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Biological treatment of heavy metals using sulfate-reducing bacteria.

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BIOLOGICAL TREATMENT
OF HEAVY METALS
USING SULFATE REDUCING BACTERIA

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ABSTRACT

The use of sulfate reducing bacteria, SRB, showed promising results in removing heavy metals partly by sulfides precipitation and partly by biosorption, simultaneously, in upflow anaerobic fixed film reactors, UAFFRs, for different hydraulic retention times, HRTs. The SRB were capable to grow optimally under certain growth conditions for each HRT by utilizing lactate as organic carbon source. The mathematical relations for design of UAFFR for optimum metal removal for different hydraulic retention times, HRTs, have been developed.

The first phase (Phase I) of this research studied the occupation and productivity of SRB in the entire reactor height for different hydraulic retention times, HRTs. They were found in almost constant concentrations in the entire height and different for different HRTs, which proves that growth of SRB was achieved in the lowest region (upto 0.3 m) . Also, the sulfide concentration were found different at different heights and different for different HRTs, which concludes that the production of sulfide was attained all along the reactor height. A mathematical equation has been developed to correlate the sulfide productivity to different reactor heights.

In the second phase (Phase II), the performance of SRB in removing heavy metal at different HRTs was studied. Copper was applied in different concentrations, for each HRT, until complete failure of the reactor. The 18 h HRT reactor was capable to remove 90% of over 200 mg/L influent copper, 85% of over 300 mg/L influent copper and 80% of over 400 mg/L influent copper. Whereas, the 9 h HRT reactor removed 87% of over 200 mg/L influent copper, 75% of over 300 mg/L influent copper and 67% of over 400 mg/L influent copper.

KEY WORDS: Sulfate reducing bacteria; Upflow anaerobic fixed film reactor; Theoretical oxygen demand; Sulfate loading rate; Organic loading rate; Lactate; Hydraulic retention time; Heavy metal removal; Biosorption; Sulfide production; Total solids; Volatile solids; Suspended Solids: Volatile suspended solids; Metal precipitation by sulfide.

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Chapter 1: INTRODUCTION

The search for an appropriate, inexpensive, easy to operate and maintain and highly efficient method to treat industrial wastes is always on and picking up high momentum as the twenty first century is in the sight. The presence of heavy metals in the wastes causes many problems as high concentrations of heavy metals have been known to be toxic and carcinogenic to living organisms. Therefore, their discharge to the environment poses a serious problem and has to be handled properly.

In order to minimize the environmental damages caused by heavy metals, presently, the international regulating agencies have established the following limits for the maximum allowable heavy metals when discharged into the water bodies. In future, they will be setting further lower limits to control the environmental damage to the water bodies in the twenty first century. So, lot of research on controlling the concentrations of heavy metals is continuing all the times.

Table 1.1 : The Maximum Permissible Limits for Heavy Metals discharged to Water Bodies (Lappan, 1987)

Metals	Concentration (mg/L)
Cadmium	0.0001
Chromium	1.0
Copper	1.0
Lead	1.0
Nickel	1.0
Zinc	1.0

The main sources of the heavy metals discharged into the municipal wastewaters or natural water bodies are industries such as electroplating, petroleum refining, fertilizers manufacturing, basic steel works, basic non-ferrous metal works, automobile manufacturing, and aircraft plating and finishing. Copper is reported to contribute significantly from pulp and paper mills, paperboard mills, and building paper and board mills. Inorganic chemicals industries are sources for cadmium. The typical concentrations of these heavy metals range from 2 mg/L to 300 mg/L in some of these industrial wastewaters (Paterson *et al.*, 1975).

Due to low permissible concentrations of heavy metals in the effluents from the wastewater, it has become important to optimize wastewater treatment for metal removal. There are different methods available to remove these heavy metals. The prime factors to be considered in choosing one of these methods are the economic considerations, availability of the raw materials, and regulatory requirements.

Basically, there are two techniques for metal removal: Recovery and Solid Removal. Recovery techniques are treatment methods used for the purpose of recovering or regenerating process constituents which would otherwise be lost in the wastewater or discarded. Included in these groups are evaporation, ion-exchange, electrolytic recovery, electrodialysis and reverse osmosis (Cherry, 1982).

Solid removal techniques are employed to remove metals and other pollutants from process wastewaters, to make water suitable for reuse or discharge. These methods include hydroxide and sulfide precipitation, sedimentation, diatomaceous earth filtration, membrane filtration, granular bed filtration, peat adsorption, insoluble starch xanthate treatment and flotation (Cherry, 1982). In addition, chemical coagulation with lime, chemical oxidation and reduction and activated carbon adoption have been proposed (Patterson *et al*, 1975). The most common and successful method of reducing heavy metal concentrations in solutions is chemical precipitation. Most metals are relatively insoluble as hydroxide, carbonate or sulfide and can be precipitated in one of these forms (McAnally *et al.*, 1984).

The common form is hydroxide precipitation in which lime or caustic is added to the wastewater to produce an alkaline pH. The metal hydroxide precipitates are thus formed and settled down, and a supernatant with a low metal concentration is produced. However, precipitation of metals by sulfides has proven to be one of the preferred methods because of the following disadvantages of other physical/chemical methods:

.Large volumes of sludge are produced in other methods, specially with hydroxide precipitation which is characterized by its poor filterability due to the gelatinous nature of metal hydroxide.

.For maximum efficiency of other methods, certain pre- or post- treatments are required and this increases the total cost.

.Hydroxide precipitates tend to resolubilize if the solution pH is increased or decreased from their minimum solubility points. Thus, maximum metal removal efficiency will not be achieved unless the pH is controlled back within a specified narrow range.

.In case of Chromium, reduction of Cr^{-6} to Cr^{-3} must be accomplished prior to neutralization.

.Theoretical minimum solubilities for different metals occur at different pH values. The solubility products of metal hydroxide and carbonate are higher than that for the metal sulfide. This increases the chances for metals to be precipitated as sulfide than in any other form. Table 1.2 gives the values of the solubility products of these metals in various forms (Cherry, 1982).

On the other hand, sulfide precipitation has been proven to be a successful method for the treatment of heavy metals due to the following advantages:

.High metal removal efficiency can be achieved with sulfide precipitation because of their much lower solubilities, as shown in Table 1.2.

.Sulfide will precipitate metals complexes with the most complexing agents.

.Sulfide have the ability to remove chromate and dichromate from the wastewater without requiring the reduction of chromium to its trivalent state.

.Sulfide precipitates exhibit less of an amphoteric nature than the corresponding hydroxide precipitates, and hence have a less tendency to resolubilize.

.Lower sludge volumes are produced with this treatment.

Table 1.2 : The Molar Solubility Products, K_s, between 18 ^{0}C and 25 ^{0}C. (Cherry, 1982)

Compounds	K_s
$Cu(OH)_2$	1.0×10^{-19}
$Ni(OH)_2$	6.5×10^{-18}
$Pb(OH)_2$	3.0×10^{-16}
$Zn(OH)_2$	1.2×10^{-17}
$CuCO_3$	1.0×10^{-10}
$NiCO_3$	6.6×10^{-9}
$PbCO_3$	3.3×10^{-14}
$ZnCO_3$	1.4×10^{-11}

Cu_2S	3.0×10^{-48}
CuS	6.0×10^{-36}
NiS	1.0×10^{-28}
PbS	1.0×10^{-28}
ZnS	2.0×10^{-24}

Some studies have reported that the disadvantage of sulfide precipitation treatment methods are the high cost of the chemical sulfide precipitant, generally sodium sulfide, and hydrogen sulfide generation. The former could be overcome by using anaerobic sulfate reducing bacteria (SRB) for the sulfide production from sulfate inside the reactor. A study conducted by Wong *et al.* (1985), attempted to remove heavy metals from sewage sludge by utilizing sulfide oxidizing and sulfate reducing bacteria to precipitate metals from the wastewater (Fig. 1.1). The achieved metal removal efficiency was high, greater than 90%. Furthermore, simultaneous biosorption of heavy metals by SRB had also assisted in increasing the efficiency and speed of metal removal.

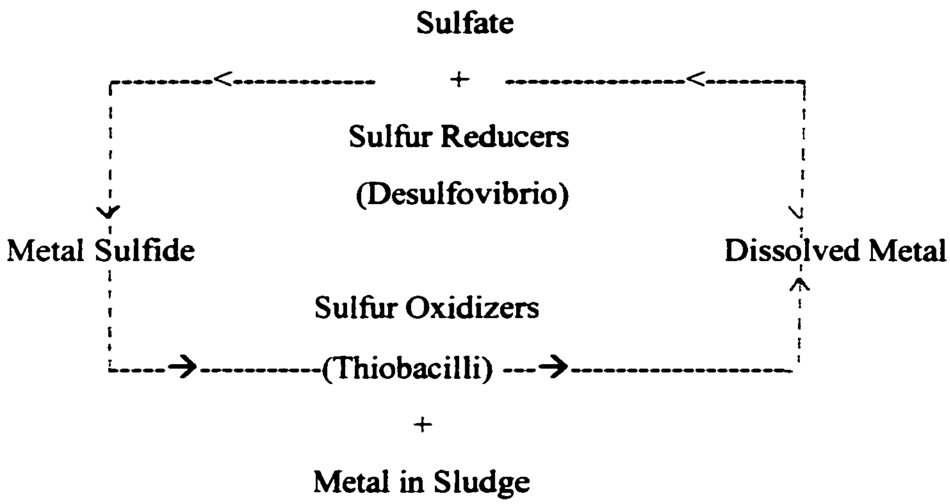


Figure 1.1 : Biological sulfur reduction/sulfide oxidation process and their relationship to metals. (Wong *et al.*, 1985)

The simple principal in the use of biological treatment for the removal of heavy metals and some of the accompanied organic matter is dependent mainly on the appropriate environment for the presence and the growth of the SRB. The SRB grow and utilize the sulfate, seeded with an organic substrate, and reduce them into sulfide. The sulfide produced in this bioreaction react with the heavy metals in the influent wastes and produce fast settling precipitates. In addition, significant quantity of heavy metals are removed by biosorption on the biomass.

1.1 Objective

Sulfide is the major constituent that removes the heavy metal by precipitating it as metal sulfide, whereas biosorption aids the metal removal rate and hence increases the efficiency of metal removal needed to achieve permissible limits for heavy metals discharged to water bodies established by the ministry of the environment/international regulating agencies.

The objective of this research was to investigate the removal of selected heavy metal from the synthetic wastewater using sulfate reducing bacteria (SRB), which were developed and maintained from the canal of an industrial unit, in the upflow anaerobic fixed film reactor (UAFFR) and to optimize the SRB production and hence reactor's performance. The optimization of reactor's performance was done with respect to biosorption and sulfide production. The study also focused on finding the maximum loading rate of the heavy metal that sulfate reducing bacteria (SRB) can tolerate, for the different specified reactor's hydraulic loading rates, without sacrificing removal efficiencies.

1.2 Scope of Work

Lactate was used as organic matter to develop and maintain sulfate reducing bacteria (SRB) in an upflow anaerobic fixed film reactors (UAFFRs). The scope of the study involved:

(1). Establishing the highest concentration of sulfide precipitant using the established optimum parameters required by the sulfate reducing bacteria (SRB) for the various reactor's hydraulic retention times, HRTs.

(2). Establishing the maximum limit of the heavy metal loading rate which the reactor can treat satisfactorily for the various HRTs without affecting SRB's growth.

(3). Determining the efficiencies of biosorption and soluble metal precipitation at different metal loading rates for various/different HRTs.

(4). Studying the variation in SRB activity along the reactor's height to establish the effective working reactor heights at various/different hydraulic retention times optimum biosorption on the sulfate reducing bacterial biomass and optimum sulfide production.

(5). Studying the metal removal by biosorption on the sulfate reducing bacterial biomass and determine its maximum capacity for various/different filter speeds.

Chapter 2 : LITERATURE SURVEY

2.1 General

The environmental effects of metals in water and wastewater range from beneficial through troublesome as heavy metals are dangerously toxic to most of the organisms and cause serious problems in the environment. Some metals are essential, others may adversely affect water consumers, wastewater treatment systems, and receiving waters, depending on their concentration (APHA, AWA & WPCF, 1995). These metals may be present both in solution and in suspension. This has led to the investigation of possible ways to remove the heavy metals from the wastewaters, prior to discharging them to the natural water bodies. This review covers the biosorption of metals on sulfate reducing bacterial biomass and conversion of sulfate into sulfide by the same SRB, in upflow anaerobic fixed film reactors, UAFFRs, which in turn can precipitate heavy metals as metal sulfides according to the following reactions:

$$C_2H_5COO^{-1} + SO_4^{-2} \rightarrow HS^{-1} + 2HCO_3^{-1} \rightarrow S^{-2} + H_2O + CO_2 \qquad (2.1)$$

$$S^{2-} + M^{2-} \rightarrow MS \qquad (2.2)$$

Toxicity has been defined as the reaction of a substance, or a combination of substances reacting with each other, to inhibit the metabolic process of cells without completely altering or destroying them in a particular species under a given set of physical and biological environmental conditions for a specified concentration and time of exposure (Bewtra and Biswas, 1990). Most heavy metals, e.g., copper, zinc, lead, nickel, chromium, cadmium, silver, mercury, uranium, and vanadium are toxic to aerobic and anaerobic biological processes, even at very low concentrations as shown in Table 2.1 (Bewtra and Biswas, 1990).

Table 2.1 : Heavy Metals Concentrations Inhibitory to Biological Processes

Pollutant	Concentration (ug/L)	
	Aerobic	Anaerobic
Cu	1.0	1.0
Zn	5.0	5.0
Cr^{6+}	2.0	5.0
Cr, total	5.0	5.0
Ni	1.0	2.0
Pb	0.1	NA*
Cd	NA*	0.02

*: Insufficient Data

Investigations regarding the toxic effects of heavy metals on anaerobic digestors are dated as far back as the 1920's. Lawrence and McCarty (1965), found biogas production by anaerobic digestors under high heavy metal loading was dependent on the presence of sulfate, the precursor used by sulfate reducing bacteria (SRB) for sulfide production. Sulfide precipitated the toxic heavy metal ions which were present in the influent wastewater.

Cheng *et al.*, (1975) and Elenbogen *et al.*, (1985) studied the heavy metals uptake by activated sludge. Cheng reported that activated sludge treatment reduced influent levels of iron, copper, lead, nickel and zinc by 30% to 90%. At lower influent metal concentrations, metals were taken up by the biofloc through the formation of metal-organic complexes. It was postulated that at higher metal concentrations, metal ion precipitations from solution might occur in addition to the sludge uptake.

Thomas and Theis (1978) studied the distribution of heavy metals in an anaerobic sludge stabilization digestor. Their experiments confirmed Lawrence and McCarty's observations of metal influence on biogas production. In addition, it was demonstrated that high metal loadings caused a drop in the percentage of methane in the biogas and subsequent accumulation of intermediate organic acids within the reactor. This accumulation was less at shock loadings because of rapid toxification of all active bacterial forms in the digestor. Further testing gave results which allowed the ranking of the metals in order of toxicity on a mass by mass or molar basis. Nickel was the most toxic, while copper, lead, chromium, zinc and cadmium followed in order of toxicity (Ni > Cu > Pb > Cr > Zn > Cd). In general, heavy metals removal from digestor supernatant was greater than 95%. It was concluded that heavy metals chemistry was controlled not only by the solubility of inorganic precipitates but also by the ability of digestor bacteria to concentrate metal ions around the cell walls through complexation with proteins and acid groupings (sorption) that served as the binding sites. Controls for minimizing the impact of heavy metals in anaerobic digestor were those which resulted in a reduced degree of metal association with the biomass. Thus, microbial uptake assisted sulfide precipitation in removing heavy metals from the wastewater supertanant.

Chian and Dewalle (1977) studied the heavy metal removal efficiency of a completely mixed anaerobic filter. It was found that the filter was effective and the effectiveness of the removal of heavy metals increased with the increase in the influent metal concentration. The total metal removals in the filter were also a function of the rate of inflow and hydraulic retention time (HRT). Total metal removals generally decreased when the HRT decreased due to the increase in suspended solids and associated metals in the effluent. However, soluble metal removals were independent of the reactor's HRT. It was concluded that the metals were precipitated as sulfide, carbonate and hydroxide; and were removed in the lower 500 mm of the filter. At pH of less than 7, the sulfide determined the soluble heavy metal concentrations, where as at higher pH values, carbonate dominated the soluble concentrations (precipitation). Additional experiments also proved that the process could separate heavy metals from a fatty acid wastewater stream which contained high levels of heavy metals.

Paterson *et al.* (1975) investigated optimum carbonate precipitation and it was concluded that there was no benefit in using carbonate precipitation for zinc or nickel to reduce either the soluble metal concenteration below that obtained by hydroxides or to obtain treatment equivalent to that obtained by hydroxides. At lower pH, the minimum concenteration with either system was 0.25 mg/L for zinc at pH = 9.5 and about 0.3 to 1.0 mg/L for nickel at pH = 11.

Rivera (1983) found the Freudlich-type equation useful in modeling the separation of heavy metals in a packed bed upflow anaerobic fixed film reactor (UAFFR). High cell sorption and the precipitation of metals as sulfide and carbonate were concluded as being the mechanisms for metal separation. Overall, the process was described as operating like an ion exchange column. The reactor was fed with a wastewater containing nutrient broth and glucose having high 2000 mg O_2/L of COD and 75 mg SO4/L of sulfate. Removal efficiencies for soluble zinc were greater than 95% when the influent concentration was 100 mg/L, about 90% for 300 mg/L and about 85% for 1000 mg/L.

Lewandowski (1987) developed a model for the influence of toxic compounds on the biological processes in wastewater treatment reactors. The model can predict the behavior of reactors influenced by toxic compounds acting as non-competitive inhibitors. The effect of a toxic compound on the process was quantified in terms of the inhibition coefficient, K_i, for the compound and the reactor resistance to the inhibition values. The proposed model was utilized for the analysis of data obtained in a packed bed reactor for denitrification in the presence of Cr^{+6}. The inhibition coefficient for chromium was found to be 1.2 mg Cr^{+6}/L and the reactor resistance to inhibition was 2.9 mg Cr^{+6}/L.

Maree and Strydom (1985) employed a UAFFR for the treatment of mine water with high sulfate but low metal levels. The optimum operating retention time was 11 hours when a stone packing was used. Speciation of effluent sulfur compounds indicated that sulfide were the prime metabolic end products existing at levels seldom exceeding 100 mg/L as S^{2-} while sulfite were typically less than 4.2 mg/L as SO_3.

Lappan (1987) studied the heavy metal removals using sulfate reducing bacteria (SRB) in the upflow anaerobic fixed film reactor (UAFFR). SRB were able to generate sulfide which would react with heavy metals to produce metal sulfide precipitates. It was found that soluble metal removal efficiencies were not a function of HRT when excess sulfide were present. However, total metal separation efficiencies depended on the reactor's HRT. Total metal removals in terms of separation efficiency were Cu > Zn > Ni > Pb.

The basic soluble sulfide dissociation versus pH showed that at pH = 7, 50% of soluble sulfides exist as H_2S and 50% exist as HS^{-1}. As the pH increases to 8, the HS^{-1} in soluble sulfide exceeds H_2S with less than 10% of soluble sulfide exist as H_2S with more than 90% as HS^{-1}. While at pH=6, the H_2S in soluble sulfide exceeds HS^{-1} with almost 97% of soluble sulfide exist as H_2S. Fig. 2.1 shows the proportions of H_2S, HS^{-1} and S^{-2} at different pH values.

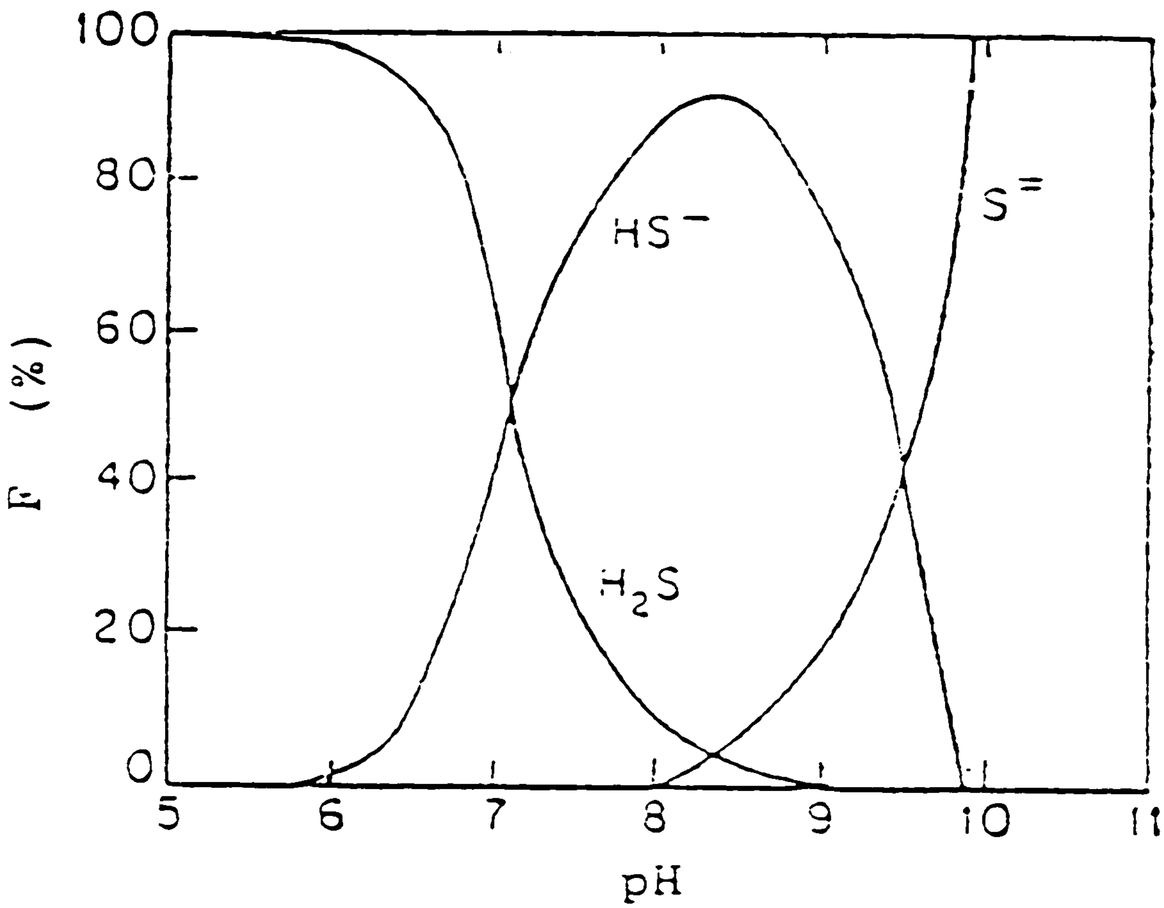


Figure 2.1: Proportions of H_2S, HS^{-1} and S^{-2} at Different pH Values

2.2 Bioleaching of Heavy Metals from Sludge

Sreekrishnan *et al.* (1993) studied the bioleaching of heavy metals from sewage sludge through indigenous sulfur oxidizing bacteria. Metal contents upto 4% of sludge could be removed from the sludge by lowering the pH by addition of acids or by the production of acids via microbial actions.

2.3 Biosorption

Microbial biomass has been shown to be able to sequester a variety of metal ions from aquatic solutions. The selective extraction of metal ions from dilute complex solutions by microbial biomass has been termed biosorption (Tsezos and McGready, 1991). Gram-positive bacteria, fungal cells and algal cells display a high affinity for heavy metals (Darnell *et al.*, 1986; Ross and Townsley, 1986). Langmuir and freundlich isotherms conform to the biosorption of metals to activated sludge solids (Mullen *et al.*, 1989).

Biosorption is caused by different physicochemical mechanisms, depending on the external environmental factors. Metal sequestration by different parts of the cell can occur via: complexation, coordination, chelation of metals, ion-exchange, adsorption, and inorganic-micro precipitation. Any one or a combination of the above mechanisms may be functional to various degrees in immobilizing one or more metallic species on the biosorbent. Metallic cations are attracted to negatively charged sites at the surface of the cell, a number of anionic ligands participate in binding the metal: phosphoryl, carboxyl, sulfhydryl, and hydroxyl groups of membrane proteins (Volesky, 1989).

Tsezos and Bill (1989) studied the adsorption and desorption of lindane, diazion, pentachlorophenol, and 2-chlorobiphenyl by living and dead activated sludge. A generalization concerning the relative magnitude of biosorptive uptake between live and dead biomass could not be made based on the experimental data. For contaminants which were not readily biodegradable, the overall uptake by live biomass appeared to be less than that by dead biomass. A part of the observed biosorptive uptake can be attributed to the cell walls of the microbial biomass.

Churchill *et al.* (1995) examined the biosorption of Cr, Cu, Ni and Co on prepared biomass (from two gram-negative and one-gram positive bacterial strains) using a batch equilibrium method. The binding of each metal by all three bacterial cells could be described by the freundlich sorption model. The general metal affinity observed was Cr > Cu > Ni > Co.

2.4 Advantages of Biological Treatment for Metal Removal

.It has economical advantage over other methods.

.Toxic substances have started appearing even in municipal WWTP normally designed for treating nontoxic substrate.

.It has shown resilience and diversity which makes it capable of degrading many of the toxic organic compounds produced by the industries.

The available information strongly indicates that immobilized biological systems are less sensitive to toxicity and have a higher efficiency in degrading toxic and hazardous materials (Bewtra and Biswas, 1990). Fixed-film wastewater treatment plants are regarded to be more stable than suspended growth processes because of the higher biomass concentration and greater mass transfer resistance from bulk solution into the biofilm in the fixed film. For the microbial growth kinetics, the Monod Equation has been used successfully to model the substrate degradation and microbial growth in the biological processes. However, in the presence of the toxic substances, which may inhabit the biological activity, the Haldane Equation is preferred:

Monod Equation:

$$u = \frac{u_{max} S}{S + K_s} \qquad (2.3)$$

Haldane Equation:

$$u = \frac{u_{max} S}{S + K_s + S^2/K_i} \qquad (2.4)$$

where,

u = specific growth rate, d^{-1}

u_{max} = maximum specific growth rate, d^{-1}

S = substrate concentration, mg/L

K_s = saturation constant, mg/L

K_i = inhibition constant, mg/L (It reflects, toxic substances react with S, destroying proteins).

2.5 Sulfate Reducing Bacteria

Domestic and industrial wastewaters contain several species of sulfur compounds, but only six species are thermodynamically stable at room temperature (ASCE, 1989):

.Sulfate, SO_4^{-2}

.Bisulfate, HSO_4^{-1}

.Sulfur, S^0

.Hydrogen Sulfide, H_2S

.Hydrosulfide, HS^{-1}, and

.Sulfide, S^{-2}.

Thiosulfate, polysulfide, and polythionate are unstable and are not found in significant concentrations. Many of the organic sulfur compounds, such as organic sulfur compounds, are volatile and possess unpleasant odors.

Sulfate reducing bacteria are responsible for the production of sulfides under anaerobic conditions. They utilize sulfates as their terminal electron acceptor. The respiratorial reaction followed by SRB is:

$$SO_4^{-2} + 8e^{-1} \rightarrow S^{-2} + 4O^{-2} \qquad (2.5)$$

Sulfide ion produced would be available to react with any metals present in the feed to form stable metal precipitates as expressed by the following reaction:

$$S^{-2} + M^{+2} \rightarrow MS \qquad (2.6)$$

where M^{2+} is any divalent metal ion (Brock, 1984).

A cyclic pathway of the SRB, postulated by Postgate (1984), is presented in Figure 2.2. The sulfate ions, outside the cell, are accumulated by a process which selenate inhibits competitively. Once inside, these react to form adenosine

SO_4^{-2} → → → enters cell → → → SO_4^{-2} + ATP ═ APS + PP → 2P

(outside the cell)

/

/ $2e^-$

/

SO_3^{-2} + AMP

/ /

/ / H^-

/

[$HS_2O_5^{-2}$]

/

/ $2e^-$

/

[$S_2O_4^{-2}$]

/

/ $2e^-$

/

S^{-2} ← ← ← $2e^-$ ← ← ← $S_2O_3^{-2}$ ← ← ← $2e^-$ ← ← ← $S_3O_6^{-2}$

(outside the cell)

Figure 2.2 : A Possible Cyclic pathway for Dissimilatory Sulfates Reduction (Postgate, 1984)

phosphosulfate (APS) and pyrophosphate (pp), a reaction which only proceeds to the right because the pyrophosphate is removed as inorganic phosphate. APS is reduced to sulfite, $SO3^{-1}$, and sulfite dehydrates to metabisulfite, $HS_2O_5^{-2}$, which is reduced via intermediates to give trithionate, $S_3O_6^{-2}$. This is reductively split to give thiosulfate and to regenerate some sulfite; the thiosulfate is reduced to give sulfide and more sulfite.

There are eight genera of the dissimilating sulfate reducing bacteria, SRB, and they categorized into two broad groups (Brennan, 1991):

.Desulfovibrio genera : - Capable of utilizing lactate, pyruvate, ethanol or certain fatty acids as carbon and energy sources.

.Desulfotonaculum genera : - Specialize in the oxidation of fatty acids, particularly acetates.

The following reactions represent the overall metabolic reactions used by the Desulfovibrio subgroup (Postgate, 1984):

$$\underset{\text{(Lactate)}}{2CH_3CH(OH)COO^{-1}} + SO_4^{-2} \rightarrow \underset{\text{(Acetate)}}{2CH_3COO^{-1}} + 2CO_2 + 2H_2O + S^{-2} \qquad (2.7)$$

$$\underset{\text{(Pyruvate)}}{4CH_3COCOO^{-1}} + SO_4^{-2} \rightarrow \underset{\text{(Acetate)}}{4CH_3COO^{-1}} + 2H_2O + S^{-2} + 2H^{+1} \qquad (2.8)$$

$$\underset{\text{(Ethanol)}}{2C_2H_5OH} + SO4^{-2} \rightarrow \underset{\text{(Acetate)}}{2CH_3COO^{-1}} + 2H_2O + S^{-2} + 2H^{+1} \qquad (2.9)$$

The desulfotonaculum subgroup can only dissimilate acetate as follows:

$$\underset{\text{(Acetate)}}{CH_3COO^{-1}} + SO_4^{-2} \rightarrow H_2O + CO_2 + HCO_3^{-1} + S^{-2} \qquad (2.10)$$

There are other environmental conditions that affect the growth of SRB. The SRB are anaerobes and require anoxic conditions for significant growth. The redox potential must range from -150 to -250 mV. The SRB are either mesophyllic or thermophyllic and are limited to a pH range of 6 - 8 (Postgate, 1984).

Minerals are also required in the right measure for the growth of these SRB. These minerals can be separated into two main groups, macronutrients and micronutrients as per their quantity representation. They are used primarily for the formation of cell membrane, enzymes, phospholipid and nucleic acids. Table 2.2 represents the essential nutrients for the growth of SRB and their main groups.

Table 2.2 : Lists of essential macro- and micro- nutrients (Brennan, 1991).

Macronutrients	Micronutrients
Phosphorus (P)	Zinc (Zn)
Potassium (K)	Copper (Cu)
Magnesium (Mg)	Cobalt (Co)
Calcium (Ca)	Manganese (Mn)
Sodium (Na)	Molybdenum (Mo)
Iron (Fe)	

Maree and Strydom (1987) described the use of upflow packed bed reactor for the removal of sulfate by using molasses as organic carbon source. The sulfate were converted to sulfur via sulfide and molasses to bicarbonate. The SRB were responsible for the reduction of sulfate to sulfide:

$$SO_4^{-2} \rightarrow S^{-2} \qquad (2.11)$$

whereas, photosynthetic sulfur bacteria , PSB, oxidized sulfide to sulfur:

$$S^{-2} \rightarrow S^0 \qquad (2.12)$$

The process was accompanied by the precipitation of heavy metal sulfide and calcium carbonate. The reduction process was completed in 6 hours and consumed 1.2 mL molasses/g sulfate at optimum temperature of 31 ^{0}C.

Matsui *et al.* (1993) conducted experiments using a fluidized bed reactor on glucose decomposition with and without sulfates reduction. Glucose in the reactor was first decomposed into lactate and ethanol. Subsequently, lactate was decomposed into propionate and acetate, while ethanol into propionate, acetate and hydrogen. Sulfate reduction was related mainly to propionate and acetate decomposition. The stepwise reactions were modeled using either Monod expression or first order reaction kinetics and coefficient of kinetic equations were determined experimentally.

Maillacheruvu et al. (1993) used upflow anaerobic filters fed with acetate and propionate and completely mixed suspended growth reactors fed with acetate, propionate, lactate and glucose to investigate the effect of electron donor and reactor type on the interaction between SRB and MPB. Results indicated that organisms involved in the conversion of lactate and glucose into simpler products were not affected by sulfide toxicity. Levels of 60 to 75 mg S/L of H_2S and 150 to 200 mg S/L of dissolved sulfide caused stress in all suspended growth reactors. Up to 100 to 150 mg S/L of H_2S and 200 to 400 mg S/L of dissolved sulfide could be tolerated in lactate and glucose systems, although with diminished COD and sulfate removal. Anaerobic filters were observed to tolerate higher dissolved sulfide and higher hydrogen sulfide levels than suspended growth reactors.

2.6 Removal of Heavy Metals by Sulfate Reducing Bacteria

Gundry *et al.* (1989) reported that the removal of heavy metals could be achieved in biological treatments (aerobic and anaerobic) by the adsorption of metal ions on the biomass and/or the biologically mediated precipitation. Polymers produced by microorganisms have been shown to adsorb cations; similarly cell wall proteins contain anionic ligands which can adsorb cations. It was observed that lead, zinc, and copper had a high affinity for the biosorption, while nickel had a low affinity for the same. Biological reactions included both methane producing bacteria, MPB, and sulfur reducing bacteria, SRB, as shown below:

$$\text{MPB :-} \qquad CH_3COO^{-1} + H_2O \rightarrow CH_4 + HCO_3^{-1} \qquad (2.16)$$

$$\text{SRB :-} \qquad CH_3COO^{-1} + SO_4^{-2} \rightarrow HS^{-1} + 2HCO_3^{-1} \qquad (2.17)$$

Plexiglass anaerobic filters, utilizing SRB, and 80 mm x 600 mm size were studied for the removal of metals from nickel electroplating wastewater. At COD:TKN:P of 120:10:1 and HRT of 24 hours, anaerobic washed stones packed filters could achieve high nickel removal rates of 96 to 99%. The corresponding concentration in the feed ranged from 15 mg/L to 73 mg/L. The wastewater containing 80 mg/L of Ni and 210 mg/L of SO_4 was considered to be adequate and supported a culture provided carbon source was available for SRB to grow. Above this influent concentrations, the filter became deficient in sulfide.

Dvorak *et al.* (1991) used barrels and tanks filled with spent mushroom compost as pilot scale biological reactor systems to treat metal contaminated wastewater. Bacterial sulfate reduction allowed 95% of iron, zinc, manganese, nickel, and cadmium to precipitate as insoluble sulfides by reaction with bacterially generated hydrogen sulfide.

Wang (1993) investigated the possibility of isolating a strain of sulfate reducing bacteria, capable of reducing hexavalent chromium from electroplating sludge, by using anaerobic technique. The strain was a motile curved rod, possessing singly polar flagella. The cell was 0.5 to 0.8 um in length, non-sporing, non-capsules, gram negative, thus characterizing it as Desulfovibrio species. A high removal rate of 99.8% for Cr^{-6} was achieved.

2.7 The Reactor

The configuration and operation of reactor has significant influence on its performance. Young and Yang (1989) recommended that the primary performance parameter for upflow anaerobic filters was the hydraulic retention time, HRT. Type of media played a secondary role, and specific surface of about 100 to 140 m^2/m^3 was adequate for high performance. Reactor height above 3 m seemed to have little effect on the performance, at a given HRT, as long as media height was at least 2/3 of the total height. Organic loading rate should be less than 12 kg $COD/m^3.d$ and the media should be placed on the upper 2/3 of the reactor height. Wastes should be uniformly distributed across the inlet zone and orifices should be placed no more than 2 m apart (generally spacing of 1.0 m was preferred).

The following optimum parameters for the substrate fed to the upflow anaerobic fixed film reactor UAFFR were developed for SRB growth(Bayoumy, 1997):

.Optimum Th.O.D. to sulfate ratio of 1.5 to 2.25 was accomplished by keeping the organic loading constant at 6 kg/d/m^3, and changing the sulfate loading. The corresponding sulfide production and sulfate reduction were measured to observe the SRB growth.

.Optimum organic loading rate of 6 kg/d/m^3 was established by maintaining the optimum Th.O.D./sulfate obtained above and changing the OLR. The concentration of the organic carbon source was changed while the sulfate loading was changed accordingly. Sulfide production and sulfate reduction were used as indicators of bacterial growth.

.Optimum total nitrogen load of Th.O.D. : N of 20:1 was established by feeding the pretreated samples with different nitrogen loading. The total nitrogen loading was measured by the amount of nitrogen used in the feed as ammonium chloride. Since a lack of sufficient nitrogen can limit the growth of SRB, whereas higher loading may cause toxicity to the SRB due to ammonium ions. Sulfide production, sulfate reduction, pH, ORP were used as indicators of bacterial growth.

.Optimal total Phosphorus load of Th.O.D. : P of minimum 100:1 was established feeding the pretreated samples of different sulfide concentration with different phosphorus loading. Contrary to the case of nitrogen, there is only a minimum requirement of phosphorus in any bacterial growth and any higher phosphorus loading will cause no adverse effect. The total phosphorus load was measured by the amount of phosphorus applied in the feed as potassium Di-hydrogen phosphate and Di-potassium hydrogen phosphate. Sulfide production, sulfate reduction, pH, ORP were used as indicators of bacterial growth.

2.8 Effect of Heavy Metals on Reactors

Chian and Dewalle (1977) showed that the effectiveness of heavy metal removal in a completely mixed anaerobic filter increased with an increase of influent metal concentration. The metals were precipitated as sulfide, carbonate and hydroxide. Also, it was observed that the percent removal of total metals decreased with decrease in the HRT and was due to the increase in suspended solids and associated metals in the effluent.

Chang *et al.* (1986) conducted research to evaluate the toxic effect of Cd (5 to 20 mg/L) and Cu (1 to 50 mg/L) on a fixed-film biological reactor (RBC). Experimental results indicated that the biological treatment efficiency was not adversely affected by the presence of copper at a concentration of 10 mg/L or less; however, when it was increased to 25 mg/L and 50 mg/L, removal of dissolved organic carbon was reduced by 7 and 10% respectively. Toxicity also caused about 8% reduction in efficiency when Cd was either 5 or 20 mg/L. The major portion of dosed metal was effectively retained by the biofilm. The efficiency of metal removal in the treatment system varied from 85 to 95% for Cd and 30 to 90% for Cu, depending on their initial concentration.

Rivera (1983) analyzed 100, 300, 1000 mg/L of soluble zinc as zinc chloride complexed with sodium citrate in anaerobic flow reactor for various hydraulic retention times, HRTs. The overall removal efficiency of soluble zinc varied from 95 to 85%. Most of the metals were removed in the bottom of the column.

Dohanyos et al. (1985), based on their comparative study of the upflow anaerobic fixed film reactor, UAFFR, the downflow anaerobic fixed film reactor, DAFFR, and the upflow anaerobic sludge blanket reactor, UASBR, concluded that the UAFFR was less sensitive to inhibitors, lower temperature, and loading fluctuations.

Chapter 3: EXPERIMENTAL PROCEDURE

3.1 Experimental Set-Up

Similar set-ups were used while conducting experiments with lactate as substrate, and for metal removal. In all, three identical parallel reactors A, B, and C were used as shown in Fig. 3.1. Each line had the following components:

.Feed Container and Magnetic Stirring Device

.Peristaltic Pump

.Transparent Upward Anaerobic Fixed Film Reactor

.Effluent Sampler Unit

.Gas Effluent Valve

.Connecting Tubes

The substrate was pumped from the glass feed container to the bottom inlet of the reactor by means of a variable speed peristaltic pump. These pumps were calibrated at the beginning of the experiment and checked regularly. Calibration of the pumps was done by measuring the time required to collect a known volume of the reactor's effluent.

Each reactor was constructed from a transparent material, plexiglass. This helped in the observation of SRB growth and its distribution along the reactor height. The reactor had the following dimensions:

Overall Height	=	1300 mm
Distance between Inlet and Outlet	=	1220 mm
Internal Diameter	=	102 mm
Net Empty Working Volume	=	9.80 L.

Each reactor was filled with 15.9 mm polypropylene pall rings with a porosity of 90% to provide a void volume of 8.9 L. The reactors were kept air tight by using rubber stoppers and screws to control and close all the openings. Also, the reactors were kept inside a closed light-tight wooden chamber during operation, except when sampling, to prevent any possibility for photosynthetic sulfur bacteria to grow and disturb the required environment inside the reactors.

The effluent sampler used was made up of glass cylinder of 50 mm diameter and 250 mm height. Samples were collected from a controlled opening at the bottom. Another opening at 180 mm above bottom was also used during continuous flow. The total volume collected was 350 mL. The retention time inside the sampler unit ranged from 21.1 to 91.4 minutes and, since the HRT inside the reactor ranged from 9 to 40 hours, it was assumed that each sample was representative of the reactor's output.

Additional three outlet ports were added at different heights in each reactor to collect samples for analysis and to study the change in SRB activity with reactor's height. These outlets were equally spaced at 300 mm at height of 300, 600, and 900 mm measured from the bottom of reactor.

Since plastic tubing is considered to be inert to any chemical reaction, specially to the sulfide, all connecting tubes used in the set-up were made up of plastic. Tygon tubes were used for joints and inside the sampler unit. The entire apparatus was made either from glass or plastic to prevent corrosion. Fig. 3.1 displays a complete illustration of the whole system.

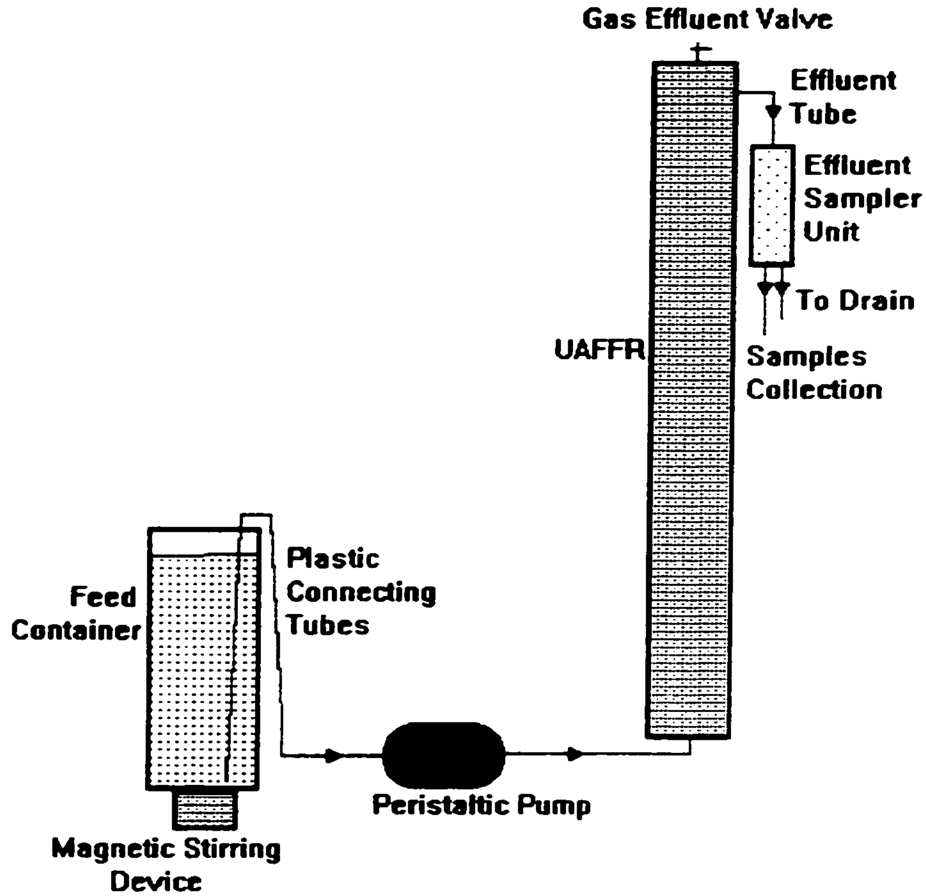


Figure 3.1 Experimental Set-Up

The experiments were conducted at room temperature which varied between 18 and 25 ^{0}C.

The flow chart describing the sequence in which experiments were conducted is represented in Figure 3.2.

Start:

PRELIMINARY STAGE 1 →→→ PRELIMINARY STAGE 2 A→→→
(Batch Reactors) (UAFFRs) /
/
/
PHASE II ←←← PHASE I ←←← PRELIMINARY STAGE 2 B←←
(UAFFRs) (UAFFRs) (UAFFRs)

end :

Fig. 3.2 : Flow Chart for Experimental Sequence.

3.2 Operational Parameters

There are several operational parameters that affect the performance of biological anaerobic fixed film reactors, seeded with sulfate reducing bacteria (SRB). These include hydraulic retention time (HRT), contact surface area, pH, temperature and oxidation- reduction potential (ORP). The bacterial growth depends on temperature, pH and redox potential whereas HRT additionally regulates the metal removal efficiency (Lappan, 1987).

3.2.1 Hydraulic Retention Time

Hydraulic retention time is the contact time between the wastewater and the biomass and is measured as the time required for any particle to pass through the reactor from the inlet to the outlet. The contact time affects the mass transfer and metabolic kinetic of the biomass. As a result, it influences the sulfide production. The decrease in HRT would decrease the sulfide production. Furthermore, the total heavy metal removal is also time dependent. It has been shown that the decrease in HRT would decrease the heavy metal removal efficiency, due to the decrease in the suspended solids and associated metals in the effluent (Lappan, 1987). However, the increase in HRT would prolong the time taken to treat the wastewater and increase the cost. Thus, the designed HRT should maintain a good reactor performance and be economically feasible.

Research was conducted to determine the most suitable HRT for the optimum performance of the UAFFR. The literature reports that a retention time in the range of 10 to 30 hours is most suitable. Lappan (1987) and Bayoumy (1997) showed that a retention time of about 11 hours was able to maintain the desired recommended bacterial growth and heavy metal separation, specially with SRB fed with lactate as organic carbon source. Maree and Styrdom (1985) indicated that at 6 hours, the sulfate reduction was too slow. During this research, the HRT of 9 hours, 18 hours during Phases I & II and 10 hours, 20 hours during Preliminary stages 1 & 2.

3.2.2 Contact Surface Area

The surface area represents the area available for the bacteria to adhere and be exposed to their substrate. In this study, packing materials of polypropylene pall rings were used to increase the surface area. The purpose of increasing the surface area was to retain more biomass, while maintaining sufficient contact between the biomass and the wastewater.

3.2.3 Temperature, pH and ORP

Postgate (1984) observed that the SRB were able to tolerate and grow in a temperature range of -5 to 75^0 C. In this research, the reactors were operated at the room temperature of 18 to 25^0 C. Postgate (1984) also showed that SRB could work successfully in a pH range of 5.0 to 8.0. In this research, the pH depended on the nature of substrate and was kept around 7.0.

Redox potential indicates the electron activity of the bacterial environment. An initial value of redox potential below -100 mV is desirable for the initiation of SRB growth (Postgate 1979). Sulfide, the product of sulfate reduction, can maintain redox potential below -150 mV (-150 to -250 mV).

3.3 Experimental Procedure

The main objective of this study was to establish the ideal environment to assure the best growth of sulfate reducing bacteria indicated by the highest sulfides production rate while providing the highest heavy metals and organic wastes removal rates. Consequently, the experiments were conducted in the following phases:

3.3.1 Preliminary Start-Up Experiments

Six 1.0 L flasks were seeded with a strain of bacteria from a sulfides-smelling wastewater sample for a suitable start up of the bacterial activities.

Preliminary Stage 1 :

The literature lacks information on the behavior of the SRB fed with the acetate for the activation and production of the same in the beginning. In the previous studies, the substrate was gradually switched to acetate after achieving the SRB growth and production as well as steady state conditions with other substrates. This, unnecessarily complicates the procedure if one wants to use acetate as a source of organic carbon for the SRB. Therefore, research was conducted with directly feeding acetate as a source of carbon in the substrate. Analyses of sulfide and sulfate were carried out during this stage to detect any change. Appendix II provides all the details and problems encountered in start up of the batch reactors during this phase.

Preliminary Stage 2A & 2B :

Then substrate with acetate as the main organic source was fed. Analysis of sulfide, sulfate and pH were carried out during this stage to detect any change. Appendix III provides all the details and problems encountered in start up of the reactors. Later, substrate was changed to lactic acid as the main organic source to determine the growth of SRB in acidic medium with pH around 4.5. Again, the analysis of sulphide, sulfate and pH were carried out to detect any significant improvement. Appendix III provides all the details and problems encountered in start up of the reactors for phase I.

3.3.2 Phase I

In all the three Upward Anaerobic Fixed Film reactors, a substrate with lactate as the main carbon source was fed. Table 3.1 shows the composition of this substrate. The concentration of lactate was measured as its equivalent theoretical oxygen demand (Th.O.D.).

Table 3.1 : Substrate Composition - phase I

Magnesium Sulfate	(as SO_4^{-2} source)
Ammonium Chloride	(as N source)
Potassium Di-hydrogen Phosphate	(as P source)
Di-Potassium Hydrogen Phosphate	(as P source)
Lactic Acid	(as Organic Carbon source)
Sodium Hydroxide	(as pH-raiser)

The HRT was maintained at either 9 or 18 hours for the reactors and the temperature was kept at the room temperature of 18 to 25^0 C.

The following optimum parameters were maintained during these experiments :

Optimum Th.O.D. to Sulfate Ratio : 2

Optimum Organic Loading Rate (OLR) : 6 $Kg/d/m^3$

Optimum Total Nitrogen Load : Th.O.D.:N = 20:1

Optimum Total Phosphorus load: Th.O.D.:P = 100:1

SRB Activity inside the reactor:

This was studied by analyzing samples from different effluent ports along the reactor's height and identifying the optimum height in which the sulfide was produced. Also, visual observations were made to monitor the changes in the density, settling, and growth of biomass that took place during the SRB growth.

3.3.3 Phase II

This phase of the study was carried out on the behavior of the reactors in the removal of heavy metal, with the same set-up as described in Section 3.1. The substrate composition was the same as in Table 3.1 and all of the earlier parameters established earlier were maintained. The main parameter that was varied in this phase was:

Heavy Metal Removal. With lactate as the feed, heavy metals were applied in different concentrations and their removal rates were measured. The highest removal rates of metals at different heights of reactors, without affecting the reactors performances, were determined for various influent metal concentrations.

3.4 Methods of Analysis

The parameters measured were:

Sulfide	:as an indicator of bacterial growth.
Sulfate	:as an indicator of the total sulfate used by the bacteria.
Total solids	:as an indicator of dissolved solids
Suspended solids	:as an indicator of suspended solids
Volatile suspended solids	:as an indicator of bacterial growth
Flow rate	:as a control for the HRT
pH	:as an indicator and controller of the reactor performance
ORP	:as an indicator and controller of the reactor performance
Metals	:as an indicator of the heavy metal removal
Bacterial Count	:as an indicator of the existence and growth of SRB

All analytical methods used during this research conformed to the "*Standard Methods* (APHA 1995)". Table 3.2 lists the methods of analysis, testing frequency and the sample size used. All samples were taken by collecting the needed aliquot in a beaker just before the test was to be performed.

Table 3.2 : Methods of Analysis, Testing Frequency and Sample Volume

Parameter	Method used	Sample volume	Frequency
Sulphide	4500-S^{-2} B, C, E	10 mL	5-6 per week
Sulfate	4500-SO_4^{-2} E	5 mL	3-4 per week
Total fixed solids	2540 E	50 mL	5-6 per week
Total dissolved solids	2540 E	50 mL	5-6 per week
Total volatile suspended solids	2540 E	50 mL	5-6 per week
pH	Electrode 290 A	As required	As required
ORP	Electrode 290 A	As required	As required
Metal	DC Plasma 3030 E	100 mL	Daily

3.4.1 Sulfide

The Iodometric Method, described by the "*Standard Methods* (APHA, 1995) was used to determine the sulfide concentration in the effluent and samples taken at intermediate heights. Periodically sulfide were tested in the influent to detect any contamination of the feed containers. However, this method suffered interference from reducing substances, such as thiosulfate, sulfite and various organic compounds. In order to overcome this problem, the sample was pretreated with zinc acetate, as described in the STDM 4500-S C (1995). However, in the metal loading study, some sulfide had precipitated as metal sulfide. Thus, residual sulfide were measured instead of total sulfide. For measuring the residual sulfide, the insoluble matter in the sample was removed with aluminum hydroxide floc that was settled, leaving a clear supernatant for analysis. The procedure is described in 4500 S B.

The following precaution were taken during the analysis of sulfide as this significantly affected the values:

.A properly prepared fresh chemical stocks was used, specially during the determination of the normality of the iodine solutions and the sodium thiosulfate solutions as described in the *Standard Methods* (APHA, 1995).

.The samples for sulfide analysis were pretreated, as described earlier, to obtain representative sulfide concentration values. Generally, pretreated samples gave values which were 85% to 90% of the values for untreated samples.

3.4.2 Sulfate

Sulfate were analyzed by Turbidimetric Method as described by STDM 4500-SO_4^{-2} E (APHA, 1995). Barium chloride was added to the sample to form barium sulfate crystals of uniform size. A nephelometer measured the light absorbance of the barium sulfate suspension and the reading was converted to sulfate ion concentration from a standard curve (see Appendix I). Proper dilution of samples was used so that the nephelometer readings did not exceed the standard curve limit, because for the turbidity values higher than the standard curve limit the relation is no longer a straight line. For this reason, *Standard Methods* (APHA, 1995) states that the maximum value for the standard sulfate should not exceed 40 mg/L.

3.4.3 Bacterial Count

Bacterial count was done by using Rapid Check II, " Immunoassay Test Kit", supplied by Conoco (1995), for the detection and intensity of sulfate reducing bacteria. It used purified antibodies to detect the enzyme adenosine-5'-phosphosulfate (APS) reductase which was common to all SRB strains.

3.4.4 Biomass

The suspended solids and the volatile suspended solids were analyzed according to the *Standard Methods* (1995) as described in 2540 D, E.

The suspended solids were determined by weighing a portion of the biomass samples (from the effluent, influent and intermediate heights of the reactors), and then weighing again after drying in an oven of 105° C. The difference in mass gave the moisture content of the sample.

The volatile suspended solids, VSS, was determined by igniting the above mentioned samples in furnace at 550° C for a period of about two hours. The residue mass gave the fixed suspended solids, while the difference between the mass before and after ignition gave the volatile content.

3.4.5 ORP (Redox Potential)

The platinum and calomel electrodes were used to measure the oxidation-reduction potential, ORP. Orion instrument Model 290A, was used with an advantage of giving the readings after reaching high degree of equilibrium. The calibration of the instrument for the ORP measurements was made by immersing the electrode in a solution whose oxidation-reduction potential was known. One of the ideal solution, used in this research, was the quinhydrone solution. It was prepared by adding quinhydrone crystals to a suitable acid-base buffer solution until a state of saturation had reached. The ORP of this solution depended only on the solution pH, according to the following relation:

$$\text{ORP, in mV} = +699 - 59.2\,(\text{pH})$$

The same instrument was used for measuring the pH with appropriate electrode, after calibration with standard solutions of pH 4, 7, and 10. Both the pH electrodes and the ORP electrodes cannot be used simultaneously, and had to be used separately for each analysis.

3.4.6 Heavy Metal

Directly Coupled Plasma (DCP) method, as described in the Standard Methods (APHA, 1995) was utilized to measure the dissolved and total metal concentrations. The samples for the total metal analysis were first digested with nitric acid, as prescribed by STDM 3030 E (APHA, 1995), whereas the samples for the dissolved metal analysis were filtered through 0.45 *um* cellulose acetate filter paper and then acidified. All samples were stored at 4^0 C before being analyzed on a Backman Spectraspan V Plasma Spectrophotometer (Spectrametric). Each time the spectrophotometer was used, high and low standard solutions were prepared to calibrate the instrument. The low standard solutions had concentrations near zero mg/L of heavy metals, whereas the high standard solution had concentrations in the anticipated range of metal concentrations in the samples. Thus, each run produced different instrument limits of detection. The free ion concentrations of the metal was analyzed using a combined technique of dialysis and ion-exchange methods as described by Bhattacharya *et al.* (1995). They showed that dialysis simulates metal transport through the cell wall and ion-exchange presumably simulates heavy metal assimilation into intracellular molecule. Dower 50W-X8, Na^- form, 20-50 mesh resin (300 mg), and 10 mL deionized water were placed in dialysis bags (MW cut off of 10,000, Spectrum, Los Angeles, California). The dialysis bags were placed in a glass beaker containing the sample and mixed with a magnetic stirrer. The equilibrium was reached after 24 hours, then the samples were filtered and analyzed as described previously.

Chapter 4 : RESULTS AND DISCUSSION

The use of sulfate reducing bacteria, SRB, in an upflow anaerobic fixed film reactor, UAFFR, showed great promise for the removal of heavy metals in industrial wastes. This easy, comparatively inexpensive, and efficient method can be used by maintaining optimum environment conditions for the SRB growth. It is important that SRB should be the dominant bacteria in the reactor in order to achieve high efficiencies, as higher efficiencies are imperative in this modern world of stricter environmental standards set by the governments or their environmental agencies.

Lactate is considered as the preferred carbon source for the SRB, although acetate which is cheaper. Lactate was used as substrate in this research. It is possible that the general conclusions drawn with the lactate as the source of organic carbon in the synthetic wastewater in this study, can be used for other organic carbon sources available in any industrial wastewater.

The research study was divided in two parts, with and without the presence of heavy metals: The first phase used lactate as the substrate and studied and experimented the growth of SRB and respective parameters. After optimizing the system for maximum growth of sulfur reducing bacteria (biomass production) and maximum sulfide production, with respect to hydraulic retention time, HRT, further experiments, phase II, again using lactate as the source of carbon, were conducted on the removal of heavy metal, copper, under different operating conditions. It is possible that the general conclusions drawn with copper as heavy metal in this study, can be relegated to the removal of other heavy metals present in the industrial wastewaters.

It is to be noted that, whenever any change was made in the feed or mode of operation during phase I, minimum five days were needed to achieve steady state condition. It is recommended to operate the system for about four to six weeks to collect sufficient data under steady state condition for each run. However, during phase II, three days of operation were sufficient to achieve the steady state condition.

4.1 Phase I

4.1.1 Optimum Substrate Composition

Four substrate parameters were identified (Bayoumy, 1997) and their optimized values were used for the optimal conditions for the sulfate reducing bacteria, SRB, growth and maximum sulfide production in the upflow anaerobic fixed film reactor (UAFFR). These parameters were:

. Optimum Th.O.D. to SO_4 Ratio,

. Optimum Organic Loading Rate,

. Optimum Total Nitrogen Loading, N, and

. Optimum Total Phosphorus Loading, P.

4.1.1.1 Optimum Th.O.D./SO_4 Ratio

The theoretical oxygen demand, Th.O.D., which was selected as a parameter to measure the organic carbon concentration in the substrate, is defined as the amount of oxygen, mg/L required to stabilize an equivalent amount of the organic carbon in the substrate, mg/L, into stable compounds, CO_2 and H_2O. Here, when sodium lactate was the source of organic carbon, the Th.O.D. was calculated as follows:

$$\text{Lactic acid} + \text{Th.O.D.} \rightarrow CO_2 + H_2O \qquad (4.1)$$

i.e.,

$$C_3H_6O_3 + 3O_2 \rightarrow 3CO_2 + 3H_2O \qquad (4.2)$$

The molecular mass for lactic acid is (3x12 + 6x1 + 3x16 = 90), and the Th.O.D. is (3x16x2 = 96). Therefore, according to the stoichiometric equation 4.2, Th.O.D./lactic acid = 96/90 =1.078, or

$$\text{Th.O.D. (g/L)} = 1.078 * \text{Lactic Acid (g/L)} \qquad (4.3)$$

Sulfate reducing bacteria, SRB, are known to out-compete methane producing bacteria, MPB, for lactate utilization., since the SRB reaction yields higher energy, -151 kJ, than the MPB reaction, -34 kJ (McCartney and Oleszkiewicz, 1989). Lactate was used as a substrate and the Th.O.D./SO_4 equal or less than 1.6 resulted in an SRB pathway that proceeded with sulfate reduction and had acetate as a product. Equation 4.4 shows the stoichiometric equation for the balanced reaction:

$$2C_3H_5O_3^{-1} + SO_4^{-2} \rightarrow 2CH_3COO^{-1} + 2HCO_3^{-1} + HS^{-1} + H^{+1} \qquad (4.4)$$

This reaction for lactate yields more energy for bacterial growth than other reactions producing hydrogen sulfide.

In sulfate-poor environment, ratios higher than 2.25, the MPB start to out-compete the SRB due to the deficiency of the sulfate inside the reactor, whereas sulfate-rich environment, ratios lower than 1.5, also produced low activity of SRB. Optimal range of 1.5 to 2.25 for the ratio of Th.O.D. to sulfate was recommended by Gundry *et al.* (1989) and confirmed by Bayoumy (1997). (It should be noted that this suggestion contradicts the recommendation of Harada (1993) for a ratio of 0.8. This difference may be attributed to the difference in the experimental conditions. Bayoumy (1997), used a ratio of 0.75 which resulted in the sulfide production of about 86 mg/L with an OLR of 4 kg/d/m3, and when the optimum OLR, 6 kg/d/m^3 was used, the sulfide production improved.

In this research, optimal ratio, Th.O.D/SO_4 = 2, was applied in the feed throughout this phase to maintain maximum SRB growth activity. Table 4.1 shows the steady state substrate constituents concentrations during the application of different hydraulic retention times, HRTs.

Table 4.1 : Steady State Substrate Constituents Concentrations for each HRT - Phase I

HRT (hours) :	**9.0**	10.0	**18.0**	20.0
OLR, kg/d/m3	**6.00**	6.00	**6.00**	6.00
Th.O.D., g/L	**2.25**	2.50	**4.50**	5.00
Lactic acid, g/L	**2.10**	2.34	**4.20**	4.67
SO4, g/L	**1.12**	1.25	**2.25**	2.50
MgSO4.7H2O, g/L	**2.88**	3.21	**5.76**	6.41
NaOH, g/L	**0.93**	1.03	**1.85**	2.06

4.1.1.2 Optimum Organic Loading Rate

The optimization of OLR is essential as a design criterion for any biological treatment system. Wijaya (1993) had recommended that OLR of 6 $kg/d/m^3$ was optimum for highest sulfides productivity of about 250 mg/L in small reactors of 500 mL volume. Bayoumy (1997) found that the sulfide production increased gradually upto 120 mg/L and consequently, the SRB growth increased with an increase in the OLR until about 6 $kg/d/m^3$, any further increase caused no more increase in the sulfide production for 9 L reactors. It was mentioned that the differences in the values of sulfide production was due to the different nature of SRB culture used and/or different reactor sizes.

Optimal organic loading rate, OLR of 6 $kg/d/m^3$ as lactate, for maximum SRB growth and hence maximum biosorption and sulfide production, was applied throughout this phase for the source of organic carbon in the substrate. When lactic acid was used as the source of organic carbon, the amount of sodium hydroxide required to adjust pH was calculated as follows:

$$\text{Lactic Acid} + \text{Sodium Hydroxide} \rightarrow \text{Sodium Lactate} + H_2O \qquad (4.5)$$

i.e.,

$$C_3H_6O_3 + NaOH \rightarrow C_3H_5O_3Na + H_2O \qquad (4.6)$$

The molecular mass of lactic acid is (3x12 + 6x1 + 3x16 = 90)and molecular mass of sodium hydroxide is (1x23 + 1x16 + 1x1 = 40). Therefore, according to the stoichiometric equation 4.5, sodium hydroxide/lactic acid = 40/90 = 0.44, or

$$NaOH\ (g/L) = 0.44 * \text{Lactic Acid}\ (g/L) \qquad (4.7)$$

Table 4.1 shows the steady state concentrations of lactic acid and sodium hydroxide concentrations for each hydraulic retention time applied in Phase I.

4.1.1.3 Optimum Total Nitrogen Load

The total nitrogen loading was measured by the amount of nitrogen used in the feed as ammonium chloride, NH_4Cl. Optimum total nitrogen load was essential in the substrate, since a lack of sufficient nitrogen can limit the growth of SRB, whereas higher loading may cause toxicity to the SRB due to ammonium ions (Bayoumy, 1997). Optimal Th.O.D.:N = 20:1 was used throughout to maintain healthy growth of SRB without generating toxicity.

N	in	NH_4Cl	=	14	in	53
(14)		(14 + 4x1 + 35)				

$$\text{Ammonium Chloride, (g/L)} = 3.78 * \text{Nitrogen, (g/L)} \qquad (4.7)$$

Therefore, for any nitrogen concentration required in mg/L, the corresponding amount of NH_4Cl in feed in mg/L can be calculated. The substrate constituents during these runs for different hydraulic retention times are shown in Table 4.2.

Table 4.2 : Nitrogen Concentration of Substrate for each Hydraulic Retention Time - Phase I

HRT, hours	**9.0**	10.0	**18.0**	20.0
OLR, kg/d/m^3	**6.0**	6.0	**6.0**	6.0
Th.O.D.	**2.25**	2.50	**4.50**	5.00
Th.O.D.:N	**20:1**	20:1	**20:1**	20:1
Nitrogen, N, g/L	**0.112**	0.125	**0.225**	0.250
NH_4Cl, g/L	**0.42**	0.47	**0.84**	0.94

4.1.1.4 Optimum Total Phosphorus Load

Contrary to the case of nitrogen, there is only a minimum requirement of phosphorus in any bacterial growth and any higher phosphorus loadings will cause no adverse effect (Bayoumy, 1997). Optimal Th.O.D.:P ratio of 100:1 was used throughout for optimum sulfate reducing bacterial growth and satisfactory sulfide production.

The total phosphorus concentration was measured by the amount of phosphorus applied in the feed as potassium Di-hydrogen phosphate (KH_2PO_4) and Di-potassium hydrogen phosphate (K_2HPO_4). According to the molecular mass basis:

P in KH_2PO_4 = 31 in 136

(31) (39 + 2x1 + 31 + 4x16)

and

P in K_2HPO_4 = 31 in 174

(31) (39 + 2x1 + 31 + 4x16)

Therefore, for any phosphorus concentration required in g/L, the corresponding amounts of KH_2PO_4 and K_2HPO_4 in g/L in the feed can be calculated based on the ratio between KH_2PO4 and K_2HPO_4 as 1:4. The phosphorus concentration of substrate for each hydraulic retention time during these runs are shown in Table 4.3.

Table 4.3 : Phosphorus Concentration of Substrate for each Hydraulic Retention Time - Phase I

HRT, hours	9.0	10.0	18.0	20.0
Th.O.D.:N:P	100:5:1	100:5:1	100:5:1	100:5:1
Th.O.D., g/L	2.25	2.50	4.50	5.0
Phosphorus, g/L	0.022	0.025	0.045	0.050
KH_2PO_4, g/L	0.024	0.027	0.048	0.044
K_2HPO_4, g/L	0.094	0.107	0.193	0.214

The packing material used in all the reactors were polypropylene pall rings. The size of pall rings was 15.9 mm, which provided the surface area of 1020 mm^2.

4.1.2 Biomass production at Different Reactor Heights

Volatile suspended solids, VSS, production with time was measured as the main indicator of the biomass as SRB growth inside the reactors. Other indicators were total solids, volatile solids and total suspended solids. Tables V. 1 to V.3 show the data for the volatile suspended solids for each reactor, viz. A, B, and C respectively, for Phase I, over eight months under different operating conditions. The samples were taken from different port heights along with effluent for each reactor. Figures 4.1 to 4.3 represent the same data in graphical form for each reactor.

Tables V.4 to V.6 represent the data for total solids and volatile solids for the same samples of the reactors A, B, and C. The same data are reproduced in graphical forms for total solids and volatile solids in Figures 4.4 to 4.9 for each reactor respectively.

Tables V.7 to V.9 represent the data for total suspended solids for the same samples of the reactors A, B, and C. The same data are reproduced in graphical forms for total suspended solids in Figures 4.10 to 4.12 for each reactor respectively.

Tables 4.4 to 4.6 show average volatile suspended solids concentrations, total suspended solids concentration, total solids concentration and volatile solids concentrations, for the three reactors at different heights. The volatile suspended solids concentration as a percentage of total suspended solids (at 50, 300, 600, 900, 1200 mm) are also shown. It is to be noted that hydraulic retention time for reactor A was 9 hours, whereas for reactors B and C was 18 hours.

Table 4.4 : Average VSS, TSS, TS, and VS Concentrations and Percentages at Different Heights - Reactor A (HRT = 9 hours)

Port Height	0.05 m	0.3 m	0.6 m	0.9 m	1.2 m
Average VSS, mg/L	374	248	249	232	294
STD VSS, mg/L	47.9	39.5	37.4	36.7	28.3
Average TSS, mg/L	597	448	455	425	452
STD TSS, mg/L	87.4	55.4	48.4	42.8	36.1
Percentage VSS, %	63	55	55	55	65
Average TS, g/L	8.55	7.87	7.59	7.38	7.21
STD TS, g/L	0.50	0.31	0.24	0.25	0.21
Average VS, g/L	4.23	3.54	3.33	3.12	3.01
STD VS, mg/L	0.28	0.26	0.26	0.25	0.23

Table 4.5 : Average VSS, TSS, TS, VS Concentrations and Percentages at Different Heights - Reactor B (HRT = 18 hours)

Port Height	0.05 m	0.3 m	0.6 m	0.9 m	1.2 m
Average VSS, mg/L	405	261	225	186	207
STD VSS, mg/L	34.9	36.6	30.4	27.9	39.1
Average TSS, mg/L	611	489	442	404	427
STD TSS, mg/L	49.9	43.0	35.6	34.0	35.0
Percentage VSS, %	66	53	51	46	48
Average TS, g/L	8.71	7.97	7.76	7.53	7.46
STD TS, g/L	0.46	0.33	0.37	0.37	0.43
Average VS, g/L	4.33	3.83	3.58	3.32	3.26
STD VS, g/L	0.33	0.28	0.25	0.29	0.32

Table 4.6 : Average VSS, TSS, TS, VS Concentrations and Percentages at Different Heights - Reactor C (HRT = 18 hours)

Port Height	0.05 m	0.3 m	0.6 m	0.9 m	1.2 m
Average VSS, mg/L	414	250	218	182	222
STD VSS, mg/L	58.4	45.7	43.4	38.1	45.4
Average TSS, mg/L	633	485	437	413	434
STD TSS, mg/L	57.8	42.4	35.6	37.5	39.6
Percentage VSS, %	65	52	50	44	51
Average TS, g/L	8.80	7.80	7.46	7.24	7.16
STD TS, g/L	0.42	0.32	0.26	0.36	0.32
Average VS, g/L	4.48	3.70	3.33	3.08	3.04
STD VS, g/L	0.41	0.41	0.23	0.25	0.22

SRB concentration was observed in the entire reactor height. Volatile suspended solids measurement represent/indicate the volatile SRB biomass. Statistical analysis for the entire VSS data was done and it shows that at 95% confidence level, the concentration of SRB is constant along the height of reactors except in the lowest part (upto 0.3 m) of all the reactors, which proves that growth of SRB was achieved in the lowest region (upto 0.3 m) of UAFFRs.

Figure 4.1 :VOLATILE SUSPENDED SOLIDS - REACTOR A

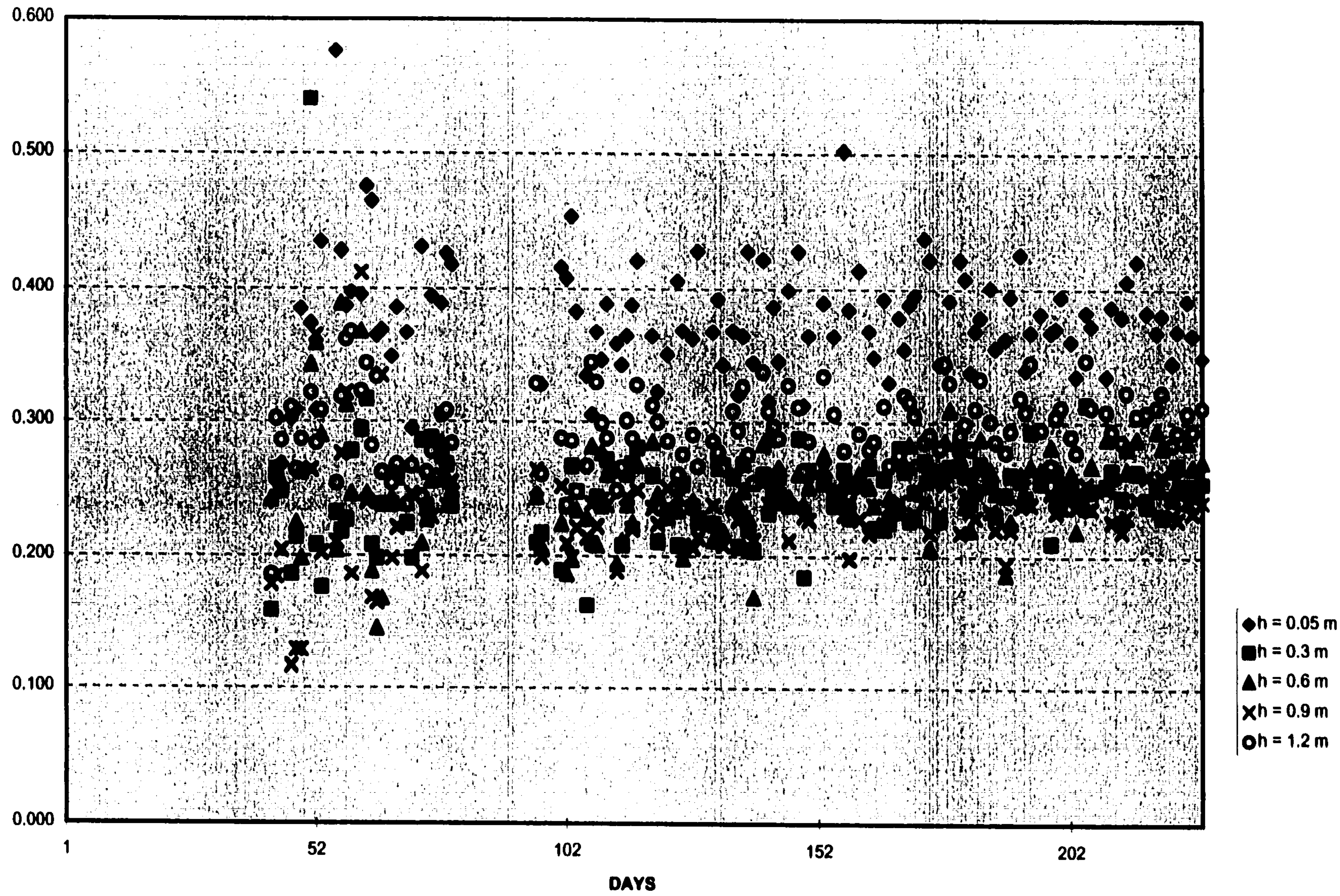


Figure 4.2 :VOLATILE SUSPENDED SOLIDS - REACTOR B

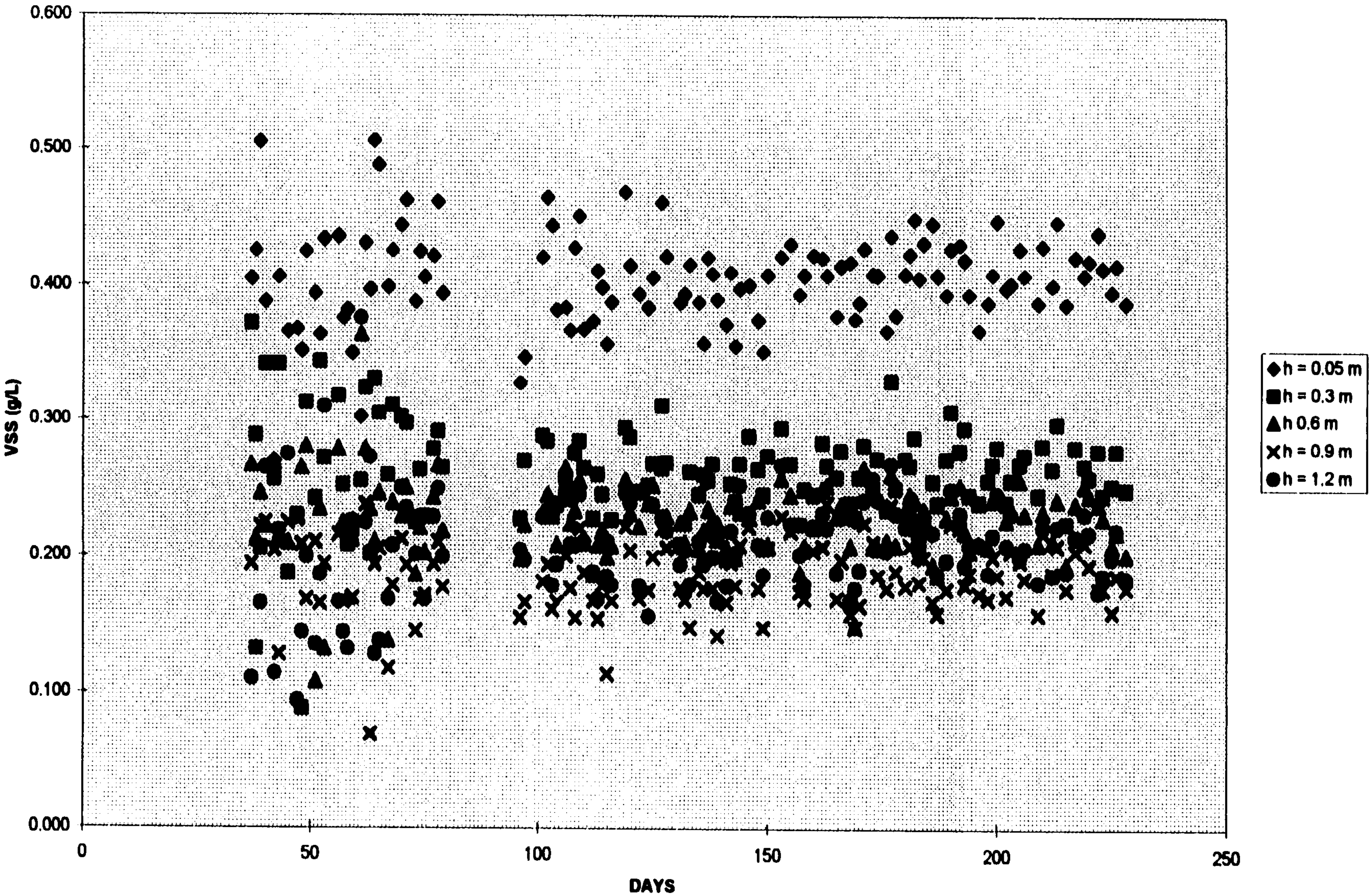


Figure 4.3: VOLATILE SUSPENDED SOLIDS - REACTOR C

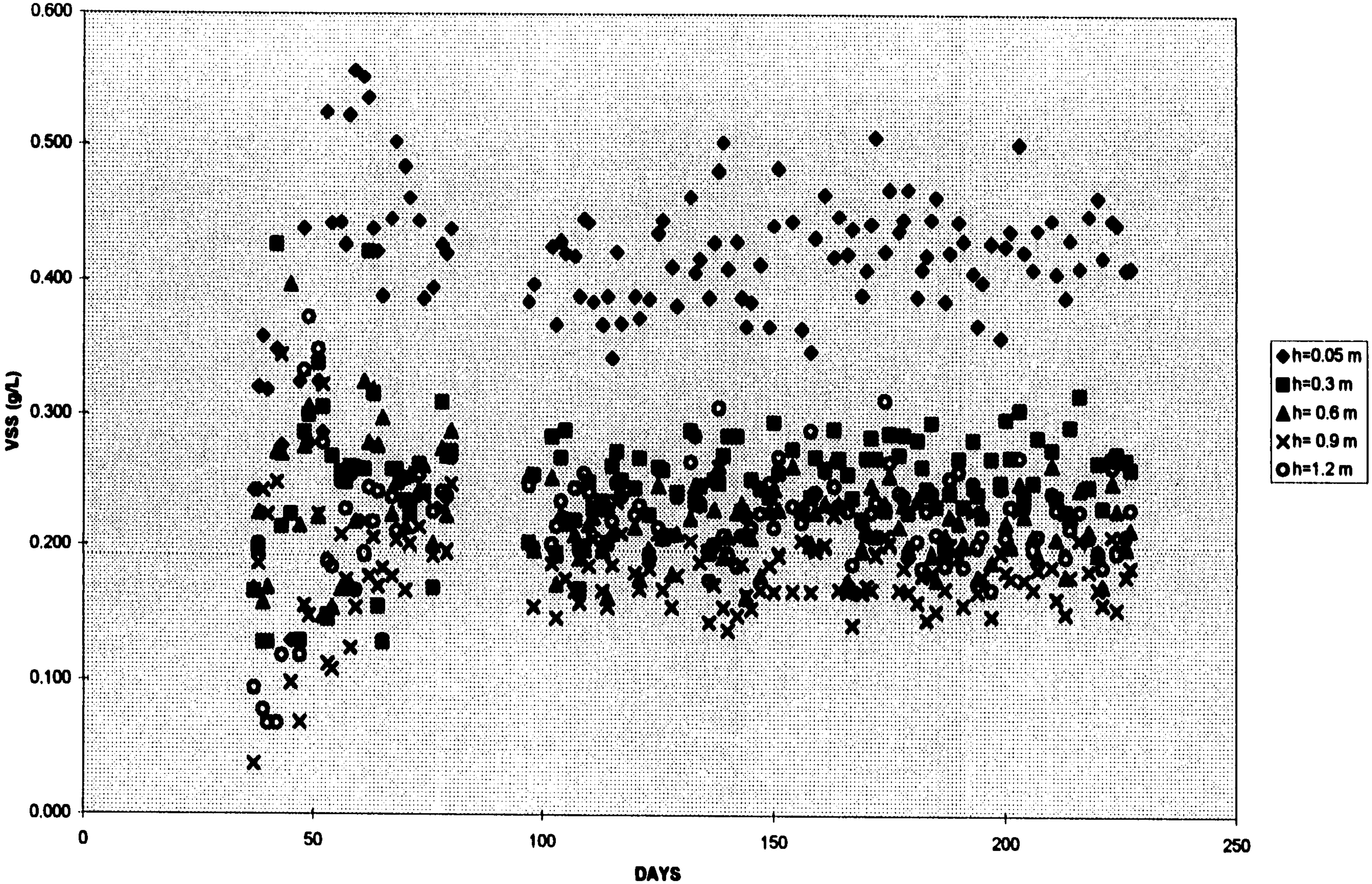


Figure 4.4: TOTAL SOLIDS - REACTOR A

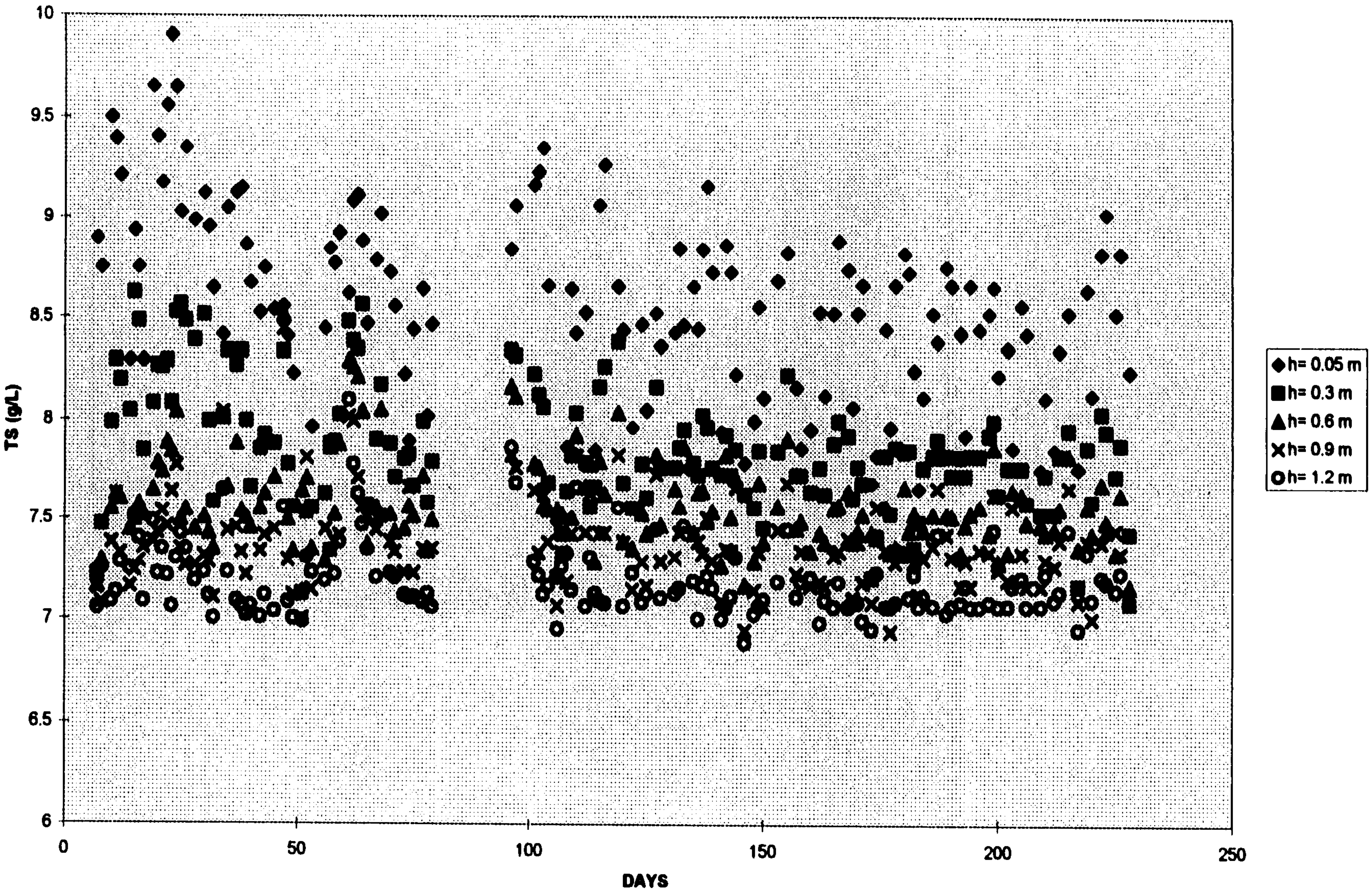


Figure 4.5: VOLATILE SOLIDS - REACTOR A

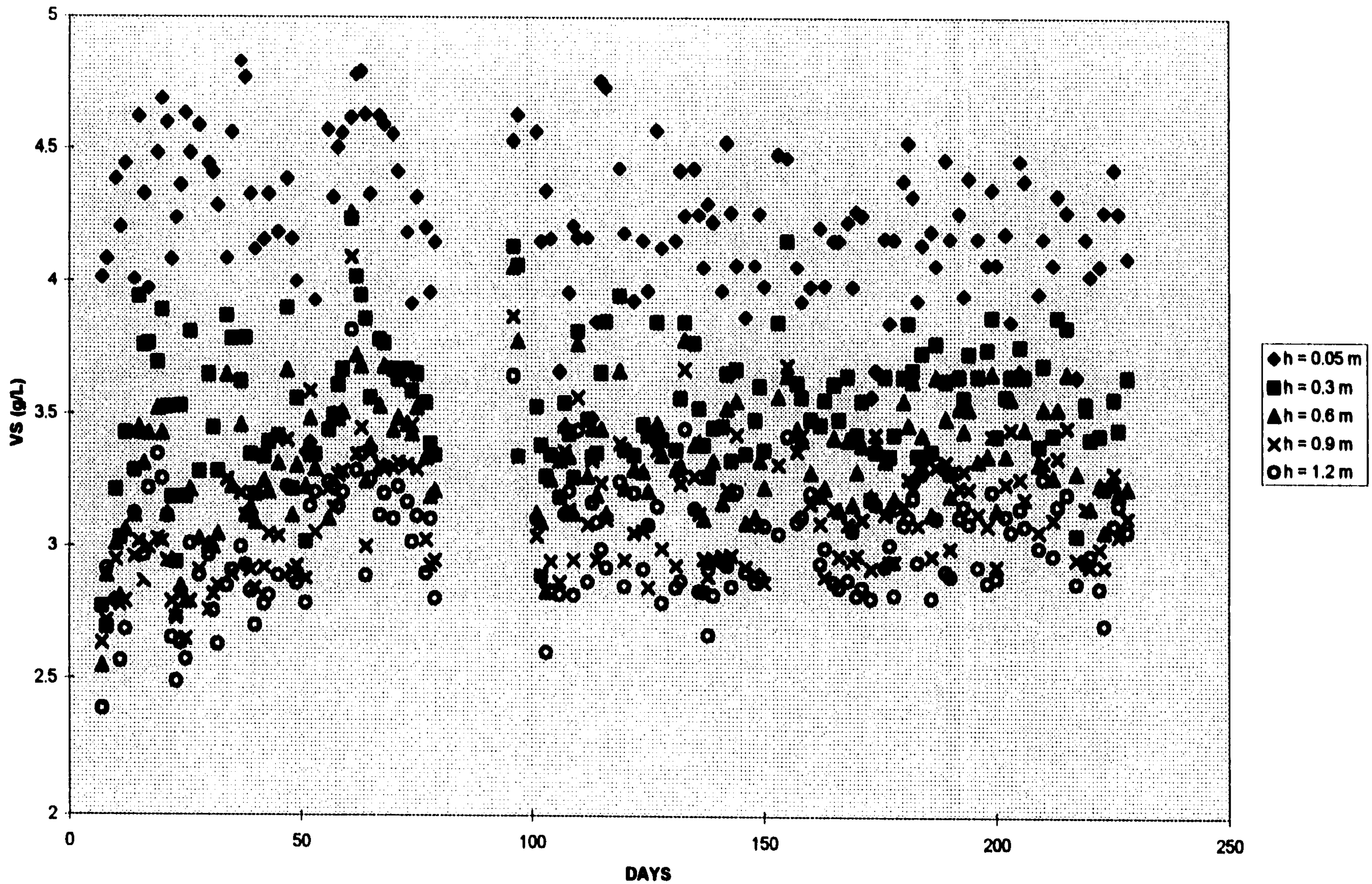


Figure 4.6: TOTAL SOLIDS - REACTOR B

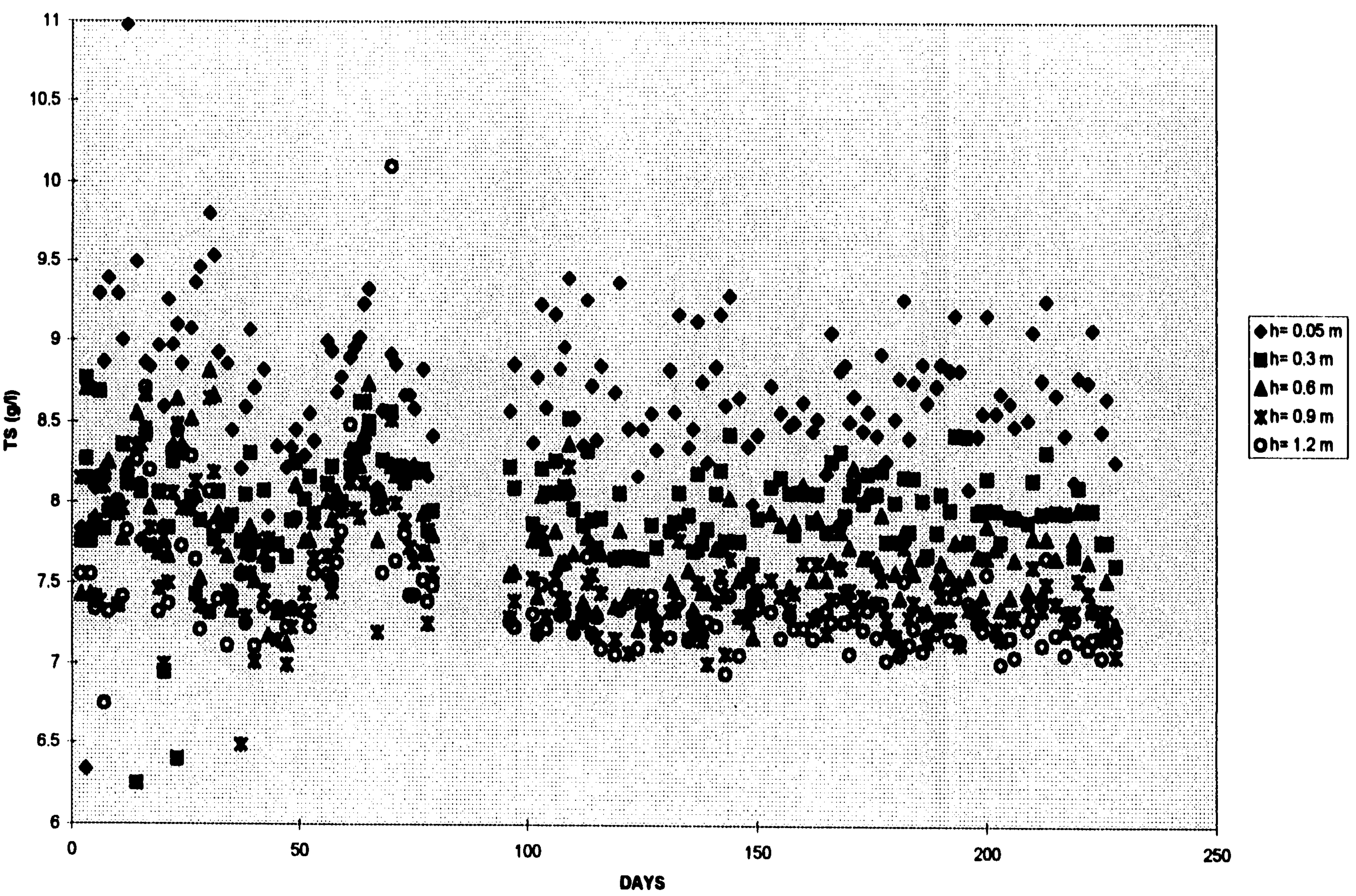


Figure 4.7: VOLATILE SOLIDS - REACTOR B

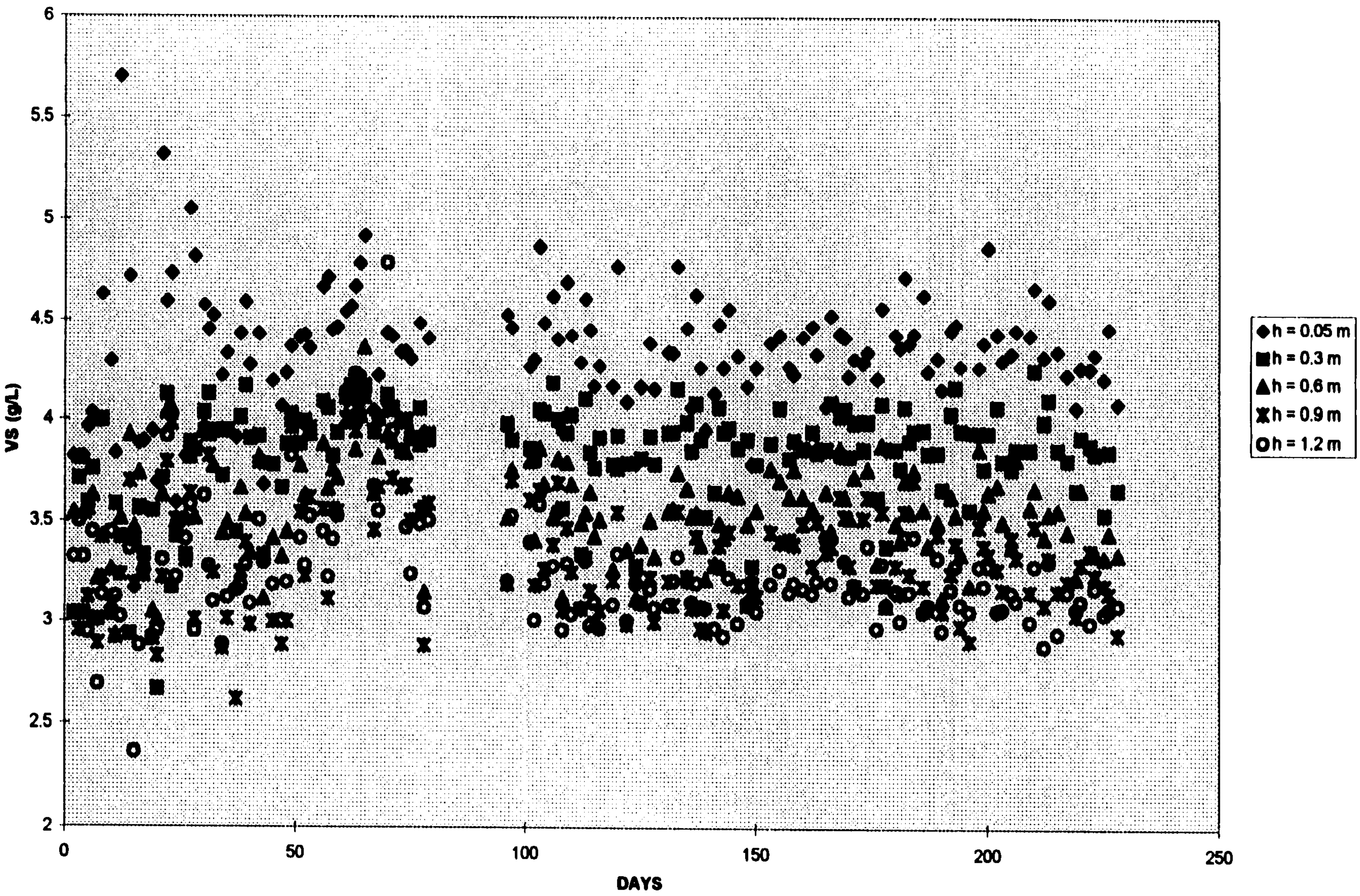


Figure 4.8: TOTAL SOLIDS - REACTOR C

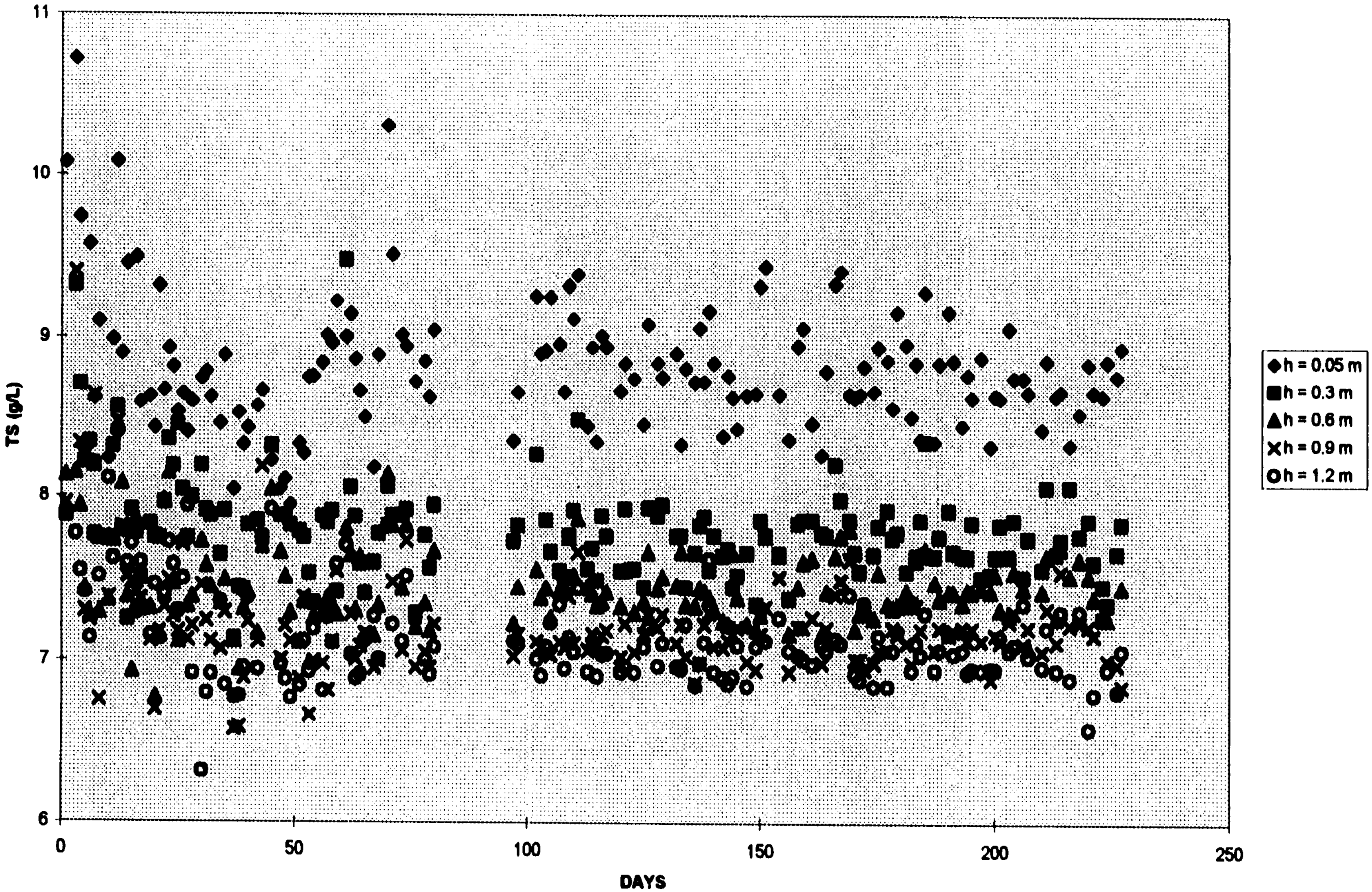


Figure 4.9: VOLATILE SOLIDS - REACTOR C

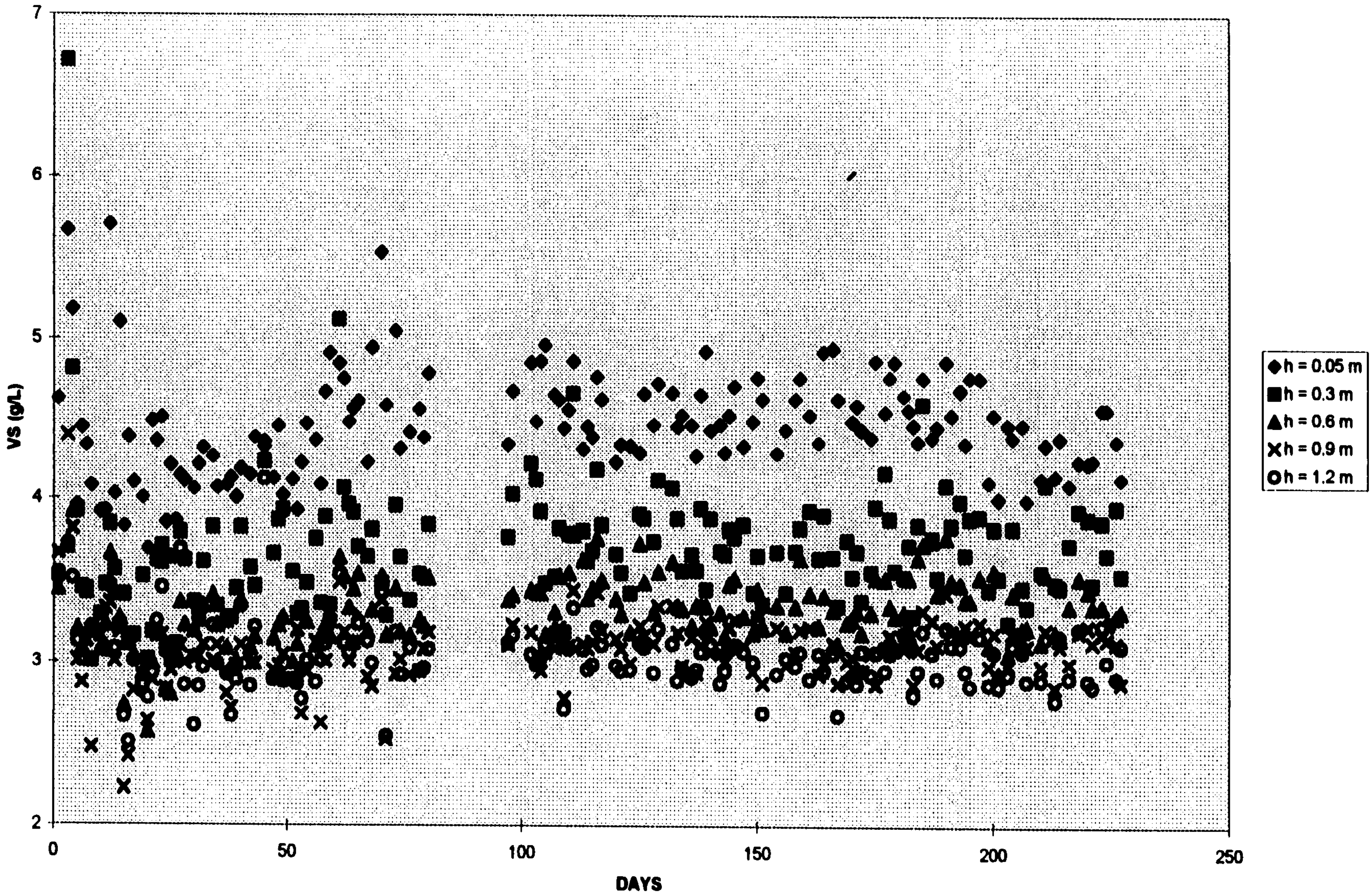


Figure 4.10: TOTAL SUSPENDED SOLIDS - REACTOR A

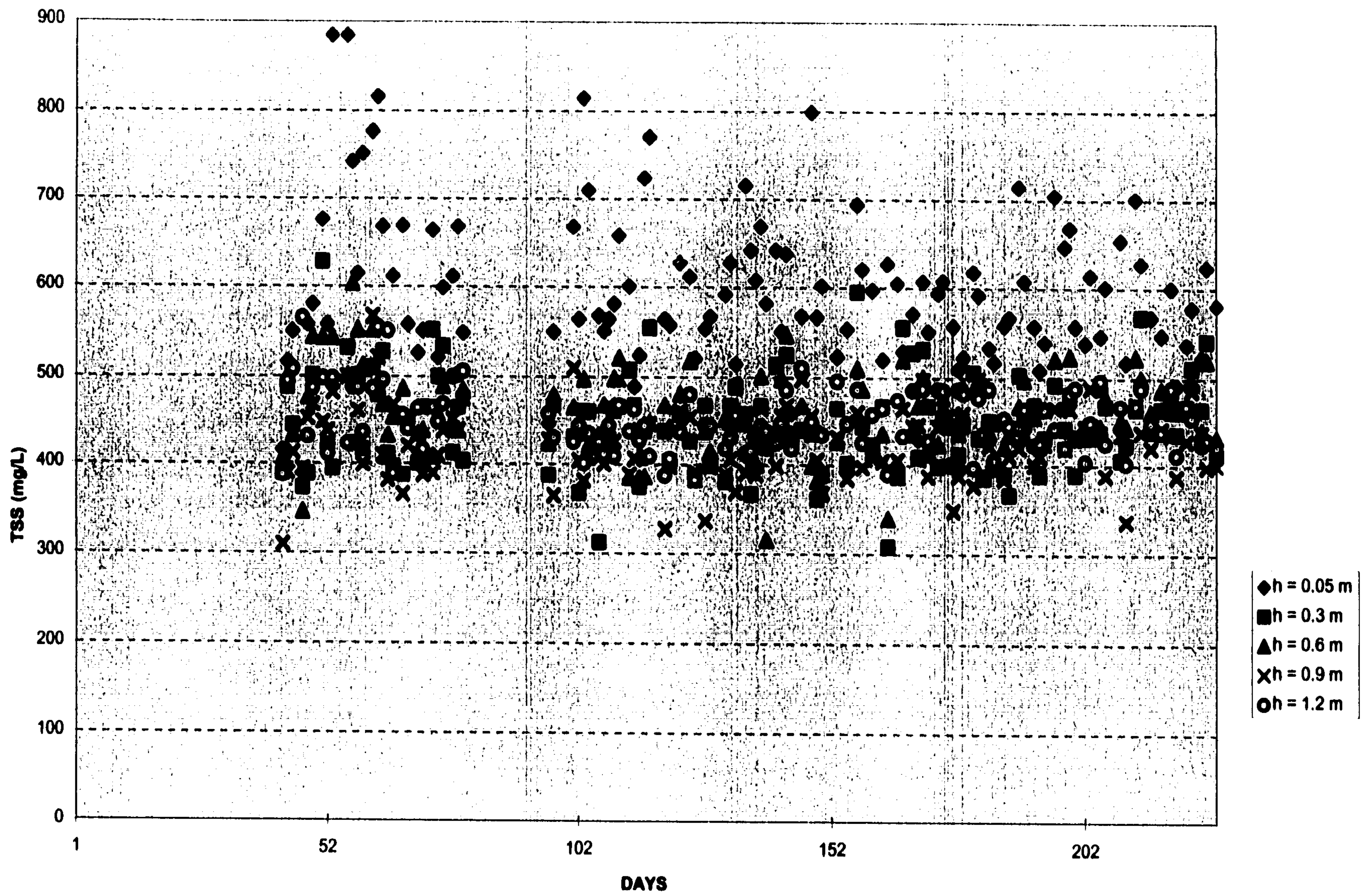


Figure 4.11:TOTAL SUSPENDED SOLIDS - REACTOR B

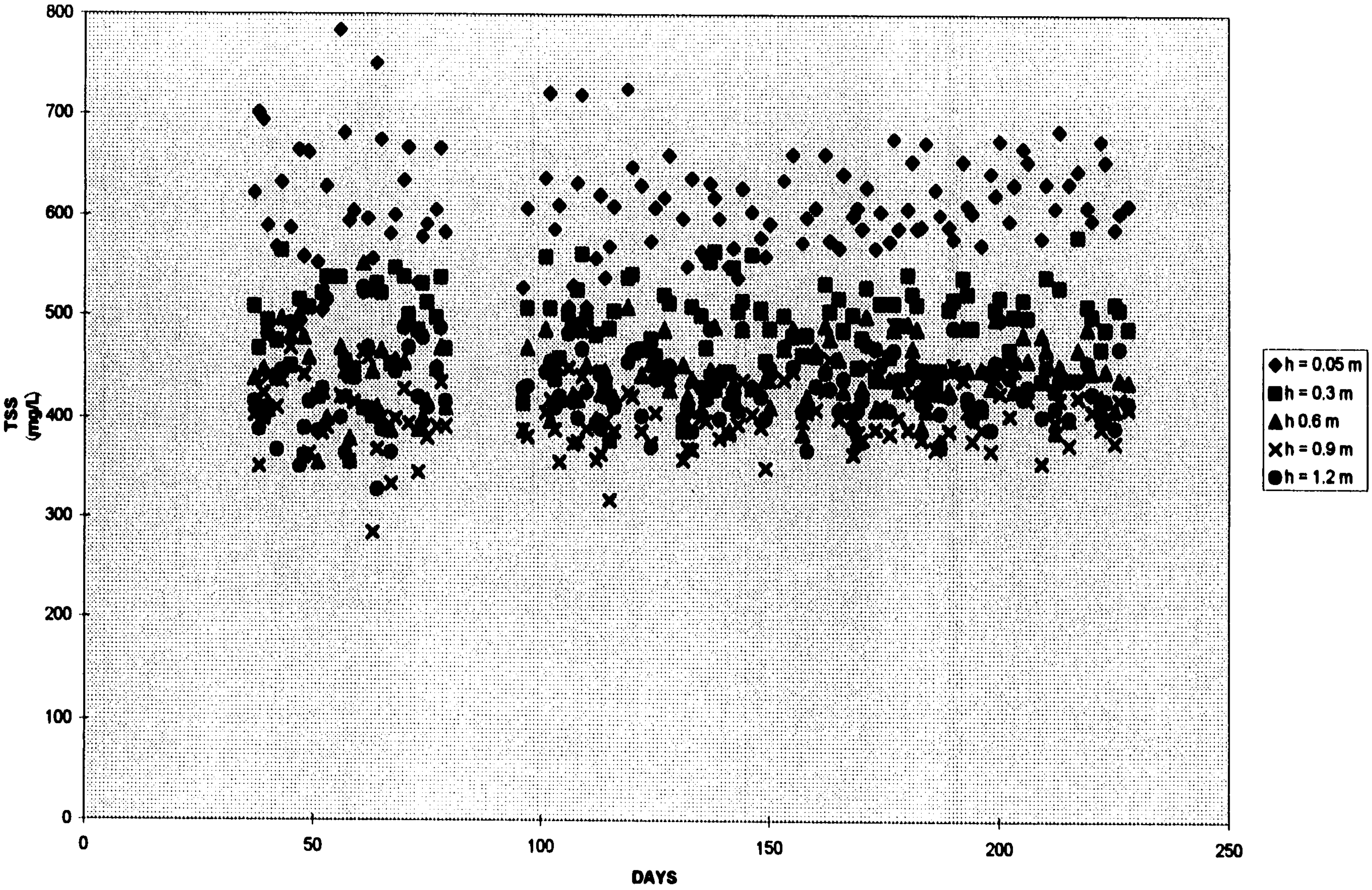
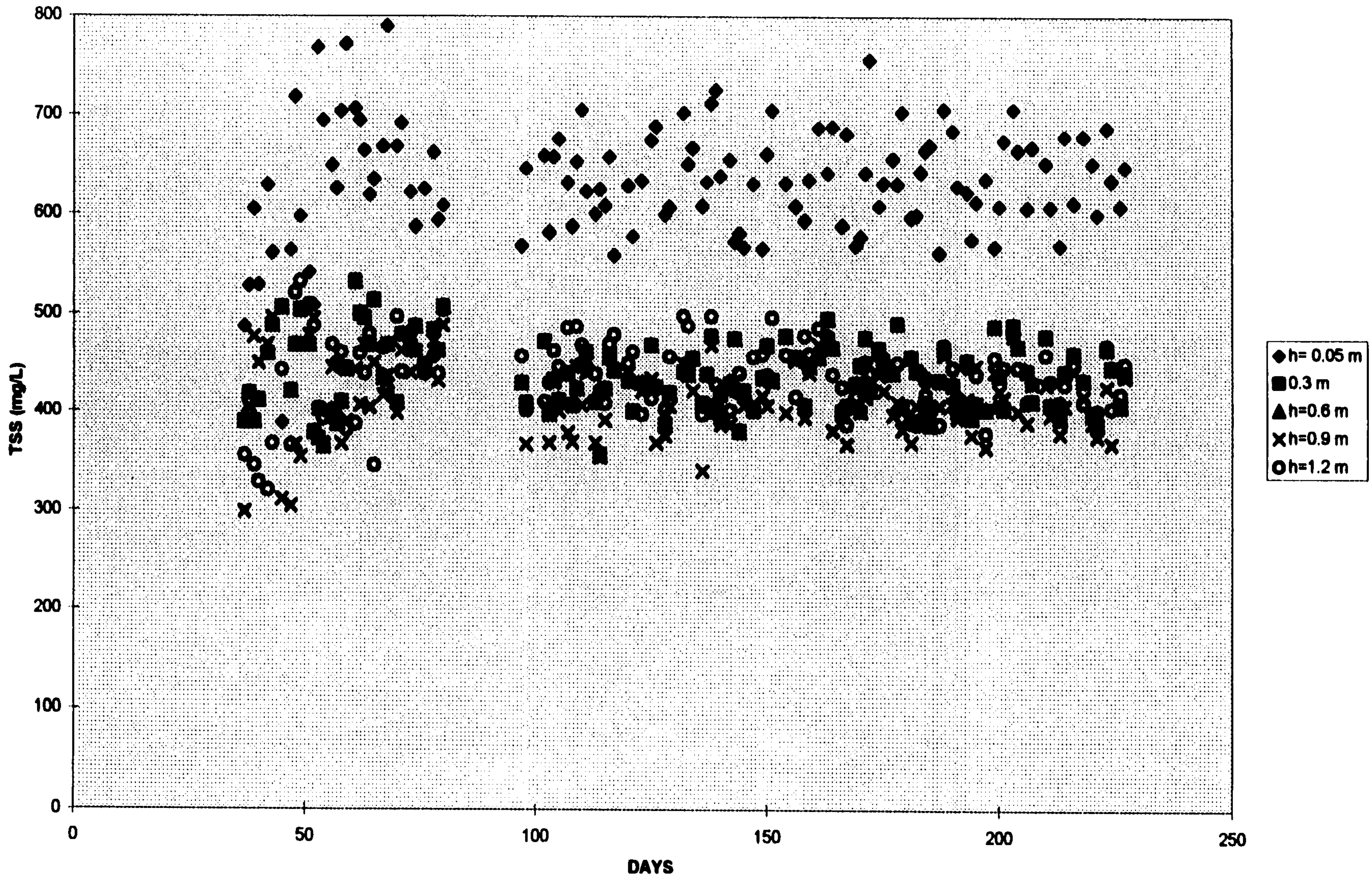


Fig. 4.12 : TOTAL SUSPENDED SOLIDS - REACTOR C



4.1.3 Sulfide Production (and Sulfate reduction) at Different Reactor Heights

As found in the previous as well as this study, the ratio of the observed sulfide concentration to the calculated sulfide concentration (from sulfate consumption) was an average equal to about 1.0, the sulfide production in relation with height, can be used as an indicator of the SRB activity/growth. Other related indicator being sulfate reduction in relation with time, as according to stoichiometry, relationship between sulfate reduction and sulfide production can be calculated, theoretically, according to the stoichiometric equation 4.8 :

$$[\,SO_4^{-2}]_e = [SO_4^{-2}]_i - (3 \times [\,S^{-2}\,]) \qquad (4.8)$$

Analysis of sulfide production and sulfate reduction was carried out for the samples taken from various heights for each operating UAFFRs for the Phase I over a long range of time. Table V.10 represent the same measured values of sulfide production and sulfate reduction. The sampling ports were located at heights of 300, 600, 900, and 1200 mm measured from the bottom inlet of each reactor. The measured values are represented in Figures 4.13 to 4.15 for each reactor in the graphical form.

Tables 4.7 to 4.9 show average sulfide concentrations in mg/L from the three reactors at different heights. Also, the sulfide concentrations at each height, as a percentage of the final effluent sulfide concentrations (at 1200 mm) are shown. It is to be noted that hydraulic retention time for reactor A was 9 hours, whereas for reactors B and C was 18 hours.

Figure 4.13:EFFLUENT SULFIDE CONENTRATION - REACTOR A

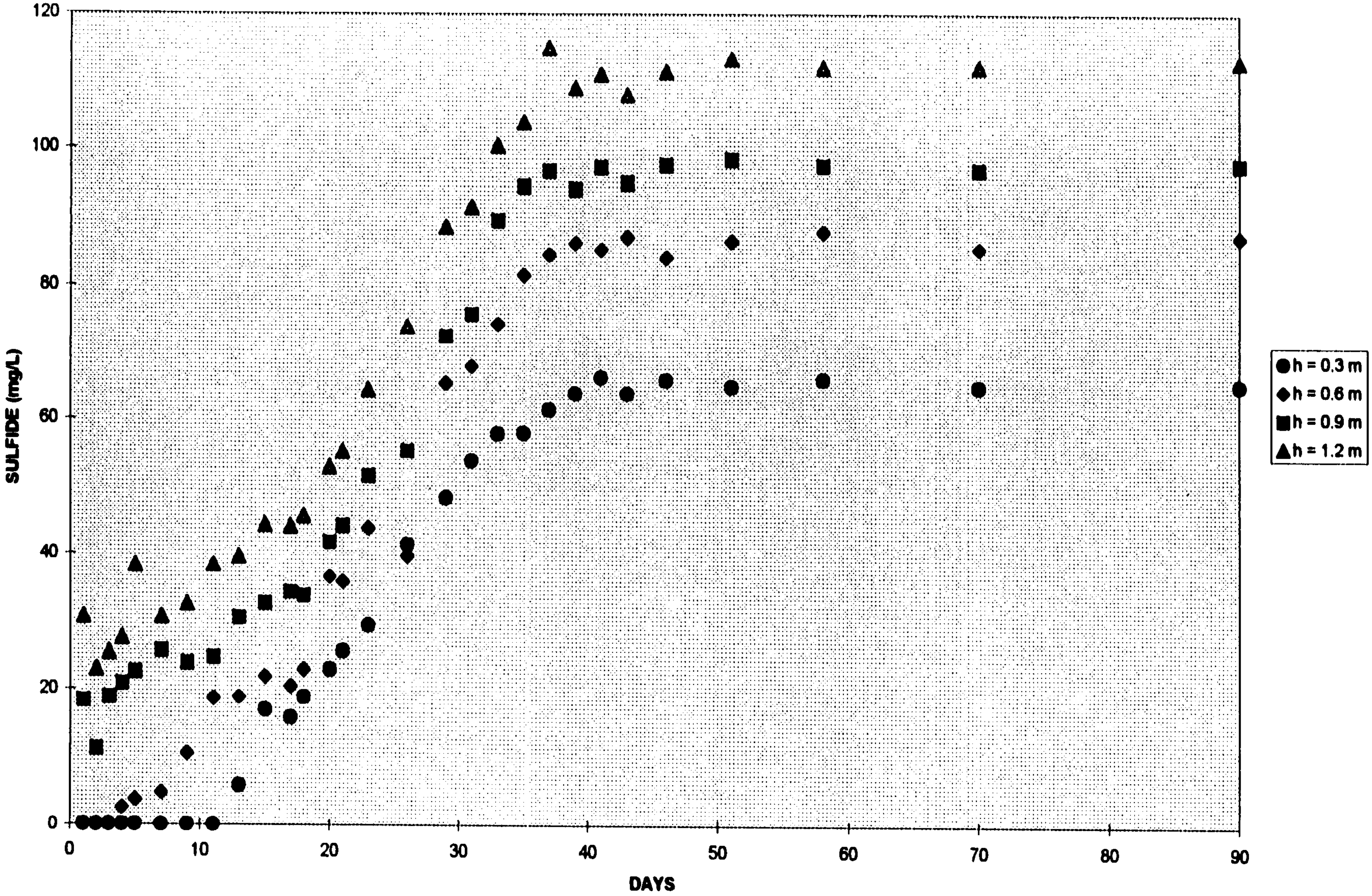


Figure 4.14: EFFLUENT SULFIDE CONENTRATION - REACTOR B

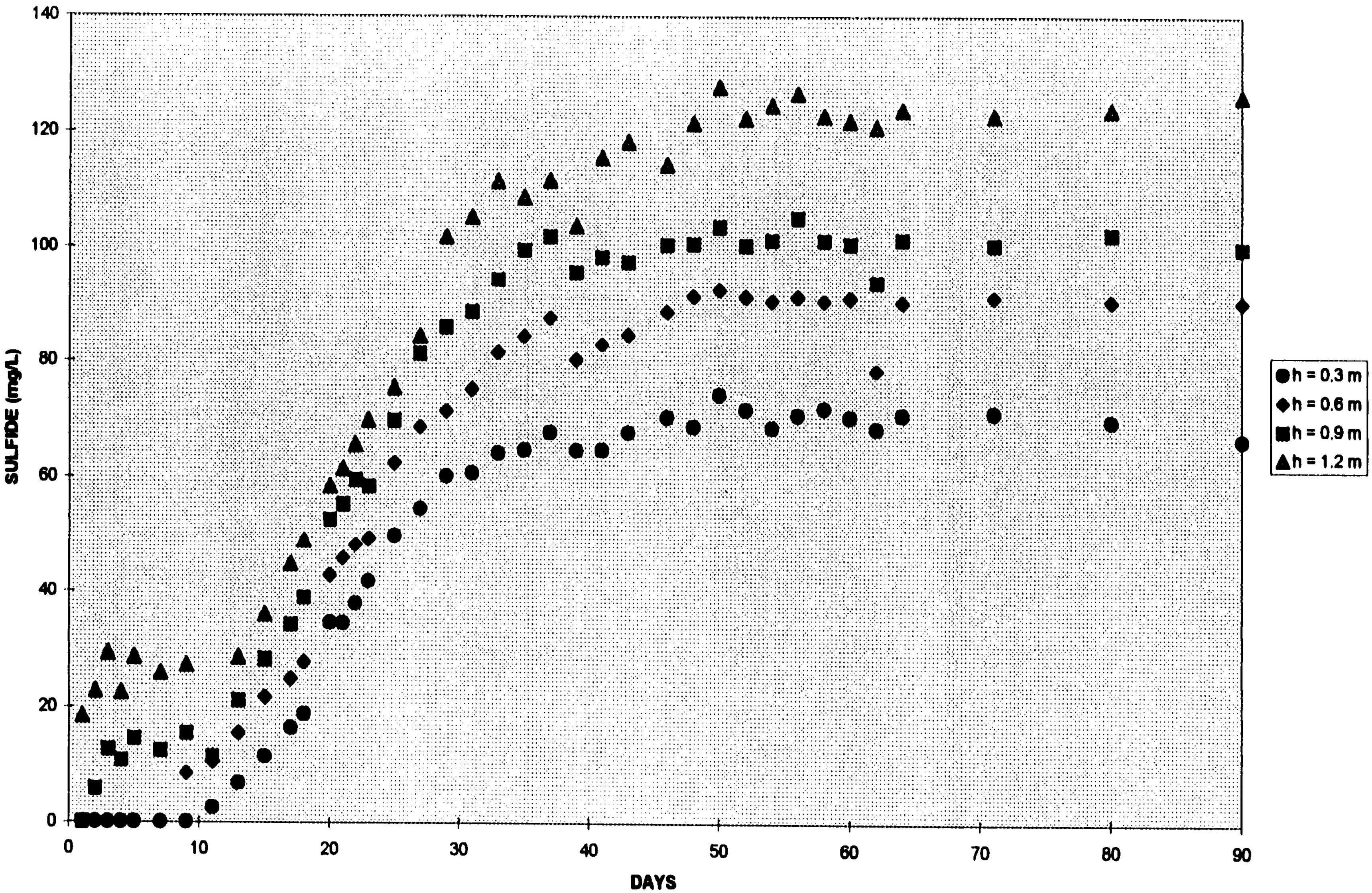


Figure 4.15: EFFLUENT SULFIDE CONENTRATION - REACTOR C

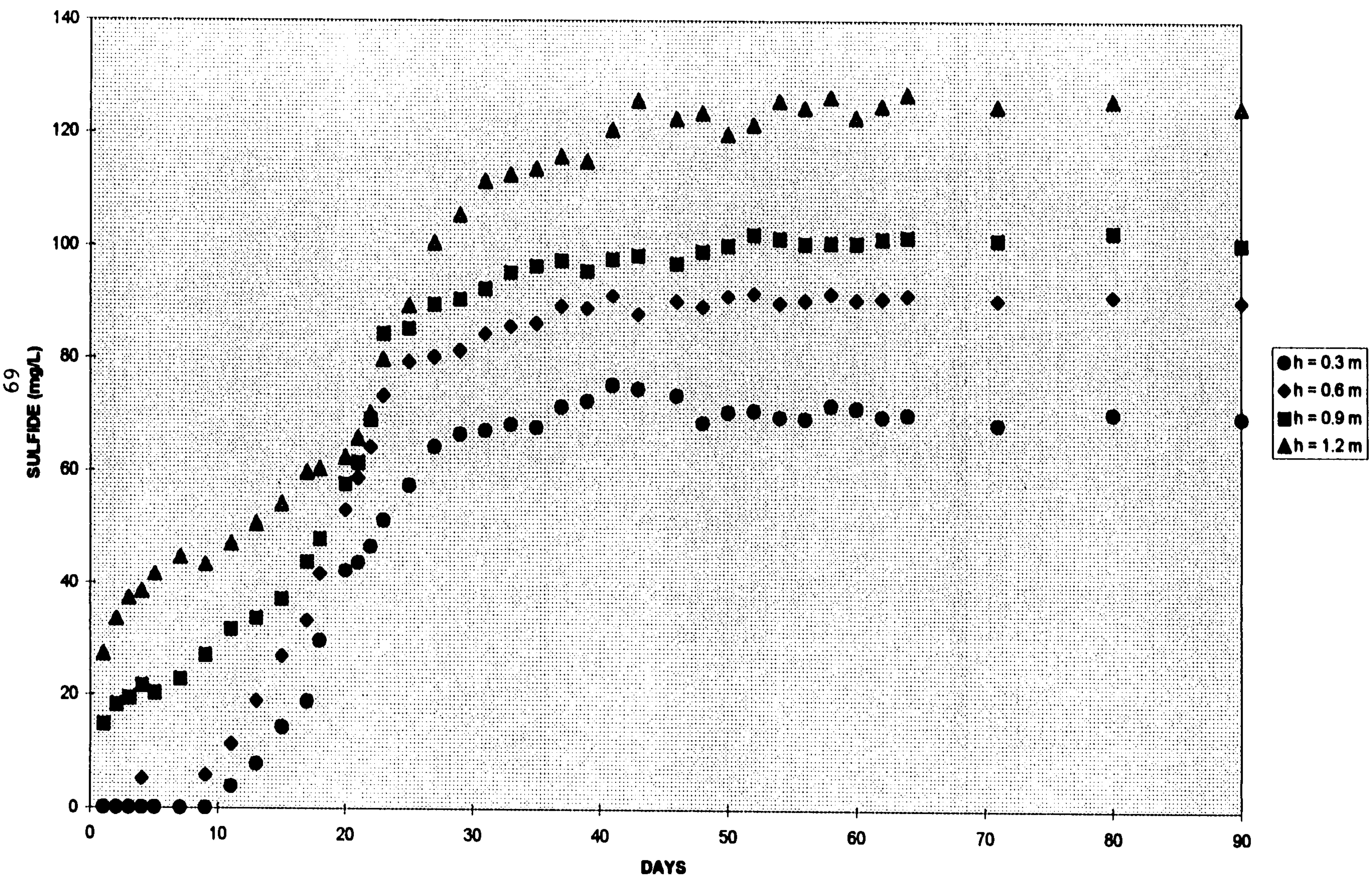


Table 4.7 : **Average Sulfide Concentrations and Percentages at Different Heights Reactor A (HRT = 9 hours)**

Port Height	0.05 m	0.3 m	0.6 m	0.9 m	1.2 m
Average S^{-2}, mg/L		65.0	87.5	97.5	112.5
Percentage S^{2-}, %		57.8	77.8	86.7	100

Table 4.8 : **Average Sulfide Concentrations and Percentages for Different Heights for Reactor B (HRT = 18 hours)**

Port Height	0.05 m	0.3 m	0.6 m	0.9 m	1.2 m
Average S^{-2}, mg/L		70	90	101	124
Percentage S^{-2}, %		56.5	72.6	81.5	100

Table 4.9 : **Average Sulfide Concentrations and Percentages for Different Heights for Reactor C (HRT = 18 hours)**

Port Height	0.05 m	0.3 m	0.6 m	0.9 m	1.2 m
Average S^{-2}, mg/L		70	90	100	125
Percentage S^{-2}, %		56.0	72.0	80.0	100

The sulfide concentration with respect to the reactor's height, shown in Tables 4.7 to Table 4.9 and Figures 4.13 to 4.15, can be correlated by the following equation (Bayoumy, 1997):

$$dS/dH = K(S^* - S) \quad (4.9)$$

and by integration, the following relationship is obtained/satisfied:

$$[S] = S^* (1 - e^{-KH}) \quad (4.10)$$

where,

dS/dH	=	Rate of sulfide production with height, mg/L/m,
[S]	=	Sulfide concentration at any height H, mg/L,
S^*	=	Ultimate sulfide concentration, mg/L, (140 mg/L),
K	=	Sulfide production constant, m^{1-}, and
H	=	Reactor's height, m.

Tables 4.10 and 4.11 reproduce the average concentrations for the sulfide produced, without metal application, for the three reactors with different HRT, namely 9 hours and 18 hours. The average sulfides production K, was calculated to be 1.60 for HRT=9 h and 1.92 for HRT=18 h. The ultimate sulfide concentration, S^*, was 140 mg/L for all the reactors. However, it should be recognized that this K value is an average value for the entire reactor height and it decreases with an increase in reactor height except at the top.

The distance traveled by the flow along the reactor, H, is equal to the velocity of flow(Q_o) x time of flow in the reactor (t). Therefore,

$$H = (Q/A) \times t = Q_o \times t \quad (4.11)$$

and

$$[S] = S^* (1 - e^{-K Q_o t}) = S^* (1 - e^{-K_o t}) \quad (4.12)$$

Here, Q_o was equal to 0.134 m/h for HRT = 9 h, and is equal to 0.067 m/h for HRT =18 hours.

Table 4.10 : Calculations for sulfide Production Constants, K and K_o for HRT = 9 h (Reactor A)

Reactor's Height, m	0.3	0.6	0.9	1.2
Average Observed Sulfide Conc., mg/L	65	87.5	97.5	112.5
Sulfide Production Constant., K, m^{-1}	2.08	1.63	1.32	1.35
Average Sulfide Production Const., K, m^{-1}		1.60		
Average K_o, h^{-1}		0.214		
Calc. Sulfide Conc. with Aver. K, mg/L	53	86	106	119

Table 4.11 : Calculations for sulfide Production Constants, K and K_o for HRT = 18 h (Reactor C)

Reactor's Height, m	0.3	0.6	0.9	1.2
Average Observed Sulfide Conc., mg/L	70	90	100	125
Sulfide Production Constant., K, m^{-1}	2.31	1.71	1.39	1.86
Average Sulfide Production Const., K, m^{-1}		1.82		
Average K_o, h^{-1}		0.122		
Calc. Sulfide Conc. With Aver. K, mg/L	59	93	113	124

Sulfide production was observed in the entire reactor height and the following equation was established/confirmed to represent sulfide concentration at different heights:

$$S = S^*(1 - e^{-KH})$$
$$S^*(1 - e^{-K_o(HRT)})$$

where,

S	=	Sulfide concentration at any height, H, mg/L,
S*	=	Ultimate sulfide concentration = 140 mg/L,
K	=	Sulfide production constant, = 1.60 m^{-1} for HRT = 9 h
		= 1.92 m^{-1} for HRT = 18 h
K_o	=	Sulfide production constant, = 0.214 h^{-1} for HRT = 9 h
		= 0.128 h^{-1} for HRT = 18 h
H	=	Reactor height, m, and
HRT	=	Hydraulic retention time, h.

It is to be noted that, K_o value for HRT = 9 h is nearing double than that for HRT = 18 h, which synchronizes with the fact that sulfide production varies with the flow rate. Whereas, a little higher difference in values of K, for each HRT, attributed to the fact that enough time was not allowed for faster reactor to achieve the desired sulfide concentration.

When the metals are applied to these reactors, correction factors are needed in both K and S* values to correct for the inhibition caused by metals on growth of SRB. An increase in the metal loads increased the toxicity of that metal and consequently decreased the SRB productivity of sulfides until complete failure.

4.2 Heavy Metal Loading - Phase II

One of the objectives of this study was to determine the behavior of sulfate reducing bacteria, SRB, in removing heavy metal under different loading conditions in order to confirm and establish the design criteria, particularly height of the upflow anaerobic fixed film reactor, for the system. Different design specifications could be made for different loading conditions, hydraulic retention times, and level of efficiencies required. Copper, Cu, was selected for the application in the UAFFR. This heavy metal is the most significant metal because it is widely used and is found in the industrial wastes and is considered to be representative of other heavy metals.

Copper is applied separately in different reactors operated at different hydraulic retention times with increasing concentrations until complete failure of the reactor had occurred. This failure of reactor was defined as the metal loading rate at which there was zero metal removal and zero residual sulfides.

Reactors A (HRT=9 h)and C (HRT=18 h) with the plexiglass body and effluent ports at different heights were used for the application of the metals. Table 4.12 illustrates the different substrate compositions used for each of the reactors. The constituents of the substrate as organic carbon, sulfate, nitrogen and phosphorus are the same as established earlier as the optimum substrate composition for the SRB in Phase I.

Table 4.12 : Different Reactors Substrate Compositions - Phase II

Reactor	A	C
HRT, h	9	18
Copper, mg/L	upto 400	upto 400
Lactic Acid. g/L	2.10	4.20
$MgSO_4.7H_2O$, g/L	2.88	5.76
NaOH, g/L	0.93	1.85
NH_4Cl, g/L	0.42	0.84
KH_2PO_4, g/L	0.024	0.048
K_2HPO4, g/L	0.094	0.193

Optimum environment for sulfur reducing bacteria, SRB, with pH of about 7 and oxidation reduction potential, ORP, of less than -150 mV was established and maintained throughout this Phase II.

Prior to the application of heavy metal, jar tests were conducted to determine if the metal has dissolved properly with the substrate and had not formed precipitates. One liter of the substrate solution including 10 mg of copper metal was placed in each jar. The stirrers were allowed to run at a moderate speed of 30 revolutions per minute for thirty minutes. After the mixture was allowed to settle for 4 hours, samples were collected from the supernatant and analyzed for the remaining concentration of the heavy metal. The difference was considered as the correction concentration per liter of substrate and an equivalent additional metal concentration was added to assure the required concentration for the metal application. Table 4.13 shows these values for copper, before and after the jar test and the corresponding correction concentration.

Table 4.13: Jar Tests Results for the Correction of the Copper Concentrations - Phase II

Reactor	HRT (hours)	Initial Conc. (mg/L)	Final Conc. (mg/L)	Correction Conc. (mg/L)
A	9.0	10	9.62	+0.38
C	18.0	10	9.58	+0.42

The copper was used in the form of cupric sulfate, and since the applied concentration of this heavy metal was low, it was decided to neglect the effect of this sulfate concentration on the substrate constituents, in comparison with the MgSO4.7H20 concentration which was kept as shown in Table 4.12.

During the application of copper, the following data were collected from each reactor: influent metal and effluent metal concentrations from each effluent port to determine the behavior of SRB under different metal loading. Both dissolved and total metal concentrations were measured in the influent and effluent for all the loading of copper and all ports of the reactors. Tables V.11 to Table V.16 present these values for different influent concentrations of 25, 50, 100, 200, 300, 400 mg/L for HRT = 9 h by Reactor A. Table V.17 to Table V.22 give these effluent dissolved and total copper for HRT= 18 h by Reactor C. This was used for designing the reactor, i.e., establishing the height of the reactor for different metal loading rates.

Tables 4.14 and 4.15 present the average dissolved and total copper concentrations and percentages for the different influent concentration for HRT=9 h and 18 h respectively.

Table 4.14 : Average Dissolved and Total Copper Concentrations and Percentages* at Different Heights for HRT = 9 hours (Reactor A)

Port Height	Influent	0.3 m	0.6 m	0.9 m	1.2 m
(Avg. Dissolved	25	0	0	0	0
Cu Conc., mg/L)	50	0	0	0	0
	100	23(23%)	0	0	0
	204	168(82%)	105(51%)	39(19%)	27(13%)
	305	276(90%)	221(72%)	143(47%)	78(25%)
	407	390(96%)	345(85%)	252(62%)	134(33%)
(Average Total	25	0	0	0	0
Copper Conc., mg/L)	50	0	0	0	0
	101	24(24%)	0	0	0
	208	172(83%)	108(52%)	40(19%)	28(13%)
	310	280(90%)	226(73%)	148(48%)	80(26%)
	412	395(96%)	350(85%)	256(62%)	140(34%)

* : Percentage = (Effluent/Influent) x 100

Table 4.15 : Average Dissolved and Total Copper Concentrations and Percentages* at Different Heights for HRT = 18 hours (Reactor C)

Port Height	Influent	0.3 m	0.6 m	0.9 m	1.2 m
(Average Dissolved	25	0	0	0	0
Copper Conc.,	50	0	0	0	0
mg/L)	100	17(18%)	0	0	0
	210	165(79%)	97(46%)	22(11%)	20(10%)
	306	276(90%)	217(71%)	124(41%)	45(15%)
	405	389(96%)	338(84%)	237(59%)	69(17%)
(Average Total	25	0	0	0	0
Cu Conc., mg/L)	50	0	0	0	0
	101	18(18%)	0	0	0
	214	168(79%)	99(46%)	23(11%)	21(10%)
	307	281(91%)	223(72%)	129(42%)	48(16%)

* : Percentage = (Effluent/Influent) x 100

Tables 4.14 and 4.15 clearly indicate that the system showed great tolerance for high concentration of this heavy metal, namely, copper. UAFFR was capable of removing 100 % of the metal in less than full height (1200 mm) when the influent concentration was less than 100 mg/L. Removal ratio of about 90 % could be achieved in full height (1200 mm) for 200 mg/L of influent concentration. Removal ratio of 85 % could be achieved in full height (1200 mm) for 300 mg/L of influent heavy metal concentration for slow reactor (HRT=18 h), whereas, for the fast reactor (HRT=9 h), the removal ratio is 75% for the same influent concentration. It should be noticed that the above concentrations were as dissolved metal concentrations represented about 95-97% of the total metal concentrations.

So, depending upon the influent concentration, desired removal efficiency, and hydraulic retention time the reactor could be designed.

Chapter 5: CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

5.1.1 General

The research showed that the sulfate reducing bacteria strain, SRB, can be developed optimally with lactate as the source of organic carbon under different flow rate (hydraulic retention time, HRT) when theoretical oxygen demand to sulfate ratio, organic loading rate, nitrogen requirements as ammonium, total phosphorus, pH, and oxidation reduction potential are controlled for maximum sulfide production in an upflow anaerobic fixed film reactor, UAFFR. However, acetate as the source of organic carbon could not successfully develop the SRB in the preliminary stages. Also, SRB could not be satisfactorily developed under the acidic media.

The SRB showed capability to remove high concentrations of heavy metal, needed to purify polluted industrial wastewater upto high degree of removal efficiency required by new government/environmental agency laws, not only by precipitation through the sulfate reduction in the substrate, but also by biosorption by its volatile biomass.

5.1.2 Phase I

.SRB have grown successfully by utilizing lactate as source of organic carbon and have produced sufficient sulfide for removing high concentration levels of heavy metal.

.Measurement of volatile SRB biomass also confirmed to the SRB growth through utilization of lactate as source of organic carbon.

.Most of the SRB growth was observed in the lower region (upto 0.3 m) of the reactor.

.It may not be necessary to use fixed film reactor, plug flow reactor might serve the purpose.

.Sulfide production was observed in the entire reactor height.

.

5.1.3 Phase II

.Copper was fed to the reactors in different stages of operation. The system showed great tolerance for high concentration of this metal. UAFFR was capable of removing upto 100 % of the metal in less than/full height (1200 mm) for higher than 100 mg/L of influent concentration. Removal ratio of about 90 % could be achieved in full height (1200 mm) for 200 mg/L of influent concentration for slow reactor (HRT=18 h), whereas, for the fast reactor (HRT=9 h), the removal ratio is 75% for the same influent concentration.

.Depending upon the influent heavy metal concentration, desired removal efficiency, and desired hydraulic retention time, the UAFF reactor can be designed.

Generally, the use of SRB in an UAFFR, for removing heavy metals is considered a very promising technique for biological treatment of industrial wastes with heavy metals as pollutants with low cost, low maintenance cost and ease in operation. These major advantages would make this system ideal for the developing countries.

5.2 Future Work

This study has covered different aspects of the performance of SRB in UAFFR in terms of their development and growth using optimum controlling conditions for biomass and sulfide production, and their behavior during heavy metal, copper, loadings. Finally, this research has established design of UAFFR in terms of the pollutant concentrations and efficiency requirements. The following future work is recommended:

.More studies are required on the behavior of SRB fed with domestic/industrial wastewaters. This will establish the possibilities of adopting this system to use such wastes as sources of carbon under different organic loading conditions and its effect on the biosorption of heavy metals.

.The metals were removed in this system by transferring them from the liquid phase to the solid phase. Further work is required to establish procedures for possible recycling of these metals for industrial processes/purposes, saving the environment and lowering the budget.

.Attempt to be made to develop SRB at low pH, high toxic concentration.

.It may not be necessary to use fixed film reactor, plug flow reactor might serve the purpose, more studies in the corresponding field are required.

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APPENDIX I

CALIBRATION CURVES

APPENDIX I

CALIBRATION CURVES

I.1 Sulfates

Sulfates were measured using Turbidimetric Method (*Standard Methods*, APHA, 1995). Light absorbency of $BaSO_4$ was measured by a photometer. The sulfate concentration was determined by comparing the reading of the turbidimeter with a standard curve. The preparation of the standard curve was carried out as recommended in the *Standard Methods* (APHA, 1995) and a typical plot is shown in Fig. I.1. A straight line plot was obtained. Therefore, the following equation was used for relationship between the sulfate concentrations and the turbidimeter readings (Equation I.1). This equation is not valid over the curve limits, i.e. for sulfate concentration over 40 mg/L, because the relationship was no longer a straight line over this concentration as explained in the *Standard Methods* (APHA, 1995). Also, as recommended by *Standard Methods* (APHA, 1995), the standard curve was updated every two to three weeks for accurate results.

$$SO_4 = 0.25\ \text{NTU} \qquad \text{(I.1)}$$

The minimum detectable concentration was approximately 1 mg/L.

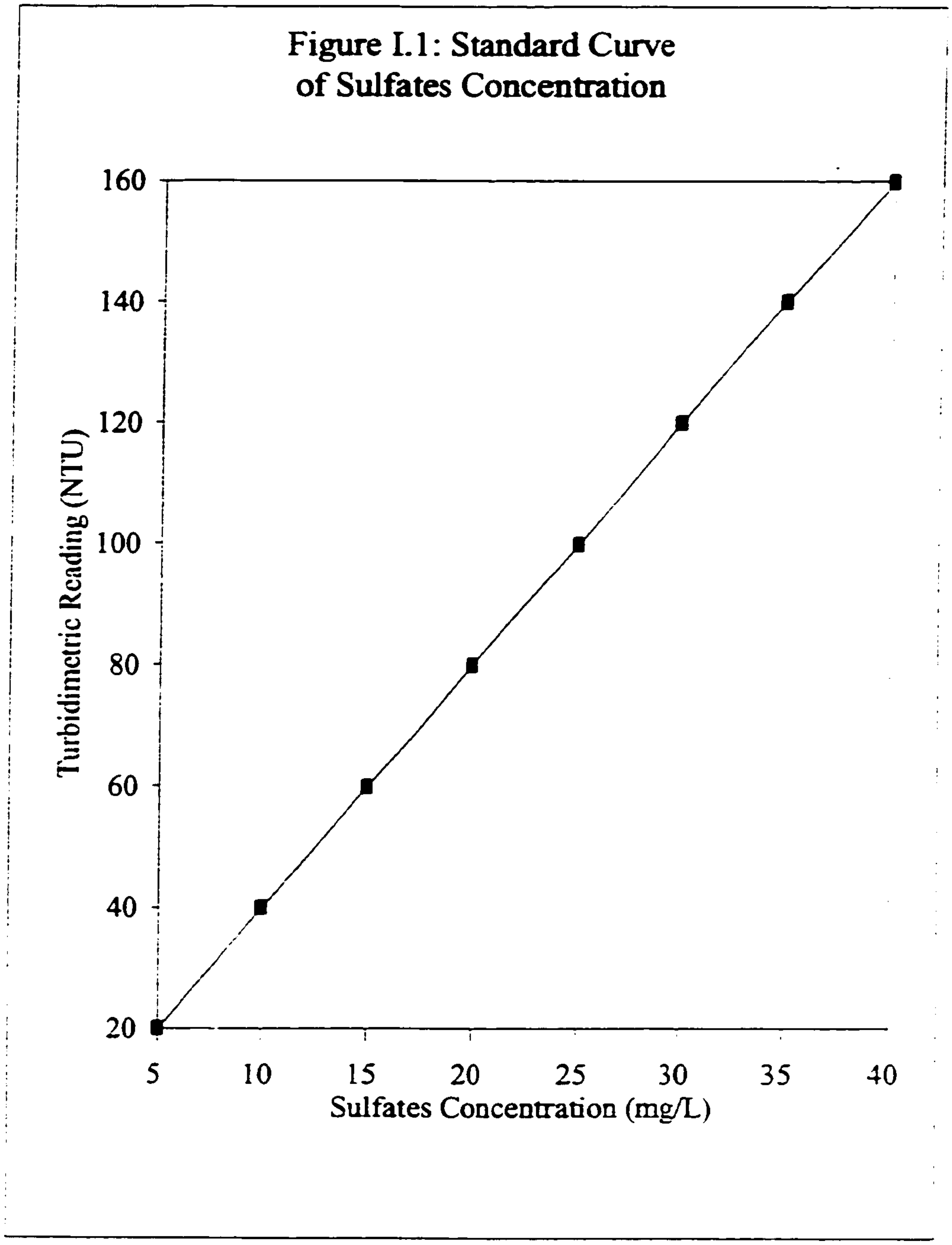


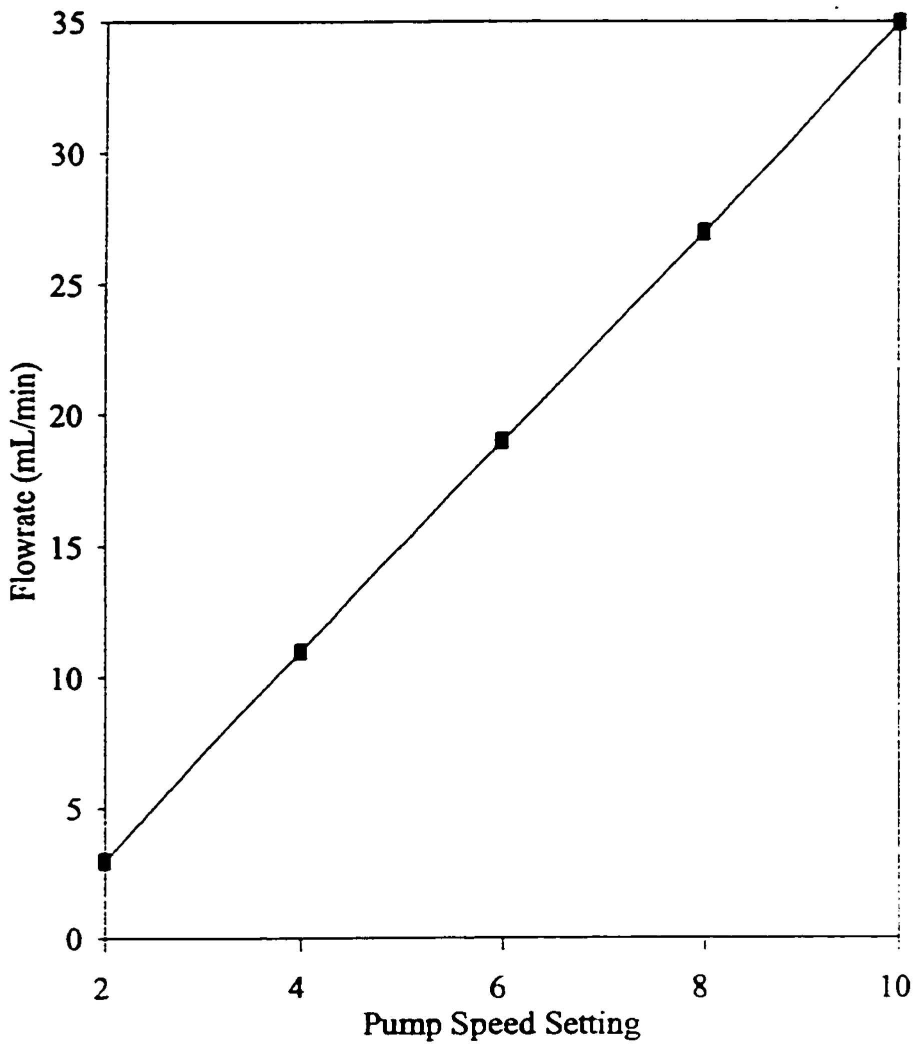
Figure I.1: Standard Curve
of Sulfates Concentration
160
140
120
100
80
60
40
20
Turbidimetric Reading (NTU)
5
10
15
20
25
30
35
40
Sulfates Concentration (mg/L)

I.2 Peristaltic Pumps

The peristaltic pumps were calibrated everyday, because the speed of the pump affected the operating flow rate. The continuous change in the pump's flow rate was due to the change in the tubing cross sectional area caused by the settling of particles on its inner surface.

The calibration was carried out by measuring the flowrate at different pump speeds and plotting the curve. Figure I.2 shows an example of one of these calibration curves.

Figure I.2
Standard Curve of Peristaltic Pump



APPENDIX II

PRELIMINARY START-UP EXPERIMENTS

STAGE 1

APPENDIX II

PRELIMINARY STAGE 1

Use of Acetate as Source of Carbon at Initial Stage in Batch Reactors:

The literature has little or no information on the behavior of the sulfate reducing bacteria fed with the acetate as the main organic source of carbon. For example, Parkin *et al.* (1990) have reported a maximum sulfide production of about 60 mg/L with acetate fed SRB.

Normally, when acetate was preferred as main source of carbon, some other form of carbon, preferably lactate or pyruvate was used for activation and growth of SRB inside the reactors. After the steady state for growth of SRB, gradual switching to acetate in increments was initiated until it became the only source of carbon in the substrate over a period of time.

In this study, attempt was made to do research by feeding only acetate as a source of carbon in the substrate in the preliminary first stage in the batch reactors. Six batch reactors of size 1.0 L were seeded with a strain of bacteria from a sulfide-smelling wastewater for a suitable start of the bacterial activities.

Three batch reactors were filled with the polypropylene rings of size 15.9 mm, whereas the remaining three did not carry any media. Optimum organic loading rate of 6 $kg/d/m^3$ was maintained for four days on daily basis. Optimum Th.O.D. to Sulfate ratio of 2 was maintained. Optimum nitrogen and phosphorus were used with Th.O.D.:N:P = 100:5:1. The following materials dissolved in distilled water were used for the substrate composition:

Sodium acetate

$MgSO_4.7H_20$

NH_4Cl

KH_2PO_4

K_2HPO_4

The pH of the feed solution was observed to be 6.4 to 6.5.

Sulfide and sulfate analyses for the batch reactors were carried out to detect any change. But, for couple of months hardly any change was observed. Also, rapid test for the sulfur reducing bacteria, by immunoassay kit was carried out, but it also showed little progress.

Later, after two months, S^{-2} in the form of sodium sulfide was added in three stages of 10 mg/L, 15 mg/L, and 15 mg/L. Altogether upto 40 mg/L added to the batch reactors, but that also served no purpose as no satisfactory growth in the SRB or in sulfide production was observed.

APPENDIX III

PRELIMINARY START-UP EXPERIMENT
STAGE 2

APPENDIX III

PRELIMINARY STAGE 2

A. Use of Acetate as Source of Carbon in Initial Stage in UAFFR:

The contents of the batch reactors used in preliminary stage 1 were used in the continuous flow pexiglass reactors A, B, and C as described earlier. Each UAFFR was filled with 2 x 1L contents of the batch reactors and the rest volume was filled with the distilled water. The composition of the substrate was same as described in the preliminary stage 1. The pH of nearly 6.7 was maintained.

The reactors were used as the batch reactor for three days after flushing for one day. Then they were changed to UAFFR continuous flow reactors for ten days feeding acetate as the main component of substrate. Sulfide and sulfate analyses were carried out for the samples retrieved from the various port heights of the reactors and effluent. No growth of SRB was observed and no detection in change of sulfide was observed.

B. Low pH with Lactic Acid as Source of Carbon in UAFFR:

To determine the growth of sulfur reducing bacteria in acidic medium with pH = 4.5 and lactate as feed, the composition of substrate was changed from sodium acetate to lactic acid from preliminary stage 2A as the main source of organic carbon. All the other parameters were kept the same. The optimum OLR of 6 kg/d/m^3 was maintained. Again, analyses of sulfide and sulfate were carried out for the samples retrieved from various port heights and effluent of the reactors A, B, and C for over two weeks. But, acidic medium i.e. low pH showed no noticeable change in the sulfide concentration for two weeks. Immunoassay kit test also showed no satisfactory growth in SRB.

Later, S^{-2}, in the form of sodium sulfide, also added to the reactor upto the concentration of 60 mg/L in the feed, but no satisfactoty growth was observed in the SRB.

APPENDIX IV

OXIDATION REDUCTION POTENTIAL

APPENDIX IV

OXIDATION REDUCTION POTENTIAL

Oxidation Reduction potential (ORP) measurement indicates the electron activity of a solution. A solution always contains both reduction and oxidation agents. A reduction agent is defined as a substance capable of liberating electrons. On the other hand, an oxidation agent is defined as a substance capable of accepting electrons. The reduction and oxidation process can be written as follows:

$$\text{Reduction} \Longrightarrow \text{Oxidation} + e^{-} \qquad \text{(IV.1)}$$

Thus,

$$S^{-2} + 4H_2O \Longrightarrow SO_4^{-2} + 8H^{+} + 8e^{-} \qquad \text{(IV.2)}$$

A redox system is a reduction agent and its corresponding oxidation counterpart.

ORP was measured by immersing a platinum electrode and a reference electrode in the solution to be measured. The platinum potential can be expressed as:

$$e = k + \left({}^{R*T}/_{F}\right) \ln\left({}^{a}Ox / {}^{a}Red\right) \qquad \text{(IV.3)}$$

where :

k = temperature dependent constant;

F= Faraday constant;

R = gas constant;

T = temperature in ^0K;

^aOx = activity of the oxidation agent; and

^aRed = activity of the reduction agent.

If the reference electrode is a standard hydrogen electrode, then the potential difference between the platinum and the reference electrode is :

$$E_h \quad = \quad E^0_{Ox\text{-}Red} \quad + \quad (^{R*T}/_F)\ \ln(\,^aOx\,/\,^aRed\,) \qquad (IV.4)$$

Where,

$E^0_{Ox\text{-}Red}$ = Standard potential which is depended on temperature, and the nature of the redox system.

The normal equation for redox potential when hydrogen ions are involved in the chemical reaction is :

$$Red + H_2O \rightleftharpoons Ox + mH^+ + ne^- \qquad (IV.5)$$

Then,

$$E_h \quad = \quad E^0_{Ox\text{-}Red} \quad + \quad (^{R*T}/_{n*F})\ \ln(\,^aOx/\,^aRed\,) \quad - \quad (^{R*T*M}/_n)\ pH \qquad (IV.6)$$

In practice, the standard hydrogen electrode is not suitable as a reference electrode. The most common reference electrode used is calomel electrode. Any measurement performed with the platinum and the calomel electrodes can be converted to yield :

$$E_h = E + E_{ref.\ electrode} \quad (IV.7)$$

where,

E = measured potential difference between the platinum and the calomel electrodes;

$E_{ref.\ electrode}$ = potential difference between the reference electrodes.

The potential difference between calomel and standard hydrogen electrodes is 244.4 mV at 25 ^{0}C. Therefore, equation (IV.7) can be rewritten as :

$$E_h = E + 244.5 \quad (IV.8)$$

It is difficult to obtain stable ORP measurements in biological fluids. They would tend to shift towards more negative values. The difficulty for obtaining a well-defined redox potential is due to the fact that, frequently, the redox system in the solution slowly exchanges electrons with the platinum electrode (Petersen, 1966).

In order to obtain a stable measurement, Petersen (1966) recommended the addition of a "mediator" to the test solution. A mediator is a redox system capable of making both a rapid and a simple exchange of electrons with the platinum electrode. The requirement for the mediator to function satisfactorily is that the activity (concentration) occurring in its oxidized form should be equal to that in its reduced form.

On the other hand, Lappan (1987) reported no differences in instrumental response rates when the mediators were employed, as suggested by Petersen. As such, Lappan suggested the adoption of a consistent method for redox measurement. Measurements were taken ten minutes after immersing the electrodes in the sample. Lappan found that the instrument reached at least 95% of the equilibrium reading within ten minutes.

APPENDIX V

DATA

APPENDIX V

DATA

Abbreviations Used:

i	=	Influent
e	=	Effluent

V.1 Data obtained during Phase I

Table V.1: VSS Concentrations (g/L) at Different Heights - Reactor A

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
40					
41					
42	0.240	0.158	0.242	0.178	0.186
43	0.255	0.264	0.262	0.184	0.302
45	0.268	0.248	0.254	0.204	0.286

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
46					
47	0.302	0.186	0.186	0.116	0.310
48	0.308	0.214	0.224	0.128	0.264
49	0.384	0.262	0.198	0.128	0.287
50					
51	0.373	0.540	0.342	0.264	0.321
52	0.308	0.208	0.358	0.364	0.284
53	0.435	0.176	0.290	0.202	0.308
54					
55					
56	0.576	0.232	0.204	0.210	0.254
57	0.428	0.218	0.388	0.276	0.318
58	0.386	0.227	0.312	0.321	0.361
59	0.397	0.278	0.246	0.186	0.367
60					
61	0.395	0.294	0.367	0.412	0.322
62	0.476	0.316	0.246	0.240	0.343
63	0.465	0.208	0.188	0.168	0.282
64	0.364	0.198	0.144	0.164	0.333
65	0.368	0.238	0.167	0.334	0.262
66					
67	0.348	0.238	0.242	0.198	0.254
68	0.385	0.261	0.258	0.221	0.268
69					
70	0.366	0.224	0.239	0.224	0.238
71	0.295	0.198	0.268	0.246	0.267
72					
73	0.431	0.286	0.209	0.188	0.244
74	0.286	0.237	0.227	0.226	0.262
75	0.394	0.288	0.256	0.229	0.278
76					
77	0.388	0.274	0.284	0.259	0.305
78	0.426	0.268	0.257	0.237	0.308
79	0.418	0.237	0.249	0.255	0.284
80					
81					
82					
83					
84					
85					
86					
87					
88					
89					
90					
91					
92					
93					

		Height (m)			
Day	0.05	0.3	0.6	0.9	1.2
94					
95					
96	0.246	0.210	0.244	0.264	0.328
97	0.327	0.217	0.206	0.199	0.261
98					
99					
100					
101	0.416	0.189	0.224	0.252	0.288
102	0.408	0.237	0.186	0.209	0.238
103	0.454	0.267	0.197	0.199	0.286
104	0.382	0.248	0.234	0.221	0.248
105					
106	0.334	0.162	0.228	0.214	0.267
107	0.305	0.209	0.282	0.239	0.344
108	0.367	0.244	0.208	0.222	0.329
109	0.346	0.237	0.277	0.242	0.299
110	0.388	0.272	0.261	0.238	0.288
111					
112	0.358	0.264	0.194	0.188	0.249
113	0.342	0.208	0.211	0.208	0.266
114	0.364	0.261	0.238	0.244	0.301
115	0.387	0.269	0.224	0.220	0.288
116	0.421	0.281	0.268	0.249	0.327
117					
118					
119	0.364	0.260	0.285	0.236	0.312
120	0.322	0.211	0.246	0.224	0.300
121					
122	0.350	0.234	0.229	0.251	0.286
123					
124	0.406	0.208	0.234	0.244	0.261
125	0.368	0.254	0.198	0.208	0.276
126					
127	0.362	0.237	0.241	0.206	0.291
128	0.428	0.228	0.226	0.214	0.267
129					
130					
131	0.367	0.224	0.212	0.238	0.286
132	0.392	0.271	0.266	0.215	0.278
133	0.342	0.268	0.218	0.208	0.266
134					
135	0.368	0.259	0.242	0.236	0.308
136	0.320	0.207	0.238	0.227	0.294
137	0.364	0.269	0.249	0.250	0.326
138	0.428	0.220	0.228	0.206	0.276
139	0.344	0.204	0.168	0.212	0.255
140					
141	0.422	0.261	0.284	0.255	0.337

		Height (m)			
Day	0.05	0.3	0.6	0.9	1.2
142	0.315	0.232	0.288	0.239	0.308
143	0.386	0.251	0.258	0.241	0.297
144	0.345	0.260	0.266	0.246	0.288
145					
146	0.399	0.238	0.244	0.212	0.327
147					
148	0.428	0.288	0.262	0.238	0.311
149	0.312	0.184	0.238	0.230	0.264
150	0.364	0.264	0.252	0.227	0.286
151					
152					
153	0.389	0.255	0.276	0.266	0.334
154					
155	0.364	0.238	0.249	0.244	0.306
156					
157	0.502	0.264	0.255	0.231	0.279
158	0.384	0.229	0.242	0.198	0.246
159					
160	0.414	0.254	0.261	0.228	0.292
161					
162	0.368	0.267	0.252	0.217	0.280
163	0.348	0.221	0.238	0.238	0.286
164					
165	0.392	0.258	0.221	0.224	0.312
166	0.329	0.226	0.244	0.237	0.268
167					
168	0.378	0.281	0.234	0.241	0.276
169	0.354	0.264	0.268	0.265	0.320
170	0.388	0.227	0.284	0.268	0.315
171	0.395	0.248	0.229	0.232	0.305
172					
173	0.438	0.271	0.257	0.241	0.286
174	0.422	0.264	0.206	0.218	0.291
175					
176	0.343	0.227	0.259	0.232	0.281
177	0.342	0.264	0.286	0.255	0.344
178	0.391	0.267	0.309	0.266	0.329
179					
180	0.422	0.282	0.274	0.218	0.291
181	0.408	0.261	0.238	0.246	0.299
182	0.337	0.242	0.220	0.234	0.281
183	0.368	0.249	0.251	0.229	0.310
184	0.378	0.269	0.288	0.264	0.332
185					
186	0.401	0.254	0.264	0.234	0.301
187	0.355	0.231	0.248	0.220	0.286
188					
189	0.362	0.246	0.186	0.194	0.278

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
190	0.394	0.261	0.226	0.220	0.294
191					
192	0.426	0.257	0.261	0.238	0.318
193	0.339	0.241	0.244	0.244	0.308
194	0.367	0.293	0.267	0.239	0.344
195					
196	0.381	0.255	0.264	0.256	0.295
197					
198	0.367	0.210	0.282	0.248	0.268
199	0.370	0.263	0.244	0.233	0.304
200	0.394	0.251	0.238	0.237	0.311
201					
202	0.360	0.249	0.262	0.249	0.290
203	0.334	0.245	0.219	0.237	0.278
204					
205	0.382	0.313	0.237	0.254	0.346
206	0.372	0.249	0.268	0.236	0.311
207					
208					
209	0.334	0.253	0.288	0.251	0.308
210	0.386	0.264	0.261	0.226	0.294
211					
212	0.379	0.244	0.228	0.219	0.286
213	0.406	0.281	0.264	0.230	0.322
214					
215	0.421	0.263	0.288	0.243	0.305
216					
217	0.382	0.238	0.242	0.260	0.307
218					
219	0.367	0.251	0.294	0.255	0.311
220	0.380	0.230	0.282	0.260	0.322
221					
222	0.344	0.244	0.266	0.231	0.284
223	0.368	0.268	0.255	0.228	0.293
224					
225	0.391	0.253	0.286	0.242	0.307
226	0.365	0.247	0.267	0.233	0.294
227					
228	0.348	0.255	0.271	0.241	0.311
AVERAGE	0.374	0.248	0.249	0.232	0.294
STD	0.048	0.039	0.037	0.037	0.028

Table V.2: VSS Concentrations (g/L) at Different Heights - REACTOR B

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37	0.405	0.372	0.266	0.194	0.110
38	0.426	0.288	0.212	0.132	0.132
39	0.505	0.205	0.245	0.221	0.165
40	0.388	0.342	0.221	0.224	0.264
41					
42	0.269	0.255	0.267	0.204	0.114
43	0.406	0.342	0.214	0.128	0.218
45	0.366	0.187	0.209	0.224	0.274

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
46					
47	0.368	0.229	0.228	0.226	0.094
48	0.352	0.088	0.264	0.208	0.144
49	0.425	0.313	0.280	0.168	0.199
50					
51	0.394	0.241	0.108	0.210	0.135
52	0.364	0.344	0.234	0.165	0.186
53	0.434	0.271	0.132	0.194	0.310
54					
55					
56	0.436	0.318	0.278	0.215	0.166
57	0.376	0.251	0.224	0.166	0.144
58	0.382	0.208	0.169	0.218	0.132
59	0.350	0.218	0.212	0.169	0.225
60					
61	0.302	0.254	0.364	0.224	0.376
62	0.431	0.324	0.278	0.237	0.224
63	0.397	0.201	0.234	0.069	0.272
64	0.506	0.331	0.210	0.194	0.128
65	0.488	0.305	0.245	0.205	0.138
66					
67	0.399	0.258	0.138	0.118	0.168
68	0.426	0.311	0.238	0.178	0.207
69					
70	0.444	0.302	0.229	0.212	0.249
71	0.462	0.297	0.249	0.193	0.234
72					
73	0.388	0.224	0.186	0.145	0.201
74	0.425	0.262	0.220	0.168	0.228
75	0.406	0.228	0.202	0.171	0.168
76					
77	0.422	0.278	0.242	0.194	0.228
78	0.461	0.291	0.266	0.210	0.248
79	0.394	0.264	0.218	0.177	0.199
80					
81					
82					
83					
84					
85					
86					
87					
88					
89					
90					
91					
92					
93					

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
94					
95					
96	0.328	0.227	0.198	0.155	0.204
97	0.347	0.269	0.222	0.166	0.197
98					
99					
100					
101	0.421	0.288	0.231	0.181	0.228
102	0.464	0.284	0.244	0.194	0.232
103	0.444	0.231	0.229	0.161	0.178
104	0.382	0.237	0.208	0.166	0.194
105					
106	0.384	0.256	0.264	0.200	0.246
107	0.367	0.241	0.223	0.176	0.208
108	0.428	0.275	0.233	0.155	0.207
109	0.451	0.284	0.254	0.220	0.244
110	0.368	0.264	0.209	0.188	0.210
111					
112	0.374	0.227	0.186	0.167	0.188
113	0.411	0.259	0.208	0.154	0.168
114	0.399	0.244	0.218	0.178	0.210
115	0.357	0.209	0.199	0.114	0.185
116	0.388	0.226	0.207	0.167	0.179
117					
118					
119	0.468	0.294	0.255	0.221	0.245
120	0.415	0.287	0.231	0.204	0.238
121					
122	0.394	0.246	0.221	0.169	0.178
123					
124	0.384	0.251	0.238	0.175	0.156
125	0.406	0.267	0.251	0.199	0.237
126					
127	0.461	0.311	0.264	0.220	0.228
128	0.422	0.268	0.229	0.206	0.218
129					
130					
131	0.388	0.208	0.224	0.176	0.194
132	0.394	0.224	0.209	0.168	0.204
133	0.416	0.261	0.233	0.148	0.179
134					
135	0.388	0.244	0.205	0.188	0.210
136	0.358	0.259	0.218	0.176	0.194
137	0.421	0.255	0.234	0.214	0.254
138	0.409	0.267	0.227	0.176	0.199
139	0.390	0.212	0.224	0.142	0.167
140					
141	0.372	0.198	0.206	0.166	0.178

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
142	0.410	0.252	0.237	0.196	0.218
143	0.356	0.239	0.199	0.178	0.202
144	0.398	0.267	0.232	0.208	0.251
145					
146	0.401	0.288	0.228	0.221	0.231
147					
148	0.375	0.263	0.241	0.176	0.208
149	0.352	0.244	0.206	0.148	0.186
150	0.408	0.273	0.208	0.206	0.228
151					
152					
153	0.422	0.294	0.256	0.229	0.266
154					
155	0.431	0.267	0.244	0.218	0.223
156					
157	0.394	0.223	0.188	0.174	0.201
158	0.408	0.248	0.207	0.169	0.179
159					
160	0.423	0.244	0.221	0.204	0.222
161					
162	0.421	0.283	0.248	0.207	0.231
163	0.408	0.266	0.251	0.238	0.220
164					
165	0.378	0.257	0.229	0.169	0.188
166	0.415	0.277	0.237	0.197	0.228
167					
168	0.418	0.238	0.207	0.158	0.168
169	0.376	0.228	0.149	0.148	0.176
170	0.388	0.257	0.227	0.164	0.190
171	0.428	0.281	0.264	0.224	0.240
172					
173	0.409	0.250	0.207	0.210	0.256
174	0.408	0.271	0.206	0.186	0.241
175					
176	0.367	0.234	0.211	0.176	0.204
177	0.437	0.330	0.259	0.237	0.267
178	0.379	0.249	0.208	0.189	0.231
179					
180	0.409	0.271	0.233	0.178	0.221
181	0.424	0.266	0.244	0.208	0.235
182	0.449	0.287	0.241	0.221	0.225
183	0.406	0.212	0.201	0.181	0.204
184	0.432	0.223	0.234	0.199	0.229
185					
186	0.446	0.254	0.194	0.167	0.217
187	0.408	0.238	0.186	0.158	0.187
188					
189	0.394	0.271	0.228	0.176	0.197

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
190	0.428	0.307	0.244	0.223	0.248
191					
192	0.431	0.277	0.251	0.221	0.231
193	0.420	0.294	0.218	0.179	0.194
194	0.394	0.244	0.204	0.188	0.208
195					
196	0.368	0.239	0.209	0.173	0.209
197					
198	0.388	0.255	0.207	0.169	0.188
199	0.409	0.267	0.241	0.200	0.215
200	0.448	0.280	0.244	0.186	0.245
201					
202	0.399	0.239	0.226	0.171	0.208
203	0.402	0.255	0.235	0.204	0.231
204					
205	0.428	0.267	0.255	0.197	0.199
206	0.408	0.274	0.231	0.184	0.206
207					
208					
209	0.388	0.244	0.209	0.158	0.181
210	0.430	0.281	0.232	0.217	0.221
211					
212	0.401	0.264	0.211	0.188	0.186
213	0.447	0.297	0.241	0.208	0.221
214					
215	0.387	0.224	0.194	0.176	0.189
216					
217	0.422	0.280	0.238	0.204	0.214
218					
219	0.408	0.266	0.251	0.210	0.231
220	0.419	0.257	0.244	0.194	0.217
221					
222	0.439	0.277	0.238	0.176	0.174
223	0.414	0.244	0.228	0.177	0.186
224					
225	0.396	0.251	0.208	0.160	0.199
226	0.416	0.277	0.218	0.186	0.219
227					
228	0.388	0.248	0.201	0.177	0.184
AVERAGE	0.405	0.261	0.225	0.186	0.207
STD	0.035	0.037	0.030	0.028	0.039

Table V.3: VSS Concentrations (g/L) at Different Heights - Reactor C

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
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18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37	0.242	0.166	0.168	0.038	0.094
38	0.320	0.198	0.225	0.188	0.201
39	0.358	0.128	0.158	0.242	0.078
40	0.318	0.128	0.169	0.224	0.068
41					
42	0.348	0.426	0.271	0.248	0.068
43	0.276	0.214	0.270	0.344	0.118

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
45	0.129	0.224	0.396	0.098	0.224
46					
47	0.324	0.129	0.215	0.069	0.118
48	0.438	0.286	0.275	0.156	0.332
49	0.278	0.299	0.305	0.148	0.372
50					
51	0.324	0.338	0.222	0.224	0.348
52	0.286	0.305	0.148	0.322	0.278
53	0.524	0.148	0.146	0.112	0.189
54	0.442	0.268	0.154	0.108	0.185
55					
56	0.443	0.256	0.168	0.208	0.248
57	0.426	0.248	0.168	0.175	0.228
58	0.522	0.260	0.170	0.124	0.254
59	0.556	0.259	0.218	0.154	0.167
60					
61	0.551	0.258	0.324	0.218	0.194
62	0.535	0.421	0.278	0.178	0.244
63	0.438	0.315	0.318	0.206	0.218
64	0.421	0.155	0.276	0.170	0.241
65	0.388	0.128	0.297	0.184	0.129
66					
67	0.446	0.258	0.224	0.178	0.237
68	0.502	0.258	0.248	0.204	0.211
69					
70	0.484	0.234	0.214	0.167	0.251
71	0.461	0.224	0.254	0.201	0.231
72					
73	0.444	0.262	0.242	0.214	0.254
74	0.386	0.241	0.261	0.238	0.241
76	0.394	0.169	0.201	0.194	0.226
77					
78	0.426	0.309	0.274	0.228	0.241
79	0.420	0.268	0.223	0.196	0.238
80	0.438	0.272	0.287	0.247	0.267
81					
82					
83					
84					
85					
86					
87					
88					
89					
90					
91					
92					

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
93					
94					
95					
96					
97	0.384	0.202	0.254	0.203	0.246
98	0.397	0.254	0.198	0.155	0.198
99					
100					
101					
102	0.425	0.283	0.252	0.188	0.201
103	0.367	0.194	0.172	0.147	0.215
104	0.429	0.267	0.224	0.185	0.234
105	0.420	0.288	0.217	0.176	0.221
106					
107	0.418	0.220	0.208	0.167	0.244
108	0.388	0.168	0.192	0.158	0.198
109	0.446	0.198	0.199	0.201	0.255
110	0.443	0.249	0.216	0.186	0.241
111	0.384	0.229	0.222	0.205	0.234
112					
113	0.367	0.234	0.198	0.167	0.228
114	0.388	0.202	0.162	0.155	0.228
115	0.342	0.261	0.209	0.187	0.219
116	0.421	0.272	0.252	0.234	0.248
117	0.368	0.250	0.241	0.209	0.238
118					
119					
120	0.388	0.244	0.214	0.181	0.224
121	0.372	0.267	0.176	0.168	0.231
122					
123	0.386	0.224	0.197	0.184	0.194
124					
125	0.435	0.260	0.246	0.209	0.214
126	0.445	0.258	0.206	0.168	0.205
127					
128	0.410	0.208	0.180	0.155	0.208
129	0.381	0.241	0.209	0.179	0.238
130					
131					
132	0.462	0.288	0.221	0.204	0.264
133	0.406	0.234	0.246	0.231	0.284
134	0.416	0.246	0.233	0.189	0.233
135					
136	0.387	0.196	0.199	0.144	0.175
137	0.428	0.251	0.228	0.172	0.201
138	0.481	0.248	0.261	0.261	0.305
139	0.502	0.269	0.193	0.155	0.208

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
140	0.409	0.284	0.207	0.138	0.194
141					
142	0.429	0.284	0.226	0.149	0.186
143	0.387	0.227	0.232	0.188	0.208
144	0.366	0.208	0.162	0.164	0.223
145	0.384	0.251	0.206	0.154	0.214
146					
147	0.412	0.244	0.179	0.168	0.225
148					
149	0.366	0.238	0.227	0.187	0.248
150	0.441	0.294	0.244	0.167	0.214
151	0.483	0.256	0.228	0.194	0.268
152					
153					
154	0.444	0.274	0.261	0.167	0.231
155					
156	0.364	0.228	0.229	0.204	0.218
157					
158	0.347	0.238	0.202	0.167	0.288
159	0.432	0.268	0.226	0.198	0.241
160					
161	0.464	0.259	0.233	0.201	0.257
162					
163	0.418	0.289	0.266	0.224	0.246
164	0.448	0.267	0.232	0.168	0.231
165					
166	0.420	0.255	0.175	0.167	0.227
167	0.439	0.237	0.169	0.142	0.188
168					
169	0.389	0.221	0.198	0.166	0.219
170	0.408	0.267	0.213	0.171	0.209
171	0.442	0.283	0.246	0.168	0.226
172	0.506	0.267	0.208	0.195	0.234
173					
174	0.422	0.228	0.233	0.208	0.311
175	0.468	0.286	0.254	0.202	0.264
176					
177	0.437	0.270	0.215	0.168	0.241
178	0.446	0.285	0.232	0.185	0.238
179	0.468	0.226	0.199	0.167	0.194
180					
181	0.388	0.281	0.236	0.159	0.204
182	0.409	0.261	0.241	0.179	0.185
183	0.419	0.244	0.183	0.146	0.227
184	0.446	0.294	0.195	0.181	0.241
185	0.462	0.231	0.176	0.152	0.209
186					

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
187	0.385	0.197	0.208	0.169	0.187
188	0.421	0.241	0.223	0.201	0.252
189					
190	0.444	0.267	0.218	0.194	0.257
191	0.430	0.231	0.202	0.157	0.186
192					
193	0.406	0.281	0.246	0.227	0.248
194	0.367	0.240	0.178	0.167	0.201
195	0.399	0.223	0.227	0.179	0.208
196					
197	0.428	0.267	0.190	0.149	0.168
198					
199	0.358	0.249	0.247	0.197	0.245
200	0.426	0.297	0.218	0.182	0.207
201	0.437	0.268	0.202	0.177	0.231
202					
203	0.501	0.304	0.248	0.229	0.268
204	0.422	0.237	0.224	0.176	0.231
205					
206	0.409	0.249	0.208	0.169	0.199
207	0.438	0.283	0.195	0.184	0.208
208					
209					
210	0.446	0.274	0.262	0.186	0.241
211	0.406	0.238	0.206	0.162	0.229
212					
213	0.388	0.227	0.179	0.151	0.194
214	0.431	0.291	0.224	0.179	0.214
215					
216	0.410	0.315	0.244	0.205	0.227
217					
218	0.449	0.246	0.212	0.183	0.207
219					
220	0.462	0.264	0.196	0.169	0.196
221	0.418	0.230	0.172	0.158	0.186
222					
223	0.446	0.267	0.249	0.208	0.261
224	0.442	0.271	0.228	0.154	0.197
225					
226	0.409	0.266	0.201	0.179	0.208
227	0.410	0.259	0.213	0.186	0.229
228					
229	0.388	0.220	0.227	0.175	0.241
AVERAGE	0.414	0.250	0.218	0.182	0.222
STDEV	0.058	0.046	0.043	0.038	0.045

Table V.4: TS & VS Concentrations (g/L) at Different Heights - REACTOR A

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
1										
2										
3										
4										
5										
6										
7	8.894	4.012	7.222	2.766	7.164	2.544	7.154	2.628	7.052	2.388
8	8.746	4.084	7.468	2.688	7.288	2.886	7.08	2.712	7.248	2.912
9										
10	9.498	4.386	7.984	3.212	7.55	3.008	7.38	2.946	7.086	2.788
11	9.39	4.206	8.29	3.03	7.626	2.804	7.626	2.774	7.13	2.562
12	9.208	4.442	8.194	3.428	7.604	3.062	7.324	2.786	7.28	2.68
13										
14	8.292	4.006	8.042	3.286	7.446	3.118	7.158	2.958	7.246	3.124
15	8.936	4.616	8.62	3.936	7.496	3.448	7.24	3.016	7.512	3.428
16	8.748	4.328	8.48	3.752	7.574	3.312	7.284	2.864	7.398	2.964
17	8.29	3.968	7.846	3.758	7.52	3.428	7.354	2.994	7.086	3.218
18										
19	9.65	4.482	8.082	3.688	7.648	3.52	7.384	3.028	7.486	3.348
20	9.402	4.682	8.264	3.886	7.782	3.428	7.428	3.018	7.22	3.256
21	9.172	4.594	8.26	3.524	7.74	3.12	7.54	2.944	7.346	3.114
22	9.554	4.082	8.288	3.185	7.886	2.944	7.462	2.786	7.212	2.648
23	9.904	4.24	8.084	2.936	7.844	2.74	7.64	2.724	7.06	2.488
24	9.646	4.362	8.524	3.528	8.042	2.846	7.774	2.812	7.298	2.628
25	9.028	4.628	8.564	3.186	7.496	2.786	7.348	2.644	7.424	2.568
26	9.346	4.482	8.482	3.804	7.548	3.214	7.264	2.786	7.344	3.008
27										
28	8.986	4.584	8.388	3.282	7.448	3.028	7.264	2.908	7.186	2.886
29										
30	9.12	4.442	8.512	3.644	7.506	3.006	7.314	2.754	7.228	2.964
31	8.954	4.41	7.992	3.448	7.428	2.996	7.284	2.812	7.114	2.75
32	8.644	4.286	7.586	3.284	7.348	3.048	7.106	2.848	7.002	2.624
33										
34	8.414	4.086	8.012	3.864	8.012	3.644	8.04	3.254	7.646	2.846
35	9.048	4.558	8.336	3.776	7.662	3.228	7.44	2.892	7.228	2.906
36										
37	9.126	4.824	8.268	3.62	7.884	3.458	7.456	3.2	7.088	2.996
38	9.148	4.764	8.338	3.778	7.54	3.118	7.328	3.116	7.064	2.926
39	8.864	4.328	7.994	3.348	7.506	3.146	7.218	2.908	7.02	2.824
40	8.672	4.12	7.66	3.196	7.456	3.092	7.04	2.836	7.064	2.696
41										
42	8.522	4.158	7.854	3.338	7.552	3.248	7.338	2.918	7.008	2.776
43	8.746	4.328	7.924	3.394	7.628	3.206	7.414	3.048	7.116	2.808
45	8.54	4.186	7.882	3.418	7.712	3.314	7.444	3.04	7.038	2.886

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
46										
47	8.554	4.386	8.334	3.894	8.512	3.662	8.448	3.402	7.558	3.226
48	8.41	4.162	7.778	3.216	7.496	3.118	7.292	2.904	7.084	2.882
49	8.228	3.998	7.558	3.556	7.338	3.306	7.118	2.924	7.002	2.856
50										
51	7.136	3.356	7.124	3.016	7.644	3.228	7.002	2.876	6.988	2.78
52	7.308	3.392	7.532	3.344	7.708	3.484	7.812	3.584	7.304	3.152
53	7.964	3.924	7.554	3.348	7.348	3.294	7.146	3.054	7.228	3.204
54										
55										
56	8.448	4.568	7.628	3.44	7.286	3.106	7.448	3.22	7.188	3.244
57	8.846	4.316	7.882	3.496	7.862	3.498	7.336	3.146	7.338	3.226
58	8.77	4.502	7.892	3.608	7.524	3.482	7.382	3.274	7.218	3.15
59	8.924	4.556	8.028	3.664	7.882	3.508	7.416	3.286	7.38	3.204
60										
61	8.62	4.612	8.48	4.236	8.288	4.26	8.016	4.092	8.1	3.812
62	9.084	4.776	8.386	4.016	8.262	3.716	7.994	3.348	7.78	3.288
63	9.114	4.786	8.348	3.942	8.212	3.678	7.712	3.448	7.628	3.348
64	8.884	4.624	8.562	3.854	8.042	3.248	7.564	2.998	7.468	2.886
65	8.468	4.328	7.568	3.56	7.368	3.384	7.508	3.356	7.344	3.256
66										
67	8.786	4.618	7.902	3.774	7.558	3.528	7.444	3.306	7.206	3.118
68	9.02	4.588	8.172	3.76	8.052	3.676	7.512	3.292	7.516	3.2
69										
70	8.726	4.552	7.882	3.664	7.524	3.44	7.382	3.298	7.224	3.106
71	8.554	4.414	7.712	3.628	7.432	3.486	7.332	3.318	7.204	3.228
72										
73	8.226	4.186	7.806	3.664	7.448	3.462	7.228	3.31	7.118	3.168
74	7.896	3.912	7.828	3.584	7.564	3.428	7.664	3.46	7.104	3.016
75	8.442	4.318	7.668	3.648	7.512	3.524	7.226	3.294	7.108	3.116
76										
77	8.642	4.204	7.992	3.542	7.716	3.338	7.348	3.024	7.084	2.896
78	8.018	3.954	7.582	3.388	7.336	3.19	7.098	2.926	7.124	3.106
79	8.466	4.148	7.792	3.346	7.493	3.212	7.35	2.946	7.06	2.798
80										
81										
82										
83										
84										
85										
86										
87										
88										
89										
90										
91										
92										
93										

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
94										
95										
96	8.844	4.528	8.342	4.132	8.164	4.054	7.824	3.864	7.864	3.642
97	9.062	4.624	8.316	4.062	8.116	3.752	7.764	3.342	7.684	3.344
98										
99										
100										
101	9.164	4.562	8.226	3.528	7.782	3.128	7.648	3.042	7.284	3.106
102	9.228	4.152	8.124	3.384	7.764	3.094	7.328	2.888	7.216	2.884
103	9.348	4.342	8.064	3.268	7.564	2.824	7.622	2.828	7.122	2.596
104	8.658	4.164	7.684	3.348	7.548	3.256	7.384	2.942	7.164	2.828
105										
106	7.484	3.658	7.208	3.188	7.548	3.328	7.064	2.864	6.954	2.814
107	7.328	3.456	7.424	3.542	7.524	3.46	7.328	3.362	7.262	3.124
108	7.864	3.954	7.642	3.428	7.428	3.342	7.184	3.142	7.324	3.21
109	8.642	4.212	7.824	3.264	7.508	3.128	7.424	2.948	7.142	2.812
110	8.426	4.168	8.036	3.808	7.924	3.76	7.824	3.564	7.664	3.442
111										
112	8.526	4.168	7.786	3.482	7.664	3.268	7.428	3.086	7.066	2.864
113	7.656	3.488	7.56	3.342	7.782	3.448	7.628	3.328	7.304	3.168
114	7.852	3.844	7.664	3.356	7.284	3.196	7.108	2.948	7.126	3.094
115	9.064	4.752	8.164	3.654	7.794	3.446	7.426	3.244	7.092	2.99
116	9.264	4.728	8.264	3.846	7.624	3.128	7.428	3.104	7.078	2.918
117										
118										
119	8.654	4.428	8.386	3.942	8.038	3.662	7.828	3.392	7.558	3.248
120	8.442	4.186	7.684	3.368	7.386	3.224	7.384	2.948	7.064	2.848
121										
122	7.964	3.924	7.554	3.348	7.348	3.294	7.146	3.054	7.228	3.204
123										
124	8.468	4.157	7.782	3.464	7.528	3.286	7.284	3.062	7.084	2.914
125	8.052	3.962	7.608	3.424	7.424	3.212	7.164	2.844	7.124	3.084
126										
127	8.524	4.568	8.164	3.844	7.828	3.468	7.728	3.368	7.448	3.154
128	8.364	4.128	7.764	3.408	7.468	3.348	7.286	2.992	7.104	2.784
129										
130										
131	8.428	4.158	7.764	3.368	7.654	3.296	7.308	2.928	7.128	2.842
132	8.848	4.42	7.864	3.562	7.562	3.308	7.428	3.242	7.154	2.868
133	8.464	4.252	7.954	3.844	7.864	3.776	7.762	3.668	7.464	3.448
134										
135	8.654	4.428	7.786	3.764	7.428	3.388	7.422	3.268	7.188	3.146
136	8.448	4.256	7.726	3.524	7.636	3.398	7.386	3.128	7.004	2.828
137	8.844	4.056	8.024	3.386	7.644	3.108	7.324	2.954	7.164	2.826
138	9.158	4.296	7.964	3.268	7.488	2.944	7.506	2.886	7.214	2.664
139	8.728	4.228	7.762	3.452	7.538	3.326	7.288	2.956	7.154	2.812
140										
141	7.944	3.964	7.728	3.458	7.264	3.168	7.088	2.964	7.004	2.944

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
142	8.864	4.524	7.926	3.652	7.828	3.524	7.348	3.22	7.062	2.928
143	8.728	4.264	7.724	3.328	7.506	3.208	7.338	2.968	7.112	2.848
144	8.228	4.064	7.854	3.668	7.708	3.552	7.662	3.428	7.308	3.212
145										
146	7.786	3.864	7.628	3.354	7.168	3.092	6.948	2.922	6.886	2.904
147										
148	7.996	4.064	7.558	3.482	7.286	3.116	7.142	2.896	7.028	2.864
149	8.556	4.26	7.848	3.608	7.684	3.328	7.33	3.084	7.064	2.888
150	8.112	3.984	7.456	3.368	7.382	3.228	7.066	2.864	7.098	3.082
151										
152										
153	8.684	4.482	7.846	3.844	7.562	3.568	7.444	3.314	7.186	3.052
154										
155	8.828	4.468	8.224	4.158	7.906	3.648	7.684	3.682	7.448	3.422
156										
157	8.164	4.058	7.728	3.62	7.454	3.448	7.226	3.364	7.11	3.096
158	7.862	3.924	7.726	3.566	7.488	3.406	7.336	3.428	7.186	3.116
159										
160	7.956	3.982	7.642	3.484	7.338	3.284	7.164	3.168	7.204	3.206
161										
162	8.528	4.208	7.764	3.464	7.428	3.198	7.186	3.092	6.984	2.936
163	8.124	3.986	7.628	3.556	7.384	3.228	7.164	2.884	7.094	2.996
164										
165	8.524	4.156	7.884	3.616	7.556	3.416	7.316	3.148	7.062	2.864
166	8.888	4.156	7.996	3.484	7.568	3.142	7.336	2.964	7.182	2.844
167										
168	8.742	4.228	7.924	3.644	7.642	3.408	7.402	3.088	7.062	2.872
169	8.064	3.982	7.608	3.412	7.386	3.164	7.104	2.946	7.082	3.064
170	8.524	4.268	7.768	3.428	7.438	3.288	7.384	2.968	7.084	2.812
171	8.664	4.252	7.684	3.552	7.524	3.386	7.184	3.108	6.994	2.844
172										
173	7.684	3.568	7.206	3.184	7.428	3.194	7.084	2.918	6.954	2.802
174	7.826	3.664	7.414	3.362	7.406	3.382	7.564	3.428	7.228	3.164
175										
176	8.448	4.168	7.824	3.644	7.564	3.328	7.342	3.128	7.062	2.924
177	7.964	3.844	7.528	3.346	7.332	3.152	6.944	2.942	7.062	3.008
178	8.662	4.164	7.864	3.428	7.358	3.184	7.282	2.944	7.084	2.814
179										
180	8.824	4.384	7.844	3.642	7.662	3.552	7.342	3.158	7.32	3.086
181	8.726	4.524	7.852	3.842	7.442	3.464	7.334	3.262	7.108	3.116
182	8.248	4.324	7.354	3.664	7.528	3.628	7.286	3.228	7.22	3.188
183	7.658	3.928	7.486	3.348	7.328	3.284	7.122	3.086	7.064	2.942
184	8.116	4.142	7.764	3.728	7.444	3.428	7.302	3.304	7.114	3.284
185										
186	8.524	4.194	7.824	3.364	7.524	3.128	7.364	2.964	7.068	2.804
187	8.388	4.064	7.906	3.764	7.822	3.642	7.66	3.308	7.422	3.112
188										
189	8.754	4.462	7.824	3.628	7.524	3.488	7.424	3.324	7.032	2.906

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
190	8.664	4.168	7.724	3.284	7.514	3.198	7.308	2.996	7.064	2.888
191										
192	8.428	4.264	7.82	3.644	7.328	3.528	7.164	3.228	7.082	3.116
193	7.928	3.946	7.726	3.564	7.468	3.442	7.288	3.292	7.164	3.156
194	8.664	4.394	7.824	3.726	7.528	3.524	7.164	3.224	7.062	3.092
195										
196	8.448	4.168	7.824	3.644	7.564	3.328	7.342	3.128	7.062	2.924
197										
198	8.524	4.068	7.928	3.742	7.428	3.348	7.332	3.084	7.084	2.864
199	8.654	4.352	7.996	3.864	7.864	3.654	7.628	3.424	7.444	3.212
200	8.224	4.068	7.628	3.424	7.284	3.144	7.248	2.926	7.064	2.882
201										
202	8.356	4.186	7.764	3.568	7.332	3.348	7.198	3.244	7.068	3.12
203	7.864	3.848	7.764	3.644	7.648	3.562	7.562	3.448	7.164	3.062
204										
205	8.562	4.458	7.762	3.752	7.624	3.662	7.328	3.262	7.204	3.148
206	8.426	4.384	7.584	3.644	7.482	3.448	7.164	3.186	7.064	3.082
207										
208										
209	7.754	3.954	7.528	3.384	7.468	3.318	7.164	3.062	7.068	2.998
210	8.112	4.168	7.728	3.684	7.428	3.524	7.294	3.324	7.224	3.262
211										
212	7.854	4.068	7.528	3.428	7.448	3.268	7.264	3.108	7.094	2.968
213	8.344	4.328	7.824	3.864	7.556	3.524	7.394	3.342	7.134	3.158
214										
215	8.526	4.268	7.954	3.826	7.824	3.654	7.664	3.456	7.442	3.204
216										
217	7.762	3.644	7.168	3.048	7.354	3.284	7.092	2.954	6.954	2.862
218										
219	8.642	4.168	7.864	3.544	7.564	3.528	7.388	3.152	7.328	2.942
220	8.128	4.024	7.592	3.412	7.424	3.152	7.008	2.926	7.096	2.968
221										
222	8.826	4.064	8.038	3.428	7.682	3.242	7.382	2.996	7.208	2.842
223	9.024	4.268	7.946	3.228	7.488	3.064	7.442	2.928	7.182	2.704
224										
225	8.524	4.428	7.726	3.562	7.328	3.248	7.444	3.284	7.142	3.086
226	8.824	4.264	7.882	3.448	7.628	3.208	7.332	3.048	7.228	3.162
227										
228	8.242	4.094	7.428	3.642	7.164	3.228	7.084	3.116	7.084	3.064
AVERAGE	8.546	4.225	7.870	3.537	7.588	3.329	7.380	3.116	7.205	3.010
STD	0.498	0.284	0.309	0.256	0.242	0.256	0.245	0.253	0.210	0.233

Table V.5: TS & VS Concentrations (g/L) at Different Heights - REACTOR B

Day	Height 0.0 m TS	VS	0.3 m TS	VS	0.6 m TS	VS	0.9 m TS	VS	1.2 m TS	VS
1										
2	7.835	3.819	7.759	3.038	7.424	3.541	8.147	3.038	7.55	3.322
3	6.333	3.03	8.766	3.712	8.704	3.812	8.27	2.952	8.272	3.5
4	7.835	3.819	7.759	3.038	7.424	3.541	8.147	3.038	7.55	3.322
5	8.086	3.966	7.87	3.588	7.896	3.558	7.41	3.118	7.334	2.942
6	9.289	4.027	8.688	3.762	8.096	3.628	7.38	3.004	8.152	3.446
7	8.864	3.998	7.832	3.008	8.204	3.212	8.1	2.888	6.75	2.688
8	9.386	4.626	7.938	3.996	8.25	3.422	7.98	3.218	7.316	3.128
9										
10	9.29	4.288	7.358	3.036	7.93	3.262	7.968	3.086	8.004	3.444
11	9	3.836	8.358	3.584	7.77	2.924	7.956	2.916	7.412	3.122
12	10.974	5.698	8.138	3.422	8.228	3.514	8.112	3.234	7.82	3.018
13										
14	9.492	4.716	6.244	2.936	8.552	3.924	8.348	3.696	8.26	3.364
15	7.76	3.164	8.068	3.408	8.072	3.468	8.356	3.188	8.104	2.364
16	8.86	3.884	8.42	3.568	8.664	3.736	8.452	3.56	8.704	2.876
17	8.836	3.896	7.728	3.332	7.964	3.288	7.836	3.228	8.196	3.248
18										
19	8.964	3.944	8.062	3.552	7.682	3.048	7.462	2.908	7.318	2.916
20	8.592	3.692	6.948	2.668	7.756	3.012	6.996	2.824	7.832	2.952
21	9.252	5.316	7.84	3.712	7.664	3.628	7.496	3.22	7.368	3.308
22	8.972	4.592	8.256	4.124	8.348	4.036	8.052	3.792	8.324	3.92
23	9.096	4.732	6.396	3.172	8.64	4.052	8.48	3.98	8.444	4.016
24	8.852	3.588	8.304	3.428	8.352	3.5	7.956	3.504	7.724	3.22
25										
26	9.072	3.82	8.028	3.332	8.516	3.512	7.952	3.304	8.284	3.412
27	9.356	5.052	7.428	3.892	8.04	3.816	8.128	3.636	7.64	3.58
28	9.458	4.814	7.886	3.854	7.526	3.516	7.348	3.008	7.206	2.948
29										
30	9.8	4.572	7.316	4.036	8.812	3.96	8.64	3.94	8.064	3.624
31	9.53	4.448	7.77	4.126	8.66	3.928	8.185	3.823	7.842	3.278
32	8.924	4.522	8.068	3.946	7.924	3.772	7.716	3.244	7.396	3.096
33										
34	8.852	4.216	7.852	3.726	7.664	3.442	7.442	2.864	7.11	2.882
35	8.446	4.328	7.916	3.948	7.328	3.492	7.336	3.01	7.418	3.118
36										
37	8.208	3.91	7.756	3.448	7.564	3.176	6.484	2.616	7.548	3.156
38	8.586	4.428	8.046	4.012	7.688	3.664	7.286	3.248	7.248	3.18
39	9.066	4.588	8.31	4.166	7.844	3.536	7.552	3.394	7.668	3.284
40	8.708	4.268	7.755	3.912	7.512	3.346	7.012	2.982	7.106	3.086
41										
42	8.816	4.428	8.072	3.922	7.664	3.816	7.446	3.788	7.348	3.506
43	7.904	3.68	7.608	3.316	7.172	3.112	7.768	3.336	7.728	3.296
45	8.344	4.188	7.736	3.782	7.314	3.418	7.144	2.996	7.344	3.182

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
46										
47	8.216	4.064	7.664	3.666	7.118	3.324	6.99	2.882	7.224	3.004
48	8.338	4.228	7.886	3.884	7.338	3.448	7.224	2.996	7.338	3.196
49	8.448	4.364	8.248	4.028	8.104	4	8.22	3.968	7.896	3.824
50										
51	8.288	4.412	8.018	3.886	7.758	3.776	7.432	3.542	7.318	3.416
52	8.552	4.422	8.16	3.992	7.762	3.63	7.324	3.228	7.226	3.282
53	8.38	4.356	7.928	3.96	7.876	3.932	7.652	3.616	7.556	3.524
54										
55										
56	8.994	4.664	8.118	4.088	8.006	3.884	7.664	3.558	7.55	3.448
57	8.932	4.712	8.226	4.056	7.888	3.66	7.442	3.112	7.52	3.224
58	8.682	4.448	7.996	3.826	8.064	3.758	7.726	3.558	7.624	3.41
59	8.772	4.462	8.004	3.938	7.994	3.714	7.946	3.55	7.816	3.526
60										
61	8.892	4.544	8.212	4.108	8.324	4.144	8.12	4.004	8.48	4.128
62	8.952	4.568	8.326	4.168	8.286	3.994	7.954	3.992	8.264	4.052
63	9.015	4.668	8.624	4.112	8.228	3.854	7.902	3.946	8.336	4.224
64	9.226	4.782	8.624	4.164	8.425	4.022	8.118	4.056	8.338	4.206
65	9.32	4.916	8.504	4.168	8.736	4.36	8.46	4.108	8.452	4.12
66										
67	8.088	4.04	8.02	3.944	7.76	3.636	7.192	3.456	7.96	3.672
68	8.566	4.218	8.264	4.008	8.034	3.816	7.968	3.666	7.558	3.55
69										
70	8.912	4.432	8.56	4.12	8.228	3.924	8.512	4.048	10.092	4.784
71	8.854	4.416	8.228	4.056	8.168	3.894	7.994	3.712	7.634	3.946
72										
73	8.664	4.336	8.124	3.994	8.22	3.848	7.884	3.668	7.798	3.842
74	8.664	4.338	8.214	3.996	8.196	3.842	7.716	3.678	7.423	3.47
75	8.58	4.3	8.192	3.912	8.228	3.936	7.628	3.504	7.42	3.24
76										
77	8.82	4.484	8.206	4.056	7.928	3.882	7.69	3.552	7.514	3.486
78	8.164	3.938	7.824	3.568	7.68	3.144	7.248	2.88	7.384	3.068
79	8.414	4.406	7.95	3.932	7.794	3.906	7.558	3.588	7.482	3.506
80										
81										
82										
83										
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89										
90										
91										
92										
93										

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
94										
95										
96	8.566	4.528	8.224	3.984	7.552	3.518	7.284	3.188	7.264	3.204
97	8.854	4.462	8.092	3.906	7.568	3.752	7.388	3.702	7.226	3.526
98										
99										
100										
101	8.372	4.264	7.868	3.862	7.768	3.802	7.528	3.604	7.308	3.398
102	8.776	4.298	7.764	3.806	7.416	3.408	7.208	3.184	7.184	3.006
103	9.226	4.866	8.214	4.05	8.044	3.864	7.816	3.656	7.492	3.584
104	8.592	4.486	8.062	4.034	7.716	3.682	7.294	3.266	7.22	3.194
105										
106	9.164	4.62	8.264	4.182	7.822	3.52	7.528	3.386	7.466	3.28
107	8.826	4.404	8.064	4.002	7.622	3.808	7.402	3.69	7.304	3.548
108	8.96	3.948	8.102	3.568	7.634	3.118	7.408	3.054	7.322	2.956
109	9.392	4.692	8.526	3.942	8.364	3.794	8.224	3.468	8.064	3.294
110	8.526	4.422	7.964	4.028	7.682	3.684	7.226	3.25	7.194	3.034
111										
112	8.356	4.286	7.862	3.342	7.382	3.492	7.264	3.064	7.294	3.066
113	9.256	4.608	8.324	4.104	7.784	3.542	7.504	3.326	7.664	3.306
114	8.724	4.452	7.896	3.844	7.73	3.644	7.554	3.156	7.188	2.982
115	8.394	4.168	7.72	3.766	7.316	3.428	7.168	2.994	7.294	3.094
116	8.846	4.268	7.904	3.92	7.684	3.508	7.44	3.054	7.094	2.964
117										
118										
119	8.684	4.168	7.654	3.784	7.358	3.264	7.156	3.208	7.062	3.084
120	9.364	4.768	8.064	3.928	7.828	3.766	7.662	3.546	7.336	3.342
121										
122	8.464	4.088	7.668	3.792	7.428	3.364	7.068	2.986	7.384	3.004
123										
124	8.168	3.788	7.66	3.288	7.214	3.116	7.426	3.218	7.088	3.194
125	8.458	4.164	7.652	3.818	7.332	3.386	7.324	3.096	7.306	3.092
126										
127	8.556	4.384	7.864	3.924	7.338	3.506	7.336	3.224	7.424	3.164
128	8.332	4.152	7.728	3.788	7.224	3.328	7.124	2.996	7.264	3.068
129										
130										
131	8.824	4.338	7.828	3.942	7.508	3.552	7.328	3.204	7.166	3.082
132	8.568	4.332	7.882	3.944	7.462	3.568	7.336	3.082	7.346	3.208
133	9.164	4.772	8.068	4.156	7.882	3.742	7.764	3.552	7.388	3.328
134										
135	8.348	4.462	7.928	3.992	7.584	3.664	7.16	3.228	7.148	3.204
136	8.462	4.062	7.702	3.852	7.336	3.528	7.224	3.068	7.304	3.096
137	9.124	4.628	8.186	4.084	7.72	3.544	7.504	3.428	7.262	3.196
138	8.752	4.262	7.756	3.912	7.448	3.388	7.148	2.964	7.184	3.072
139	8.254	3.956	7.842	3.526	7.448	3.216	7.004	2.948	7.262	3.068
140										
141	8.842	4.128	8.062	3.648	7.716	3.296	7.386	3.284	7.236	2.968

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
142	9.168	4.482	8.208	4.064	7.728	3.492	7.55	3.384	7.496	3.276
143	8.608	4.26	7.766	3.944	7.432	3.424	7.064	3.06	6.944	2.928
144	9.282	4.56	8.428	3.964	8.028	3.644	7.654	3.452	7.428	3.224
145										
146	8.654	4.32	7.764	3.868	7.524	3.628	7.302	3.186	7.06	2.992
147										
148	8.356	4.168	7.56	3.912	7.332	3.488	7.268	3.082	7.306	3.092
149	7.992	3.784	7.628	3.284	7.168	3.148	7.348	3.194	7.428	3.204
150	8.426	4.262	7.904	3.788	7.42	3.556	7.462	3.128	7.352	3.052
151										
152										
153	8.728	4.386	8.108	3.892	7.942	3.764	7.524	3.452	7.328	3.192
154										
155	8.564	4.425	8.164	4.062	7.866	3.704	7.424	3.402	7.164	3.264
156										
157	8.482	4.264	8.066	3.816	7.482	3.624	7.336	3.414	7.308	3.148
158	8.504	4.228	7.812	3.908	7.882	3.762	7.444	3.392	7.224	3.196
159										
160	8.628	4.416	8.066	3.866	8.112	3.624	7.628	3.492	7.228	3.168
161										
162	8.448	4.436	7.888	3.948	7.528	3.564	7.284	3.284	7.158	3.142
163	8.524	4.328	8.064	3.848	7.908	3.868	7.628	3.504	7.306	3.208
164										
165	8.186	4.068	7.824	3.864	7.528	3.648	7.192	3.352	7.332	3.428
166	9.056	4.528	8.264	4.088	7.648	3.456	7.408	3.382	7.262	3.196
167										
168	8.824	4.432	8.324	4.028	7.824	3.864	7.564	3.624	7.864	3.828
169	8.854	4.416	7.924	4.056	7.428	3.624	7.448	3.528	7.264	3.308
170	8.506	4.218	8.064	3.828	7.728	3.524	7.462	3.284	7.068	3.128
171	8.664	4.304	8.12	3.994	8.22	3.722	7.342	3.184	7.282	3.188
172										
173	8.452	4.286	8.004	3.864	7.662	3.86	7.424	3.518	7.218	3.144
174	8.568	4.338	8.188	3.996	8.052	3.762	7.668	3.624	7.338	3.384
175										
176	8.424	4.206	8.062	3.62	7.628	3.296	7.386	3.188	7.168	2.968
177	8.924	4.564	8.206	4.082	7.928	3.882	7.528	3.552	7.38	3.294
178	8.264	3.864	7.764	3.384	7.214	3.084	7.286	3.188	7.028	3.084
179										
180	8.528	4.428	8.008	3.862	7.568	3.492	7.184	3.286	7.164	3.156
181	8.776	4.364	7.764	3.768	7.416	3.408	7.102	3.144	7.062	3.006
182	9.264	4.72	8.166	4.068	7.822	3.704	7.728	3.552	7.52	3.428
183	8.408	4.384	7.828	3.906	7.628	3.552	7.294	3.242	7.124	3.148
184	8.752	4.432	8.164	3.952	7.568	3.752	7.388	3.702	7.226	3.428
185										
186	8.864	4.628	8.024	3.956	7.668	3.564	7.32	3.184	7.088	3.052
187	8.628	4.244	7.682	3.844	7.338	3.388	7.148	3.068	7.184	3.084
188										
189	8.728	4.308	7.824	3.846	7.528	3.504	7.264	3.44	7.204	3.326

Day	0.0 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
190	8.864	4.154	8.064	3.668	7.634	3.118	7.428	3.054	7.288	2.956
191										
192	8.824	4.452	7.964	4.036	7.548	3.628	7.286	3.248	7.164	3.164
193	9.164	4.482	8.428	4.166	7.762	3.536	7.496	3.394	7.42	3.284
194	8.824	4.268	7.755	3.954	7.512	3.346	7.128	2.982	7.148	3.086
195										
196	8.094	3.944	7.768	3.564	7.552	3.186	7.344	2.906	7.384	3.054
197										
198	8.424	4.264	7.944	3.944	7.672	3.864	7.36	3.482	7.264	3.282
199	8.564	4.388	7.964	3.768	7.428	3.562	7.308	3.384	7.214	3.182
200	9.164	4.866	8.162	3.944	7.862	3.648	7.664	3.344	7.564	3.284
201										
202	8.564	4.432	7.964	4.068	7.728	3.684	7.226	3.268	7.194	3.056
203	8.684	4.298	7.764	3.806	7.348	3.504	7.16	3.164	7.008	3.064
204										
205	8.624	4.332	7.924	3.766	7.422	3.384	7.286	3.424	7.168	3.148
206	8.482	4.452	7.918	3.864	7.652	3.814	7.302	3.328	7.052	3.108
207										
208										
209	8.524	4.428	7.888	3.864	7.468	3.572	7.384	3.152	7.226	3.004
210	9.064	4.668	8.152	4.254	7.786	3.664	7.608	3.482	7.286	3.286
211										
212	8.764	4.318	7.942	3.996	7.444	3.428	7.344	3.086	7.124	2.882
213	9.256	4.608	8.324	4.104	7.784	3.542	7.504	3.326	7.664	3.306
214										
215	8.676	4.344	7.952	3.864	7.662	3.558	7.384	3.156	7.188	2.944
216										
217	8.428	4.226	7.944	3.812	7.22	3.454	7.328	3.206	7.068	3.154
218										
219	8.142	4.064	7.684	3.664	7.78	3.226	7.334	3.036	7.284	3.064
220	8.782	4.264	8.108	3.924	7.964	3.664	7.528	3.296	7.154	3.106
221										
222	8.752	4.258	7.964	3.884	7.642	3.348	7.452	3.364	7.104	2.996
223	9.076	4.328	7.964	3.844	7.368	3.352	7.34	3.24	7.164	3.172
224										
225	8.452	4.208	7.764	3.544	7.298	3.328	7.168	3.188	7.052	3.044
226	8.654	4.462	7.768	3.854	7.53	3.448	7.338	3.148	7.198	3.064
227										
228	8.264	4.082	7.624	3.668	7.258	3.344	7.058	2.942	7.158	3.086
AVERAGE	8.711	4.329	7.967	3.826	7.760	3.582	7.533	3.324	7.456	3.260
STD	0.462	0.332	0.330	0.280	0.366	0.252	0.372	0.294	0.427	0.314

Table V.6: TS & VS Concentrations (g/L) at Different Heights - REACTOR C

Day	0.05 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
1	10.076	4.624	7.884	3.527	8.132	3.451	7.958	3.667	7.888	3.545
2										
3	10.722	5.662	9.32	6.722	8.148	3.706	9.403	4.393	7.77	3.72
4	9.735	5.177	8.704	4.812	7.942	3.92	8.331	3.814	7.546	3.513
5	8.284	3.956	8.21	3.922	7.44	3.204	7.303	3.009	7.416	3.128
6	9.57	4.442	8.338	3.458	7.274	3.086	7.252	2.866	7.134	3.008
7	8.616	4.328	7.762	3.442	8.19	3.428	8.634	3.128	8.2	3.432
8	9.098	4.076	7.742	3.002	7.296	3.188	6.756	2.468	7.514	3.212
9										
10	8.236	3.916	7.736	3.288	7.37	3.08	7.382	3.162	8.108	3.228
11	8.986	3.924	8.31	3.472	7.734	3.232	7.752	3.33	7.62	3.068
12	10.084	5.698	8.558	3.842	8.442	3.666	8.468	3.364	8.4	3.462
13	8.898	4.026	7.8	3.568	8.081	3.419	7.814	3.004	7.788	3.08
14	9.456	5.1	7.252	3.216	7.388	3.268	7.516	3.188	7.59	3.236
15	7.784	3.828	7.916	3.412	6.932	2.728	7.476	2.22	7.712	2.656
16	9.492	4.384	7.78	3.136	7.864	3.112	7.412	2.412	7.288	2.496
17	8.592	4.1	7.504	3.16	7.312	3.04	7.372	2.816	7.596	3.004
18										
19	8.628	4.004	7.832	3.524	7.32	2.928	7.12	2.908	7.152	2.848
20	8.428	3.696	7.752	3.012	6.776	2.564	6.696	2.632	7.464	2.772
21	9.316	4.484	7.744	3.184	7.156	2.992	7.176	2.884	7.132	2.924
22	8.668	4.356	7.964	3.628	7.972	3.628	7.328	3.16	7.404	3.248
23	8.932	4.508	8.356	3.712	8.148	3.612	7.492	3.164	7.72	3.456
24	8.816	3.852	8.188	3.072	7.472	2.82	7.268	2.828	7.584	2.804
25	8.53	4.208	8.45	3.642	7.118	2.796	7.178	2.942	7.2996	3.016
26	8.644	3.864	8.04	3.112	7.74	3.032	7.708	3.068	7.5	3.004
27	8.404	4.144	7.744	3.796	7.332	3.368	7.124	3.096	7.944	3.692
28	8.596	4.112	7.992	3.624	7.388	3.228	7.21	2.992	6.916	2.848
29										
30	8.744	4.056	8.192	3.368	7.728	3.196	7.46	3.024	6.308	2.6
31	8.786	4.21	7.916	3.288	7.579	3.258	7.244	3.032	6.794	2.842
32	8.624	4.312	7.884	3.614	7.448	3.346	7.116	3.108	6.914	2.964
33										
34	8.456	4.258	7.644	3.826	7.354	3.412	7.068	3.008	7.358	3.222
35	8.888	4.066	7.912	3.346	7.496	3.224	7.294	3.104	6.844	2.982
36										
37	8.042	4.082	7.134	3.25	7.12	3.088	6.57	2.8	6.772	2.92
38	8.524	4.128	7.446	3.272	6.946	2.96	6.584	2.712	6.778	2.662
39	8.325	4.008	7.432	3.45	7.32	3.002	6.892	2.975	6.954	2.887
40	8.428	4.186	7.824	3.824	7.418	3.382	7.238	3.108	7.384	3.342
41										
42	8.568	4.144	7.852	3.576	7.168	3.088	7.116	2.988	6.944	2.844
43	8.668	4.38	7.742	3.468	7.694	3.156	8.184	2.99	7.756	3.214
45	8.224	4.352	8.32	4.228	8.048	4.256	8.308	4.284	7.924	4.12

Day	0.05 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
46										
47	8.047	4.124	7.884	3.664	7.664	3.144	7.008	2.947	6.974	2.887
48	8.106	4.454	7.882	3.868	7.514	3.228	7.21	2.978	6.884	2.896
49	7.948	4.02	7.824	3.928	7.292	3.276	7.116	3.048	6.768	2.876
50										
51	8.332	4.118	7.788	3.554	7.114	2.998	6.884	2.884	6.847	2.882
52	8.268	3.928	7.752	3.296	7.364	3.112	7.386	3.198	7.122	2.864
53	8.752	4.22	7.532	3.324	6.984	2.956	6.66	2.676	6.928	2.764
54	8.76	4.468	7.354	3.486	7.264	3.248	6.994	2.94	7.196	3.008
55										
56	8.842	4.362	7.882	3.754	7.286	3.104	6.98	3.124	6.812	2.868
57	9.012	4.086	7.842	3.364	7.382	3.164	6.814	2.618	7.264	3.006
58	8.966	4.668	7.912	3.886	7.338	3.228	7.118	3.008	7.108	3.114
59	9.226	4.912	7.418	3.354	7.284	3.158	7.552	3.247	7.586	3.262
60										
61	9.004	4.844	9.48	5.116	7.808	3.644	7.744	3.492	7.704	3.54
62	9.148	4.752	8.058	4.064	7.646	3.526	7.286	3.186	7.032	3.116
63	8.866	4.476	7.88	3.962	7.31	3.334	7.006	3.008	6.886	3.054
64	8.664	4.564	7.594	3.914	7.634	3.448	7.092	3.116	6.914	3.118
65	8.496	4.608	7.408	3.708	7.42	3.54	7.168	3.292	7.124	3.236
66										
67	8.18	4.22	7.6	3.648	7.156	3.192	6.952	2.904	7.272	3.128
68	8.894	4.942	7.774	3.812	7.338	3.318	6.996	2.842	7.006	2.99
69										
70	10.312	5.524	8.06	3.484	8.14	3.528	7.824	3.384	7.82	3.428
71	9.512	4.584	7.886	3.284	7.824	3.164	7.482	2.518	7.22	2.534
72										
73	9.018	5.046	7.886	3.958	7.442	3.448	7.008	2.918	7.116	3.184
74	8.946	4.31	7.924	3.644	7.824	3.188	7.732	3.016	7.518	2.918
76	8.724	4.412	7.288	3.38	7.204	3.16	6.956	2.916	7.256	3.088
77										
78	8.852	4.562	7.764	3.54	7.35	3.258	7.052	2.942	7.004	2.938
79	8.628	4.38	7.566	3.518	7.186	3.226	6.956	3.082	6.914	2.96
80	9.046	4.786	7.95	3.842	7.668	3.518	7.224	3.186	7.084	3.082
81										
82										
83										
84										
85										
86										
87										
88										
89										
90										
91										
92										
93										
94										

Day	0.05 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
95										
96										
97	8.348	4.336	7.728	3.764	7.228	3.384	7.024	3.106	7.116	3.122
98	8.658	4.676	7.824	4.028	7.448	3.414	7.16	3.228	7.094	3.168
99										
100										
101										
102	9.256	4.854	8.266	4.218	7.558	3.442	7.118	3.184	7.008	3.048
103	8.902	4.482	7.992	4.118	7.386	3.428	7.084	3.046	6.906	2.982
104	8.922	4.862	7.858	3.922	7.446	3.426	7.052	2.944	7.086	3.022
105	9.252	4.964	7.668	3.488	7.264	3.168	7.032	3.064	7.234	3.112
106										
107	8.964	4.652	7.55	3.526	7.428	3.308	7.114	3.086	7.342	3.182
108	8.662	4.622	7.514	3.822	7.448	3.526	7.082	3.212	6.948	3.162
109	9.322	4.44	7.766	3.184	7.754	3.116	7.392	2.776	7.144	2.708
110	9.116	4.558	7.918	3.784	7.526	3.552	7.108	3.104	7.052	3.084
111	9.388	4.862	8.484	4.66	7.868	3.782	7.664	3.442	7.446	3.336
112										
113	8.442	4.308	7.564	3.806	7.448	3.626	7.064	3.114	6.928	3.082
114	8.942	4.452	7.688	3.622	7.408	3.392	7.164	3.086	7.076	2.954
115	8.346	4.382	7.492	3.684	7.338	3.452	7.094	3.128	6.904	2.982
116	9.015	4.764	7.886	4.182	7.364	3.762	7.154	3.428	7.036	3.214
117	8.946	4.624	7.762	3.842	7.422	3.504	7.188	3.198	7.044	3.106
118										
119										
120	8.668	4.228	7.552	3.664	7.334	3.388	7.022	3.146	6.928	2.976
121	8.842	4.336	7.928	3.552	7.556	3.296	7.228	3.084	6.964	2.944
122										
123	8.744	4.328	7.564	3.426	7.294	3.186	7.054	2.992	6.926	2.948
124										
125	8.458	4.286	7.448	3.906	7.362	3.728	7.166	3.224	7.084	3.118
126	9.084	4.662	7.936	3.882	7.664	3.492	7.288	3.164	7.206	3.094
127										
128	8.844	4.462	7.886	3.742	7.444	3.308	7.206	3.116	6.968	2.934
129	8.754	4.724	7.954	4.116	7.512	3.556	7.284	3.344	7.108	3.208
130										
131										
132	8.906	4.668	7.762	4.068	7.464	3.618	7.108	3.354	6.964	3.118
133	8.328	4.454	7.764	3.882	7.668	3.344	7.224	3.184	6.948	2.882
134	8.812	4.524	7.448	3.564	7.342	3.33	7.028	2.98	7.224	2.964
135										
136	8.726	4.462	7.662	3.664	7.334	3.224	6.864	3.154	6.848	2.902
137	9.064	4.268	7.828	3.568	7.446	3.352	6.986	2.932	6.982	2.954
138	8.728	4.656	7.882	3.942	7.426	3.348	7.226	3.106	7.114	3.068
139	9.168	4.926	7.556	3.448	7.386	3.348	7.296	3.248	7.624	3.186
140	8.846	4.428	7.764	3.884	7.316	3.22	7.086	3.064	6.928	3.112
141										
142	8.384	4.468	7.644	3.684	7.246	3.31	7.082	3.064	6.894	2.866

Day	0.05 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
143	8.764	4.288	7.684	3.664	7.228	3.164	7.124	3.008	6.86	2.944
144	8.628	4.524	7.448	3.816	7.662	3.482	7.166	3.214	6.904	3.086
145	8.428	4.708	7.524	3.768	7.388	3.516	7.208	3.264	7.094	3.108
146										
147	8.64	4.328	7.662	3.846	7.228	3.284	6.992	3.108	6.846	3.066
148										
149	8.654	4.486	7.344	3.428	7.194	3.186	6.946	2.944	7.086	3.002
150	9.322	4.762	7.86	3.658	7.286	3.446	7.168	3.286	7.324	3.262
151	9.442	4.628	7.768	3.358	7.766	3.214	7.332	2.868	7.124	2.686
152										
153										
154	8.646	4.284	7.658	3.682	7.652	3.354	7.518	3.218	7.264	2.926
155										
156	8.364	4.432	7.384	3.428	7.168	3.184	6.934	2.984	7.064	3.026
157										
158	8.954	4.628	7.842	3.684	7.452	3.346	7.212	3.064	7.032	2.976
159	9.064	4.762	7.864	3.826	7.608	3.642	7.208	3.204	7.008	3.064
160										
161	8.464	4.528	7.864	3.928	7.628	3.424	7.268	3.218	6.976	2.894
162										
163	8.264	4.354	7.782	3.64	7.164	3.224	6.988	2.924	7.102	3.054
164	8.794	4.926	7.764	3.904	7.424	3.412	7.204	2.998	7.064	2.942
165										
166	9.336	4.946	8.204	3.648	7.644	3.324	7.406	3.12	7.138	3.056
167	9.412	4.628	7.986	3.348	7.762	3.108	7.496	2.866	7.106	2.668
168										
169	8.646	7.324	7.862	3.752	7.804	3.248	7.624	3.008	7.406	2.886
170	8.628	4.486	7.664	3.528	7.196	3.268	7.008	3.032	6.918	2.916
171	8.646	4.586	7.552	3.684	7.296	3.318	7.008	2.948	6.882	2.864
172	8.824	4.432	7.298	3.384	7.324	3.186	6.948	2.946	7.354	3.072
173										
174	8.664	4.384	7.654	3.558	7.264	3.308	6.988	3.064	6.844	2.918
175	8.946	4.866	7.824	3.954	7.544	3.524	7.064	2.864	7.154	3.064
176										
177	8.864	4.546	7.924	4.164	7.354	3.514	7.064	3.094	6.844	2.946
178	8.562	4.764	7.752	3.884	7.324	3.348	7.204	3.168	7.064	3.058
179	9.164	4.864	7.786	3.568	7.342	3.284	7.164	3.088	7.186	3.084
180										
181	8.964	4.652	7.55	3.526	7.428	3.308	7.114	3.086	7.342	3.182
182	8.506	4.562	7.358	3.722	7.348	3.524	6.984	3.224	6.944	3.152
183	8.844	4.462	7.648	3.288	7.62	3.116	7.342	2.864	7.11	2.794
184	8.364	4.358	7.864	3.844	7.654	3.644	7.196	3.084	7.038	2.944
185	9.284	4.762	8.344	4.598	7.684	3.728	7.654	3.322	7.294	3.194
186										
187	8.346	4.384	7.644	3.764	7.484	3.752	7.068	3.264	6.942	3.064
188	8.846	4.452	7.762	3.524	7.384	3.426	7.206	3.112	7.068	2.898
189										
190	9.164	4.864	7.922	4.086	7.424	3.772	7.164	3.428	7.168	3.214

Day	0.05 m		0.3 m		0.6 m		0.9 m		1.2 m	
	TS	VS	TS	VS	TS	VS	TS	VS	TS	VS
191	8.864	4.528	7.672	3.842	7.422	3.504	7.188	3.198	7.044	3.106
192										
193	8.448	4.684	7.648	3.986	7.356	3.488	7.206	3.184	7.064	3.104
194	8.772	4.346	7.642	3.664	7.432	3.388	7.128	3.228	6.928	2.946
195	8.626	4.764	7.844	3.384	7.424	3.384	7.204	3.168	6.948	2.854
196										
197	8.882	4.762	7.514	3.896	7.448	3.526	7.128	3.246	6.942	3.162
198										
199	8.322	4.106	7.532	3.45	7.428	3.106	6.892	2.975	6.954	2.864
200	8.642	4.528	7.642	3.822	7.532	3.564	7.164	3.184	6.948	3.068
201	8.628	4.004	7.832	3.524	7.32	2.928	7.12	2.908	7.152	2.848
202										
203	9.064	4.464	7.644	3.248	7.288	3.054	7.248	2.984	7.064	2.924
204	8.754	4.384	7.864	3.824	7.55	3.424	7.306	3.184	7.096	3.108
205										
206	8.754	4.464	7.52	3.464	7.448	3.208	7.108	3.148	7.354	3.072
207	8.662	3.994	7.752	3.346	7.086	3.218	7.208	3.108	7.028	2.884
208										
209										
210	8.428	4.128	7.568	3.556	7.428	3.128	7.062	2.976	6.962	2.888
211	8.864	4.338	8.064	4.092	7.644	3.542	7.322	3.206	7.206	3.154
212										
213	8.642	4.144	7.662	3.488	7.268	3.188	7.116	2.844	6.944	2.764
214	8.668	4.38	7.742	3.468	7.694	3.156	7.552	3.108	7.302	3.164
215										
216	8.328	4.086	8.064	3.726	7.528	3.348	7.226	2.996	6.892	2.904
217										
218	8.528	4.236	7.768	3.928	7.624	3.524	7.238	3.194	7.304	3.208
219										
220	8.842	4.226	7.862	3.884	7.522	3.446	7.214	3.224	6.582	2.886
221	8.664	4.238	7.608	3.484	7.388	3.346	7.162	3.128	6.796	2.848
222										
223	8.642	4.564	7.462	3.864	7.268	3.348	7.264	3.184	7.264	3.228
224	8.86	4.564	7.354	3.664	7.264	3.248	7.008	3.148	6.948	3.008
225										
226	8.764	4.362	7.664	3.948	7.286	3.288	6.98	3.124	6.812	2.904
227	8.944	4.126	7.842	3.536	7.454	3.32	6.846	2.874	7.064	3.104
228										
229	8.766	4.564	7.782	3.886	7.442	3.384	7.206	3.008	7.108	2.948
Average	8.798	4.475	7.801	3.697	7.465	3.326	7.236	3.084	7.158	3.041
STDEV	0.422	0.405	0.320	0.405	0.261	0.231	0.362	0.252	0.317	0.218

Table V.7 : TSS Concentrations (mg/L) at Different Heights - REACTOR A

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
1					
2					
3					
4					
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31					
32					
33					
34					
35					
36					
37					
38					
39					
40					
41					
42	415	388	406	309	387
43	516	488	500	389	495
45	550	444	432	412	508

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
46					
47	388	372	345	394	565
48	558	388	476	452	431
49	580	501	544	468	487
50					
51	676	628	543	448	498
52	558	421	418	438	411
53	884	394	543	482	498
54					
55					
56	884	532	501	500	423
57	743	423	603	493	488
58	615	501	552	461	488
59	752	416	512	399	436
60					
61	777	510	552	567	486
62	815	479	488	521	555
63	668	528	468	409	496
64	551	411	432	381	551
65	612	396	453	468	388
66					
67	669	387	486	365	456
68	558	452	444	420	440
69					
70	526	400	434	410	464
71	551	465	438	387	416
72					
73	664	552	408	389	465
74	521	500	456	409	448
75	599	534	489	438	469
76					
77	612	412	444	451	500
78	668	465	438	439	502
79	549	403	484	475	506
80					
81					
82					
83					
84					
85					
86					
87					
88					
89					
90					
91					
92					
93					

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
94					
95					
96	446	387	423	428	458
97	550	468	479	364	430
98					
99					
100					
101	668	431	465	510	425
102	564	367	435	404	444
103	814	461	497	381	401
104	710	460	421	408	435
105					
106	568	312	432	408	425
107	551	432	468	400	411
108	564	428	418	468	444
109	581	461	498	426	409
110	658	466	521	497	468
111					
112	601	508	384	388	438
113	489	468	438	406	463
114	524	374	384	434	427
115	724	438	385	410	444
116	771	555	448	446	409
117					
118					
119	564	438	468	327	387
120	558	403	442	397	406
121					
122	628	457	481	461	437
123					
124	612	426	518	454	481
125	521	387	382	391	382
126					
127	554	468	438	336	445
128	567	398	414	397	444
129					
130					
131	592	380	452	388	418
132	628	468	448	406	431
133	515	489	452	368	457
134					
135	716	458	447	390	412
136	642	366	397	411	415
137	608	432	400	388	435
138	669	468	501	465	444
139	582	419	315	430	438
140					
141	642	514	438	398	425

		Height (m)			
Day	0.05	0.3	0.6	0.9	1.2
142	551	432	498	456	447
143	638	525	547	468	486
144	459	428	435	438	418
145					
146	568	440	468	498	511
147					
148	799	435	398	456	449
149	567	361	381	405	438
150	602	388	368	367	434
151					
152					
153	523	465	426	431	496
154					
155	554	401	400	384	447
156					
157	694	595	510	460	487
158	621	444	487	397	425
159					
160	597	423	414	408	458
161					
162	520	468	435	404	465
163	627	308	339	395	389
164					
165	605	388	386	405	475
166	529	556	520	465	433
167					
168	571	528	435	444	486
169	429	409	468	446	487
170	607	532	501	498	488
171	552	468	413	387	428
172					
173	594	398	423	444	487
174	608	452	465	478	486
175					
176	558	400	445	348	456
177	510	412	436	387	487
178	523	446	489	460	483
179					
180	618	506	486	376	397
181	592	431	489	499	478
182	492	387	385	389	436
183	534	451	438	422	488
184	518	449	397	401	405
185					
186	559	390	421	384	454
187	567	366	435	410	445
188					
189	715	504	468	420	444

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
190	608	449	498	435	465
191					
192	558	470	456	400	423
193	509	388	423	410	425
194	540	431	465	424	464
195					
196	705	493	521	466	442
197					
198	647	442	468	419	420
199	668	482	524	465	482
200	558	389	431	435	489
201					
202	539	435	445	444	404
203	614	446	432	489	449
204					
205	547	490	444	438	497
206	601	468	478	388	425
207					
208					
209	654	406	450	435	468
210	518	423	444	337	402
211					
212	701	465	523	471	469
213	628	568	500	438	489
214					
215	568	439	461	420	448
216					
217	548	465	487	442	438
218					
219	600	482	463	435	489
220	492	436	462	387	412
221					
222	538	468	470	428	468
223	578	512	496	487	455
224					
225	523	465	440	438	424
226	624	542	520	398	429
227					
228	581	412	432	400	421
AVERAGE	597	448	455	425	452
STDEV	87.4	55.4	48.4	42.8	36.1

Table V.8 : TSS Concentrations (mg/L) at Different Heights - REACTOR B

Day	Height (m) 0.05	0.3	0.6	0.9	1.2
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
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22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37	622	508	438	402	415
38	701	467	412	351	388
39	694	399	447	424	409
40	589	494	407	440	481
41					
42	568	474	438	410	367
43	632	564	496	436	445
45	587	450	479	468	491

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
46					
47	664	515	500	487	351
48	558	361	478	442	389
49	662	507	458	364	415
50					
51	552	420	355	421	386
52	504	521	425	384	428
53	628	537	399	390	514
54					
55					
56	784	537	468	421	400
57	681	455	445	419	364
58	594	440	379	356	355
59	604	447	442	415	439
60					
61	521	409	551	464	527
62	596	524	468	458	468
63	556	401	445	284	408
64	750	531	410	368	328
65	674	521	465	400	388
66					
67	581	452	387	334	365
68	600	547	456	399	445
69					
70	634	538	453	428	487
71	667	500	497	394	468
72					
73	532	485	388	345	420
74	578	531	400	388	478
75	591	512	416	380	410
76					
77	605	497	448	391	448
78	666	537	468	435	487
79	583	467	410	391	416
80					
81					
82					
83					
84					
85					
86					
87					
88					
89					
90					
91					
92					
93					

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
94					
95					
96	527	414	387	388	428
97	607	507	468	381	431
98					
99					
100					
101	637	558	486	405	445
102	721	507	397	418	455
103	586	438	451	388	410
104	610	458	418	356	421
105					
106	508	501	488	449	482
107	529	490	423	374	416
108	632	525	418	376	400
109	719	561	486	441	467
110	508	496	451	389	426
111					
112	557	481	399	358	394
113	620	444	424	364	389
114	537	430	445	397	421
115	569	487	378	318	378
116	609	504	420	387	411
117					
118					
119	725	537	508	425	455
120	648	541	465	421	464
121					
122	630	467	442	387	402
123					
124	574	477	453	375	371
125	608	461	443	405	438
126					
127	618	520	486	445	442
128	660	512	428	438	451
129					
130					
131	597	387	452	358	399
132	549	408	421	370	407
133	637	509	438	368	387
134					
135	564	500	408	401	430
136	557	469	422	397	419
137	632	554	447	441	487
138	618	564	489	429	428
139	597	438	446	380	399
140					
141	549	445	387	384	415

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
142	568	548	433	421	422
143	538	504	410	394	408
144	627	514	487	437	487
145					
146	604	561	430	404	430
147					
148	578	507	504	391	421
149	559	456	438	350	400
150	592	487	411	437	448
151					
152					
153	635	500	468	438	470
154					
155	661	480	487	446	450
156					
157	573	462	384	397	408
158	598	481	421	406	368
159					
160	608	461	467	409	432
161					
162	661	532	490	428	445
163	575	504	478	458	429
164					
165	568	517	458	400	408
166	641	486	427	410	439
167					
168	600	501	408	364	391
169	608	450	377	386	408
170	587	478	430	379	419
171	628	528	499	451	472
172					
173	567	438	409	389	468
174	604	512	441	412	452
175					
176	574	460	438	384	408
177	676	512	487	492	466
178	587	491	429	401	439
179					
180	607	541	492	389	440
181	654	522	468	425	452
182	587	511	487	448	448
183	589	426	391	379	415
184	672	447	408	409	431
185					
186	626	431	426	370	427
187	601	447	378	372	405
188					
189	589	507	428	388	422

Day	Height (m)				
	0.05	0.3	0.6	0.9	1.2
190	577	516	449	452	488
191					
192	654	538	489	438	445
193	610	522	448	408	420
194	603	488	407	378	400
195					
196	571	409	448	389	413
197					
198	642	445	431	368	389
199	621	506	497	439	455
200	674	518	451	425	496
201					
202	595	467	461	403	441
203	631	499	428	448	456
204					
205	667	516	481	426	420
206	654	498	457	419	431
207					
208					
209	578	437	481	356	402
210	632	539	468	453	450
211					
212	608	428	387	396	410
213	684	528	451	419	438
214					
215	632	438	400	374	401
216					
217	645	579	467	421	438
218					
219	609	510	488	448	455
220	596	500	446	407	425
221					
222	674	468	421	390	404
223	654	487	447	402	418
224					
225	587	512	409	376	391
226	603	507	439	419	469
227					
228	611	488	436	410	415
AVERAGE	611	489	442	404	427
STDEV	49.9	43.0	35.6	34.0	35.0

Table V.9: TSS Concentrations (mg/L) at Different Heights - REACTOR C

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37	487	403	389	298	355
38	528	446	418	403	397
39	604	400	389	476	345
40	529	416	411	449	328
41					
42	628	608	459	468	320
43	561	478	488	492	367
45	388	468	506	311	442

Day	Height (m) 0.05	0.3	0.6	0.9	1.2
46					
47	564	386	420	304	365
48	718	531	468	366	521
49	597	535	504	354	532
50					
51	541	556	468	478	509
52	509	508	378	495	487
53	768	376	372	401	402
54	694	496	364	367	392
55					
56	648	477	399	444	468
57	625	462	387	401	448
58	703	488	409	367	460
59	771	453	443	389	381
60					
61	706	508	532	442	387
62	694	567	500	406	459
63	663	542	496	468	438
64	618	409	468	403	479
65	634	443	514	449	345
66					
67	667	477	434	416	465
68	789	499	468	436	421
69					
70	667	456	408	398	497
71	691	468	479	462	440
72					
73	621	507	466	439	480
74	587	470	487	461	462
76	624	438	447	441	438
77					
78	661	577	484	472	456
79	594	514	462	431	438
80	608	498	507	488	504
81					
82					
83					
84					
85					
86					
87					
88					
89					
90					
91					
92					
93					

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
94					
95					
96					
97	568	468	429	428	456
98	645	506	408	366	401
99					
100					
101					
102	658	523	472	405	409
103	582	428	397	368	429
104	657	500	432	429	462
105	675	529	411	400	445
106					
107	631	453	438	378	486
108	588	433	406	369	406
109	652	449	423	445	487
110	705	503	447	406	468
111	622	467	461	439	445
112					
113	600	459	409	368	438
114	624	408	356	354	420
115	608	499	423	391	408
116	657	522	455	459	469
117	559	486	442	442	479
118					
119					
120	628	476	431	440	449
121	578	516	400	401	461
122					
123	633	466	429	420	397
124					
125	674	502	468	433	413
126	688	518	425	368	425
127					
128	599	429	387	375	402
129	607	456	419	405	456
130					
131					
132	702	470	441	449	498
133	650	455	438	449	488
134	666	486	455	421	453
135					
136	608	396	408	340	397
137	632	494	438	406	406
138	712	488	478	468	498
139	725	520	403	400	428
140	638	501	418	387	390

Day	Height (m) 0.05	0.3	0.6	0.9	1.2
141					
142	654	532	429	387	401
143	573	481	475	431	421
144	581	445	380	421	439
145	567	494	421	406	418
146					
147	630	476	401	408	456
148					
149	566	444	435	416	458
150	660	531	468	406	437
151	705	468	432	431	497
152					
153					
154	631	539	478	399	458
155					
156	608	401	456	452	415
157					
158	594	468	406	394	478
159	634	506	447	440	459
160					
161	687	509	456	469	486
162					
163	641	526	496	475	478
164	688	466	466	381	438
165					
166	589	504	401	397	425
167	681	459	406	367	387
168					
169	569	418	429	408	416
170	578	494	448	400	401
171	641	532	476	415	451
172	756	500	422	429	439
173					
174	608	471	465	438	458
175	631	520	446	421	455
176					
177	655	564	440	397	439
178	630	543	489	409	450
179	703	480	406	382	394
180					
181	597	527	456	369	389
182	599	486	442	406	387
183	642	467	391	388	439
184	664	510	409	425	435
185	669	429	387	394	402
186					
187	562	438	432	406	387

	Height (m)				
Day	0.05	0.3	0.6	0.9	1.2
188	706	487	465	458	468
189					
190	684	520	428	408	445
191	628	487	411	394	397
192					
193	622	531	452	413	447
194	576	479	394	376	409
195	612	463	408	447	438
196					
197	635	502	402	364	378
198					
199	568	439	488	441	455
200	608	554	437	421	406
201	674	501	403	414	445
202					
203	706	551	489	478	479
204	664	463	467	400	445
205					
206	606	496	442	389	409
207	667	477	411	429	430
208					
209					
210	651	524	478	428	458
211	607	439	407	396	431
212					
213	569	456	394	378	409
214	678	522	441	406	428
215					
216	611	540	460	442	448
217					
218	678	499	432	416	409
219					
220	651	493	397	389	398
221	600	465	388	375	401
222					
223	687	511	465	425	468
224	634	534	445	368	403
225					
226	608	499	406	408	418
227	647	476	439	436	449
228					
229	618	444	458	422	467
AVERAGE	633	485	437	413	434
STDEV	57.8	42.4	35.6	37.5	39.6

Table V.10 : Effluent Sulfide Concentrations (mg/L) at Different Heights

	REACTOR A				REACTOR B				REACTOR C			
	Height											
Day	0.3 m	0.6 m	0.9 m	1.2 m	0.3 m	0.6 m	0.9 m	1.2 m	0.3 m	0.6 m	0.9 m	1.2 m
1	0.0	0.0	18.3	30.5	0.0	0.0	0.0	18.4	0.0	0.0	15.0	27.1
2	0.0	0.0	11.3	22.8	0.0	0.0	5.8	22.7	0.0	0.0	18.3	33.4
3	0.0	0.0	18.8	25.2	0.0	0.0	12.7	29.2	0.0	0.0	19.5	37.2
4	0.0	2.6	20.8	27.3	0.0	0.0	10.8	22.5	0.0	5.2	21.6	38.4
5	0.0	3.8	22.5	38.2	0.0	0.0	14.6	28.5	0.0	0.0	20.3	41.6
6												
7	0.0	4.8	25.6	30.5	0.0	0.0	12.5	25.8	0.0	0.0	22.8	44.8
8												
9	0.0	10.6	23.8	32.4	0.0	8.5	15.5	27.2	0.0	5.8	27.0	43.5
10												
11	0.0	18.6	24.6	38.3	2.5	10.5	11.5	11.5	3.9	11.5	31.6	47.2
12												
13	5.9	18.8	30.4	39.5	6.8	15.5	21.2	28.5	7.9	19.0	33.7	50.7
14												
15	16.9	21.8	32.6	44.3	11.5	21.7	28.2	35.8	14.5	26.8	37.2	54.2
16												
17	15.8	20.4	34.3	44.0	16.5	24.8	34.2	44.8	18.9	33.2	44.0	59.7
18	18.8	22.8	33.8	45.6	18.9	27.8	38.9	48.9	29.5	41.8	48.2	60.4
19												
20	22.8	36.5	41.8	52.8	34.4	42.8	52.6	58.4	42.3	53.2	57.8	62.4
21	25.5	35.8	44.2	55.2	34.3	45.8	55.3	61.4	43.8	58.8	61.5	65.8
22					37.8	48.2	59.6	65.7	46.8	64.2	69.2	70.2
23	29.3	43.8	51.6	64.3	41.8	49.2	58.4	69.8	51.4	73.3	84.3	79.7
24												
25					49.8	62.5	69.8	75.4	57.5	79.3	85.2	89.3
26	41.4	39.7	55.3	73.8								
27					54.6	68.7	81.3	84.3	64.3	80.2	89.6	100.5

						Height						
Day	0.3 m	0.6 m	0.9 m	1.2 m	0.3 m	0.6 m	0.9 m	1.2 m	0.3 m	0.6 m	0.9 m	1.2 m
28												
29	48.3	65.3	72.4	88.6	60.2	71.4	85.9	101.8	66.5	81.3	90.5	105.4
30												
31	53.8	67.8	75.8	91.5	60.8	75.2	88.6	105.3	67.2	84.3	92.4	111.3
32												
33	57.8	74.3	89.6	100.3	64.3	81.5	94.3	111.4	68.3	85.6	95.3	112.4
34												
35	57.9	81.5	94.6	103.8	64.8	84.3	99.5	108.7	67.7	86.2	96.4	113.5
36												
37	61.4	84.6	96.8	114.8	67.8	87.5	102.0	111.6	71.4	89.3	97.5	115.6
38												
39	63.8	86.3	94.2	108.9	64.7	80.3	95.6	103.8	72.4	88.9	95.6	114.8
40												
41	66.2	85.3	97.3	110.9	64.8	82.9	98.3	115.4	75.3	91.2	97.8	120.4
42												
43	63.8	87.2	95.2	107.8	67.8	84.6	97.5	118.2	74.6	87.9	98.4	125.6
45												
46	65.8	84.2	97.7	111.3	70.5	88.6	100.6	114.3	73.5	90.2	97.0	122.4
47												
48					68.9	91.4	100.8	121.5	68.7	89.3	99.2	123.4
49												
50					74.3	92.5	103.8	127.8	70.6	91.2	100.2	119.7
51	64.8	86.6	98.5	113.2								
52					71.8	91.3	100.5	122.3	70.8	91.6	102.2	121.4
53												
54					68.7	90.5	101.4	124.6	69.7	89.9	101.5	125.6
55												
56					70.8	91.3	105.3	126.6	69.4	90.4	100.6	124.4
57												
58	66.0	88.0	97.6	111.9	72.0	90.5	101.3	122.8	71.8	91.6	100.8	126.4
59												
60					70.5	91.0	100.8	121.8	71.3	90.5	100.7	122.7
61												

							Height					
Day	0.3 m	0.6 m	0.9 m	1.2 m	0.3 m	0.6 m	0.9 m	1.2 m	0.3 m	0.6 m	0.9 m	1.2 m
62					68.5	78.4	93.8	120.8	69.8	90.8	101.5	124.8
63												
64					70.8	90.3	101.5	123.8	70.2	91.4	101.8	126.8
65												
66												
67												
68												
69												
70	64.8	85.6	97.0	112.0								
71					71.2	91.2	100.6	122.8	68.4	90.5	101.3	124.8
72												
73												
74												
76												
77												
78												
79												
80					69.8	90.5	102.5	123.8	70.5	91.3	102.7	125.8
81												
82												
83												
84												
85												
86												
87												
88												
89												
90	65.2	87.3	97.8	112.8	66.7	90.4	100.1	126.3	69.8	90.4	100.7	124.6

V.2 Data obtained during Phase II

Table V.11: Effluent Dissolved and Total Copper witht Influent Copper Concentration of 25 mg/L at Different Heights for HRT = 9 h

Day	Dissolved Copper (mg/L)					Total Copper (mg/L)				
		Height (m)					Height (m)			
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	25	0	0	0	0	25	0	0	0	0
1	25	0	0	0	0	25	0	0	0	0
2	25	0	0	0	0	25	0	0	0	0
3	25	0	0	0	0	25	0	0	0	0
4	25	0	0	0	0	25	0	0	0	0
5	25	0	0	0	0	25	0	0	0	0

Table V.12: Effluent Dissolved and Total Copper witht Influent Copper Concentration of 50 mg/L at Different Heights for HRT = 9 h

Day	Dissolved Copper (mg/L)					Total Copper (mg/L)				
		Height (m)					Height (m)			
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	50	0	0	0	0	50	0	0	0	0
1	49.5	1.1	0	0	0	50	1.3	0	0	0
2	50	1.5	0	0	0	50	1.5	0	0	0
3	49.6	0	0	0	0	50	0	0	0	0
4	50	0	0	0	0	50	0	0	0	0

Table V.13: Effluent Dissolved and Total Copper with Influent Copper Concentration of 100 mg/L at Different Heights for HRT = 9 h

Day	Dissolved Copper (mg/L) Height (m)					Total Copper (mg/L) Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	95.8	21	0	0	0	100	22	0	0	0
1	100	24	0	0	0	100	24	0	0	0
2	100.6	23	0	0	0	101	24	0	0	0
3	100	23	0	0	0	100	24	0	0	0
4	101	23	0	0	0	101	24	0	0	0

Table V. !4: Effluent Dissolved and Total Copper witht Influent Copper Concentration of 200 mg/L at Different Heights for HRT = 9 h

Day	Dissolved Copper (mg/L) Height (m)					Total Copper (mg/L) Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	200	168	106	40	28	203	172	109	41	29
1	205	166	108	42	26	207	170	110	42	28
2	203	170	105	39	27	206	173	108	40	28
3	204	168	105	38	28	209	171	109	40	28
4	204	168	105	39	27	208	172	108	40	28

Table V.15: Effluent Dissolved and Total Copper witht Influent Copper Concentration of 300 mg/L at Different Heights for HRT = 9 h

Day	Dissolved Copper (mg/L) Height (m)					Total Copper (mg/L) Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	300	277	225	144	77	302	280	229	149	79
1	305	270	227	148	79	309	273	231	148	81
2	306	272	222	142	74	311	275	226	148	77
3	304	278	221	144	79	308	280	225	149	83
4	305	278	221	143	78	310	281	226	148	84

Table V.16 Effluent Dissolved and Total Copper witht Influent Copper Concentration of 400 mg/L at Different Heights for HRT = 9 h

Day	Dissolved Copper (mg/L) Height (m)					Total Copper (mg/L) Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	405	387	344	255	135	411	392	349	260	141
1	403	390	348	253	137	409	394	354	260	142
2	404	392	343	257	130	409	396	348	263	134
3	406	390	344	252	132	410	394	348	255	138
4	408	390	345	250	134	414	395	351	256	140

Table V.17 : Effluent Dissolved and Total Copper witht Influent Ccopper Concentration of 25 mg/L at Different Heights for HRT = 18 h

Day	Dissolved Copper (mg/L)					Total Copper (mg/L)				
		Height (m)					Height (m)			
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	25	0	0	0	0	25	0	0	0	0
1	25	0	0	0	0	25	0	0	0	0
2	25	0	0	0	0	25	0	0	0	0
3	25	0	0	0	0	25	0	0	0	0
4	25	0.04	0	0	0	25	0.04	0	0	0
5	25	0.3	0	0	0	25	0.3	0	0	0

Table V. 18 : Effluent Dissolved and Total Copper witht Influent Copper Concentration of 50 mg/L at Different Heights for HRT = 18 h

Day	Dissolved Copper (mg/L) Height (m)					Total Copper (mg/L) Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	50	0	0	0	0	50	0	0	0	0
1	49.5	0	0	0	0	50	0	0	0	0
2	50	0.6	0	0	0	50	0.6	0	0	0
3	49.6	0	0	0	0	50	0	0	0	0
4	50	0.8	0	0	0	50	0.8	0	0	0

Table V.19 : Effluent Dissolved and Total Copper witht Influent Copper Concentration of 100 mg/L at Different Heights for HRT = 18 h

Day	Dissolved Copper (mg/L) Height (m)					Total Copper (mg/L) Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	95.8	17.9	0	0	0	100	19.2	0	0	0
1	100	16.4	0	0	0	100	17.8	0	0	0
2	100.6	17.3	0	0	0	101	17.9	0	0	0
3	100	17.7	0	0	0	100	18.2	0	0	0
4	101	17.7	0	0	0	101	18.2	0	0	0

Table V.20 : Effluent Dissolved and Total Copper witht Influent Copper Concentration of 200 mg/L at Different Heights for HRT = 18 h

Day	Dissolved Copper (mg/L)					Total Copper (mg/L)				
		Height (m)					Height (m)			
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	202	166	96	24	18	204	171	98	23	19
1	206	168	94	25	19	207	171	97	24	20
2	210	166	97	21	20	211	169	99	23	21
3	208	165	96	22	21	210	168	97	23	22
4	214	165	97	22	20	216	168	99	23	21

Table V.21 : Effluent Dissolved and Total Copper witht Influent Copper Concentration of 300 mg/L at Different Heights for HRT = 18 h

Day	Dissolved Copper (mg/L)					Total Copper (mg/L)				
		Height (m)					Height (m)			
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	303	266	212	125	44	305	271	218	131	48
1	301	277	218	127	41	303	284	229	136	44
2	304	275	218	122	46	304	279	224	128	48
3	302	274	214	124	45	305	280	221	129	48
4	306	276	217	124	45	307	281	223	130	48

Table V.22: Effluent Dissolved and Total Copper witht Influent Copper Concentration of 400 mg/L at Different Heights for HRT = 18 h

Day	Dissolved Copper (mg/L)					Total Copper (mg/L)				
	Height (m)					Height (m)				
	Inf.	0.3	0.6	0.9	1.2	Inf.	0.3	0.6	0.9	1.2
0	408	386	341	235	68	410	391	346	242	71
1	407	388	344	228	64	413	389	349	235	68
2	403	391	338	226	62	410	395	343	233	65
3	405	388	339	227	63	407	392	344	238	69
4	405	389	338	229	62	408	393	344	237	69

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