81	1.007	-0.197
2	5	0.697	0.809	-0.112
2	7	0.514	0.646	-0.132
2	9	0.485	0.512	-0.027
2	11	0.44	0.405	0.035
3	0	21.151	21.151	0.000
3	2	10.144	14.396	-4.252
3	7	3.669	2.049	1.620
3	15	2.358	0.000	2.358
3	22	0.302	0.000	0.302
3	24	0.42	0.000	0.420
4	0	7.465	7.465	0.000
4	2	4.368	6.809	-2.441
4	4	3.739	6.082	-2.343
4	6	3.017	5.308	-2.291
4	8	2.422	4.517	-2.095
4	10	1.583	3.745	-2.162

Residual Plot for Experimental Data vs. Model

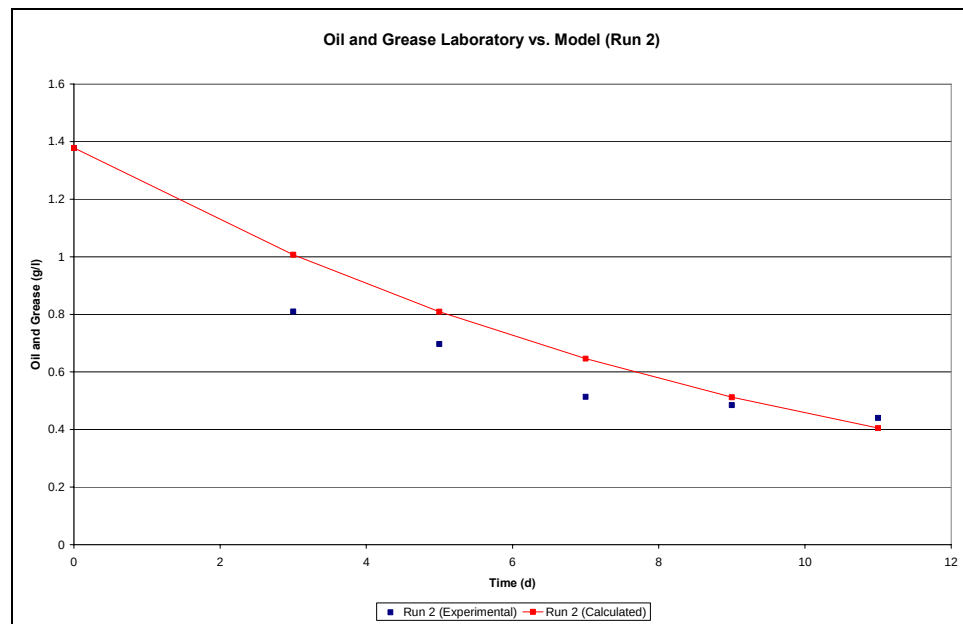


Residual Plot for the Experimental Data vs. Model

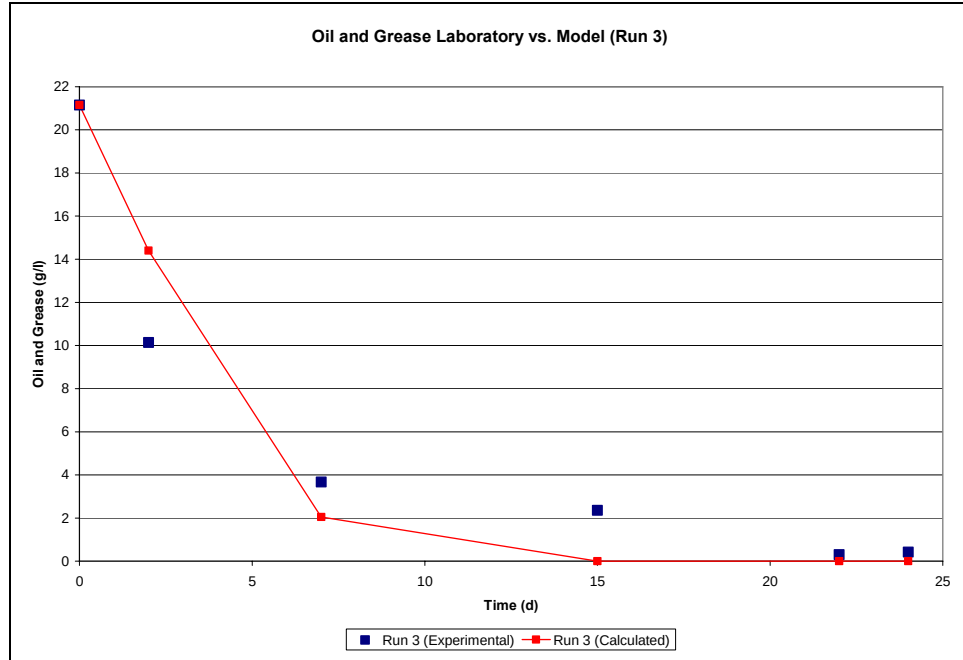
Figure Analysis between Experimental Data and Model



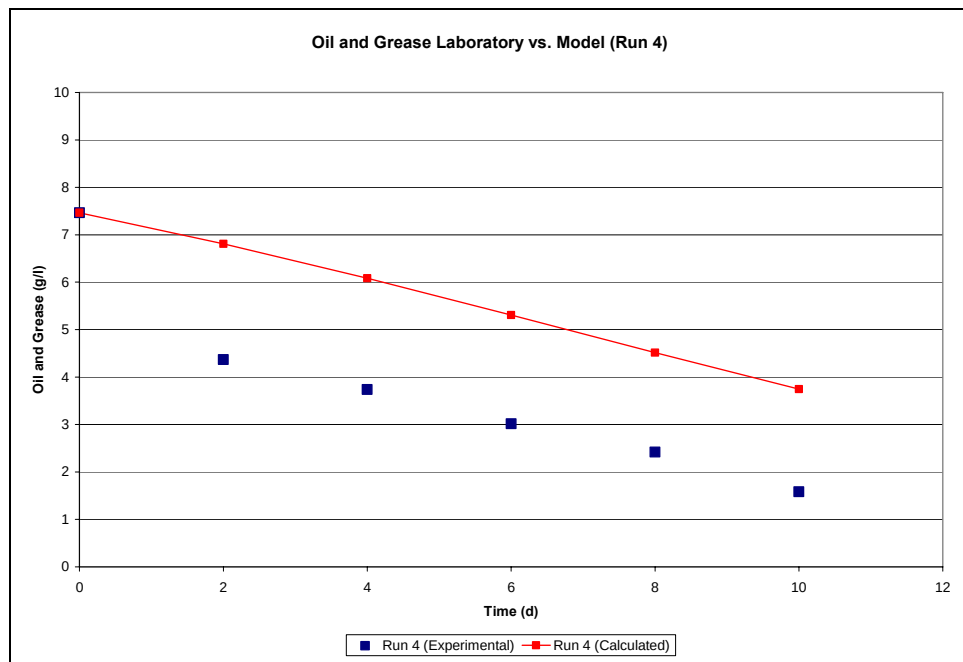
Oil and Grease Laboratory vs. Model (Run 1)



Oil and Grease Laboratory vs. Model (Run 2)



Oil and Grease Laboratory vs. Model (Run 3)



Oil and Grease Laboratory vs. Model (Run 4)

Determination for the Linear Fit for Determining Variables for Final DAF model

Y₁: Summaries of Fit for Response Variables for suspended solid concentration in the subnatant

Summary of Fit for Log (Y₁)

RSquare	0.852647
RSquare Adj	0.80164
Root Mean Square Error	0.200352
Mean of Response	5.76888
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	6.0390928	0.67101	16.7163
Error	26	1.0436672	0.040141	Prob > F
C. Total	35	7.08276		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-1.922949	4.490591	-0.43	0.672
X1&RS	-0.0006	0.078504	-0.01	0.994
X2&RS	0.2416761	0.067693	3.57	0.0014
X3&RS	0.0005955	0.000715	0.83	0.4126
X1*X1	-0.000485	0.000708	-0.69	0.4994
X1*X2	0.0018733	0.000501	3.74	0.0009
X2*X2	-0.004779	0.000708	-6.75	<.0001
X1*X3	-2.66E-06	2.83E-06	-0.94	0.3564
X2*X3	8.29E-06	2.83E-06	2.93	0.007
X3*X3	-4.36E-08	3.38E-08	-1.29	0.208

Y₂: percentage of recovery

Summary of Fit for Y₂

RSquare	0.825518
RSquare Adj	0.765121
Root Mean Square Error	0.740557
Mean of Response	96.22222
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	67.463186	7.49591	13.6681
Error	26	14.259036	0.54842	Prob > F
C. Total	35	81.722222		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	129.95482	16.59845	7.83	<.0001
X1&RS	-0.039699	0.290172	-0.14	0.8922
X2&RS	-1.030379	0.250211	-4.12	0.0003
X3&RS	-0.002712	0.002644	-1.03	0.3145
X1*X1	0.0018333	0.002618	0.7	0.49
X1*X2	-0.00575	0.001851	-3.11	0.0045
X2*X2	0.0150833	0.002618	5.76	<.0001
X1*X3	7.24E-06	1.05E-05	0.69	0.4957
X2*X3	2.05E-06	1.05E-05	0.2	0.8461
X3*X3	1.37E-07	1.25E-07	1.1	0.282

Y₃: Air to solid ratio

Summary of Fit for Y3

RSquare	0.992321
RSquare Adj	0.989662
Root Mean Square Error	0.040671
Mean of Response	1.180255
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	5.5572062	0.617467	373.2962
Error	26	0.0430065	0.001654	Prob > F
C. Total	35	5.6002127		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-6.519959	0.911569	-7.15	<.0001
X1&RS	0.0225525	0.015936	1.42	0.1689
X2&RS	0.0076284	0.013741	0.56	0.5835
X3&RS	0.0011987	0.000145	8.26	<.0001
X1*X1	0.000000075	0.000144	0	0.9996
X1*X2	0.0008359	0.000102	8.22	<.0001
X2*X2	-0.000000005	0.000144	0	0.9997
X1*X3	-0.00000237	5.751E-07	-4.12	0.0003
X2*X3	-0.00000209	5.751E-07	-3.64	0.0012
X3*X3	-5.276E-08	6.855E-09	-7.7	<.0001

Y₄: Rise Rate

Summary of Fit for Y4

RSquare	0.828796
RSquare Adj	0.769533
Root Mean Square Error	0.161903
Mean of Response	0.583056
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	3.2992401	0.366582	13.985
Error	26	0.6815238	0.026212	Prob > F
C. Total	35	3.9807639		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	12.537346	3.6288	3.45	0.0019
X1&RS	-0.032241	0.063438	-0.51	0.6156
X2&RS	-0.150317	0.054702	-2.75	0.0108
X3&RS	-0.001855	0.000578	-3.21	0.0035
X1*X1	-0.000304	0.000572	-0.53	0.5997
X1*X2	0.0018812	0.000405	4.65	<.0001
X2*X2	0.0001208	0.000572	0.21	0.8345
X1*X3	2.661E-07	0.000002289	0.12	0.9084
X2*X3	7.5873E-06	0.000002289	3.31	0.0027
X3*X3	7.6954E-08	2.729E-08	2.82	0.0091

Vita

Christian Seal was born on January 2, 1975 in Santiago, Chile. He received his B. S. Degree in Civil Engineering at Universidad de Santiago de Chile, Chile. He started his Doctorate program in Civil & Environmental Engineering Department at The University of Tennessee in January 2002 supported by a Graduate Research Assistantship from the Department of Civil & Environmental Engineering. His primary research work was in treatment of grease-trap waste by biological treatments.