Modeling of biological wastewater treatment in sequencing batch reactors

Abdisalam Mohamed Ahmed

Civil Engineering

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Abstract

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Modeling of Biological Wastewater Treatment in Sequencing Batch Reactors

by

Abdisalam Mohamed Ahmed

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

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In

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COLLEGE OF GRADUATE STUDIES

To my wife, Hodan

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TABLE OF CONTENTS

Page

Dedication i

Acknowledgements ii

Table of Contents iii

List of Tables vi

List of Figures. vii

Abstract (English) x

Abstract (Arabic) xi

Symbols x

Chapter I. INTRODUCTION 1

1.1 General 1

1.2 Physical Description of The Sequencing Batch Reactors (SBR) 2

1.3 Research Objectives 5

Chapter II. LITERATURE REVIEW 6

2.1 Biological Wastewater Treatment Using SBR. 6

2.1.1 Bench Scale Studies. 8

2.1.2 Full-Scale Plants 13

2.1.3 Mathematical Representation of the SBR 14

2.2 Present Status of the Problem 19

Chapter III. THEORY AND DEVELOPMENT OF THE MATHEMATICAL MODEL 20

3.1 Introduction 20

3.2 Development of the Mathematical Model 20

3.2.1 Mathematical Formulation 22

3.2.2 Model Parameters 28

3.2.3 Salient Features of the Model 29

3.3 Solution Methods 30

3.3.1 The Runge-Kutta Method 31

3.3.2 Development of the Computational Model 32

3.3.3 Validation of the Computational Model 32

3.4 Model Calibration. 36

3.5 Model Applications 36

Chapter IV. EXPERIMENTAL STUDIES 37

4.1 Introduction 37

4.2 Experimental Set-up 38

4.3 Experimental Procedure 39

4.4 Results and Discussion 41

Chapter V. RESULTS AND DISCUSSION 49

5.1 Introduction 49

5.2 Model Validation 49

5.2.1 Fill Period 50

5.2.2 React Period 59

5.2.3 Complete Cycle 65

5.3 Variable Organic Loading. 73

5.4 Variable Solids Residence Time 75

5.5 Sensitivity Analysis 79

5.5.1 Effect of Maximum Specific Growth Rate 80

5.5.2 Effect of Half-Saturation Coefficient 84

5.5.3 Effect of Yield Coefficient 88

5.5.4 Effect of Decay Coefficient 88

5.6 Effect of Fill to React Ratio 95

5.6.1 Effect of Fill-React Ratio on MLLVSS Build-up 96

5.6.2 The Effect of Fill-React Ratio on Effluent BOD 101

5.6.3 The Effect of Fill-React Ratio on Effluent TSS 101

Chapter VI. CONCLUSIONS AND RECOMMENDATIONS 111

6.1 Conclusions 111

6.2 Recommendations 112

REFERENCES 113

LIST OF TABLES

Table Page

3.1 Values of The Kinetic Coefficients Reported in the Literature 29

4.1 Composition of the Synthetic Phenolic Solution 40

4.2 Distribution of Psuedomonas aeruginosa 48

5.1 Values of the Kinetic Coefficients Used for Sensitivity analysis . . .80

LIST OF FIGURES

Figure		Page
1.1	Schematic SBR Operation	3
3.1	Solution Algorithm	33
3.2	Comparison Between Numerical and Analytical Solution	35
4.1	Influent and Effluent Phenol Concentrations, Reactors 3 & 4	42
4.2	Concentration of MLSS in Reactors 1 and 2	43
4.3	Concentration of MLVSS in Reactors 1 and 2	44
4.4	Concentration of MLSS in Reactors 3 and 4	45
4.5	Concentration of MLVSS in Reactors 3 and 4	46
5.1	Hypothetical BOD and MLVSS Profiles During a 2-hr Fill Period	51
5.2	Hypothetical BOD and MLVSS Profiles During a 2-hr Fill Period	52
5.3	Hypothetical BOD and MLVSS Profiles During a 4-hr Fill Period	54
5.4	Hypothetical BOD and MLVSS Profiles During a 4-hr Fill Period	55
5.5	Comparison of Model Predictions and Experimental Data	57
5.6	Comparison of Model Predictions and Experimental Data	58
5.7	Hypothetical BOD and MLVSS Profiles During The React Period	60
5.8	Hypothetical BOD and MLVSS Profiles During The React Period	61

5.9 Comparison of Model Predictions and Experimental Data 63

5.10 Comparison of Model Predictions and Experimental Data 64

5.11 Comparison of Model Predictions and Experimental Data 67

5.12 Comparison of Model Predictions and Experimental Data 68

5.13 Comparison of Model Predictions and Experimental Data 69

5.14 Comparison of Model Predictions and Experimental Data 70

5.15 Comparison of Model Predictions and Experimental Data 71

5.16 Variable Organic Loading, Phenol 74

5.17 Variable Organic Loading, O-Cresol 76

5.18 Variable Solids Residence Time, Phenol 77

5.19 Variable Solids Residence Time, O-Cresol. 78

5.20 Effect of Variation of Maximum Specific Growth Rate Coefficient on MLVSS 81

5.21 Effect of Variation of Maximum Specific Growth Rate Coefficient on Effluent BOD 82

5.22 Effect of Variation of Maximum Specific Growth Rate Coefficient on Effluent TSS 83

5.23 Effect of Variation of Half-Saturation Coefficient on MLVSS 85

5.24 Effect of Variation of Half-Saturation Coefficient on Effluent BOD 86

5.25 Effect of Variation of Half-Saturation Coefficient on Effluent TSS 87

5.26 Effect of Variation of Yield Coefficient on MLVSS. 89

5.27 Effect of Variation of Yield Coefficient on Effluent BOD 90

5.28 Effect of Variation of Yield Coefficient on Effluent TSS. 91

5.29 Effect of Variation of Decay Coefficient on MLVSS 92

5.30 Effect of Variation of Decay Coefficient on Effluent BOD 93

5.31 Effect of Variation of Decay Coefficient on Effluent TSS 94

5.32 Simulation of Fill-React Ratio, MLVSS 97

5.33 Simulation of Fill-React Ratio, MLVSS 98

5.34 Simulation of Fill-React Ratio, MLVSS 99

5.35 Simulation of Fill-React Ratio, MLVSS 100

5.36 Simulation of Fill-React Ratio, Effluent BOD 102

5.37 Simulation of Fill-React Ratio, Effluent BOD 103

5.38 Simulation of Fill-React Ratio, Effluent BOD 104

5.39 Simulation of Fill-React Ratio, Effluent BOD 105

5.40 Simulation of Fill-React Ratio, Effluent TSS 106

5.41 Simulation of Fill-React Ratio, Effluent TSS 107

5.42 Simulation of Fill-React Ratio, Effluent TSS 108

5.43 Simulation of Fill-React Ratio, Effluent TSS 109

ABSTRACT

Name: Abdisalam Mohamed Ahmed

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The Sequencing Batch Reactor (SBR) system is one of the biological methods used for the treatment of industrial and domestic wastewaters. Compared to the continuous flow activated sludge systems, the mathematical description of the SBR system is not fully developed yet. Therefore, for the improved understanding of the performance and design of the SBR, a mathematical model which takes into account fill, react and settle periods of the SBR was developed and tested against experimental data from the literature. The Monod equation was used to describe microbial growth kinetics. The developed model is capable of predicting microbial cell and substrate concentrations at various time horizon during SBR treatment of wastes. The resulting differential equations governing the SBR system, being non-linear and transient, were solved numerically using 4th order Runge-kutta method. The model predictions compared well with experimental results reported in the literature. Simulation results have indicated that an extended fill period is beneficial to the treatment of toxic and high-strength wastes as it mitigates inhibition and organic overloading effects. An experimental work was also carried out to investigate the microorganisms responsible for phenol biodegradation. It was found that the microbial species known as *Psuedomonas aeriginosa* was the predominant one over other microbial populations for biological treatment of phenolic waste.

MASTER OF SCIENCE DEGREE

King Fahd University of Petroleum and Minerals
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خلاصة الرسالة

اسم الطالب : عبدالسلام محمد أحمد

عنوان الدراسة : نمذجة المعالجة البيولوجية لمياه المجاري عن طريق الاحواض المتتابعة .

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تعتبر طريقة الاحواض المتتابعة واحدة من الطرق البيولوجية لمعالجة مياه المجاري الصناعية والمحلية وبالمقارنة مع نظام التثبيت والصرف المنشط ، فان الوصف الرياضي لطريقة الاحواض المتتابعة لم تكتمل جوانبه بعد . ولذلك ولفهم أداء وتصميم هذه الطريقة ، تم عمل نموذج رياضي حول فترات تعبئة وتفاعل واستقرار الأحواض المتتابعة . وتم تطبيق معادلة مونود لوصف النمو الميكروبي .

وشمل البحث توقعات نموذجية ونتائج نظرية مع عرض نتائج المحاكاة التي تبين أنه كلما طالت مدة التعبئة كلما كانت أفضل لمعالجة المخلفات السامة والقوية .

وكذلك تم عرض عمل تجريبي لدراسة الكائنات المجهرية المسئولة عن الخفض البيولوجي للفينول حيث تم اكتشاف أن العناصر الميكروبية المسماه بـ *Psuedomonas Aeriginosa* هي الأكثر تواجداً ضمن الميكروبات الاخرى .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران - المملكة العربية السعودية

SYMBOLS

BOD:	Biochemical Oxygen Demand
COD:	Chemical Oxygen Demand
HRT:	Hydraulic Retention Time
MLSS:	Mixed Liquor Suspended Solids
MLVSS:	Mixed Liquor Volatile Suspended Solids
SRT:	Solids Residence Time
SBR:	Sequencing Batch Reactors
TSS:	Total Suspended Solids
TKN:	Total Kjedahal Nitrogen
VSS:	Volatile Suspended Solids

Chapter 1

INTRODUCTION

1.1 General

The increasing complexity of wastewater to be treated and stringent effluent regulations require improvement of the existing wastewater treatment systems and put forward the need for more efficient treatment processes. In addition to the developments that are taking place with conventional treatment methods, alternative treatment systems and technologies are also under investigation (Metcalf & Eddy, 1979). In connection with experimental studies, nowadays it has become a common practice in the wastewater treatment processes to model biological growth in relation with substrate removal mathematically for prediction and design purposes. Modeling is an inherent part of the environmental engineering work in order to predict the general behavior or response of the treatment scheme to the stress operational and loading due to variations. Kinetic models are also useful tools for design of biological treatment facilities and control of their operations (Guady, 1980).

The Sequencing Batch Reactors (SBR) has been used for biological treatment of domestic and industrial wastewaters since the early 1950s. However, very little was known about the SBR until the late

1970's, when the University of Notre Dame, at Indiana, carried out extensive research investigating the use of SBR system as an efficient alternative to the conventional continuous flow system (Arora et al. 1985, Irvine and Bush 1979).

1.2 Physical Description of the SBR

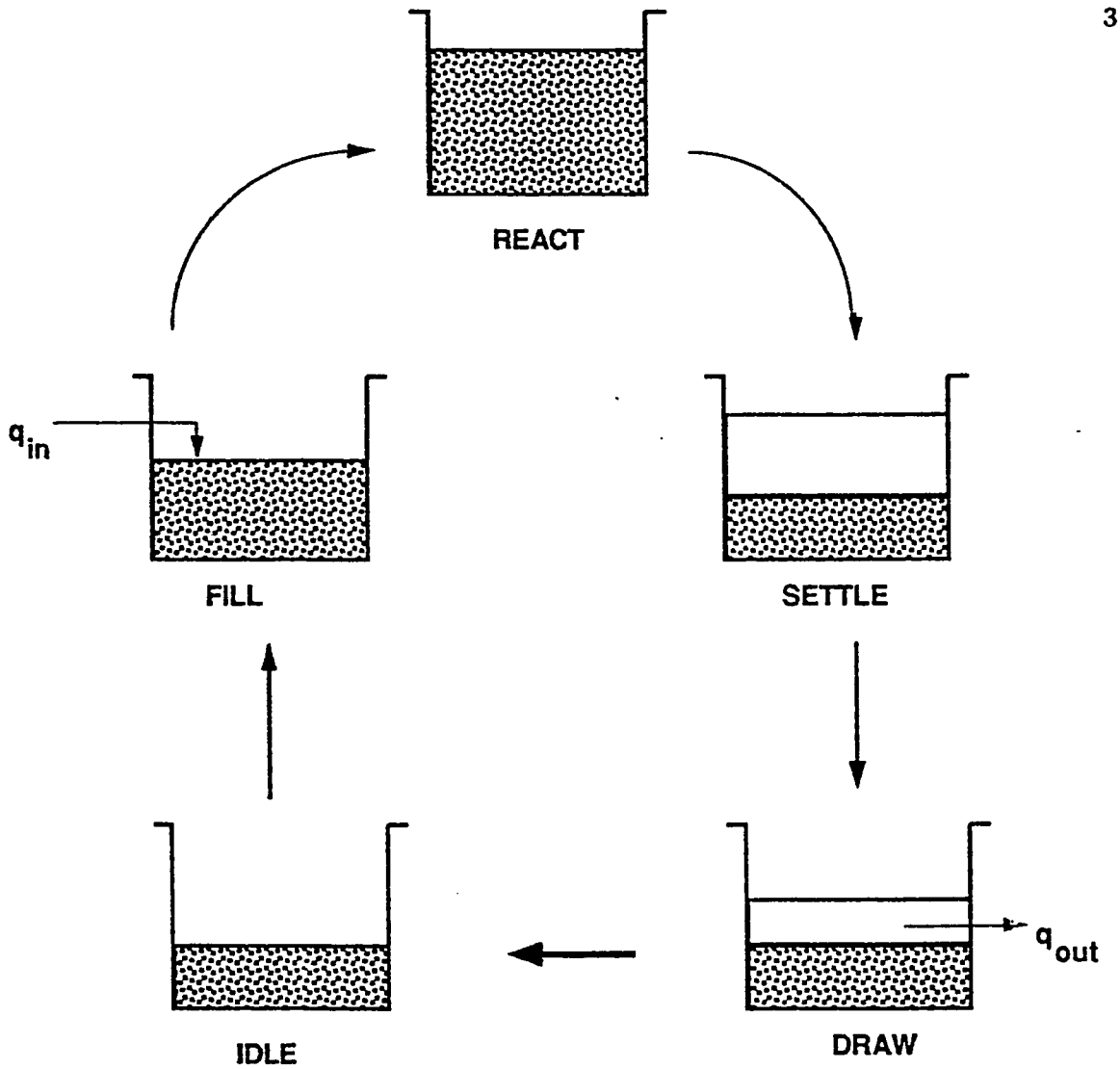
Generally, the SBR system consists of several tanks, and their mode of operation is quite similar to a fill-draw activated sludge reactor. The SBR operation consists of five consecutive periods which are fill, react, settle, draw, and idle. During fill, raw wastewater is fed to the reactors. Then follows the react period in which the reactors are operated in a batch mode. After treatment during the react period, the mixed liquor is allowed to settle and the clarified supernatant is withdrawn (Arora et al. 1985, Irvine an Bush 1979). Figure (1) shows schematically one cycle of the SBR operation. The SBR has been shown to be a cost effective treatment of hazardous organic pollutants found in industrial wastewaters (Ketchum et al. 1979, Herzburn et al. 1985). Furthermore, the SBR system has several advantages over the conventional continuous flow systems. These advantages include:

(i) use of the same tank for both aeration and settling,

(ii) carefully controlled settling,

(iii) discharge of only treated waste meeting effluent limitations, and

(iv) the possibility of using partial capacity of the plant dur-



	FILL	REACT	SETTLE	DRAW	IDLE
Air	Off	On	Off	Off	Off
Mixing	On	On	Off	Off	Off
q	>0	0	0	<0	0
V	$V_o + \int q\,dt$	V_{max}	V_{max}	$V_o + \int q\,dt$	V_o
Time	$0 \le t \le t_f$	$t_f \le t \le t_r$	$t_r \le t \le t_s$	$t_s \le t \le t_d$	$t_d \le t \le t_i$

Figure 1.1: Schematic SBR Operation

ing low waste production (Ketchum et al. 2979, Arora et al. 1985).

During the last two decades, extensive research on biological wastewater treatability in SBR has been carried out. However, most of this effort focussed on the experimental aspects of design and operation and only few papers presented mathematical expressions for the SBR system (Ketchum & Liao, 1979; Hoepker & Schroeder, 1979; Hsu, 1986; Misbahuddin & Farooq, 1990; Al-Harazin et al., 1991; Brenner et al., 1992). Compared to the continuous flow activated sludge systems, the mathematical description of the SBR system is not fully developed.

The primary objective of this study is to develop a mathematical model for the SBR system and validate it using the available experimental data from the literature. A secondary objective of this work is to assess the sensitivity of the performance of SBRs to variations in loading and operational conditions and the concomitant changes in kinetic coefficients. A numerical method is used to solve the governing system of nonlinear ordinary differential equations. The proposed model predicts the time-dependent microbial cell and substrate concentrations during SBR operation. The modeling discussion presented herein is limited to the fill, react and settle periods of the SBR system, as essentially no significant changes in the composition of the reactor contents other than the wastewater volume occur during the idle and draw periods. In addition to the modeling work,

experimental work has been carried out and one of the model assumptions, which is the predominance of one microbial species during toxic waste treatment is verified.

1.3 Objectives

The aim of this research is to develop a mathematical model for sequencing batch biological treatment system. The main objectives are summarized as follows:

1. Development of a mathematical model for SBR system, which takes into account the microbial growth as well as substrate utilization rate for fill, react and settle periods.

2. Solution of the governing equations using a suitable numerical technique and development of the appropriate computer code to implement the solution algorithm.

3. Use of the developed model to predict the performance of SBR system treating synthetic phenolic and petrochemical wastewaters at various operating conditions.

4. Investigation of the effect of the fill and react ratio on SBR treatment performance.

5. Investigation of the effect of the variation of the magnitude of the model parameters as well as initial conditions on the SBR treatment performance through sensitivity analysis.

Chapter 2

LITERATURE REVIEW

2.1 Biological Wastewater Treatment Using SBR

There are mainly two types of biological wastewater treatment methods. The first one is known as fixed film system in which the microorganisms grow attached to the solid surface. The second one is activated sludge system in which the microorganisms grow in suspension. In both cases, a mixture of heterogeneous microorganisms consume the contaminants present in domestic, industrial, and hazardous wastewaters and convert them into new cells of microorganisms, carbon dioxide, water and other end products depending on the nature of the wastewater and microorganisms present in the system as well as treatment conditions (Metcalf and Eddy, 1979).

The SBR system is a suspended growth activated sludge system. Conventional activated sludge systems, however, are space oriented. Flow moves from one tank to the next one on a continuous basis and all tanks have a fixed liquid volume. The SBR, on the other hand, is a time-oriented system, having variable flow and tank volume according to some predetermined operating strategy (Arora et al., 1985; Irvine and Bush, 1979; Ketchum et al., 1987). As a result, the SBR operates in an unsteady-state condition.

The SBR system operates under five time periods; namely fill, react, settle, draw and idle. Sludge wastage can take place during react, settle, draw or idle periods (Arora et al., 1985). Figure 1.1 shows one cycle of a typical SBR operation. A detailed discussion of each period is given below.

Fill period: During fill period, the tank is filled with raw wastewater. The tank already contains sludge or biomass retained from the previous cycle. The liquid volume increases from initial to the maximum level, and the time of fill depends on both the volume of the tank and the wastewater flow rate. During fill period, aeration and mixing mechanisms could be on or off. However, aerating and mixing the system during fill period will result in early treatment of the wastewater, particularly in the cases of longer fill period. Fill period is terminated when the tank is full, and the wastewater flow is directed to another tank to be operated under fill period (Arora et al., 1985; Irvine and Bush, 1979; Dennis and Irvine 1979).

React Period: During the react period, the liquid level remains at its maximum and both aeration and mixing are provided. The sludge wastage can take place by the end of this period to control the sludge age. The end of react period may be dictated by a time specification or the desired effluent quality (Irvine and Bush, 1979).

Settle Period: During settle period, solids separation takes place quiescently in the same tank. The settling time typically ranges from 0.7 to 1.0 hour to ensure that the sludge blanket settles properly

(Alleman and Irvine, 1980; Irvine et al., 1983).

Draw Period: During draw period, the clarified supernatant is drawn. The time required for draw is the ratio between the volume of liquid to be drawn and the flow rate during draw period (Arora et al., 1985; Irvine and Bush 1979).

Idle Period: After the draw period, the tank is ready to receive additional wastewater. The time between draw and fill is termed as idle. Sludge wastage can take place during this period. Alternatively, idle can be eliminated by starting fill after the draw period (Arora et al., 1985; Irvine and Bush 1979).

The operating policy of the SBR can be modified such as, using oxic or unoxic fill and varying duration of the fill and react periods, to meet improved effluent requirements as well as handling changes in wastewater characteristics and accommodate wide fluctuations in hourly and seasonal flow rates without increasing the physical size of the plant (Irvine and Ketchum, 1989).

2.1.1 Bench Scale-Studies

The first bench-scale studies to investigate the application of the SBR system for treatment of municipal and industrial wastewaters was carried out by researchers at the University of Nortre Dame, Indiana, in the late 1970's under sponsorship of the National Science Foundation (Dennis and Irvine,1979; Irvine et al., 1979; Ketchum et al., 1979). The SBR system has been shown to be capable of

achieving BOD Biological Oxygen Demand (BOD), Suspended Solids (SS) and nitrogen removal (Alleman and Irvine, Irvine et al., 1983), biological phosphorus removal (Ketchum and Liao, 1979; Manning and Irvine, 1985), and treatment of industrial and hazardous wastes (Brenner et al., 1992; Hsu, 1986; Misbahuddin & Farooq, 1991). Irvine and Miller (1979) were among the first who studied the use of the SBR for biological treatment of a domestic wastewater. They achieved BOD and TSS removal of 97% and 90% respectively. They also found that BOD and TSS removal and nitrification can be achieved in relatively short react times, i.e. from 6 to 15 hours, while a relatively long react period limit the extent of denitrification. A further investigation on the application of the SBR for domestic wastewater treatment was carried out by Irvine et al. (1983) using information collected from a full scale SBR treatment plant at Culver, Ind., USA. This plant was receiving 1,170 m^3 /d of domestic wastewater having two reaction tanks of 460 m^3 capacity each. The average fill time was 3.0 hours followed by 0.7 react time. They reported that the plants effluent BOD and TSS never exceeded 16 mg/l for 15 months of evaluation.

Dennis and Irvine (1979) studied experimentally the effect of fill and react ratio on treatment efficiency of the sequencing batch biological reactors. They found that the fill and react ratio affects the maximum substrate removal as well as sludge settling. Hoepker and Schroeder (1979) described in their study the relationship between

effluent quality and growth rate in SBR systems. They considered two cases, one for zero fill time and another for 8-hour fill time. They have shown that, in the case of 8-hour fill time, both the specific growth and removal rates did not vary significantly during fill period as a function of feed strength. Herzburn et al. (1985) investigated the main factors which affect the SBR treatment efficiency, such as temperature and detention time variations. The information obtained from this study was used to design a full scale SBR treatment plant. The performance of the full scale SBR plant was monitored for the first month of operation and it was found that TOC and phenol removal efficiencies of 76% and 99.0% were achieved respectively.

The SBR system has been even successfully used for tertiary treatment, particularly for phosphorus removal (Ketchum et al., 1979). Compared to continuous flow systems, less chemicals are needed and no polymer addition is required. Thus, the reduced chemical addition will reduce the sludge production. Manning and Irvine (1985) reported that soluble phosphorous can be reduced from 13 mg/l to less than 0.5 mg/l using the SBR system at relatively low COD/TKN ratio of 7.5. They mentioned that the flexible nature of SBR, such as oxic and anoxic conditions and changes in waste strength, seems ideally suited for biological removal of phosphorus. Alleman and Irvine (1980) studied denitrification capacity of a bench-scale SBR system using synthetic waste. Total organic carbon and nitrogen removal efficiencies of 99% and 92% was achieved

respectively. They have shown that the SBR process can be used for nitrification process. Silverstein and Schroeder (1983) also investigated the nitrification/denitrification performance of a bench-scale SBR system. They reported 75 % removal of organic carbon, nitrogen, and suspended solids. Palis and Irvine (1985) carried out three bench-scale studies to investigate nitrogen removal capacity in a low-loaded SBR system. An overall nitrogen removal of 94% was achieved. They also observed that the highest denitrification rate occurs during anoxic fill.

The use of bench-scale SBR system to investigate biological treatability of industrial wastewater containing toxic and hazardous pollutants has attracted many researchers (Brenner et al., 1992; Al-Harazin et al., 1991; Herzburn et al., 1985; Hsu, 1986; Irvine et al., 1983; Misbahuddin and Farooq, 1991). Misbahuddin and Farooq (1991) studied the use of the SBR system for petrochemical wastewater treatment. They achieved a BOD and COD removal of 94% and 87% respectively, using low strength industrial wastewater at HRT and SRT of 0.33 and 24 days respectively. They also investigated the effect of different operational strategies on the SBR treatment efficiency. During phase II of their study, an anoxic fill of 1 hour with different react period was studied. They found that the longer the aeration time better is the removal efficiency. Hsu (1986) also studied biological treatment of a petrochemical wastewater using the SBR system. In his experimental set-up, a conventional activated sludge unit was also run for comparison purposes. He concluded that the

SBR system had better performance in terms of the degradation of organic pollutants as well as nitrification.

Al-Harazin et al. (1991) used the SBR system for biological treatability studies of wastewater contaminated with highly toxic pollutants. A phenol concentration of 800 mg/l was reduced to less than 0.5 mg/l. However, when phenol concentration increased up to 1600 mg/l the removal was 75 %. Furthermore, they have shown that the SBR system can be acclimatized within a week using the raw sewage only. A high strength phenolic wastewater simulating a coal conversion wastewater process was treated biologically by Brenner et al. (1992) using the SBR system. They found that the extension of the anoxic period of the SBR system has an adversely affected on the removal efficiency. They mentioned that the SBR system have higher efficiency for biological treatment of the phenolic wastes compared to the continuous flow systems.

The practical application of any treatment system is influenced by its initial, operational, and maintenance cost. Ketchum et al. (1979) carried out the first cost analysis of the SBR system. In their evaluation, they considered the initial cost investment, manpower requirement, energy and chemical demand, and operational and maintenance items for a multiple tank SBR system. Compared to a conventional activated sludge system they found the SBR system is cheaper.

2.1.2 Full-Scale Plants

A full-scale application of the SBR system have been reported in many countries such as USA, Canada, Germany, Denmark, Australia and Japan (Irvine et al, 1985). Arora et al, (1985) collected information about operational conditions of a number of SBR treatment plants in U.S.A., Canada and Australia. They found that all these plants were producing effluent with pollutant concentrations of acceptable quality. The approach used in designing all the plants they visited was entirely an empirical one, particularly in sizing of the SBR reactors. In some cases there was a small reactor with detention time less than 8 hours and in other cases large reactors with detention time that was 6 times longer were used. Similar differences were observed also in another design parameters such as F/M ratio, solid retention time and cycle durations. All these variables and variations are significant in the effluent quality and cost of the plant.

Irvine et al. (1979) studied the effect of different organic loading on a full-scale SBR plant at Culvert, USA. They varied the operational strategies and compared the treatment performance for two different organic loadings. They found that the lower the organic loading better is the removal efficiency.

Irvine et al. (1985) investigated the treatment efficiency of a full-scale SBR plant in Iowa, USA. Ultrasonic level sensors were used to control tank levels so that it can be shifted automatically between fill, react, draw and settle periods. Initially, this plant was not a

true SBR, because it did not include some of the SBR features. This caused the plant to produce poor effluent quality. Later on the plant was modified into a true SBR and the effluent quality was improved significantly.

2.1.3 Mathematical Representation of the SBR

Mathematical expressions which partially describe the various phases of the SBR operation have been reported in the literature since late 1970's. Dennis and Irvine (1979) developed the following substrate mass balance equations for fill and react periods. For fill period:

$$\frac{d(C_s V)}{dt} = q\,C_{so} + V\,r_{fs} \tag{2.1}$$

where C_{so} is the influent substrate concentration C_s is the substrate concentration, at any time t, V is the volume of the SBR (l), q is the influent flow rate (l/d), and r_{fs} is the rate of utilization of substrate (mg/l.d), and r_{fs} was defined as:

$$r_{fs} = -\,K_1\,C_s\,C_b \tag{2.2}$$

where K_1 is the reaction rate coefficient (l/mg.d), C_b is the microorganism concentration (mg/l). Equation (2.1) is identical in form to an unsteady-state mass balance expression on a continuous flow system, except that the volume is a function of time in the former case. For react period:

$$\frac{dC_s}{dt} = r_{fs} \tag{2.3}$$

This equation is also the same as the mass balance equation for plug flow reactors. However, there were no mass balance equations for microbial growth presented, and without that the above mentioned equations fail to give a complete picture of substrate removal in the SBR system. Equation (2.1) was simplified into steady state condition to come up with the following expression for the volume:

$$V = \frac{q(C_{s0} - C_s)}{-r_{fs}} \tag{2.4}$$

Equation (2.4) is also identical in form to a steady state mass balance equation for completely mixed reactors. The authors have shown that a two reactor system of SBR with a total volume of 12 l would treat a wastewater flow of 25.2 l/d having influent and effluent BOD concentrations of 400 mg/l and 4 mg/l respectively. They used equation (2.4) with K_1 = 0.025 l/mg.d to calculate the volume required to treat the same wastewater flow using completely mixed reactors. Comparing the two system, they found that the later's volume is 3.3 times greater. Therefore, it is apparent that SBR system has volume advantage.

A more general formulation of the modelling of the SBR system was presented by Hsu (1986). Hsu studied the biological treatment of petrochemical wastewater using the SBR system. The mathematical

model presented was based on Monod kinetics. For the react period he suggested the following mass balance equations

$$\frac{dX}{dt} = (\mu - k_d) X \tag{2.5}$$

$$\frac{dS}{dt} = \frac{-1}{Y} \mu X \tag{2.6}$$

where X and S are bacterial cell and substrate concentrations (mg/l) respectively at any time t, μ is the specific growth rate ($time^{-1}$), according the Monod expression $\mu = \frac{\mu_{max} S}{K_s + S}$, k_d is the decay coefficient ($time^{-1}$), Y is the bacterial yield coefficient (mg of cell/mg of substrate consumed). Hsu limited his modelling discussion to the react period, assuming that biodegradation takes place only during the react period.

Braha and Hafner (1985) also discussed the use of Monod kinetics on modelling of multi stage bioreactors in steady state condition. In their analysis, they considered a system of series of bioreactors in anaerobic condition. For the first reactor, they suggested the following mathematical expression:

$$\frac{S_0 - S_1}{\theta_0} = \frac{X_v S r_{x,max}}{K_s + S_1} \tag{2.7}$$

where S_0 and S_1 are influent and effluent substrate concentrations

(mg/l) respectively, S the substrate concentration (mg/l) at steady state condition, and X_v the microbial cell concentration (mg/l), θ_0 the retention time (t), and $r_{x,max}$ the maximum substrate utilization rate (1/time).

The linearized form of equation (7) becomes:

$$\frac{X_v\theta_0}{S_0 - S_1} = \frac{K_s}{r_{x,max}S_1} + \frac{1}{r_{x,max}} \tag{2.8}$$

Using this equation, they calculated the reaction constants graphically with a coordinate system of an abscissa $\frac{1}{S_1}$ and the ordinate $\frac{X_v\theta_0}{S_0 - S_1}$. Therefore, the application of these equations is limited to calculate the kinetic coefficients of a system in steady state condition.

Silverstien and Schroeder (1983) studied experimentally the nitrification/denitrification process using bench scale SBR, and presented the following mass balance equations for substrate and microbial cell variations during fill period. For substrate:

$$\frac{d(VC)}{dt} + QC_0 = Vr_c \tag{2.9}$$

Where V = reactor volume (l), Q = inflow rate (l/min), C = substrate concentration (mg/l), C_0 = substrate concentration at influent, and r_c = the rate of substrate removal (mg/l.min). For microbial cell:

$$\frac{d(VX)}{dt} + QC_0 = V\mu \tag{2.10}$$

Where X = microbial cell concentration (mg/l), and μ = rate of increase of biomass (mg/l/min). It was assumed that the growth of microorganisms is negligible during fill so that $\mu = 0$. Thus equation (2.10) becomes

$$\frac{d(VX)}{dt} + QC_0 = 0 \tag{2.11}$$

Solving equation (2.11) with boundary condition that $V(0) = V_0$, $X(t) = X$,and $X(0) = X_0$ yields:

$$X(t) = \frac{X_0 V_0}{(V_0 + Qt)} \tag{2.12}$$

Similarly, equation (2.9) was solved assuming that $r_c = kX$ and C(0) = 0 as initial conditions. The solution became:

$$C(t) = \frac{(QC_0 - kX_0V_0)t}{(V_0 + Qt)} \tag{2.13}$$

There were no mass balance equations for react period. However, during react period, both growth of microorganisms and substrate removal takes place (Dennis and Irvine, 1979; Irvine and Ketchum, 1989). Therefore, in any modelling effort of the SBR, the react period must be included.

2.3 Present Status of the Problem

From the literature review it has been clear that only a few studies have addressed the modeling of the SBR process. In most of these works, simple models have been used to study only the react period of the SBR and some of them employed simplified kinetic models to describe microbial growth kinetics. Experimental results showed that the fill period plays an important role in the SBR treatment (Dennis and Irvine, 1979). Therefore, any mathematical model which excludes fill or react periods may not be able to simulate the real behavior of the SBR system. In other words, qualitative results obtained from simple models may not represent the system properly and may not be applicable in designing or controlling the SBR system. Up to now, there is no reference to an integrated model for the SBR system which accounts fill, react and settle periods. Therefore, in order to study the performance of a real SBR system and to design and control such systems, it is very essential to develop an integrated mathematical model that accounts for fill, react and settle periods.

Chapter 3

THEORY AND DEVELOPMENT OF THE SBR MATHEMATICAL MODEL

3.1 Introduction

The concept of modelling has been used in engineering and scientific research. Models are used to describe observed phenomena or to explain them in terms of accepted theories. In practice, predictive models are used to predict the effects of different variables in a process (Theones, 1980). In the case of the SBR system, the unsteady state nature of its operation makes it quite difficult to formulate a complete mathematical model for the system. However, mathematical expressions which partially describe the various phases of the SBR operation have been reported in the literature since late 1970's (Dennis and Irvine, 1979; Hsu 1986). From the operational point of view, in the SBR system, the fill, react and settle periods are the most important ones. Therefore, any realistic model must account for all the above mentioned operational periods to analyze the overall behavior of the system.

3.2 Development of the Mathematical Model

In order to develop a model, it is necessary to make reasonable assumptions to simplify the physical phenomena to some extent so that a set of mathematical equations can describe it. In the present

model, Monod kinetics will be used to describe the microbial growth rate. The following assumptions are taken into account in the development of the model:

1. Only one substrate is growth limiting and all others nutrients are in abundance.
2. The reactor is assumed to be well mixed so that the concentration of the substrate and microorganisms is uniform.
3. Aeration and mixing are provided only during react and fill periods.
4. The microbial cell growth rate is assumed to follow Monod kinetics, which can be expressed as:

$$\mu = \frac{\mu_{max} S}{K_s + S} \tag{3.1}$$

where μ = specific growth rate (1/time), μ_{max} = maximum specific growth rate (1/time), S = substrate concentration (M_s/L^3) K_s = half saturation coefficient (M_s/L^3)

5. The kinetic constants do not vary from one period to another, i.e, the pertinent parameters during the react period are also applicable for the fill period for n-th cycle.
6. The required solids residence time is maintained by wastage of the appropriate volume of mixed liquor at the end of the react period.

3.2.1 Mathematical Formulation

Based on the above assumptions, following are the mass balance equations on microbial cell and substrate concentration for fill, react and settle periods of the SBR. A generic n-th cycle of operation is considered.

Fill Period

During the fill period, the reactor receives raw wastewater until it is filled. Therefore, the volume varies with time and it can be expressed as

$$V_{f,n} = V_{sl,n-1} + \int_0^{t_f} q dt \tag{3.2}$$

where $V_{f,n}$ = volume of the liquid in the reactor (l), at any time t during fill, $V_{sl,n-1}$ = volume of retained sludge after effluent discharge (l), q = flow rate of the feed wastewater (L^3/T), $0 < t < t_f$ and t_f = fill time

Microbial Cell Mass Balance

The microbial cell mass balance is given by

$$\frac{d}{dt}(V_{f,n}X_{f,n}) = qX_o + r_g V_f \tag{3.3}$$

where X_o is the microbial cell concentration in the feed wastewater,

(M_x/L^3), X_f is time-varying microbial cell concentration (M_x/L^3), during fill period. r_g is the microbial growth rate $(M_x/L^3.T)$ and it is defined as

$$r_g = (\mu_{max}\frac{S_f}{K_s+S_f} - K_d)X_f \qquad (3.4)$$

where K_d is the microbial cell decay coefficient $(time^{-1})$. The subscript (f) indicates fill period.

Differentiating the left hand side term of equation (3.3), we get

$$V_f\frac{dX_f}{dt} + X_f\frac{dV_f}{dt} = qX_o + r_gV_f \qquad (3.3a)$$

but $\frac{dV_f}{dt} = q$ by definition,

Now, substituting (3.4) into (3.3a) and rearranging yields:

$$\frac{dX_f}{dt} = \frac{q}{V_f}(X_0 - X_f) + (\mu_{max}\frac{S_r}{K_s+S_f} - K_d)X_f \qquad (3.5)$$

Equation (3.5) describes the variation of microbial cell concentration in the system during the fill period.

Substrate Mass Balance

Regarding the variation of substrate concentration during fill period, a mass balance on the substrate

$$\frac{d}{dt}(V_fS_f) = qS_o + r_{ut}V_f \qquad (3.6)$$

where S_f = Substrate concentration during fill period (M_s/L^3), S_o = Substrate concentration in the feed wastewater (M_s/L^3), r_{ut} = substrate utilization rate ($M_s/L^3.T$) defined as

$$r_{ut} = -\frac{\mu_{max} S_{f,n} X_f}{(K_s + S_f)\ Y} \tag{3.7}$$

Differentiating the left side of equation (3.6), we get

$$V_f \frac{dS_f}{dt} + S_f \frac{dV_f}{dt} = qS_o + r_{ut} V_f \tag{3.6a}$$

Similarly substituting $q = \frac{dV_f}{dt}$ and using (7) into (3.6a), and after rearranging various terms, we get

$$\frac{dS_f}{dt} = \frac{q}{V_f}(S_o - S_f) - \frac{\mu_{max} S_f X_f}{(K_s + S_f)\ Y} \tag{3.8}$$

Equation (3.8) gives the substrate variation with time during fill period.

Initial condition:

At the beginning of the fill period and assuming that sludge wasted towards the end of the react period, the following equations are valid:

at $t_f = 0$ we have $V_f = V_{sl}$

$$V X_{r,n-1} = V_w X_r + V_d X_{eff} + V_{sl} X_{sl} \tag{3.9}$$

Where V_w, V_d, V_{sl} respectively denote the volume of wastewater discarded at the end of the react period to maintain the desired SRT, the volume of decanted effluent, and volume of sludge retained after settling (L^3), X_r, X_{eff} and X_d represent the VSS concentrations, in the mixed liquor at the end of the react period, in the decanted effluent and settled sludge, respectively (M_x/L^3). Assuming sludge wastage takes place at end of react period. Simplifying equation (3.9), and substituting $V = V_w + V_d + V_{sl}$ we have

$$X_{sl} = (1 + \frac{V_d}{V_{sl}}) X_r - (\frac{V_d}{V_{sl}}) X_{eff} \qquad (3.9a)$$

Similarly, for substrate mass balance

$$S_{sl} = (1 + \frac{V_d}{V_{sl}}) S_r - (\frac{V_d}{V_{sl}}) S_{eff} \qquad (3.10)$$

where V_d = volume decanted after settling, and V_{sl} = volume of the sludge retained after effluent discharge, S_r , S_{sl} and S_{eff} are substrate concentrations at react, retained sludge and in the effluent respectively.

React Period

In the react period, there will be no inflow and outflow from the reactor. Therefore, in this case the wastewater volume in the reactor is constant and is equal to maximum volume of the reactor at the end of the fill period.

Microbial Cell Mass Balance

During the react period, the variation of microbial cells is given by equation (3.5) with q is equal to zero:

$$\frac{dX_r}{dt} = \left(\frac{\mu_{max} S_r}{K_s + S_r} - K_d\right) X_r \qquad (3.11)$$

The subscript (r) indicates react period.

Substrate Mass Balance

The variation of substrate concentration during react period is given by equation (3.8) with q is equal to zero:

$$\frac{dS_r}{dt} = - \frac{\mu_{max} S_r X_r}{(K_s + S_r)\ Y} \qquad (3.12)$$

where

Y = yield coefficient (M_x/M_s).

Initial condition

The initial conditions of the react period are the same as final conditions of the fill period.

Settle Period

Regarding the settle period, a mathematical expression proposed by Knapton (1978) is used. Knapton used this expression to study

the TSS removal efficiency of the primary settling tanks in continuous flow systems. The SBR reactor have similar settling characteristics to the primary clarifiers since quiescent conditions prevail during settling and no sludge recycle is exercised. The equation proposed by Knapton was of the form

$$\frac{X_{eff}}{X_{in}} = [0.00043(X_{in}) + 0.51][1 - e^{-0.7T}] \tag{3.13}$$

The general form of equation (3.13) is as follows

$$\frac{X_{eff}}{X_{in}} = [K_1(X_{in}) + K_2][1 - e^{k_3 T}] \tag{3.14}$$

or

$$X_{eff} = K_2(X_{in})[1 - e^{k_3 T}] + K_1(X_{in}^2)[1 - e^{k_3 T}] + K \tag{3.15}$$

Where X_{in} and X_{eff} are influent and effluent TSS concentration respectively, and T is settling time. Equation (3.15) will be linear if K_3 is fixed. Therefore K_3 was set to -0.7 as suggested by Knapton (1978). Then the value of K, K_1 and K_2 was determined fitting equation (3.15) with experimental data reported in the literature (Al-Harazin et al., 1991). A multiple linear regression analysis was carried out using statistical package (SAS) available in King Fahd University of Petroleum and Minerals mainframe. Using the obtained values, equation (3.15) becomes

$$X_{eff} = [0.00025(X_{in}) + 0.75][1 - e^{-0.7r}] \qquad (3.16)$$

If equation (3.16) does not give a satisfactory results in a particular case, then equation (3.14) was used to compute applicable constants. For the purposes of this work, X_{in} is the mixed liquor concentration at the end of of the react period. The proposed model consists of equations 3.2, 3.5, 3.8, 3.9a, 3.10, 3.11, 3.12, and 3.16. Equations 3.5, 3.8, 3.11, and 3.12 are first order, non linear ordinary differential equations and the rest are normal linear equations.

3.2.2 Model Parameters

Four parameters which are, μ_{max} , K_s , K_d , and Y, appear in the model equations. Therefore, the values of these parameters have to be fixed in order to solve model equations. Table 3.1 shows typical values reported in the literature. Typical values or average parameter values for the various waste types, i.e domestic, petrochemical were identified and used for model predictions.

Table 3.1 Values of the kinetic coefficients reported in the literature

Reference	Waste Type	Ks mg/l	u 1/day	Y	Kd 1/day
Brown et al. (1990)	Phenol	1.4	4.32	0.56	-
Colvin & Rozich (1986)	Phenol	7.9	4.56	0.47	-
Knudson et al. (1982)	Phenol	2.0	2.6	-	-
Pawlowsky and Howell (1973)	Phenol	41.2	4.92	0.62	-
Rozich et al. (1985)	Phenol	75.0	4.56	0.83	0.12
Speitel and DiGiano (1988)	Phenol	57	2.64	0.5	0.15
Hsu (1986)	Petroch.	376	1.77	1.08	0.098
Surucu & E. (1975)	Domestic	--	2.45	0.48	0.045
Bnotan & Yang (1976)	Domestic	--	3.60	.33	0.072
	Domestic	22	3.75	0.67	0.007
Rebhum (1985)	Domestic	20.0	1.09	0.67	0.09

3.2.3 Salient features of the Model

Following are the salient features of the developed model.

(a) The majority of the existing models accounted only for react period of the SBR, and few of them incorporated kinetic expressions, while the present model considers fill, react, and settle periods. In addition to that, Monod kinetic equation is incorporated in the present model.

(b) The solution techniques used in most of the available models are analytical, after simplification of the nonlinear equations into a linear form. In the present work, a numerical technique is used to solve model equation preserving their nonlinear form without any simplifications.

(c) The present model is capable of to predicting the microbial cell and substrate concentration during fill, react and settle periods of the SBR operation.

(d) The proposed model can be easily adapted for different microbial degradation models, other than Monod.

(e) Because of the time-varying parameters inherent to the operation of SBRs, this model may be readily used to predict the performance during load fluctuations.

(f) This model could be a used for further investigations of the SBR system. Using this model, it is possible to analyze different operational conditions of the SBR.

3.3 Solution Methods

The development of the present model lead to a system of non linear ordinary differential equations. In most cases, the differential equations can be solved through analytical procedures such as separation of variables, similarity solutions, complex variable techniques, Fourier and Laplace transformations and Green functions. However,

unless the equation has a fairly simple form, finding analytical solution may be very difficult or even impossible sometimes. In the case of a nonlinear system of differential equation, like the one we are dealing with, the suitable solution is the use of numerical techniques for approximating the numerical value or values of the different variables (Davis, 1984; O'Neil, 1987). The development of numerical techniques coupled with the advent of super computers, many problems previously beyond our capabilities now can be solved approximately to high degree of accuracy (Cheney, 1985; Davis, 1984). Therefore, since there is no analytical solution for the present model equations, the Runge-Kutta method, one of the most popular methods used for the numerical solution of ordinary differential equations was adopted.

3.3.1 The Runge-Kutta Method

The Runge-Kutta method is an explicit algorithm that evaluates the function of f(x) at points between x_i and x_{i+1}. Runge-Kutta method of order four is commonly used for initial value problems, since it gives highly accurate solution and its computational procedures are straightforward. In an abridged form, its formulas are as follows:

$$x(t+h) = x(t)+\frac{1}{6}(F_1+2F_2+2F_3+F_4) \tag{3.19}$$

where

$$F_1 = h*f(t,x) \tag{3.20}$$

$$F_2 = h*f(t+\frac{h}{2}, x+\frac{1}{2}F_1) \tag{3.21}$$

$$F_3 = h*f(t+\frac{h}{2}, x+\frac{1}{2}F_2) \tag{3.22}$$

$$F_4 = h*f(t+h, x+F_3) \tag{3.23}$$

t is the independent variable, and h is the time increment. Like many other methods that are used to solve initial-value problems, the procedure is to carry out the solution function one step at a time. Therefore, the problem is solved in step size of h. In the present study, a step size of 0.01 hour was used.

3.3.2 Development of the Computational Model

A computational model is developed to implement the solution algorithm which consists of three main subroutines. Each subroutine will take care of one cycle, i.e, the subroutine called Fill will solve equations for fill period with appropriate initial conditions. Figure 3.1 shows the solution algorithm of the computational model.

3.3.3 Validation of the Computational Model

After the completion of the computational model, predictions of the model were compared with a simple, but similar system of differential equations, having analytical solution. The following system of differential equations was solved both numerically and analytically using the developed model and then compared.

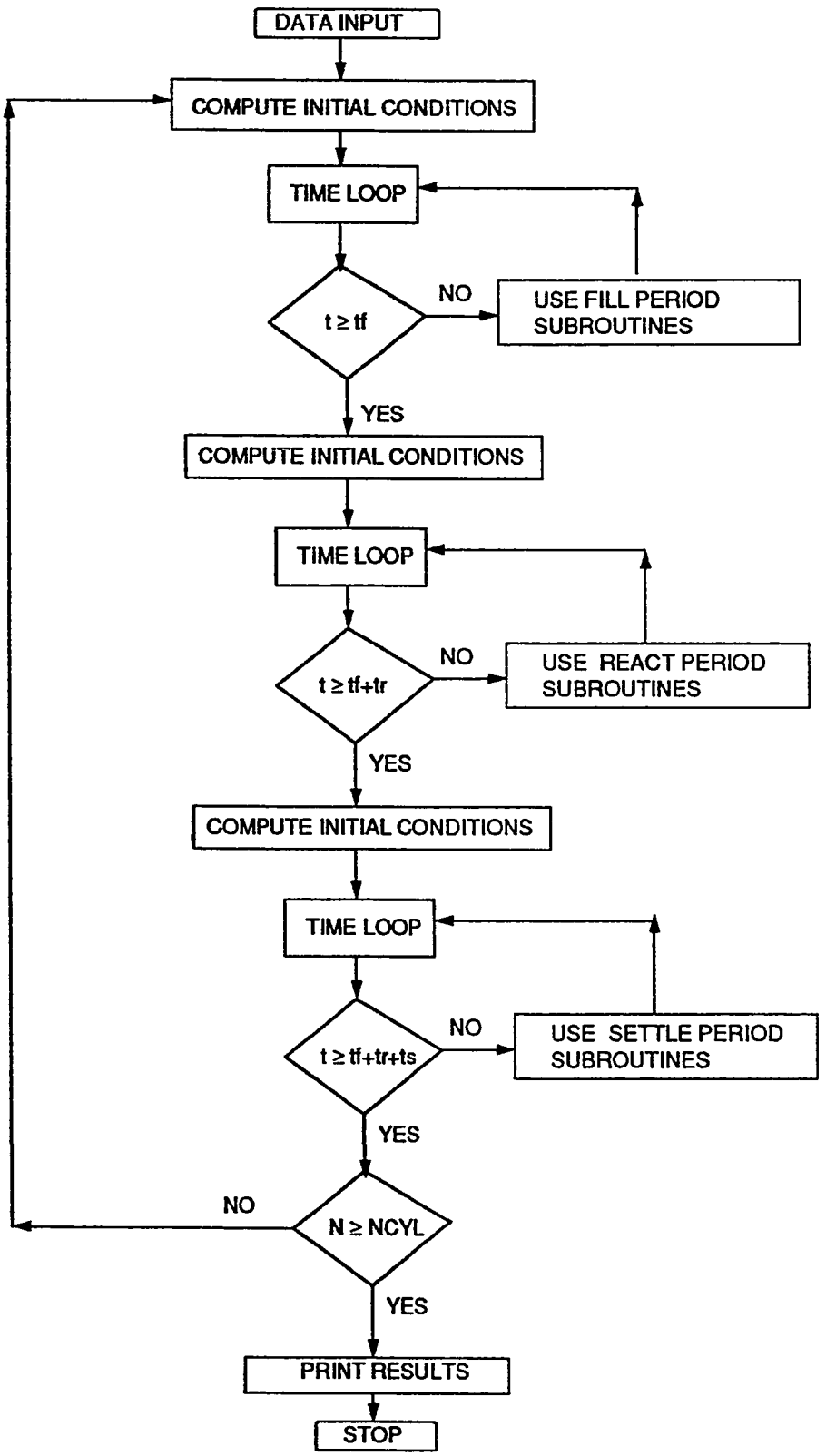


Figure 3.1 Solution Algorithm

$$\frac{dx}{dt} = x(t) - y(t) + 2t - t^2 - t^3 \tag{3.24}$$

$$\frac{dy}{dt} = x(t) + y(t) - 4t^2 - t^3 \tag{3.25}$$

With the following initial conditions:

$$x(0) = 1$$

$$y(0) = 0$$

In which the analytical solution is:

$$x(t) = e^t\cos(t) + t^2 \tag{3.26}$$

$$y(t) = e^t\sin(t) - t^3 \tag{3.27}$$

It should be noted that from above equations, it is not possible to solve either of the two differential equations independently for the first equation $\frac{dx}{dt}$ involves the unknown y, whereas the second equation governing $\frac{dy}{dt}$ involves the unknown function of x. Therefore, the two differential equations are coupled and must be solved simultaneously. Our concern in the developed model is with systems of differential equations that are coupled and demands simultaneous solution. Figure 3.2 shows a comparison between the model prediction and the analytical solutions. The excellent agreement between analytical and numerical results implies the accuracy of the numerical solution adopted.

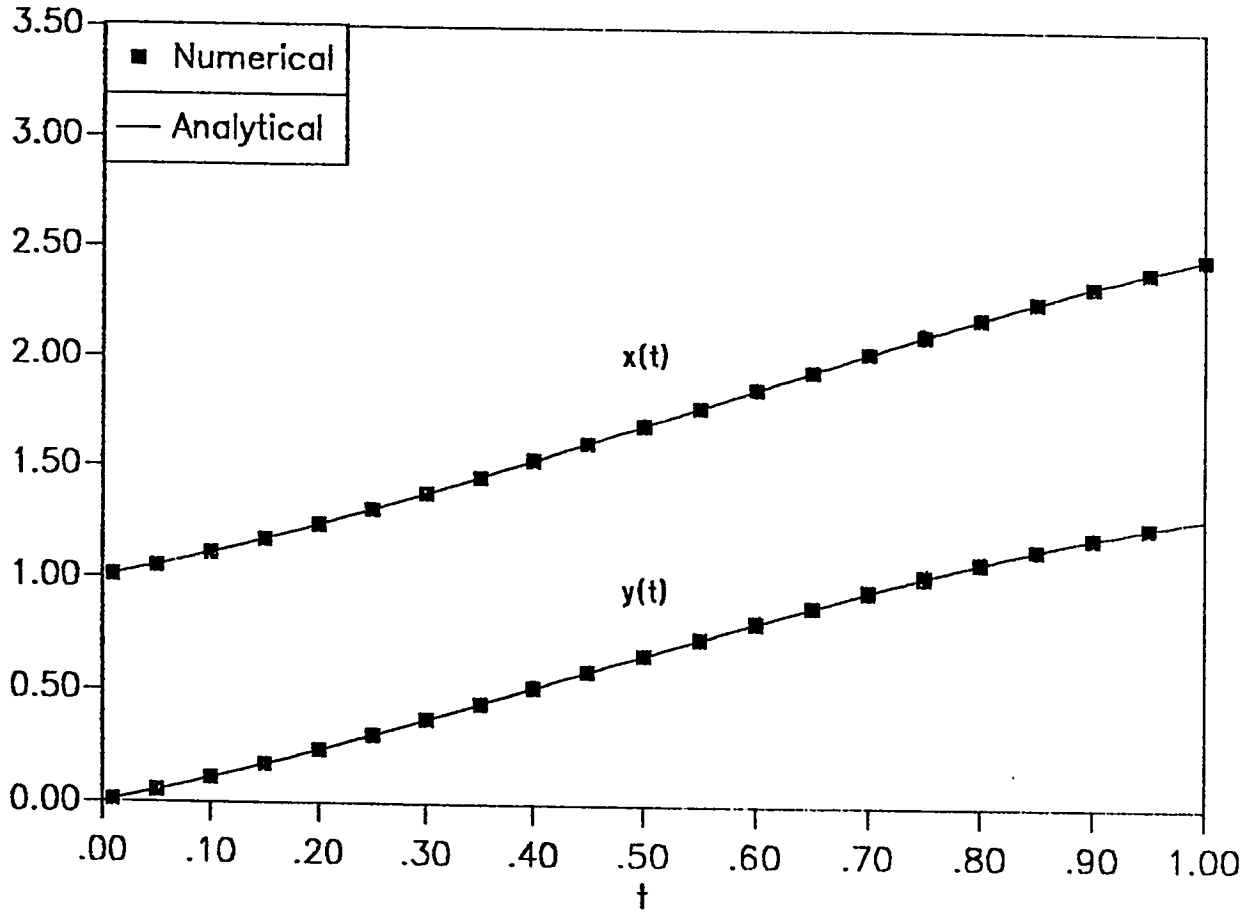


Figure 3.2: Copmarison Between Analytical and Numerical Solution

3.4 Model Calibration

The aim of the model calibration is to ensure that the model predictions are as close as possible to the experimental and/or observed behavior of a system. Generally models are calibrated using one of the following procedures:

(a) parameter adjustment,

(b) modification of boundary and initial conditions,

(c) and/or incorporation of various influencing features.

Regrading calibration of the present model, the first method, which is the parameter adjustment, was used, since the initial and boundary condition are always fixed and can not be varied and at the same time there were no other suitable variables which has to be incorporated into the model.

3.5 Model Applications

The use of the developed model is primarily for prediction purposes. Because of the time-varying parameters inherent to the operation of SBRs, this model may be readily used to predict the performance during load fluctuations. The developed model can be easily adopted for different microbial degradation models, other than Monod and used for prediction of performances of the treatment of toxic wastewaters where inhibition kinetics prevail. Furthermore, this model could be a useful tool for the researchers in this field for further investigations of the SBR system.

Chapter IV

EXPERIMENTAL STUDIES

4.1 Introduction

The major objective of the present experimental work was to verify the validity of one of the basic assumptions of the developed mathematical model. The success of any biological treatment model to predict a system behavior is closely related to how good it describes the growth kinetics in relation to the growth limiting substrate (Morley, 1979). Therefore, during the development the proposed mathematical model, Monod kinetics was used with reasonable assumptions. It was assumed that for phenolic wastes, one microbial species is predominant over the others and one substrate which, is phenol is growth limiting while the other nutrients are abundant. To check the validity of this assumption, the first step was to look for any related information reported in the literature. The following paragraphs summarize available information reported in the literature.

Phenolic wastes have been successfully treated by biological means for several years although, in most of the early studies of phenol biodegradation, pure cultures of microorganisms were used (Hill and Robinson, 1975; Radhakrishan and Ray, 1974; Wildere and Davis, 1991). However phenol biodegradation in natural environment is performed by a mixture of heterogeneous species. Radhakrishan and

Ray (1974) used a pure culture of Bacillus Cereus for phenol biodegradation. They found that Bacillus Cereus is capable of biodegrading phenol and can tolerate up to 1000 mg/l concentration. The microbial biodegradation of phenol by pure cultures of Pseudomonas Putida and Trichosporon Cutaneum has been reported by Yang and Humphery (1975). They reported that Pseudomonas Putida and Trichosporon Cutaneum species are capable of biodegrading phenol, but both species exhibit substrate inhibition at phenol concentration above 100 mg/l. Pawlowsky and Howell (1973) experimentally investigated phenol biodegradation using a mixture of microorganisms derived from soil and activated sludge. However, their study focused on the determination of kinetic coefficients rather than characterization and identification of any particular microbial species engaged for phenol biodegradation. Masunaga and Urushigawa (1986) studied the transformation of phenol and o-cresol during biodegradation using a microbial population derived form activated sludge. However, no details about the nature of the microorganisms responsible for biodegradation of phenol and o-cresol were given. Since sufficient information was not found in the literature for the above stated assumption, it was decided to run an experiment for further investigation.

4.2 Experimental Set-up

The experimental set-up consists of four bench-scale reactors with a volume of 1000 ml each. Raw sewage was collected from North Aramco Wastewater Treatment Plant and preserved in the refrigerator

prior to use, in order to retard biological activity. It was planned to use two reactors for phenolic waste treatment and the other two for raw sewage only, as control units for comparison purposes. After fifth day of the experiment, it was suspected that some of the phenol compounds might disappear due to the effect of aeration. to study the effect of the aeration, another reactor which contains distilled water and phenol was included to the experimental set-up. Daily measurements of influent and effluent phenol concentrations revealed that no phenol solution has been lost due to aeration, and it was decided to exclude the fifth reactor.

4.3 Experimental Procedure

All four reactors were filled with raw sewage up to 800 ml mark and aerated for 22 hours each day. At the third day, two of them were fed a low concentration (20 mg/l) of phenolic solution. The phenolic solution was buffered by adding 1.3 g/l of KH_2PO_4 and adjusted to a pH of 7. Each day a volume of 250 ml was wasted from each reactor after settling about 1 hour and replaced with fresh raw sewage, for the control units, while adding sewage plus a concentrated phenol solution to the other reactors. After 11 days of experimentation when complete acclimatization attested by low effluent phenol concentration has been observed, only pure phenol solution with nutrients were fed for phenol treating reactors to rule out the possibility of diauxic growth being responsible for phenol removal. The concentration of the nutrient solutions were controlled properly to

ensure a ratio of 100:5:1 of C, N and P respectively which is necessary for proper microbial growth (Metcalf & Eddy, 1979). Table 4.1 shows the composition of the synthetic phenol solution used for the experiment.

Table 4.1 Composition of the Synthetic Phenolic Solution

Parameter	Concentration (mg/l)
Calcium	7.5
Chloride	10
Iron	0.2
Magnesium	5
Manganese	0.1
Nitrogen	5
Sodium	5
Phenol	20 - 500
Phosphorus	1
Potassium	16

During the experiment, daily analyses of dissolved oxygen (DO), influent and effluent phenol concentration were carried out. Regarding biomass growth measurement, at the beginning, for the first 20 days, an optical density (OD) analysis was carried out on a daily basis. However, it was not possible to get any consistent results from the OD analysis because of nonuniformity in mixing of the sus-

pended solids in the samples. Then daily analysis of MLSS and MLVSS was started following the procedures described in the Standard Methods (1986, 16th ed.).

4.4 Results and Discussion

During the experiment, influent and effluent phenol concentrations, DO and biomass growth in terms MLSS and MLVSS was monitored. Figures 4.1 shows influent and effluent phenol concentrations respectively. Regarding the influent, a phenol concentration of 20 ppm was used at the beginning which was increased gradually to 500 ppm at the end of the experiment. As it can be noticed from Figure 4.1, about 11 days were required to reach a complete acclimatization of phenolic microorganisms. After acclimatization, only phenol and nutrient chemicals were fed to the phenol treating reactors in order to enhance the growth of phenol degrading species, and possibly to get rid of other microbial species which are not tolerant for higher phenol concentration. Referring to Figure 4.1 there was no significant increase in effluent phenol concentration even when influent was increased to 275 mg/l. However, when influent phenol was increased beyond 275 mg/l, a slight increase in the effluent phenol concentration was observed. But, the effluent phenol concentration was still less than 3 mg/l when influent concentration was increased to 500 mg/l. This implies a development of phenol degrading species.

Figures 4.4 and 4.5 show MLSS and MLVSS variations for reactors (3) and (4). The initial MLSS was close to zero, because the reactors

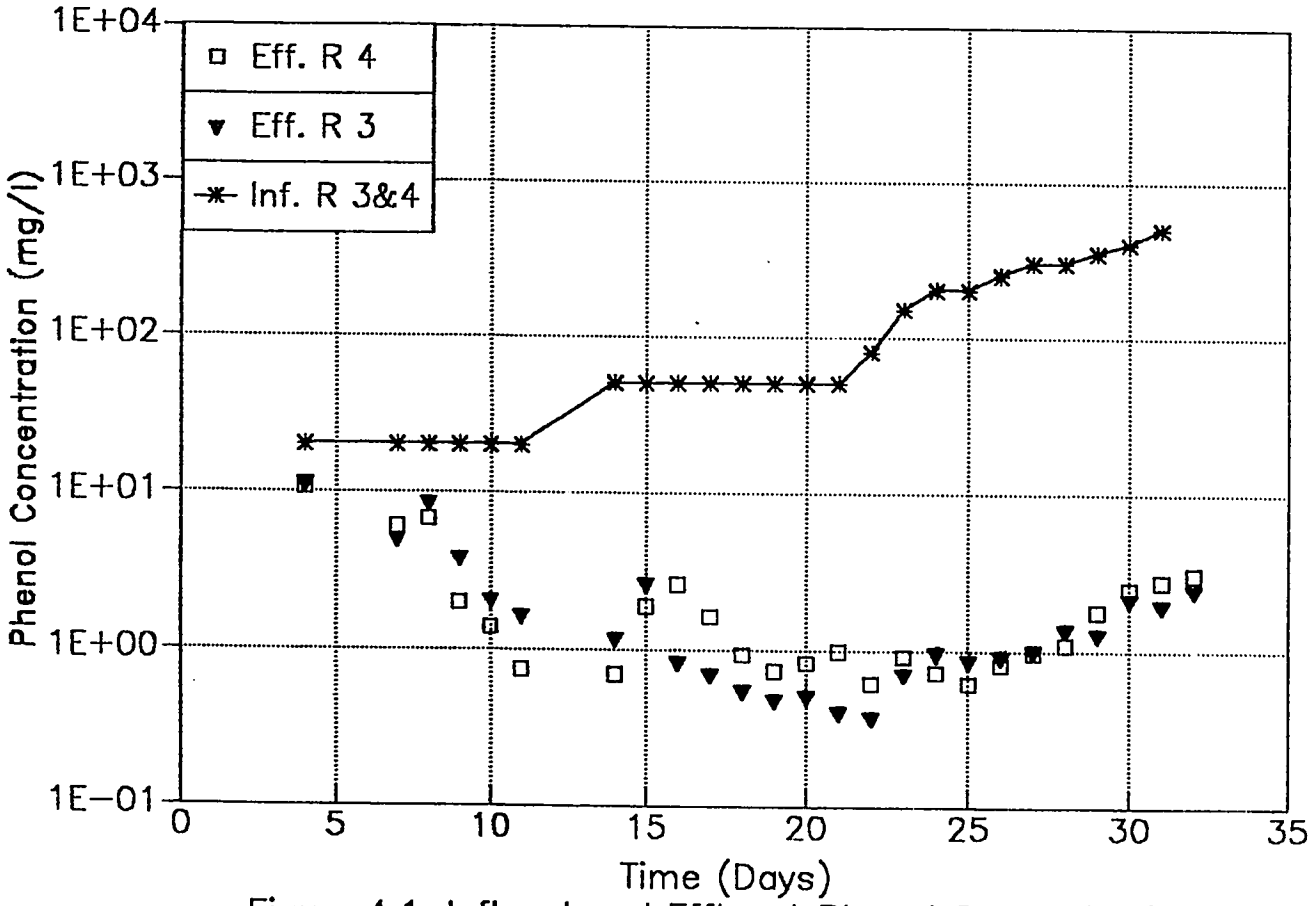


Figure 4.1: Influent and Effluent Phenol Concentrations (Reactors 3 and 4)

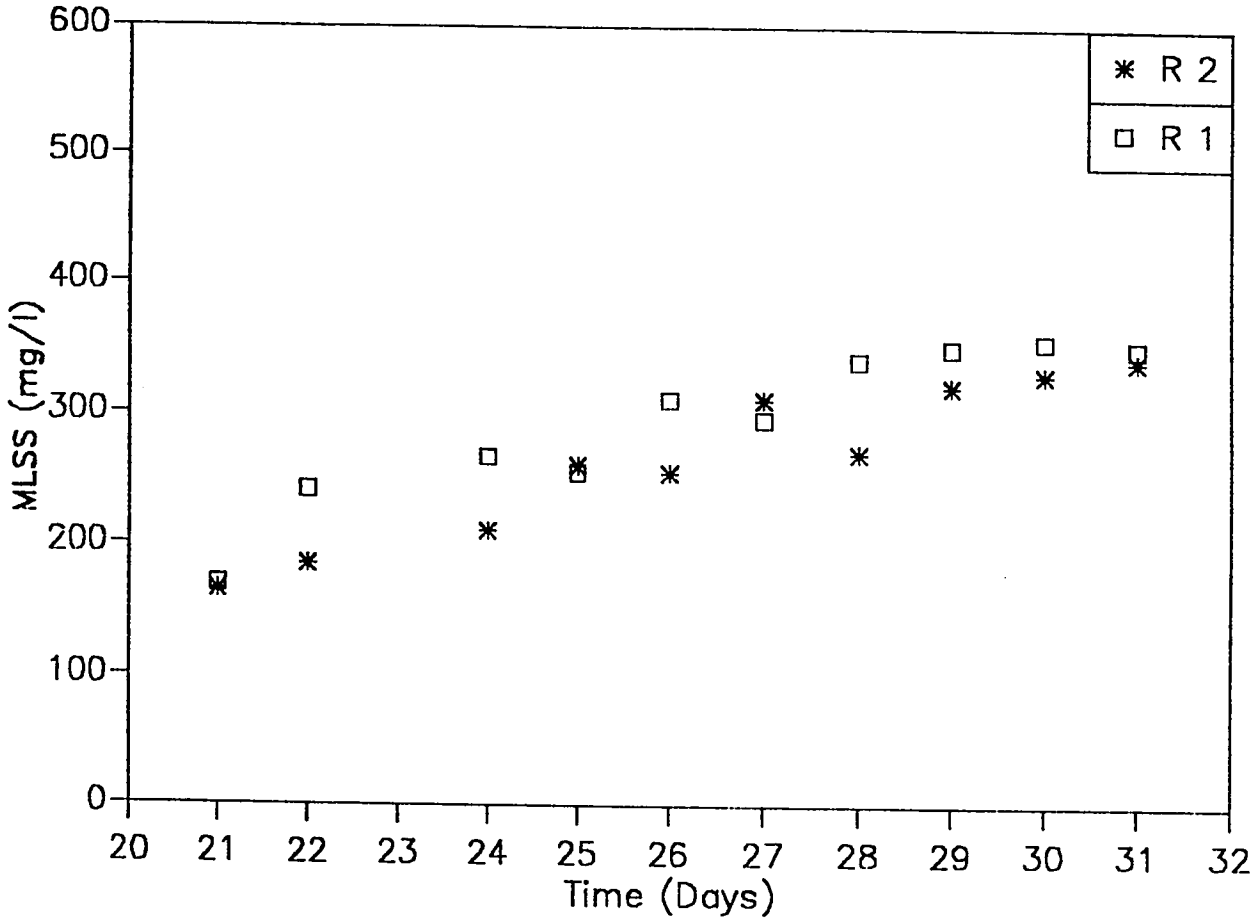


Figure 4.2: Concentration of MLSS in Reactors 1 and 2

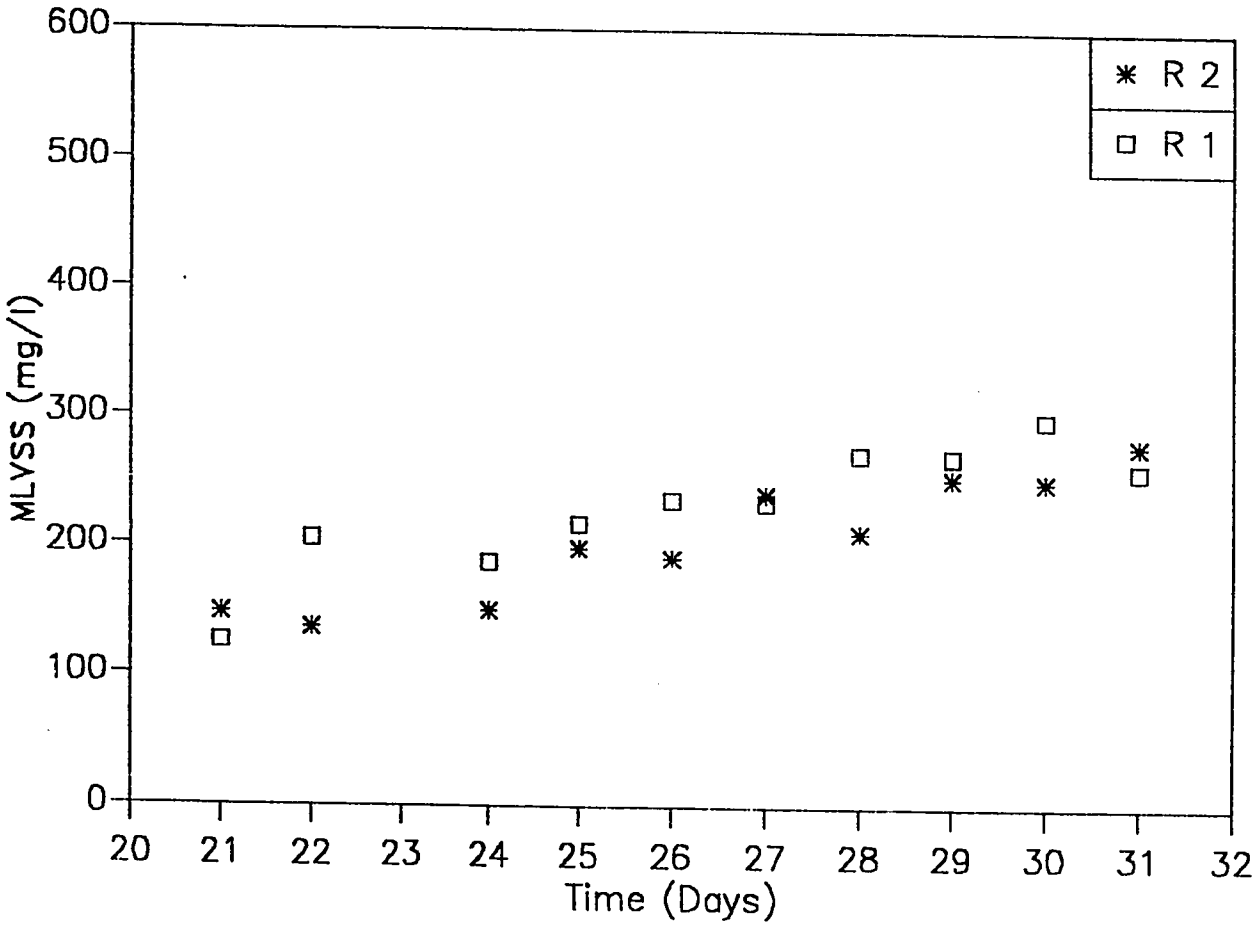


Figure 4.3: Concentration of MLVSS in Reactors 1 and 2

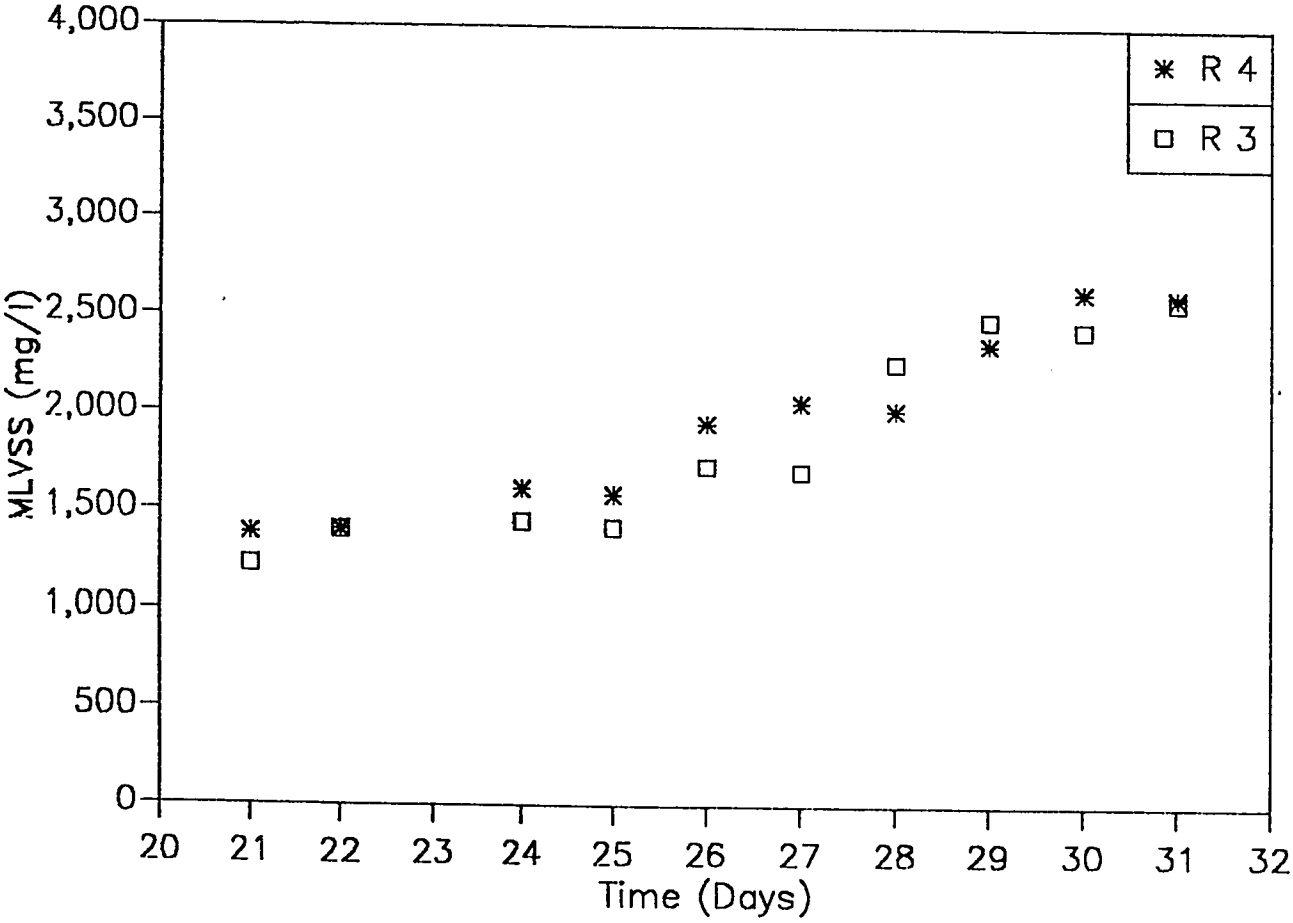


Figure 4.4: Concentration of MLSS in Reactors 3 and 4

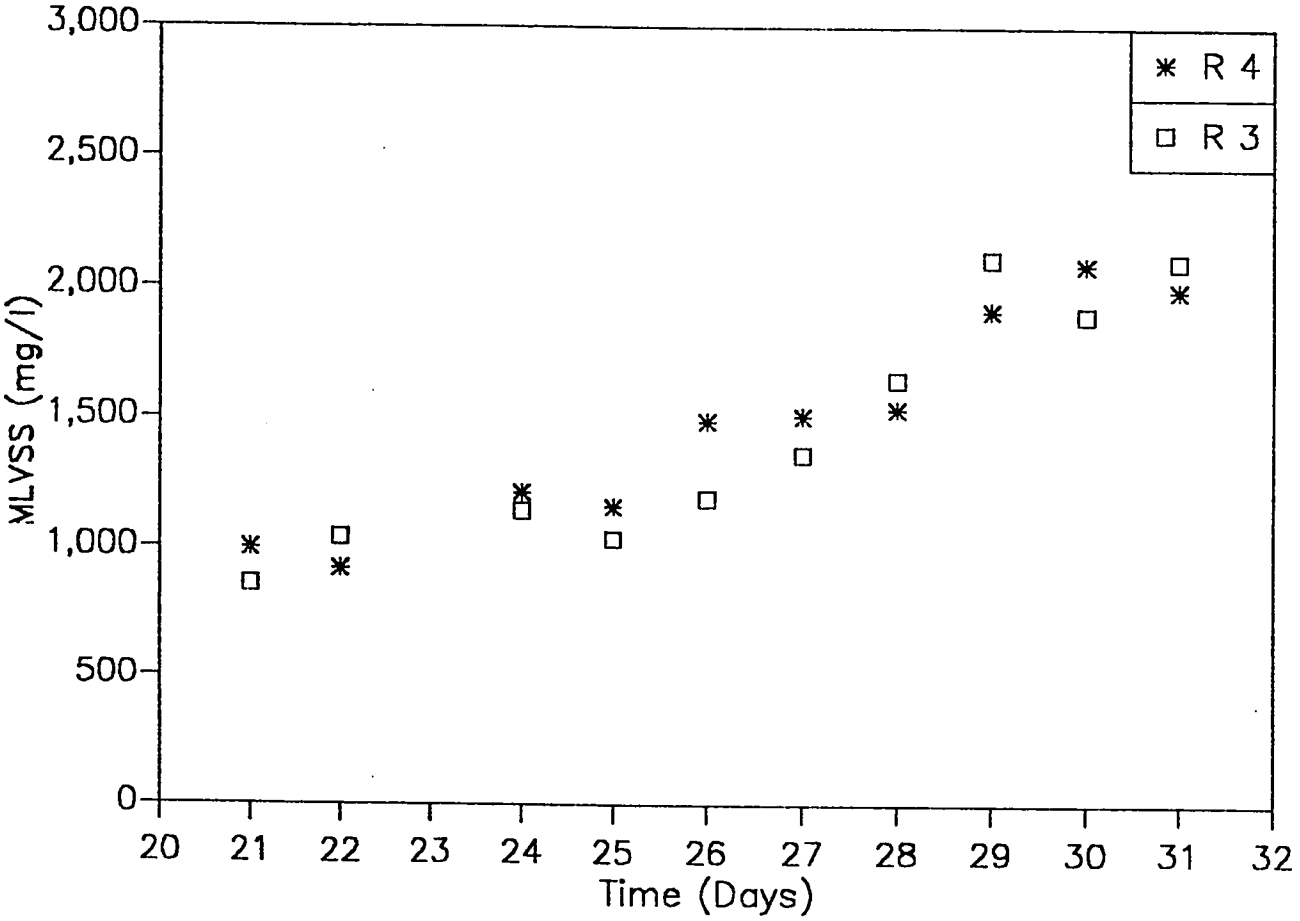


Figure 4.5: Concentration of MLVSS in Reactors 3 and 4

were started with raw sewage only. By the end of the experiment, the MLSS and MLVSS reached 2600 mg/l and 2000 mg/l respectively. In the case of reactors (1) and (2) which were treating raw sewage only, the maximum MLSS and MLVSS observed was 350 and 260 respectively (Figures 4.2 and 4.3). It can be inferred from these Figures that the higher MLSS and MLVSS in the reactors (3) and (4) is due to the addition of phenol which was consumed as a growth substrate by phenolic bacteria.

Regarding the identification of predominant species of microorganisms involved in the phenol degradation, Pseudosel Agar, special for the growth of *Pseudomonas aeruginosa* bacteria was used. *P. aeruginosa* species is reported elsewhere to be able to biodegrade phenolic compounds (Yang and Humphrey, 1975). It was also of interest also to estimate the relative concentration of *P. aeruginosa*, using pour plate method. A small volume of samples were taken from the four bench-scale reactors for bacteriological analysis. Samples were diluted with peptone water and 1, 0.1, and 0.01 ml volumes of the diluted samples were taken and placed in petri dishes mixing thoroughly with the agar medium. After solidification, the agar plates prepared in duplicates were incubated at 41.5 ± 0.5 C° for 72 hours. At the end of the incubation period P. aeruginosa colonies, which were characterized by deep brown centre and lighter borders, were counted. The number of colonies counted were multiplied by the respective dilution factors based on the unit volume of the original

sample. This analysis was continued for five days to check the consistency of the results. The results are given in Table 4.2.

Table 4.2: Distribution of P. aeruginosa (No. of Colonies/ml)

Date	Reactor			
	1	2	3	4
28/11/92	7	8	400	1900
29/11/92	2	1	100	300
30/11/92	2	1	300	100
1/12/92	1	1	600	300
2/12/92	2	1	300	300

It is clear from the above table that the P. aeruginosa distribution is higher in those phenolic reactors (3) and (4) compared with reactors (1) and (2) which were fed with raw sewage only. It can be inferred that P. aeruginosa was the predominant microbial species which was responsible for biological treatment of the phenolic waste in this experiment. Therefore, the main objective of the experiment was achieved and subsequently the assumption of single species inherent in the modelling effort was validated to a large extent.

Chapter 5

RESULTS AND DISCUSSION

5.1 Introduction

An integrated model has been developed for the SBR system, which accounts for fill, react, and settle periods. Therefore, by changing initial conditions and kinetic parameters, one can study the behavior of SBR system using this model. This model may also be used to assess the effect of changes in operating conditions or variations of the characteristics of the influent wastewater. Furthermore, while most of the previous models considered a steady state condition, the present model deals with unsteady state SBR operation. The governing system of nonlinear ordinary differential equations have been solved numerically. In the following subsections, a detailed discussion about the model validation, comparison with experimental data, and sensitivity analysis is given.

5.2 Model Validation

After the computer implementation of the numerical scheme, several runs were made using typical kinetic coefficients to study the general performance of the model and its agreement with the kinetic theories. Values of μ_{max} = 3.0 day^{-1}, K_s = 25.0 mg/l, Y = 0.65 mg

MLVSS/mg BOD, and K_d = 0.10 day^{-1}, were used, additionally hydraulic retention time (HRT) and solids residence time (SRT) were set at 1.1 and 14 days respectively. For fill and react periods, each case was initially examined separately and before the integrated model was tested.

5.2.1 Fill Period

The temporal profile of BOD and MLVSS during fill period are influenced by the initial conditions of the system, i.e, feed concentration and waste feed rate, time of fill. Fill times of 2 and 4 hours were investigated; in each case several scenarios were studied. Two levels of initial MLVSS were adopted, a MLVSS of 10 mg/l (to simulate conditions during start-up) and MLVSS of 5000 mg/l (to represent operating conditions), and two feed concentrations of 450 and 800 mg/l were employed. Figure 5.1 shows the theoretical profiles of BOD and MLVSS for an influent BOD concentration of 450 mg/l during 2 hour fill period. It is apparent from Figure 5.1 that for a low initial MLVSS, the BOD concentration at the end of the fill period approaches the influent concentration while the MLVSS continues to grow steadily. Meanwhile with a high initial MLVSS the reactor BOD concentration never exceeds 200 mg/l or 44% of the feed indicating substantial utilization by the reactor biosolids while the MLVSS decreases rapidly initially due to dilution and stabilizes thereafter.

The same trends are depicted in Figure 5.2 for a feed concentra-

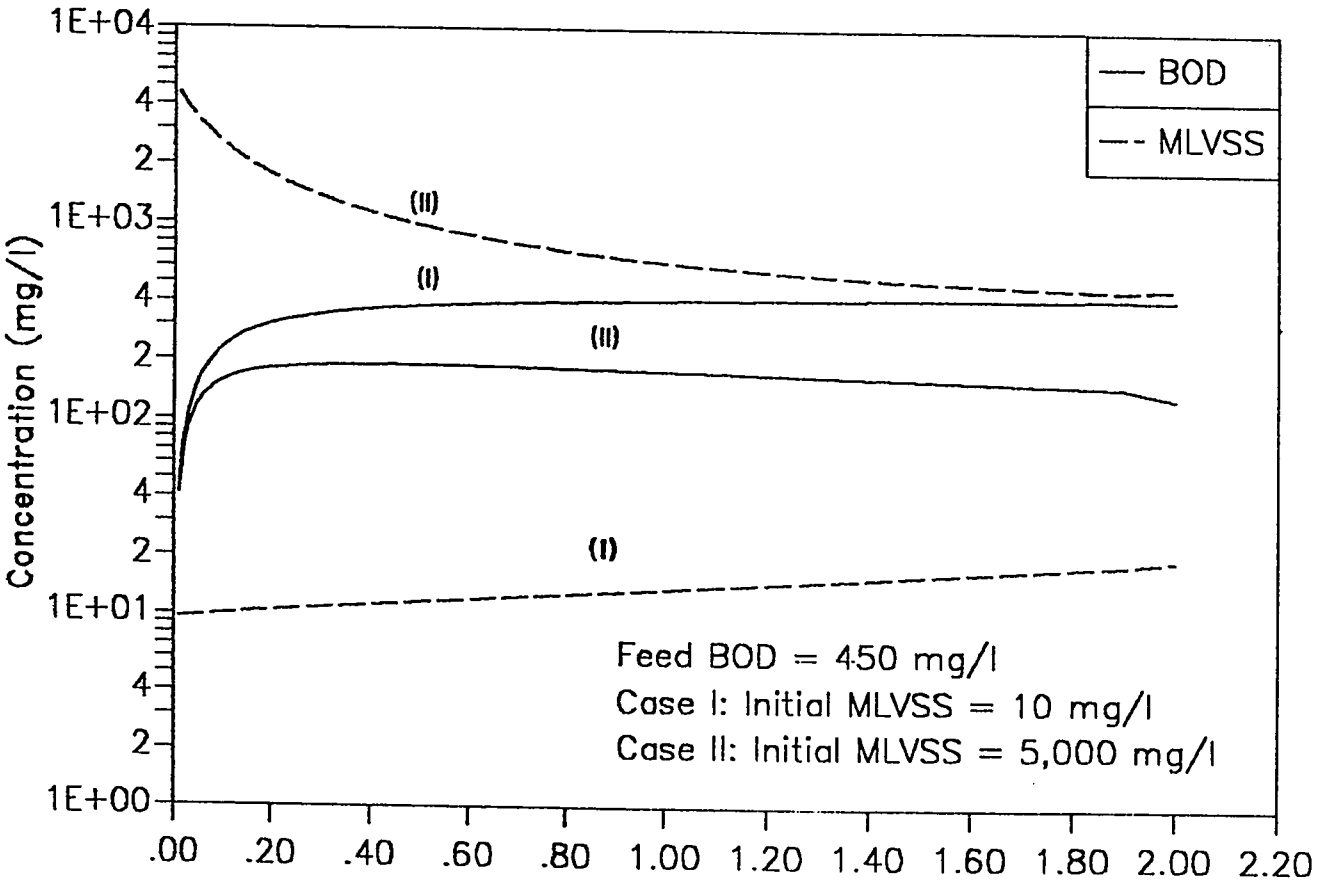


Figure 5.1: Hypothetical BOD and MLVSS Profiles During a 2-hr Fill Period

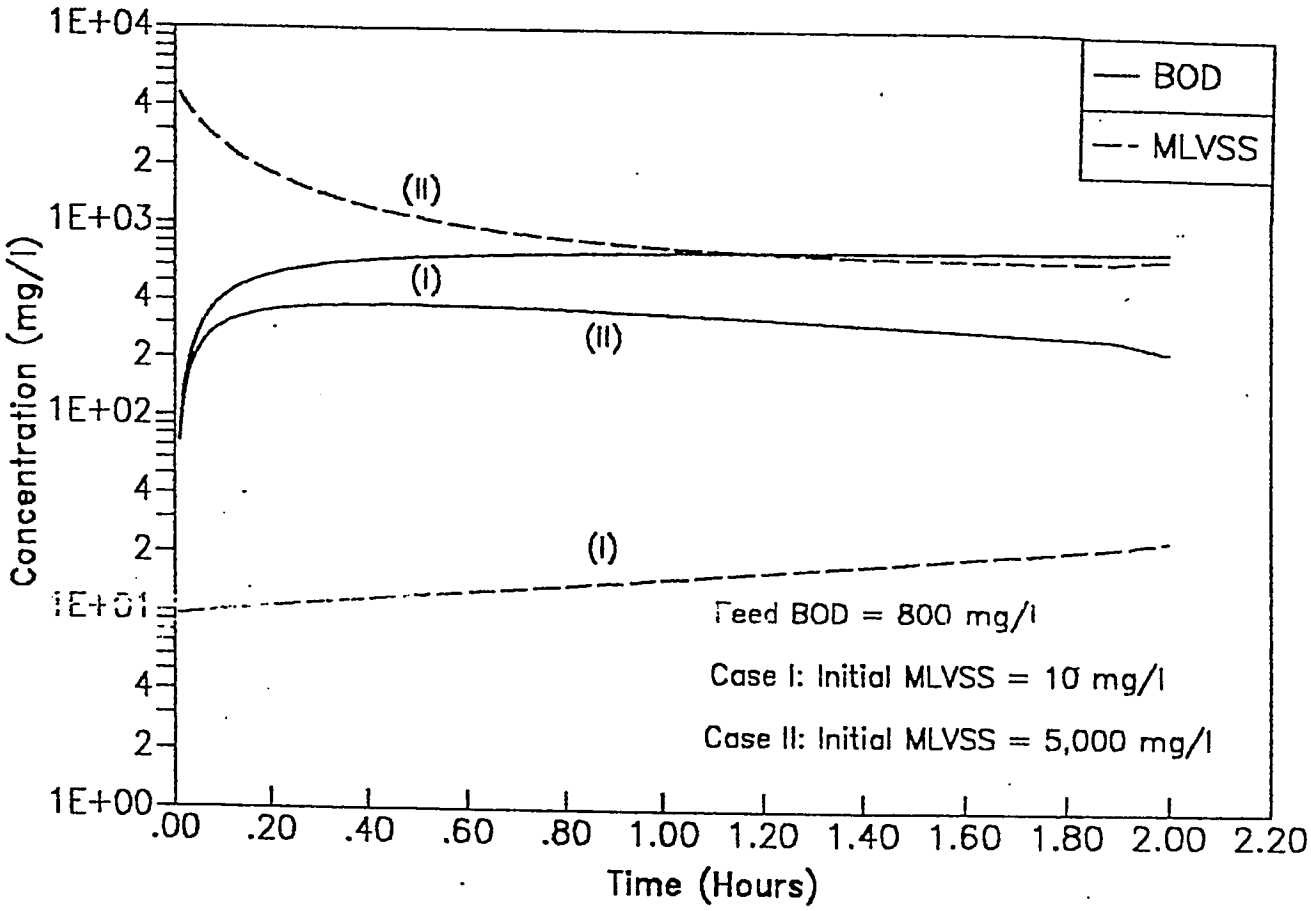


Figure 5.2 Hypothetical BOD and MLVSS Profiles During a 2-hr Fill Period

tion of 800 mg/l BOD. For an initial MLVSS of 5000 mg/l, although the rate of increase of BOD concentration is faster for the higher influent concentration and the maximum concentration reached during fill is relatively higher i.e, about 47% of the 800 mg/l feed concentration versus 44% of the 450 mg/l the specific rate of substrate utilization increased with the increase in feed concentration. This is consistent with the microbial growth rate-substrate concentration relationship described by the Monod model. For the same biomass concentrations, provided no inhibition occurs, higher feed concentration results in more rapid substrate utilization.

The hypothetical BOD and MLVSS profiles for a 4-hour fill period are depicted for a feed BOD concentrations of 450 mg/l and 800 mg/l in Figures 5.3 and 5.4 respectively. It is apparent from Figure 5.3 that the rate of biomass growth increases rapidly after the first two hours while the BOD increases steadily initially to reach a maximum concentration of 410 (90% of the feed) and declines thereafter. On comparing these trends with those illustrated in Figure 5.1 for a 2-hour fill, the extended fill period is definitely advantageous during start-up, as it results in higher MLVSS and relatively lower BOD concentrations. Similar trends are predicted for the higher feed concentration. This may have profound implications in the treatment of high-strength toxic wastes since conditions at the beginning of the subsequent react period would favor biological degradation and mitigate inhibition effects, and thereby significantly accelerate the acclimatization phase. During regular operation, the MLVSS during fill

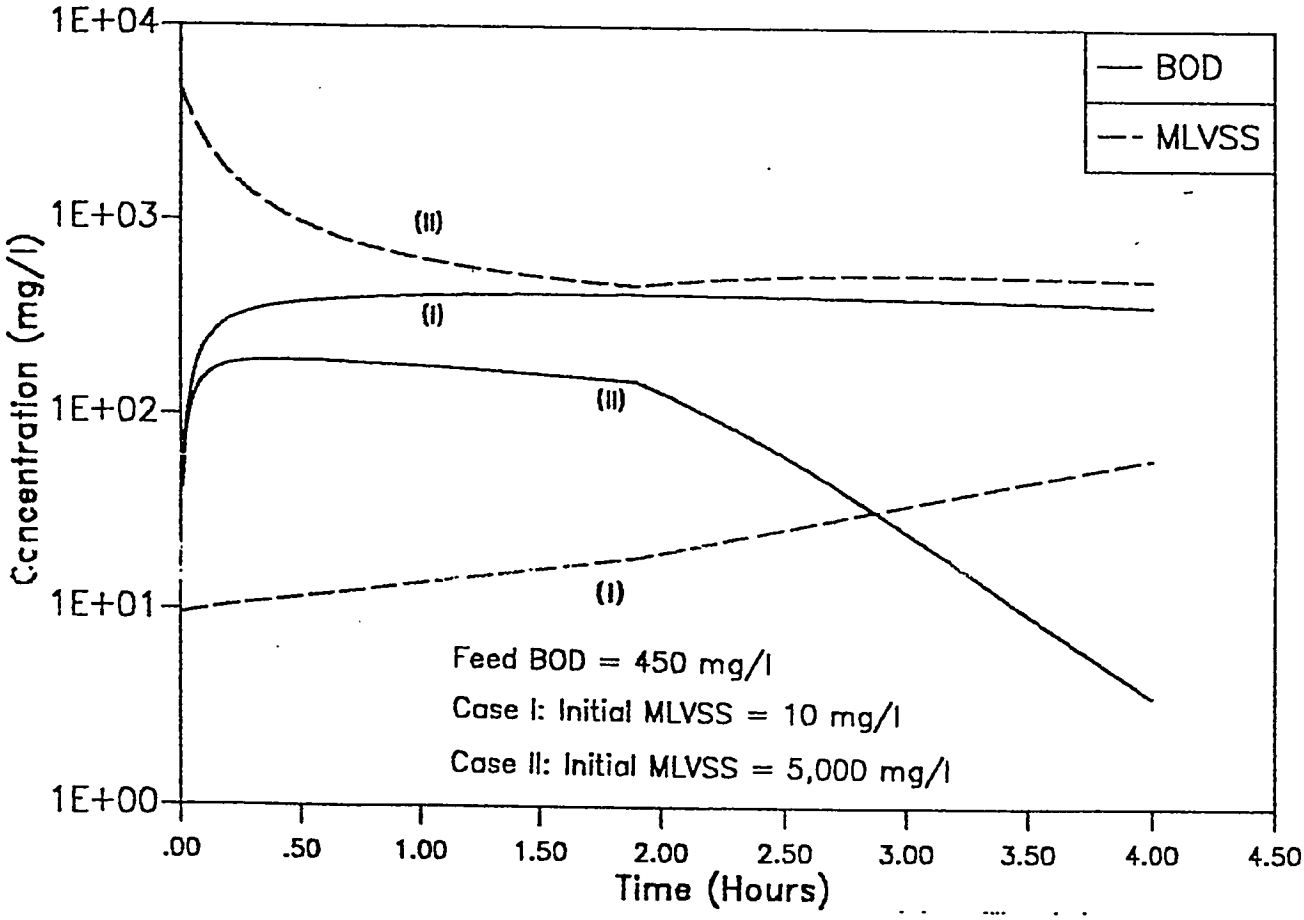


Figure 5.3 Hypothetical BOD and MLVSS Profiles During a 4-hr Fill Period

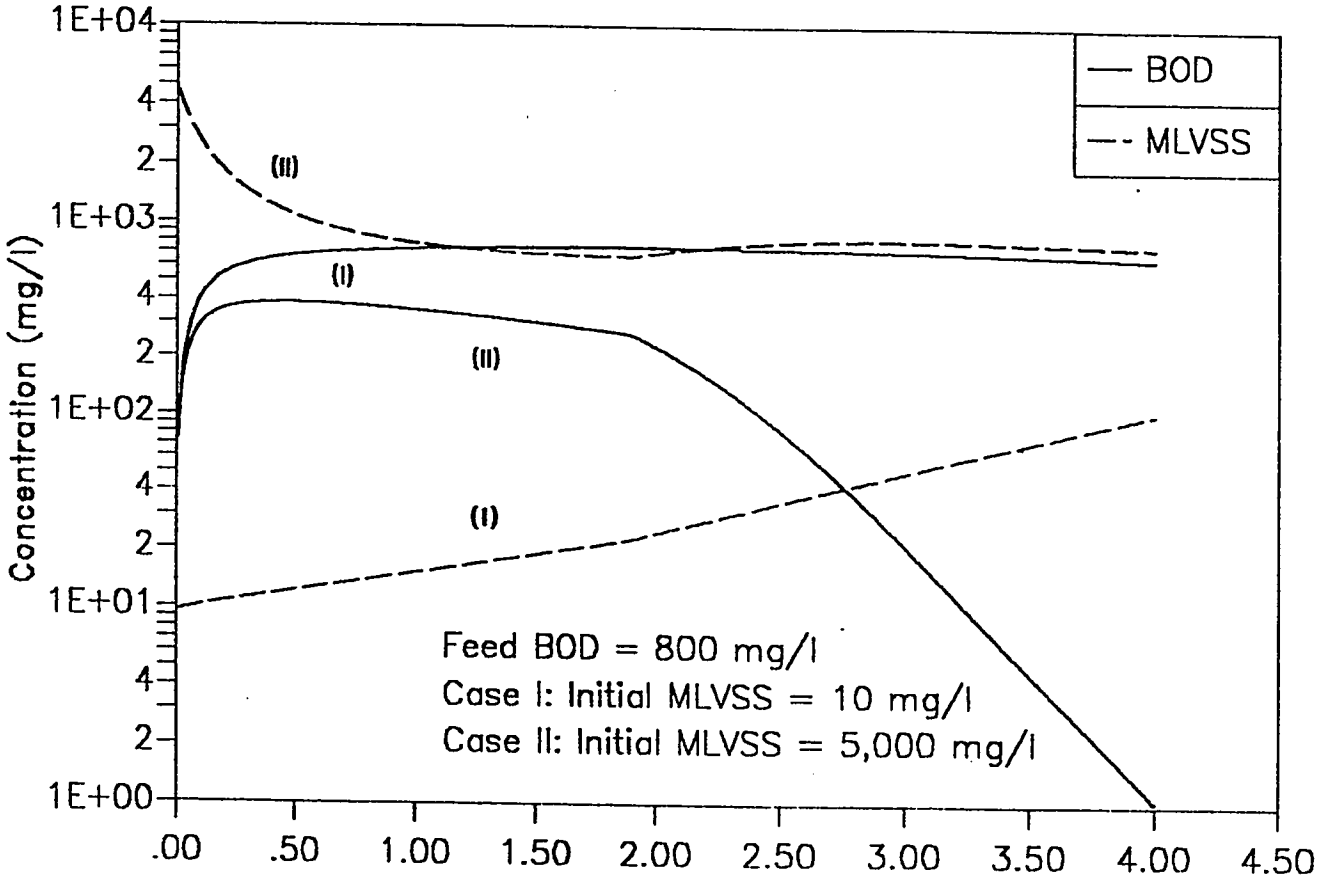


Figure 5.4: Hypothetical BOD and MLVSS Profiles During a 4–hr Fill Period

decreases rapidly initially due to dilution by the incoming waste, stabilizes for some time and subsequently increases while the BOD profile, traces the opposite curve. Initially the reactor MLVSS and BOD concentrations are governed by the feed rate and the substrate utilization rate is limited by the availability of food and thus dilution effects dominate. As the BOD concentration increases, the overall rate of microbial growth and substrate utilization increases until it exceeds the feed rate resulting in a drop of BOD and steady rise in MLVSS concentration. The identical rate of MLVSS decrease in the first half-hour for the two feed concentrations presented in Figures 5.3 and 5.4 substantiates the aforementioned dilution effects and reflects their independence of feed concentration. On the other hand, the rate of simultaneous biomass increase and BOD decline after two hours that is strongly related to feed concentration with pronounced differences between the two concentrations confirms the predominance of microbial growth effects over dilution effects. Thus it must be asserted that the reactor conditions towards the end of an extended fill period closely resemble those prevailing during the react phase.

Literature data from SBR systems are compared with the model predictions during fill period to test its validity. Data form Dennis and Irvine (1979), who investigated the effect of fill:react ratio on the SBR systems was selected to test for the fill period (Figures 5.5, and 5.6). The initial conditions reported by the authors were used and the kinetic coefficients were selected from Table 3.1 based on waste type. As apparent from Figures 5.5, 5.6 the model predictions

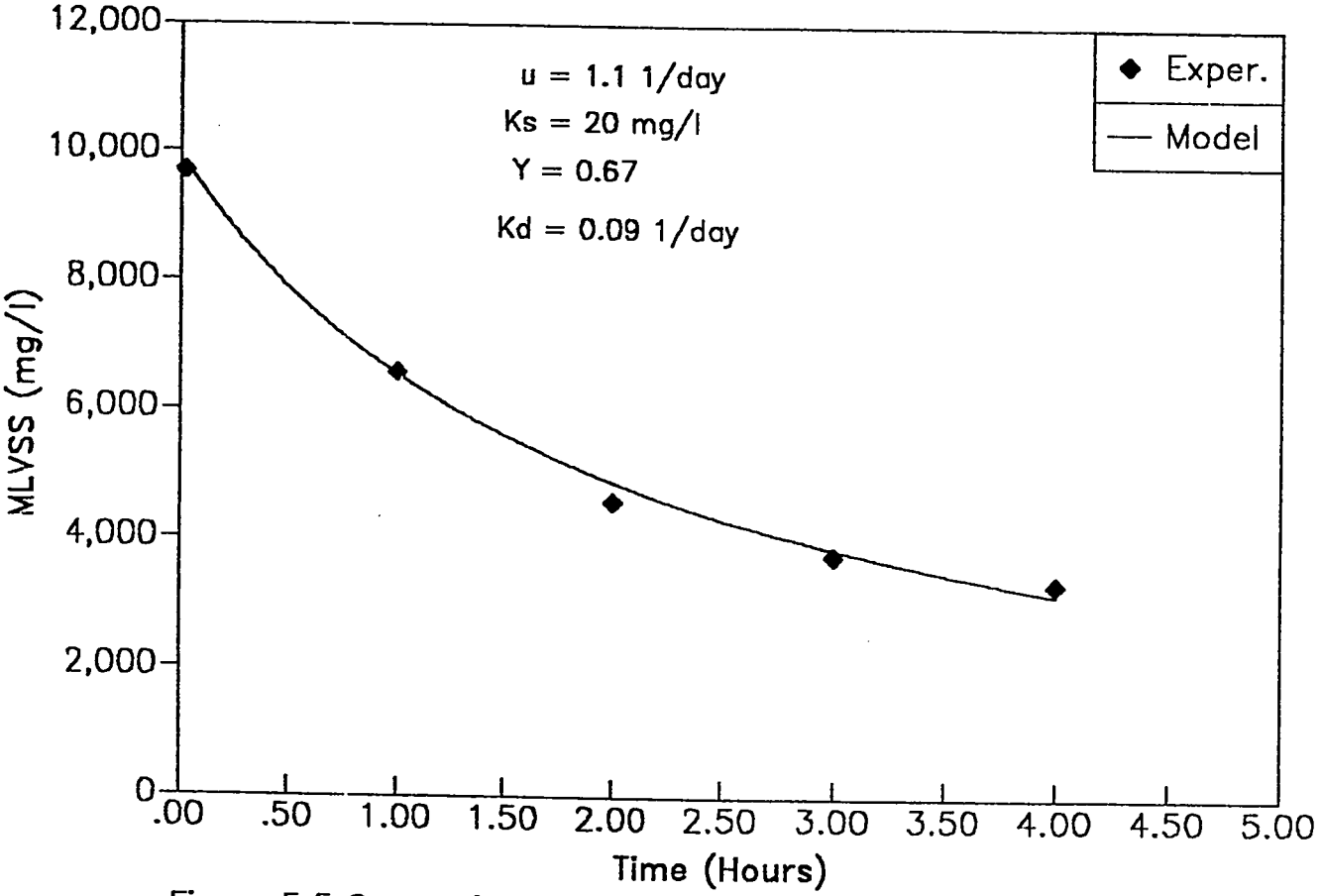


Figure 5.5 Comparison of Model Predictions and Experimental Data (Dennis and Irvine, 1979)

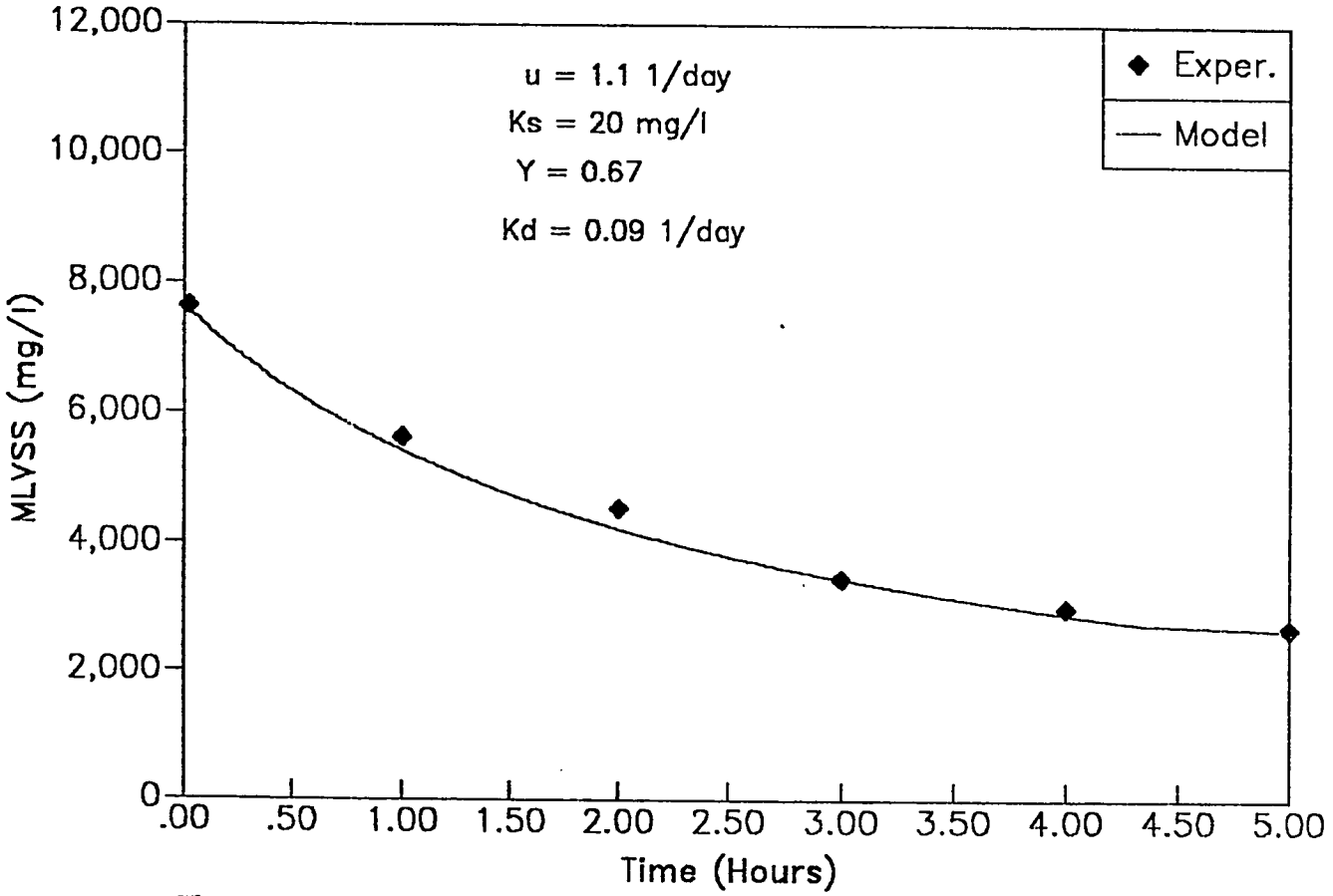


Figure 5.6 Comparison of Model Predictions and Experimental Data (Dennis and Irvine, 1979)

compared well with the experimental data for the two cases i.e. the 4-hour and 5-hour fill periods. Goodness of fit analysis using χ^2 test indicated that the predictions in Figures 5.5 and 5.6 match the experimental data at confidence levels of 95%. This confirms the validity of the equations (3.2),(3.5), (3.8), and the numerical solution adopted.

5.2.2 React Period

Simulations of the BOD and MLVSS profiles during the react period are illustrated in Figures 5.7 (initial BOD concentration of 450 mg/l) and 5.8 (initial BOD concentration of 800 mg/l). For each concentration, two levels of MLVSS were adopted, namely 10 mg/l to represent the acclimatization phase and 1500 mg/l to simulate operational conditions. It appears that during start-up (case I), characterized by low MLVSS, no marked differences in the trends followed by the reactors BOD and MLVSS concentrations existed between the various feed concentrations. While the magnitudes of the maximum MLVSS concentrations achieved, varied from one case to the other, the peak concentrations almost occurred simultaneously at approximately 2.5 hours. The BOD utilization rate was initially slow due to the biomass limitations but increased steadily with biomass growth before eventually declining due to substrate limitations. This is further substantiated by examining the BOD profile for an initial MLVSS of 1500 mg/l (case II) which lacks the initial phase of low substrate utilization rate due to biomass limitation. It is thus apparent that in

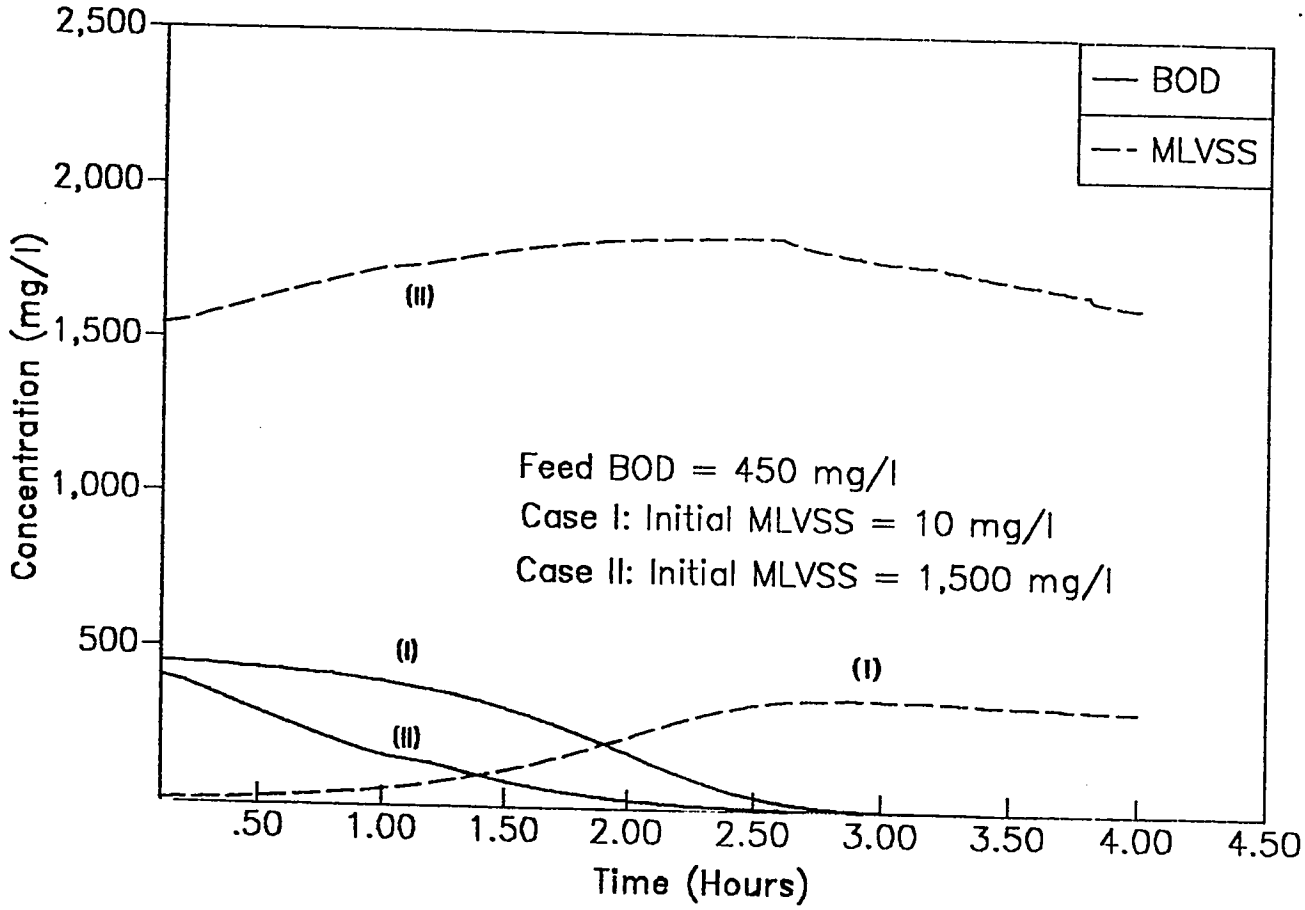


Figure 5.7: Hypothetical BOD and MLVSS Profiles During the React Period

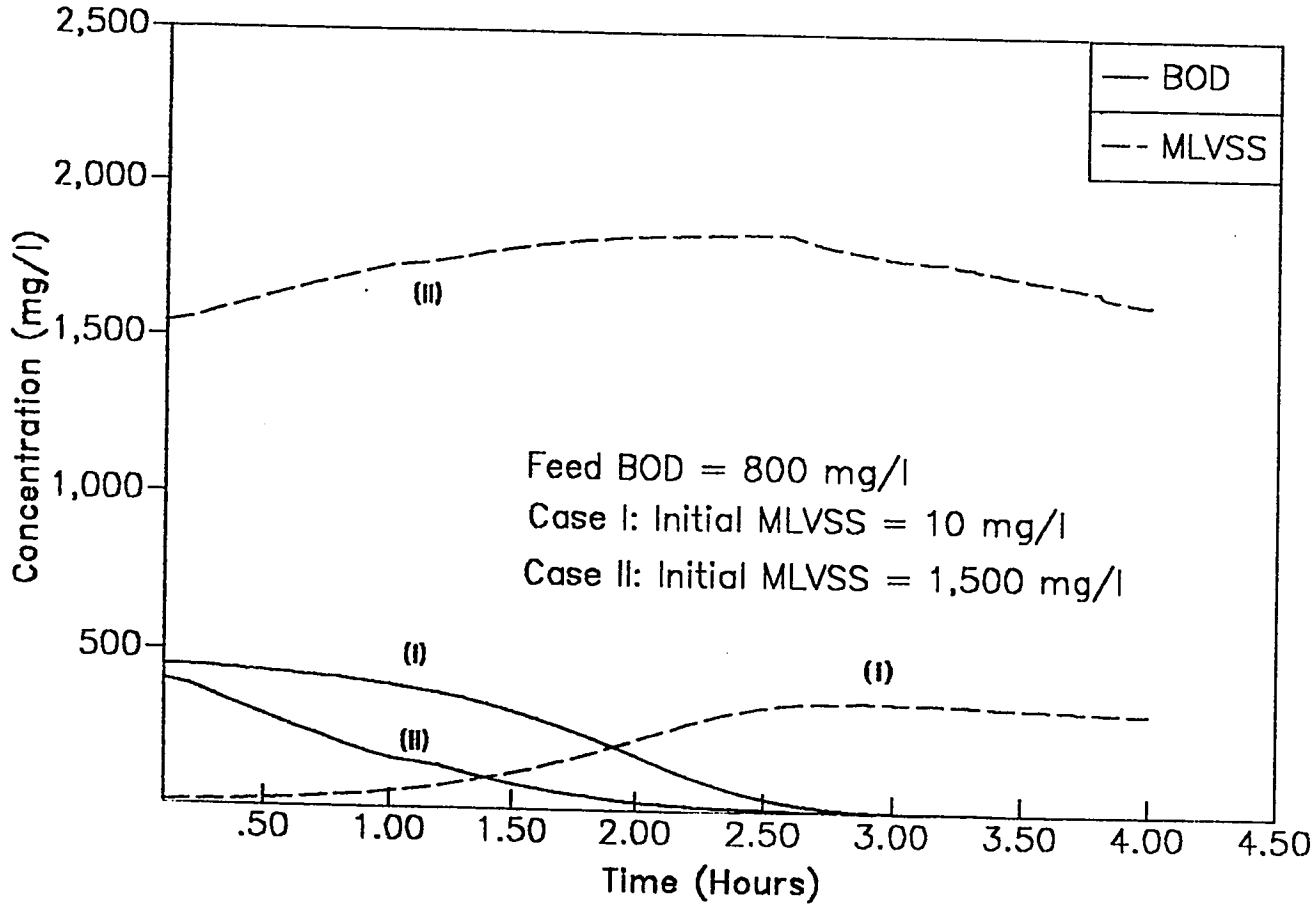


Figure 5.8: Hypothetical BOD and MLVSS Profiles During the React Period

the react period during which the reactor behaves like a closed batch system, the BOD and MLVSS profiles are consistent with the kinetic theories of substrate utilization. The simulations presented in Figures 5.7 and 5.8 clearly point to an optimum react time beyond which not only no appreciable substrate removal is accomplished but also loss of active biosolids by decay is dominant. It is clear form these Figures, that significant removal can be achieved during the fill period and the choice between an extended fill followed by a shortened react period on one hand and a shorter fill followed by an extended react period on the other hand depends on the waste strength. For low strength readily biodegradable wastes there is no advantage to using an extended fill. However, for high strength biodegradable wastes and toxic wastes an extended fill safeguards against organic overloading and toxicity.

Experimental data presented by Al-Harazin (1992) was used to compare model predictions during react period. Al- Harazin (1992) treated biologically a hazardous wastewater using SBR. As it can be seen from Figure 5.9, the model predictions agreed well with the experimental data. Another set of experimental data from Brenner et al. (1992), who investigated the biological treatment of a mixture of phenolic compounds typically found in coal conversion wastes, also was used for model validation, particularly the react period. The experimental data along with the model predictions are depicted in Figure 5.10 The close agreement between the model predictions and experimental observations in the first 90 minutes of the test time is

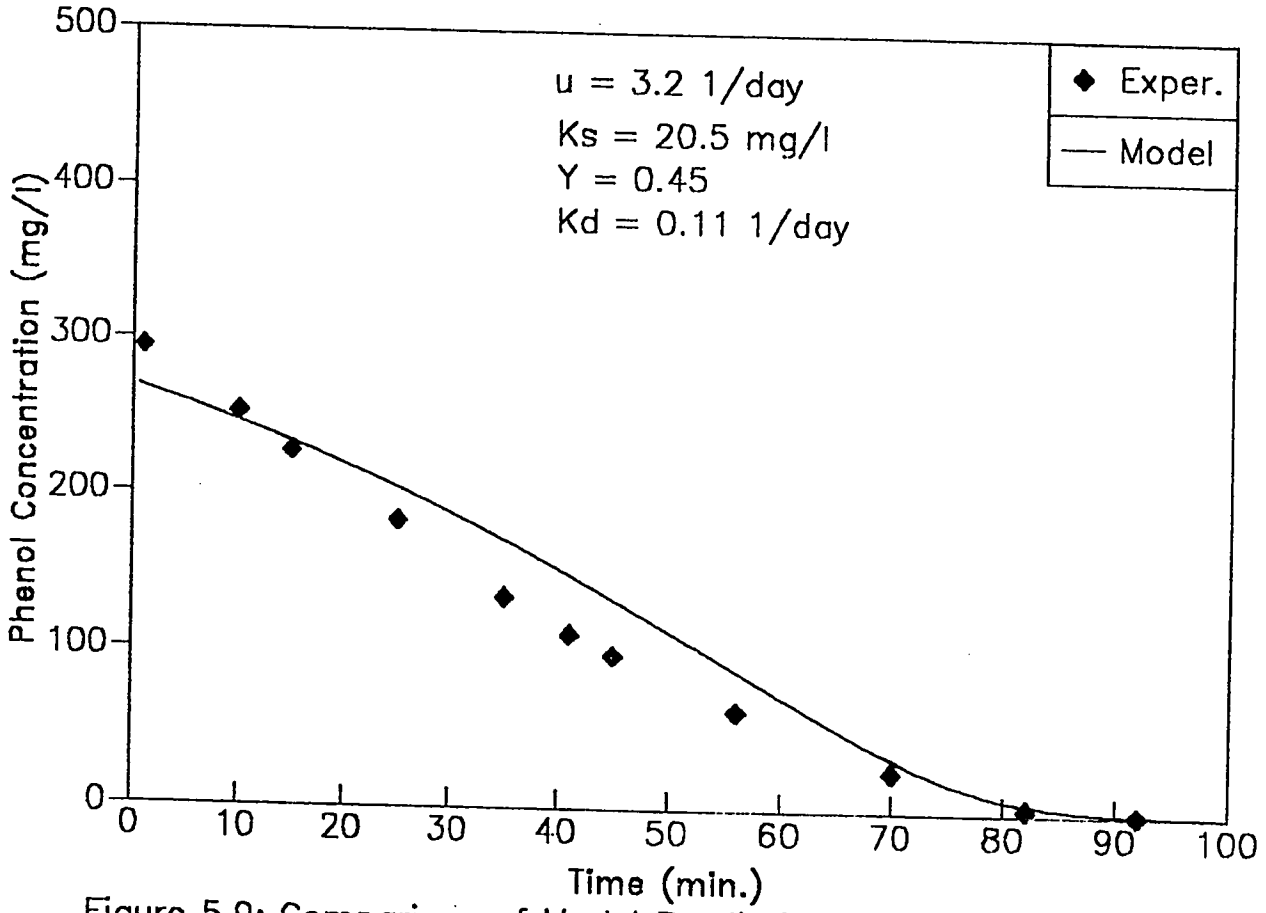


Figure 5.9: Comparison of Model Predictions and Experimental Data (Al–Harazin, 1992)

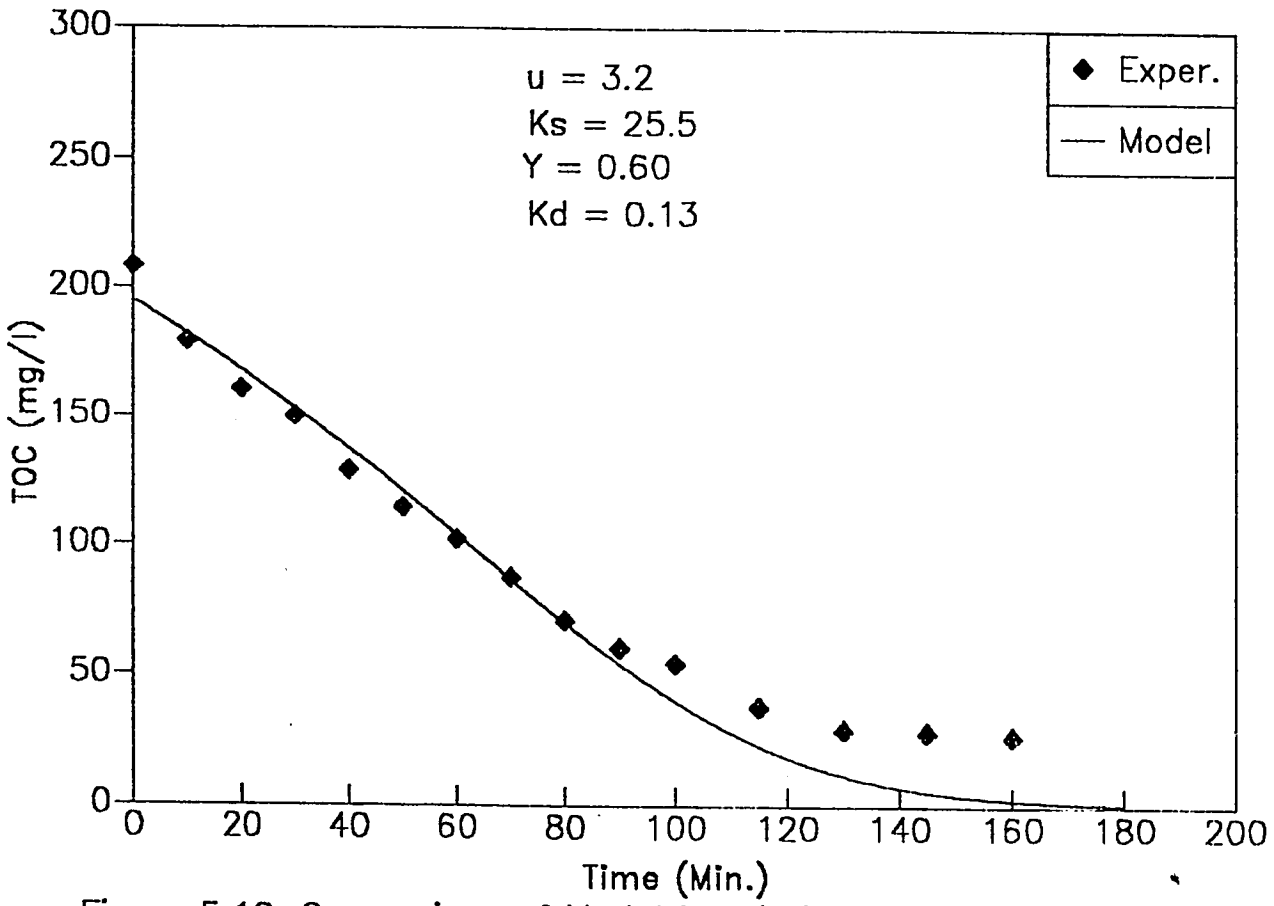


Figure 5.10: Comparison of Model Predictions and Experimental Data (Brenner et al., 1992)

noteworthy. In both cases (Figures 5.9 and 5.10) the model predictions agreed with the data at a confidence level of 95% according the χ^2 test analysis. However, in the case Figure 5.10 the model underpredicted the experimental results after the initial 90 minutes. This is due to the fact that the waste mixture contained slowly biodegradable compounds, and compounds that are preferentially utilized relative to others, typically known as diauxic growth phenomenon which is consistent with the findings of Brenner et al. (1992) and Rozich and Colvin (1986). The model, however, assumed all TOC present in the reactor to be biodegradable. Apart from this shortcoming, the validity of the governing equations for react period i.e. equations (3.11) and (3.12) is thus established.

5.2.3 Complete Cycle

After validation of fill and react periods individually, the integrated model incorporating the settling period in addition to the fill and react periods was tested. This is a more severe test of the model compared to the fill or react period separately, because all model equations with initial and boundary condition are solved simultaneously, and any errors in the model would tend to accumulate. The experimental data presented by Misbahuddin & Farooq (1991) was used for this purpose. These authors treated a low-strength petrochemical waste having a COD of 220 mg/l by the SBR process at HRT and SRT of 1.33 and 24 days respectively. The MLVSS and effluent TSS data during the acclimatization phase of their study is depicted

in Figures 5.11 and 5.12 respectively. It can be inferred that generally the model predicted the pattern of the experimental MLVSS data fairly accurately. The highest discrepancy between the model predictions and the measured MLVSS concentrations was about 23% of the predicted value and at most points discrepancies were less than 10% of the prediction. Considering the accuracy of measuring MLVSS and the difficulty of ascribing typical kinetic coefficients to a specific case, this level of prediction is outstanding. It is apparent from Figure 5.12 that the model grossly underestimated the effluent TSS data during the first week and matched the trend of the experimental data thereafter, despite the scatter. Thus when the MLVSS concentration is rapidly changing, the settling model fails to estimate the effluent TSS data but the model predictions fairly match the data when the MLVSS concentration stabilizes. A possible reason for the initial underprediction is that, rapid changes in MLVSS induce significant variability in the sludge settling characteristics that are not readily accounted for in the model.

Finally the response of the model to perturbations in the feed concentrations was tested against experimental data from Hsu (1986) who investigated the response of the SBRs applied for petrochemical wastewater treatment at HRT and SRT of 2.0 and 20 days respectively. Using the reported independently determined kinetic coefficients, the model predictions of the MLVSS and effluent BOD and TSS were compared to experimental data in Figures 5.13, 5.14 and 5.15 respectively. It is evident that the model predicted the

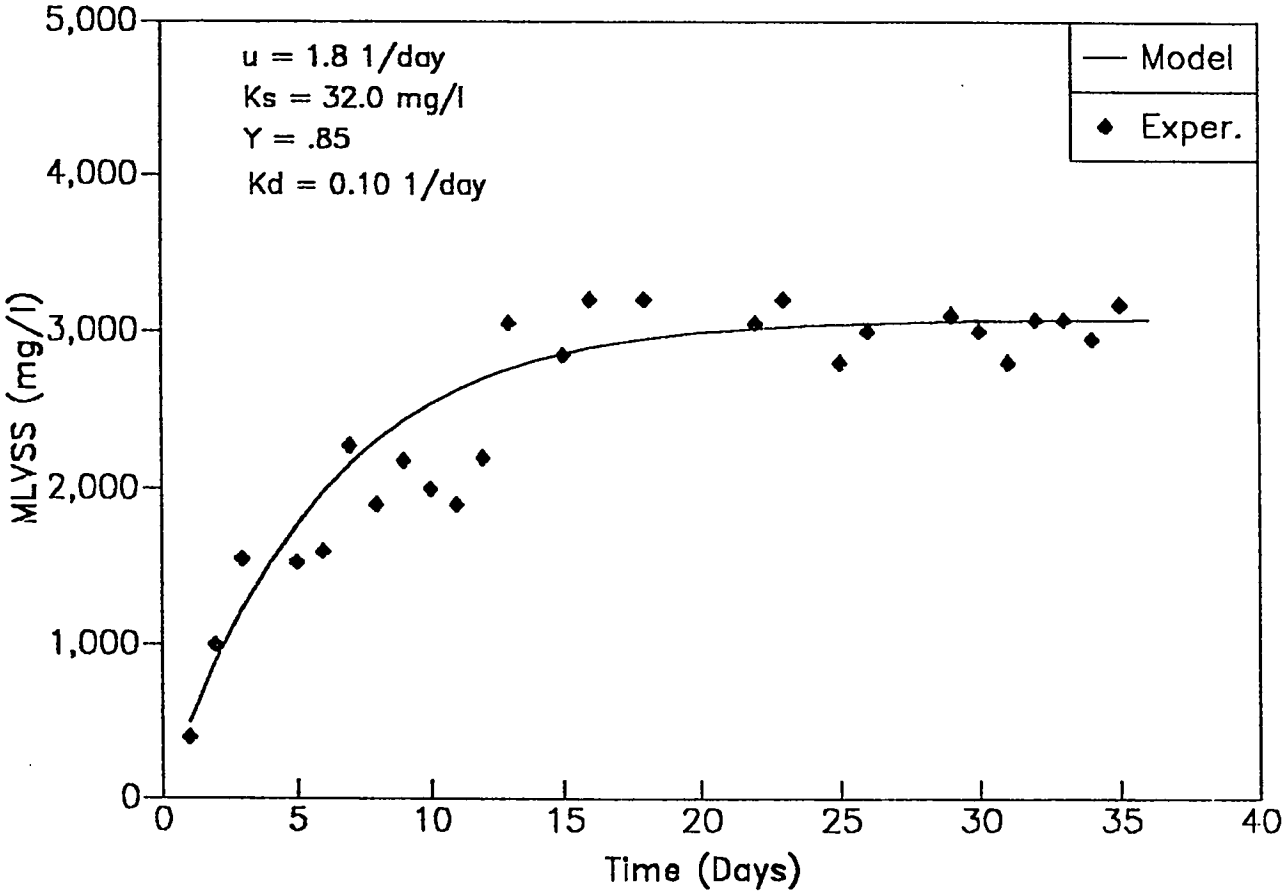


Figure 5.11: Temporal Variation of Model Predictions and Experimental Data (Misbahuddin and Farooq, 1992)

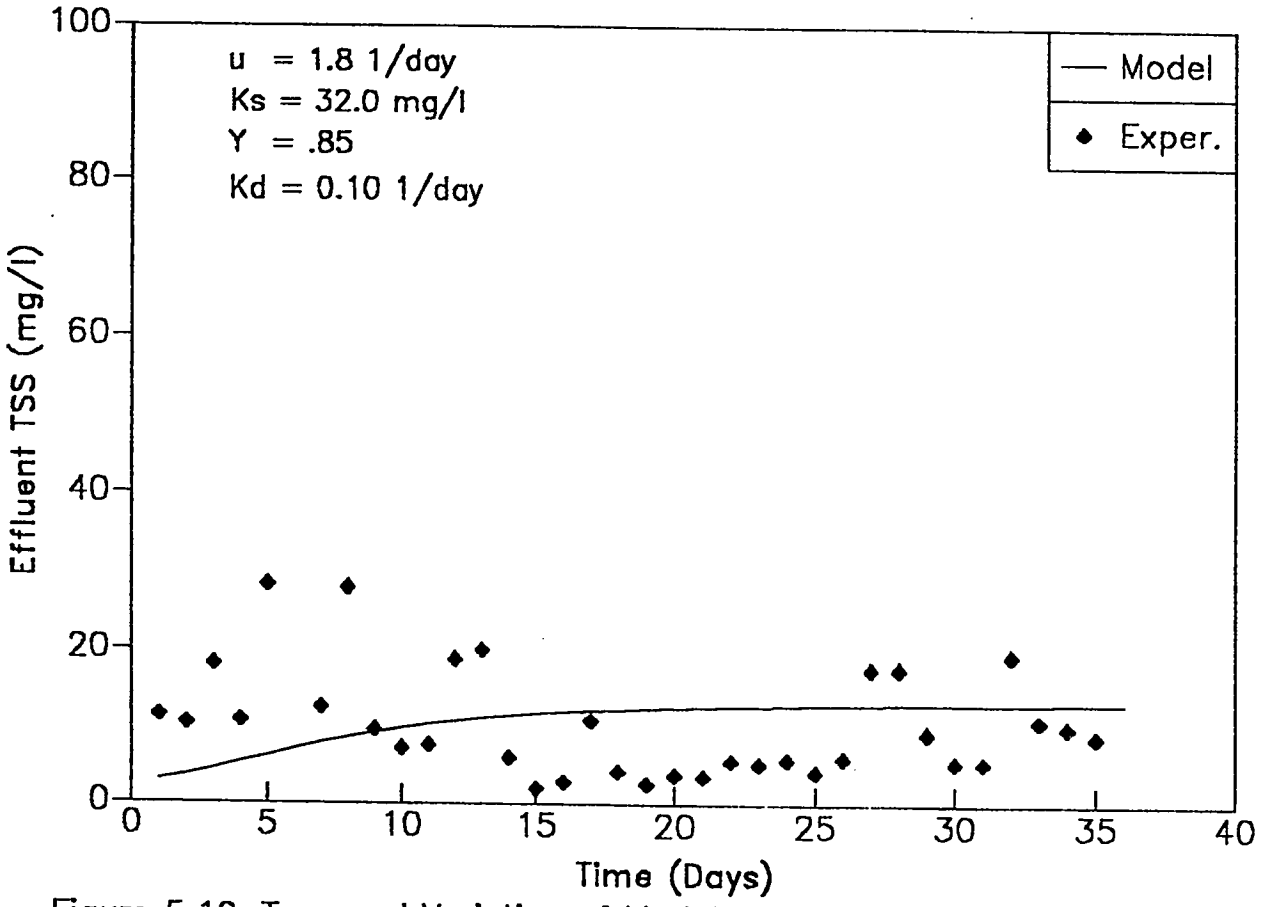
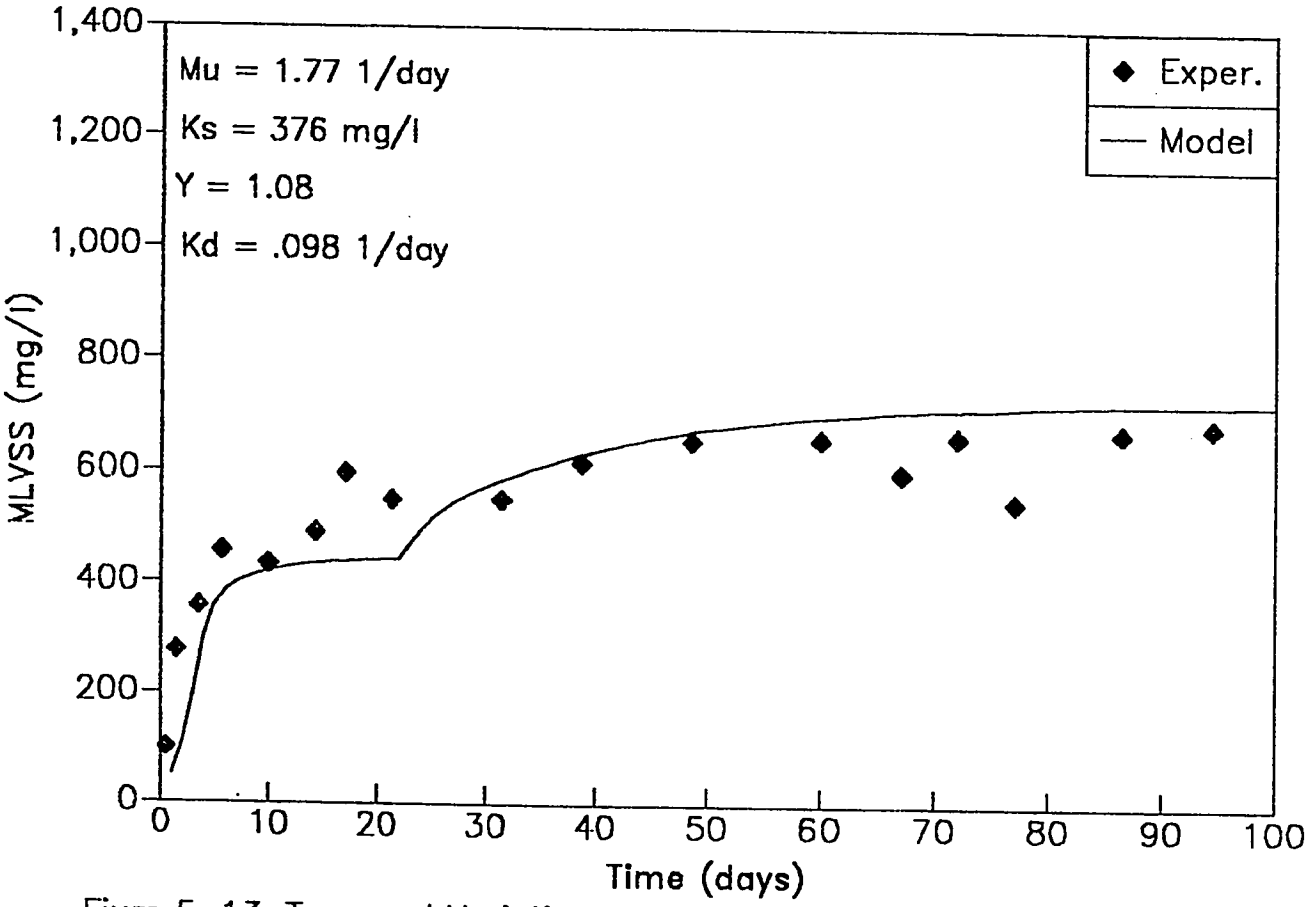


Figure 5.12: Temporal Variation of Model Predictions and Experimental Data (Misbahuddin and Farooq, 1992)



Fiure 5. 13: Temporal Variation of Model Predictions and Experimental Data (Hsu, 1986)

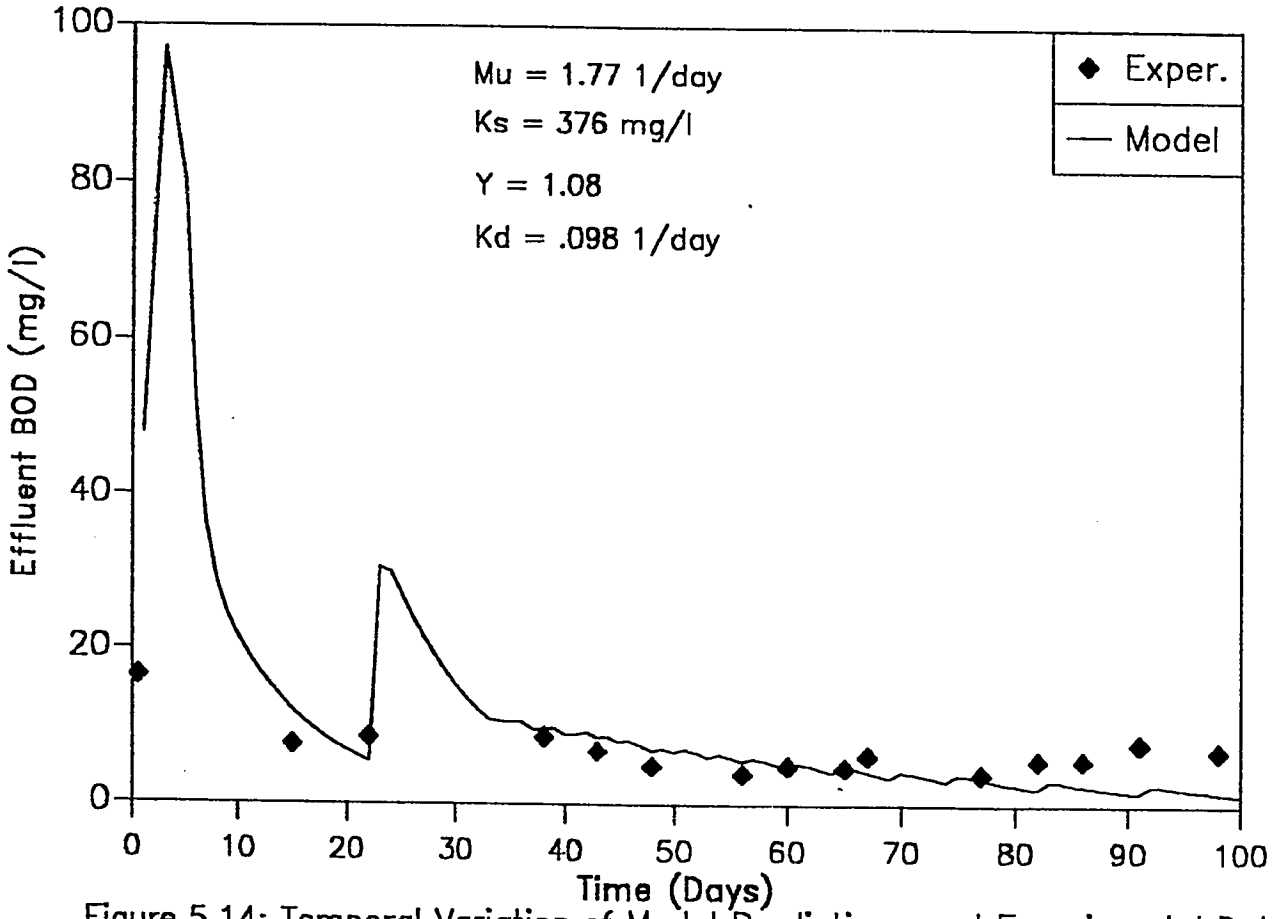


Figure 5.14: Temporal Variation of Model Predictions and Experimental Data (Hsu, 1986)

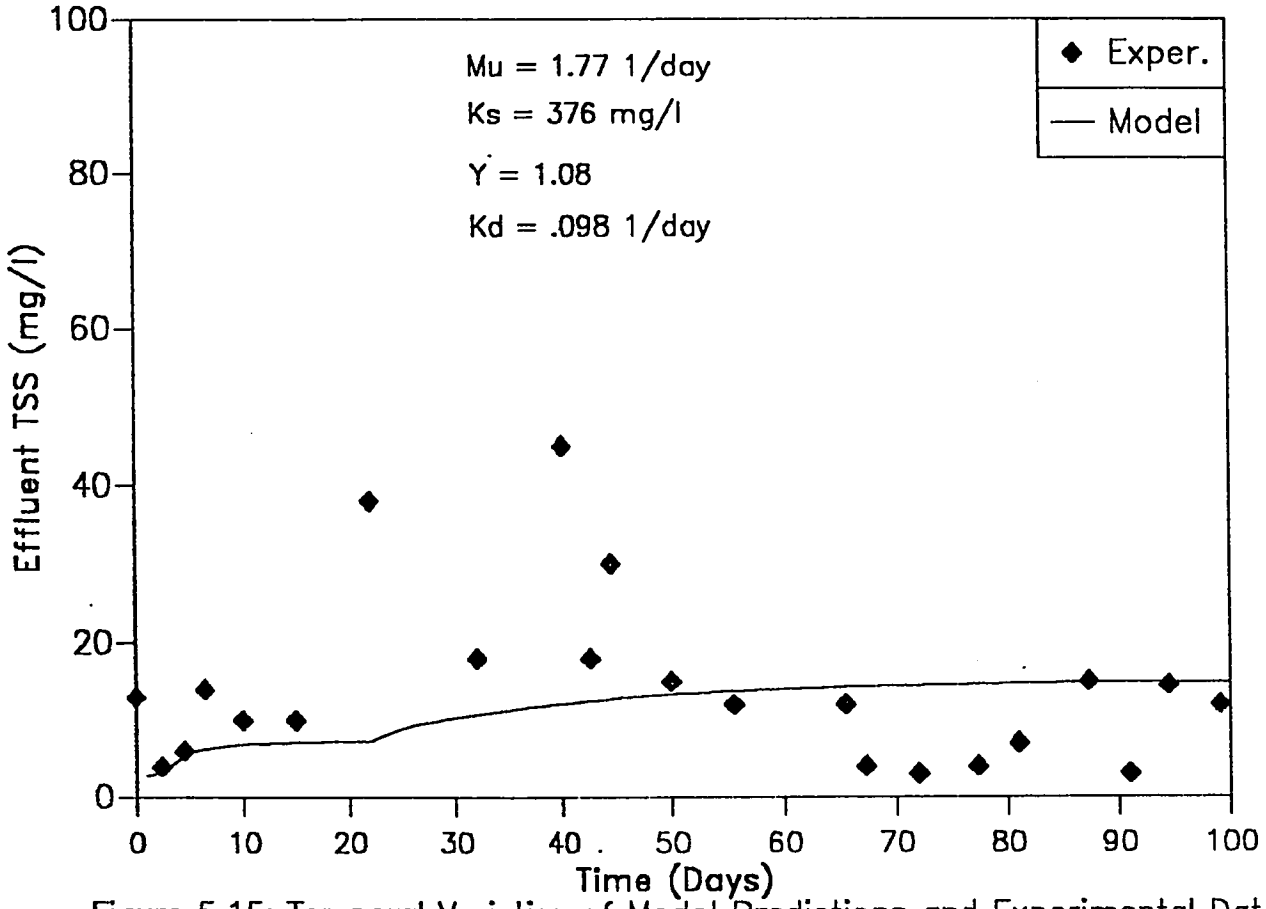


Figure 5.15: Temporal Variation of Model Predictions and Experimental Data (Hsu, 1986)

experimental MLVSS data very well, particularly after the input BOD was stepped from 169 to 244 mg/l on day 23. Generally the model underpredicted the data before the feed concentration was stepped up. The discrepancy between the model predictions and the experimental data may have stemmed, in part, from the relatively high value of K_s resulting in substantially lower substrate utilization and microbial growth rates. The model-predicted effluent BOD data shown in Figure 5.14 conform to this hypothesis. The simultaneous overprediction of effluent BOD and underprediction of MLVSS during the initial phase of acclimatization point to unrealistic kinetic coefficients. Out of all kinetic coefficients reported by the author, the half-saturation concentration K_s does not seem to be in line with literature values. With a relatively high ambient BOD concentration, the effects of erroneous K_s are particularly mitigated and therefore both the MLVSS and effluent BOD predictions closely match the experimental data after the increase in feed BOD. Although the model grossly overpredicted the first BOD point, the lack of experimental data over the following two weeks and immediately following the step increase in feed BOD does not permit fair assessment of the model prediction capacity during fluctuations in feed strength. It can be inferred from Figure 5.15 that the model predictions are generally in good agreement with the measured TSS data at pseudo steady-state conditions. Although the model responded to the perturbations in the feed concentration, it grossly underpredicted the experimental data immedi-

ately following the step change. As previously mentioned, changes in sludge settling characteristics associated with rapid changes in MLVSS concentration are not incorporated in the settling model. The data of Figures 5.13 - 5.15 clearly reflect the sensitivity of the model to input variations and also highlight the importance of accurate description of bacterial growth kinetics.

5.3 Variable Organic Loading

After validation of the model, the organic loading rate was varied and model predictions compared with experimental data presented by Al-Harazin (1992). Al-Harazin (1992) investigated experimentally the effect of different organic loading rates with constant SRT on SBR treatment efficiency. An organic loading rates of 100, 200, 400 and 800 mg/l of phenol with constant SRT of 14 days were used and compared with experimental results of a similar case (Figure 5.16). Values of μ_{max} = 3.0 day^{-1}, K_s = 25.3 mg/l, Y = 0.62 mg MLVSS/mg BOD, and K_d = 0.12 day^{-1}, were used, for Phenol treating reactors, and for of O-Cresol treating reactors, values of μ_{max} = 2.3 day^{-1}, K_s = 38.5 mg/l, Y = 0.65 mg MLVSS/mg BOD, and K_d = 0.13 day^{-1}, were used. As it is shown in Figure 5.16, in the case of reactor one, which was having the lowest organic loading rate (100 mg/l of phenol), the model predicted fairly accurate the experimental data. However, the model underpredicted the experimental data of the other

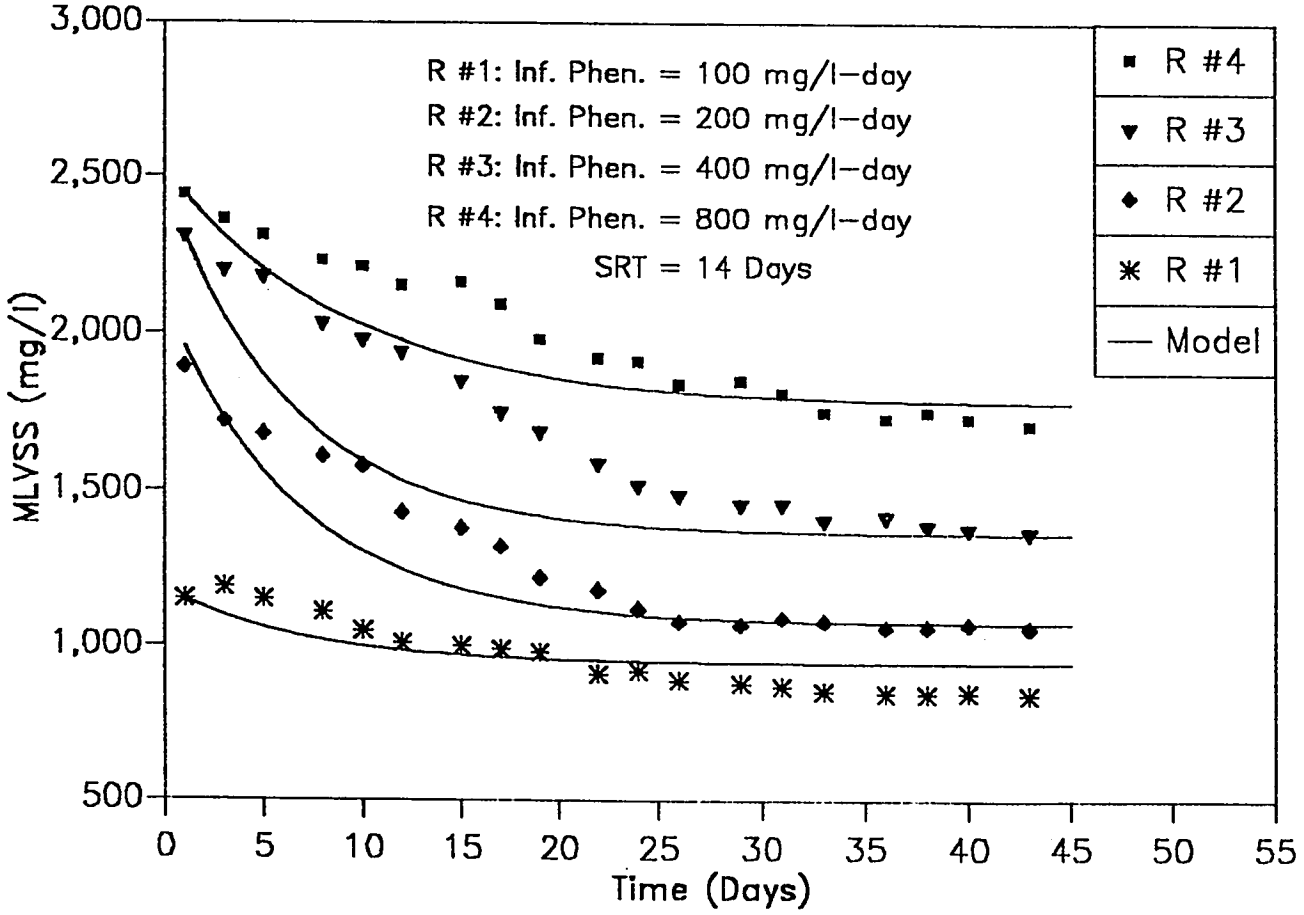


Figure 5.16: Variable Organic Loading, Phenol (Al–Harazin, 1992)

three reactors in the first 20 days of operation and closely matched thereafter, when steady state condition is reached. Figure 5.17 shows comparison of model predictions with a similar experimental data (Al-Harazin 1992), using an organic loading rates of 100, 200, 300 and 600 mg/l of O-Cresol with SRT of 14 days. In this case the model predictions closely macthed with experimental data except reactor 4 which was receiving the highiest organic loading (600 mg/l).

5.4 Variable Solids Residence Time

It was also of interest to see how the model predictions compare with experimental results using different solids residence time. Al-Harazin (1992) investigated experimentally the effect of different solids residence time (SRT) on treatability of synthetic toxic wastewater at a constant organic loading rate. Two cases were considered, in which the first one an organic loading rate of 800 mg/l of Phenol with SRT of 3, 4 and 10 days. In the second one, an organic loading rate of 600 mg/l of O-Cresol with SRT of 5, 10 and 20 were used. Figure 5.18 shows the experimental results with model predictions using an organic loading rate of 800 mg/l of phenol with SRT of 3, 4, and 10 days, while the initial MLVSS for all the three reactors was about 2350 mg/l. A similar analysis of solids residence time variation for O-Cresol is shown in Figure 5.19. In both cases there is an excellent agreement between model predictions and experimental results.

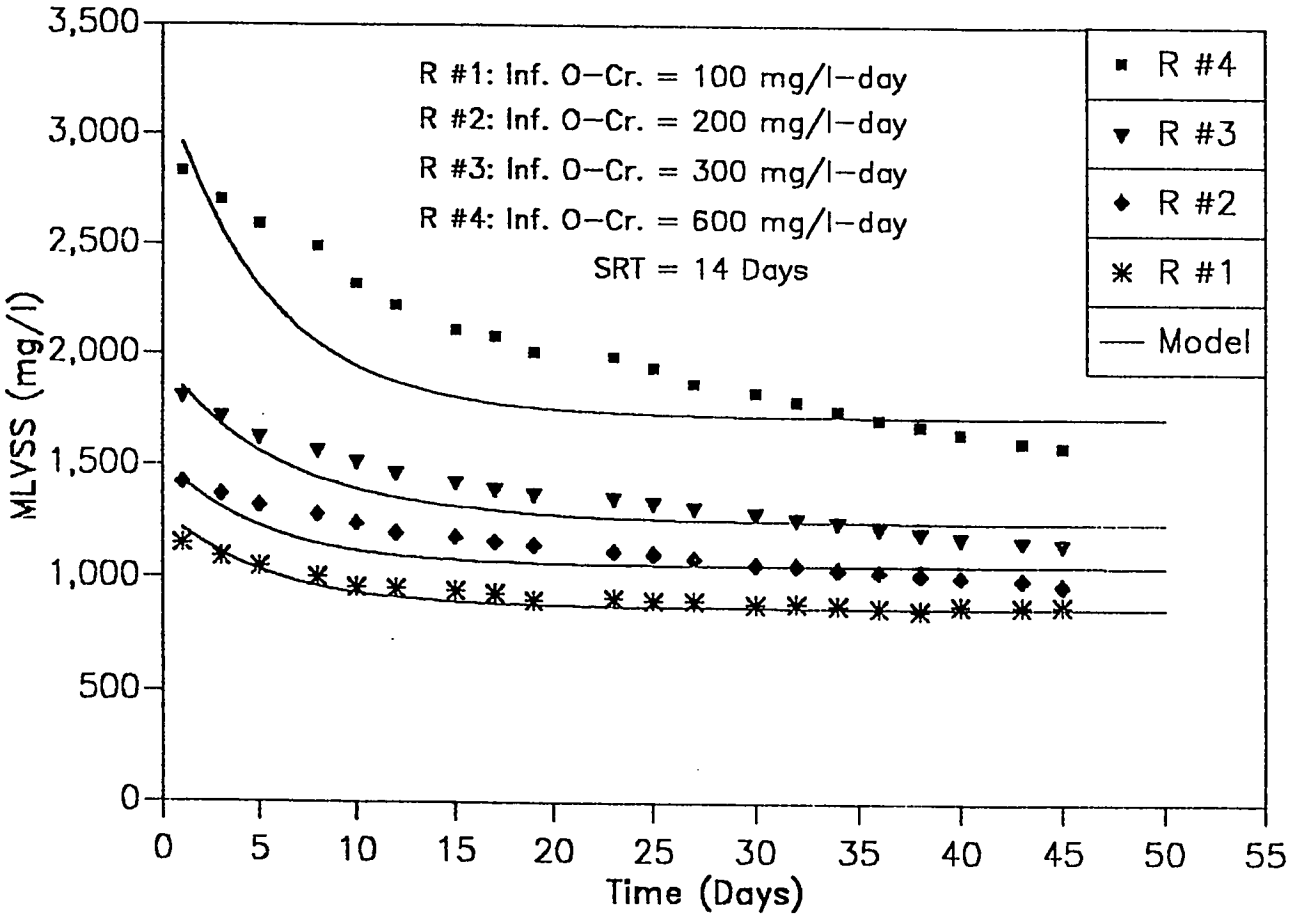


Figure 5.17: Variable Organic Loading, O-Cresol (Al-Harazin, 1992)

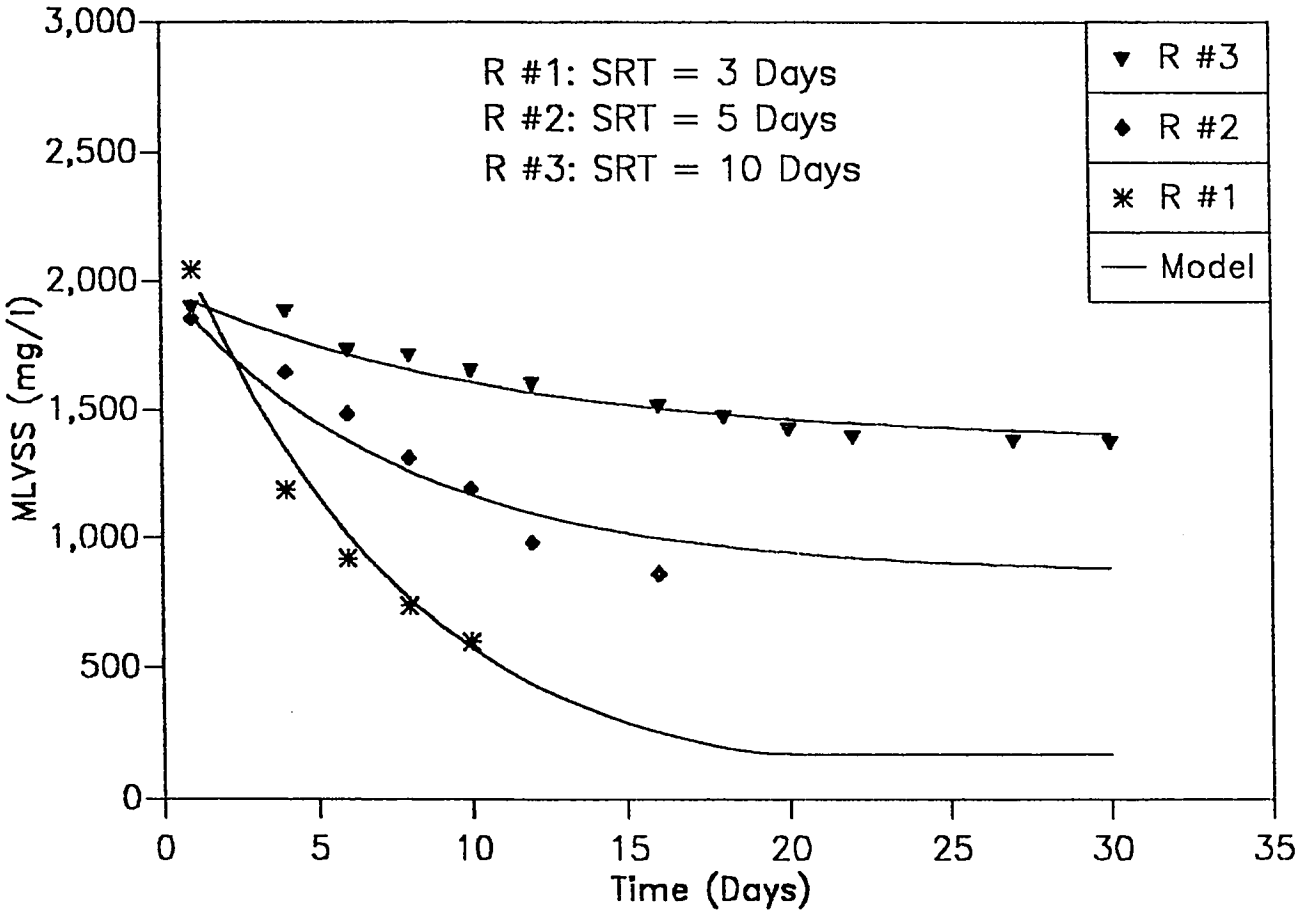


Figure 5.18: Variable Solids Residence Time, Phenol (Al–Harazin, 1992)

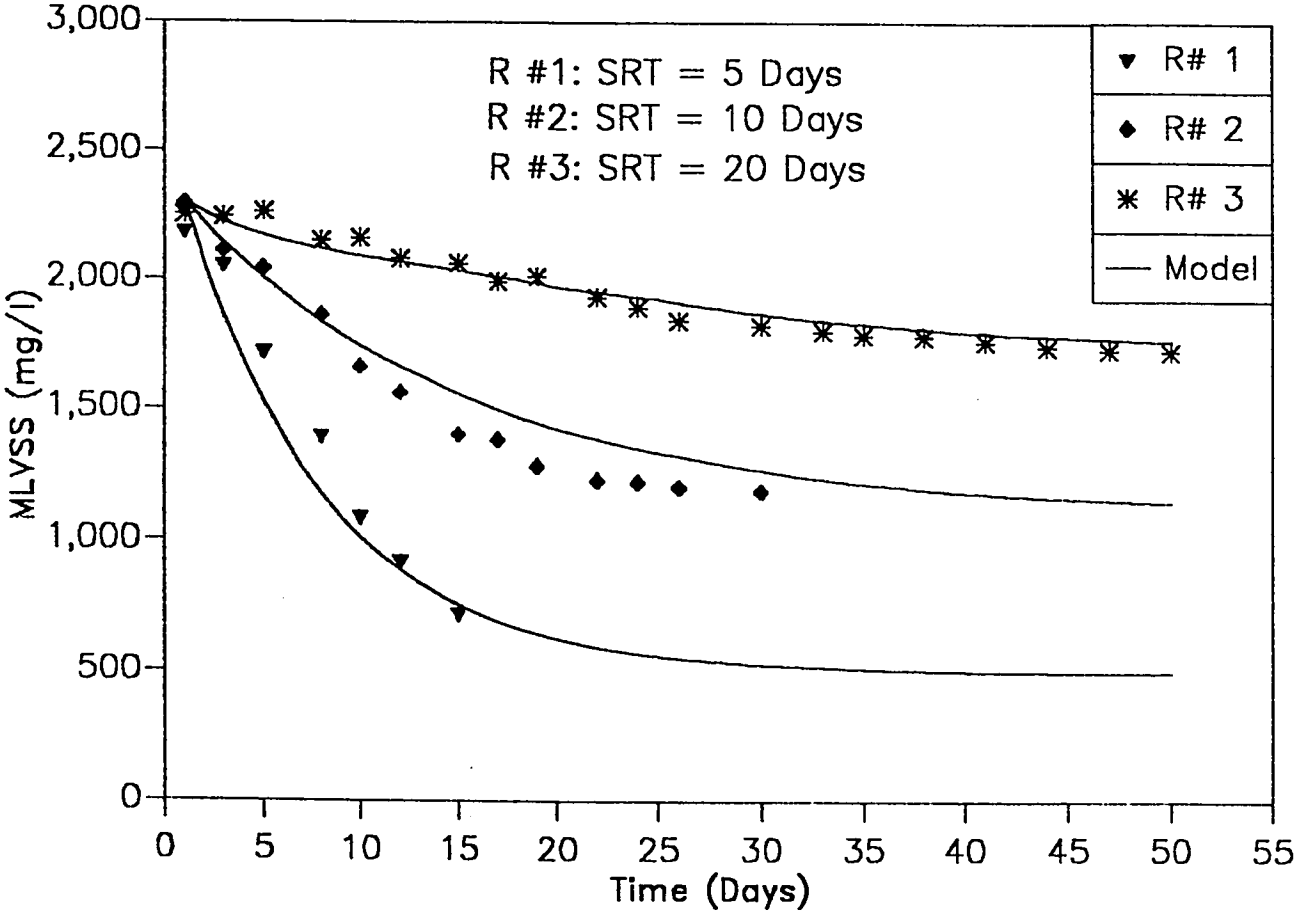


Figure 5.19: Varaible Solids Residence Time, O–Cresol (Al–Harazin, 1992)

It can be inferred from these analysis that this model could be used for analysis of SBR system with variable SRT and organic loading rates, provided that the initial conditions and kinetic parameters are given. However, calibration of the model with experimental results from the system of interest is also important.

5.5 Sensitivity Analysis

The values of kinetic parameters vary from one system to another depending on the predominant microbial species in a heterogeneous population that are strongly influenced by loading and operating conditions. Therefore it is necessary to think of these kinetic constants in terms of a range of values rather than specific numerical ones. It is also important not only to know the probable ranges to be expected, but how variation of these parameters affects the system behavior (Gaudy, 1980). For that reason, the effect of variation of the magnitude of kinetic coefficients namely, maximum specific growth rate (μ_{max}), half saturation coefficient (K_s), yield coefficient (Y), and decay coefficient (K_d), to the SBR system during acclimatization was investigated. The values of these parameters used for parametric study are given in Table 5.1. Besides, an influent BOD of 450 mg/l was used with HRT 1.33 days, and a 12 hours cycle time with 1 hour fill, 1 hour settle and 10 hours react was adopted.

These values for the kinetic parameters are in the range of those values reported in the literature (Table 3.1). However, in order to

investigate the effect of the variation of the magnitude of the kinetic coefficients each was later varied independently whilst keeping the rest constant at those values given in Table 5.1.

Table 5.1: Values of the kinetic coefficients used for sensitivity analysis

Kinetic Coefficient	Typical Value
μ_{max} (day^{-1})	3.0
K_s (mg/l)	25.0
Y (mg/mg)	0.60
K_d (mg/l)	0.10

5.5.1 Effect of Maximum Specific Growth Rate (μ_{max})

The maximum specific growth rate (μ_{max}) is one the important parameters affecting the microbial growth rate prediction. Values for this coefficient reported in the literature vary significantly (Table 3.1). Therefore, while keeping all other parameters constant at those given in Table 5.1, the effect of varying μ_{max} was investigated. Figure 5.20, illustrates the effect of μ_{max} upon the MLVSS build-up during acclimatization. It shows that, over the range studied, an increase of μ_{max} causes an increase of the rate of MLVSS build-up,

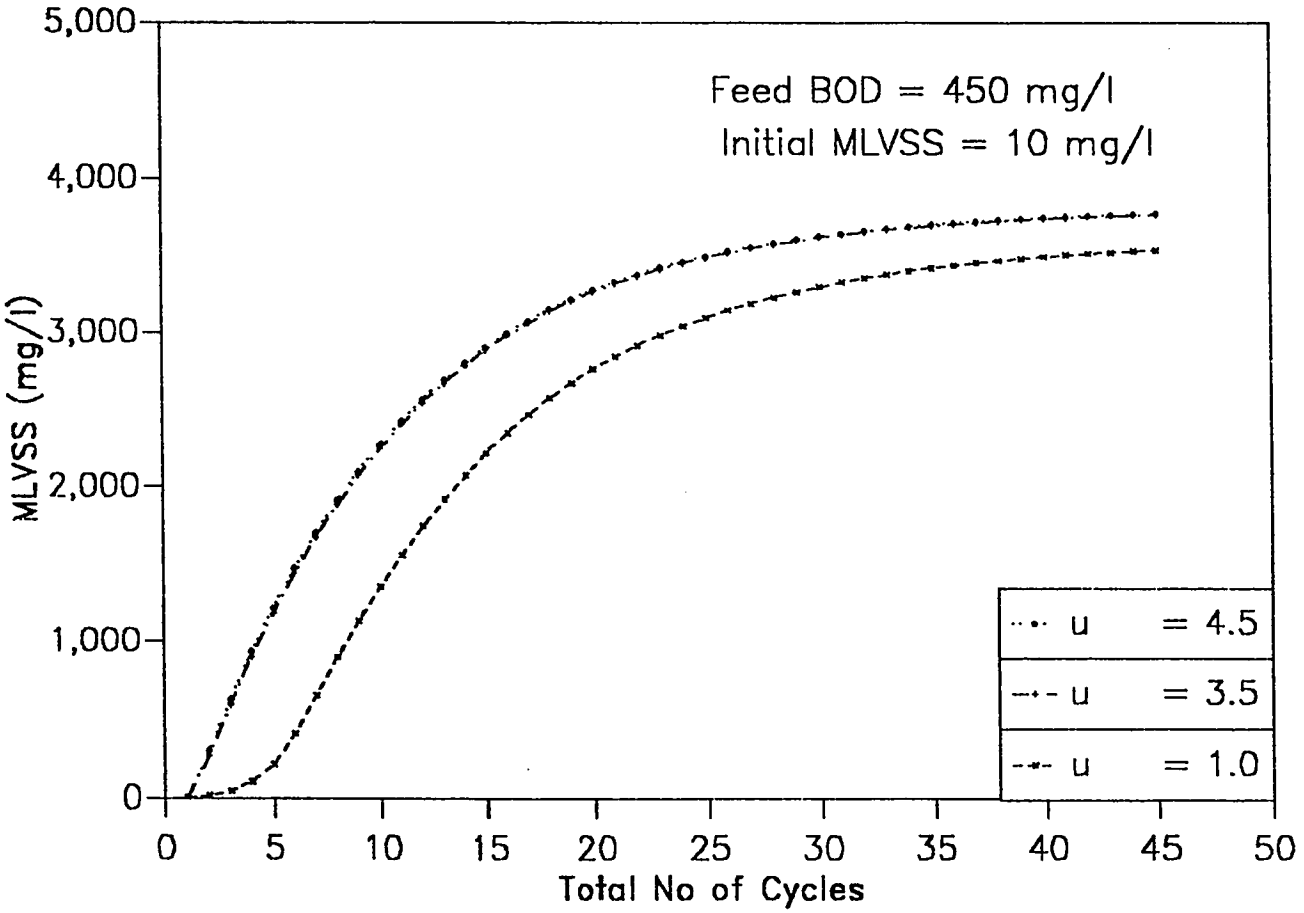


Figure 5.20: Effect of Variation of Max. Spec. Growth Rate (u max)

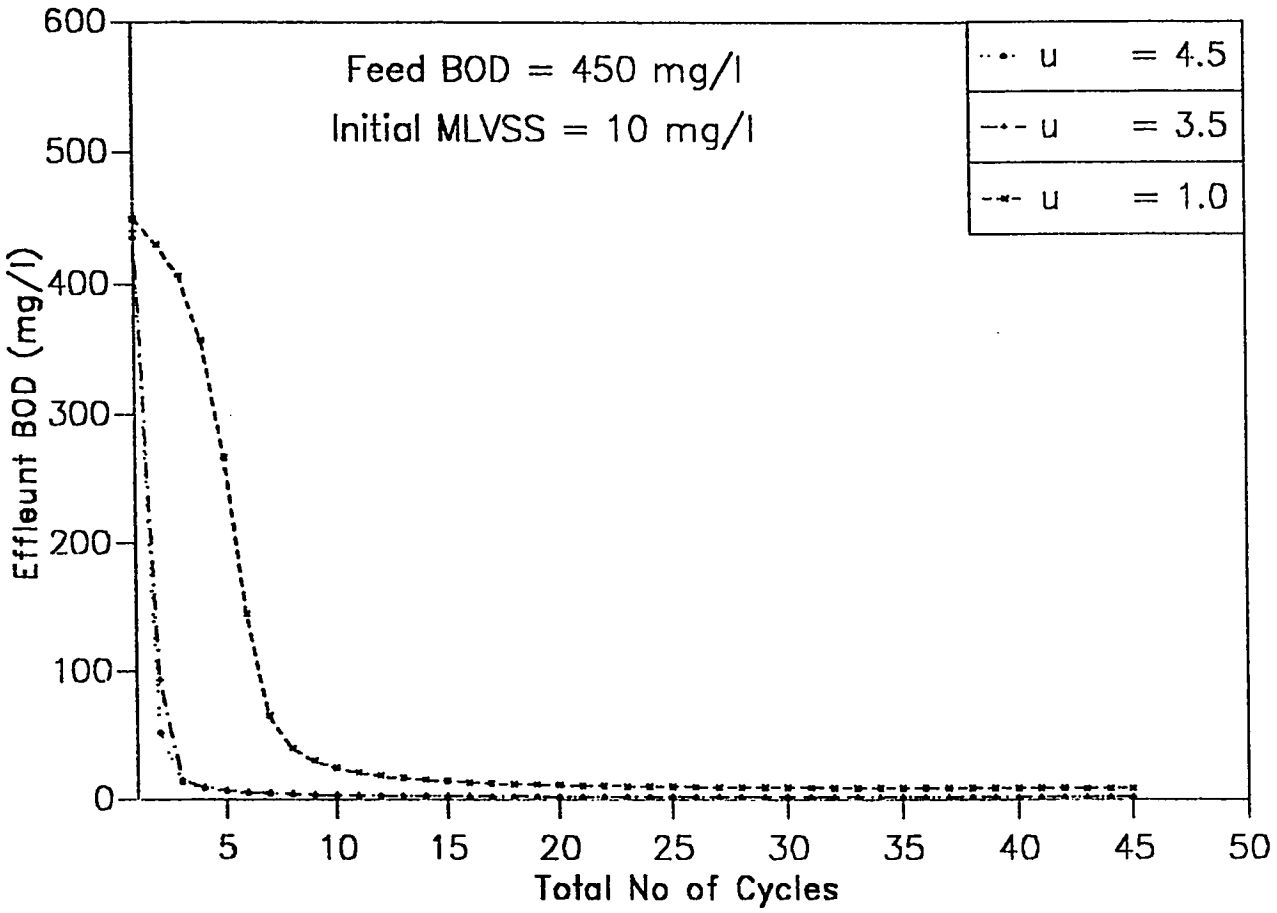


Figure 5.21: Effect of Variation of Max. Spec. Growth Rate(u max)

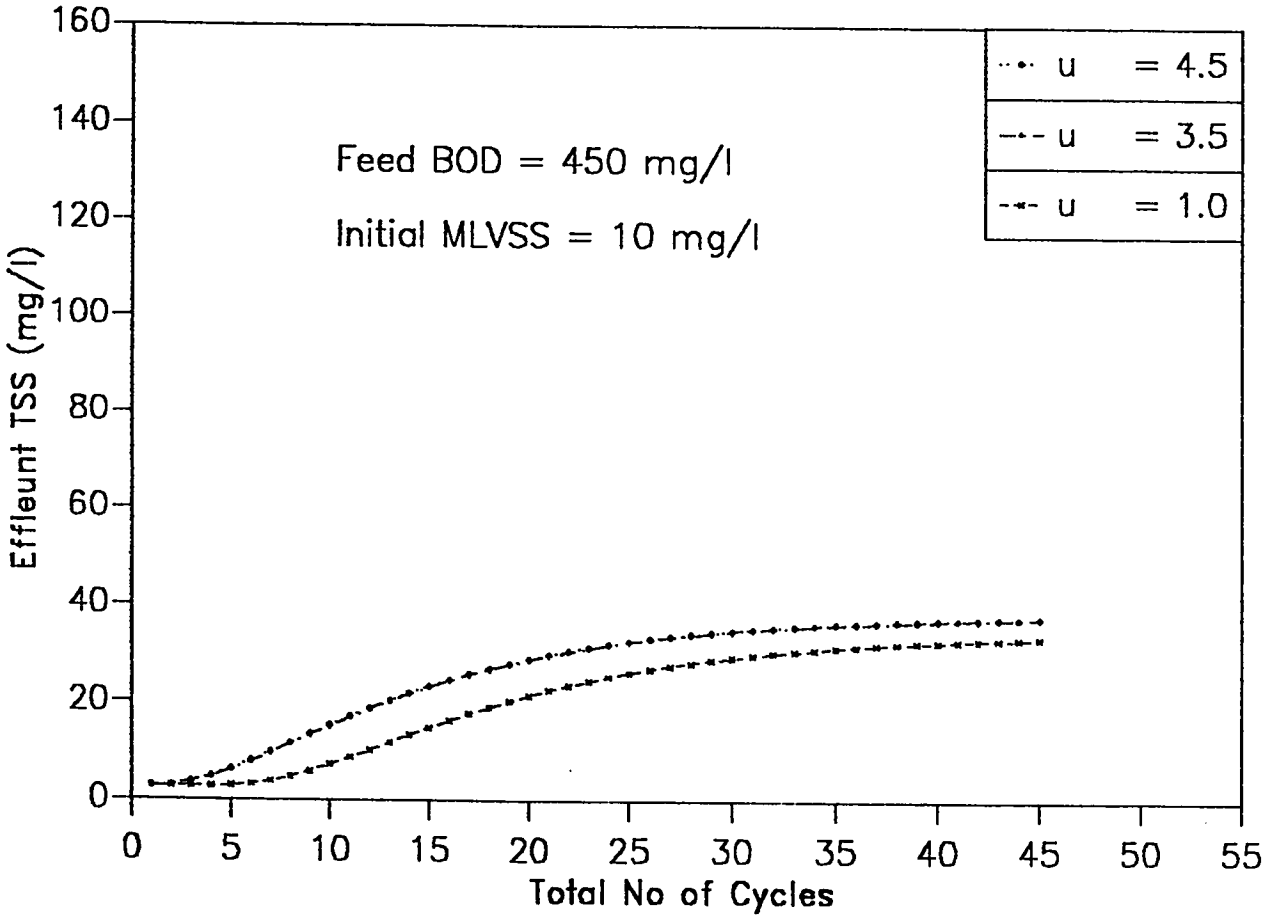


Figure 5.22: Effect of Variation of Max. Spec. Growth Rate (u max)

particularly in the lower values, while in the higher values, the effect is minimum. Increasing the value of μ_{max} from 1.0 to 4.5 $days^{-1}$, increases the MLVSS by about 23 % after 45 cycles of operation. The values of μ_{max} studied (1.0 - 4.5 day^{-1}) are in the range of those values reported in the literature (Table 3.1). Figures 5.21 and 5.22 show the effect of μ_{max} on the effluent BOD and TSS respectively. In the case of effluent BOD (Figure 5.21) the effect is relatively significant. For a μ_{max} = 1.0 day^{-1} around 15 cycles are needed to reach effluent BOD of 5 mg/l, while for a value of 4.5 only 5 cycles are required. For the effluent TSS , initially the effect is minimum and increases gradually until it reaches maximum after about 15 cycles and at the steady state the effect is minimum (Figure 5.22). The effluent TSS variations are proportional with the respective MLVSS.

5.5.2 Effect of Half Saturation Coefficient (K_s)

The half saturation coefficient (K_s) is also an important parameters for the simulation of microbial growth rate. The values of K_s was varied while keeping all other parameters constant at those values given in Table 5.1. Figures 5.23, 5.24 and 5.25, show the effect of K_s upon the MLVSS, effluent BOD and TSS respectively during acclimatization. For the MLVSS build-up, an increase of K_s causes a

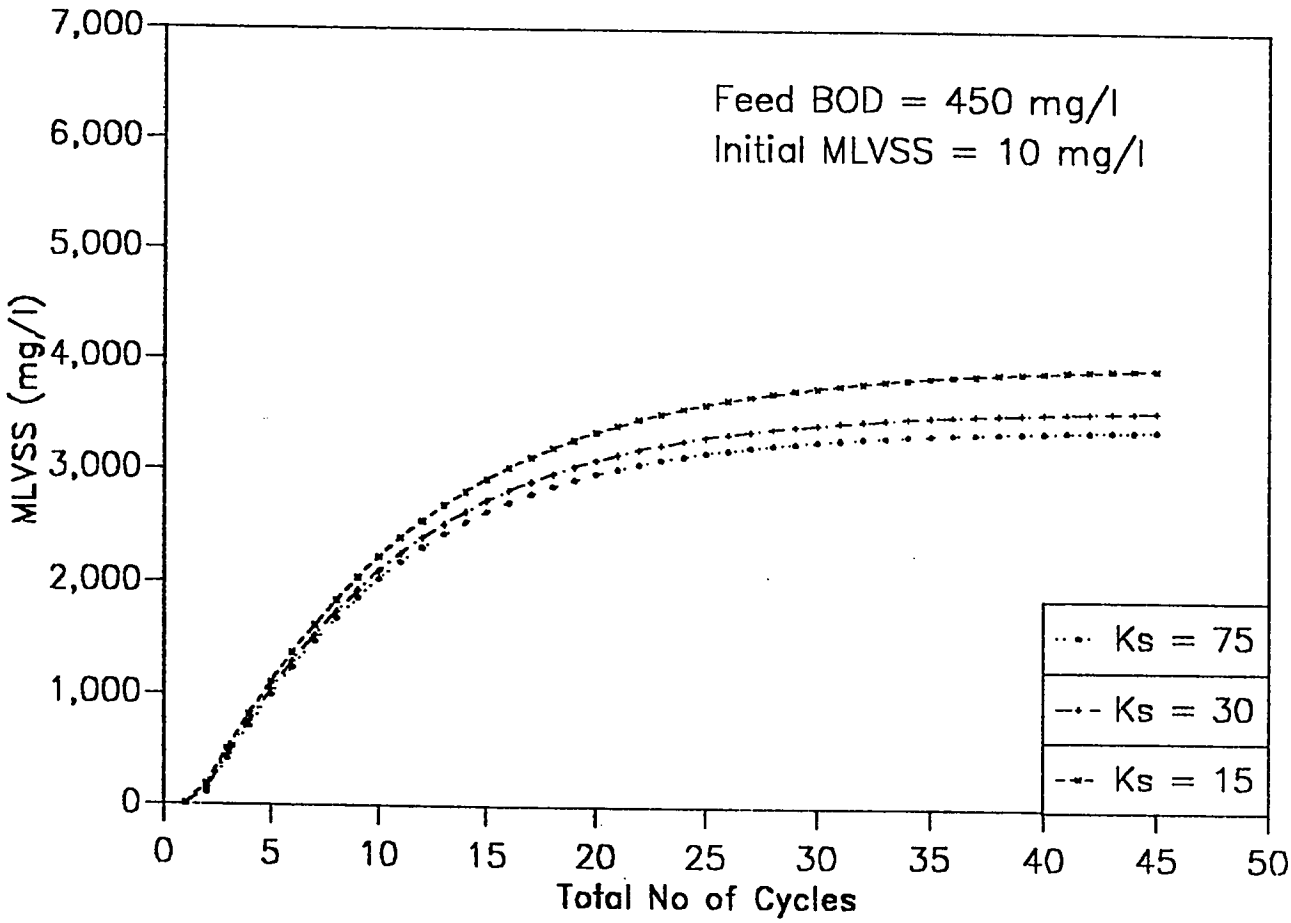


Figure 5.23: Effect of Variation of Half–Saturation Coeff. (Ks)

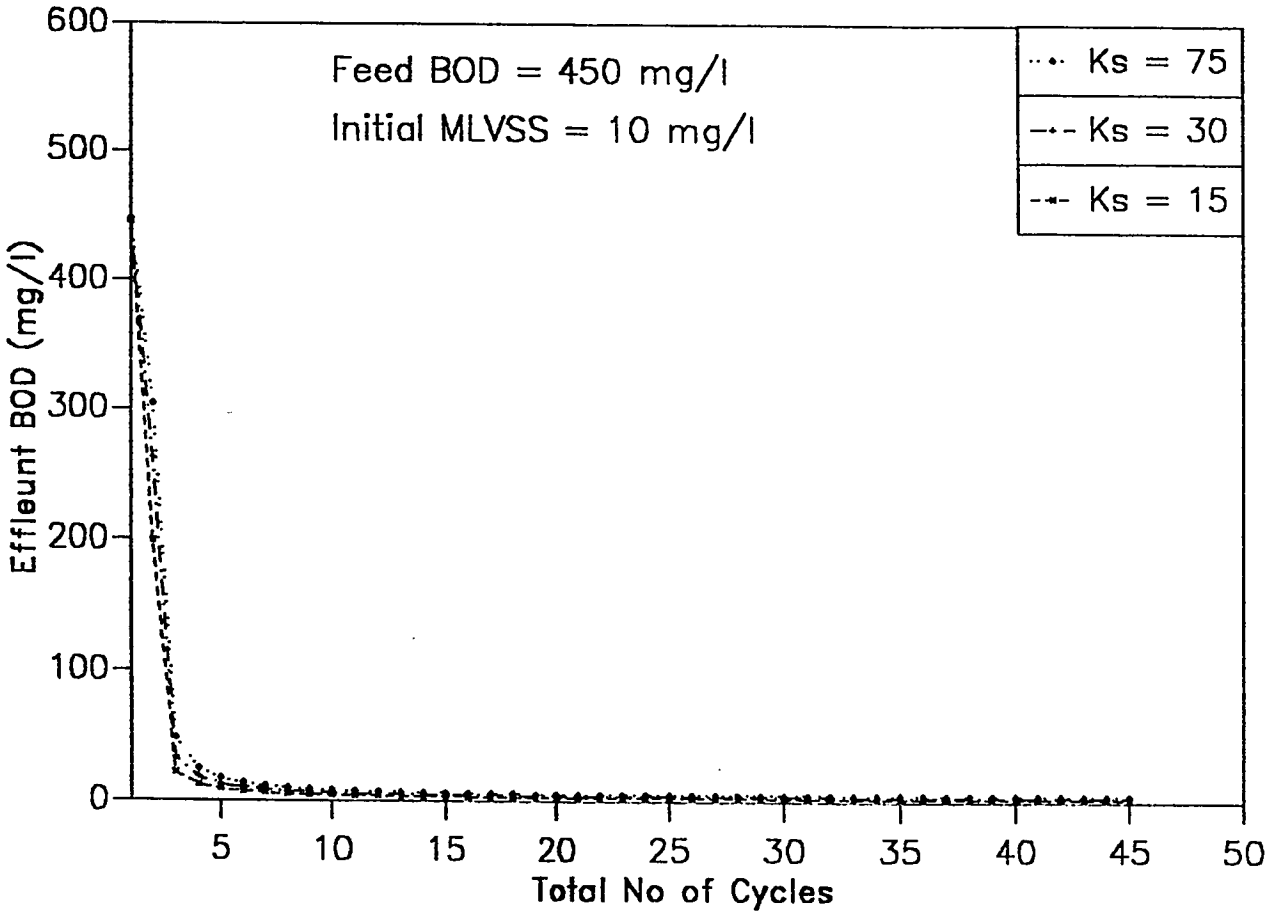


Figure 5.24: Effect of Variation of Half–Saturation Coeff. (Ks)

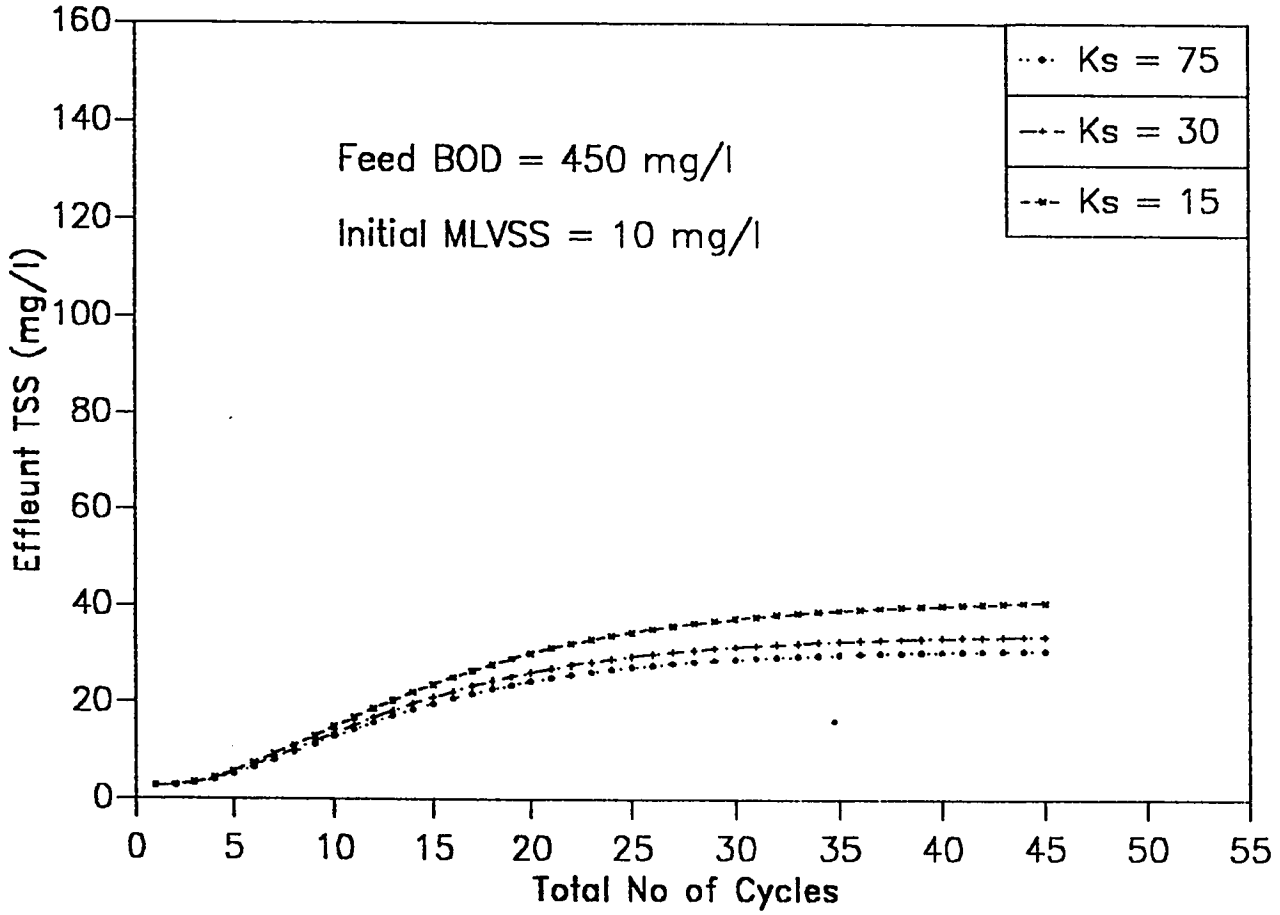


Figure 5.25: Effect of Variation of Half–Saturation Coefficient (Ks)

decrease of MLVSS build-up rate. Regarding effluent BOD, lower values of K_s resulted in lower effluent BOD and vice versa, while for effluent TSS, the opposite trend is displayed. This is because, as it has mentioned earlier, the effluent TSS follows the same pattern of the MLVSS.

5.5.3 Effect of Yield Coefficient (Y)

During biodegradation a portion of the substrate is converted in to new cells, and the ratio of the mass of cells formed to the mass of substrate consumed is defined as the yield coefficient (Metcalf and Eddy, Inc. 1979). Figures 5.26, 5.27 and 5.28 show the effect of the variation of yield coefficient over MLSS, effluent BOD and TSS respectively. Compared to other kinetic coefficients, the variation of the yield coefficient was found to be the parameter least effecting the MLVSS, effluent BOD and TSS within the range studied.

5.5.4 Effect of Decay Coefficient (K_d)

In the present analysis, the decay coefficient (K_d) was found to have a major effect on the MLVSS build-up rate. It can be seen from Figure 5.29 that a small decrease of K_d will increase significantly the MLVSS build-up. However, it seems that K_d variation has relatively no effect on effluent BOD (Figure 5.30). The reason could be that the the decay coefficient is directly proportional to the active cell mass concentration, and independent from the substrate concentra-

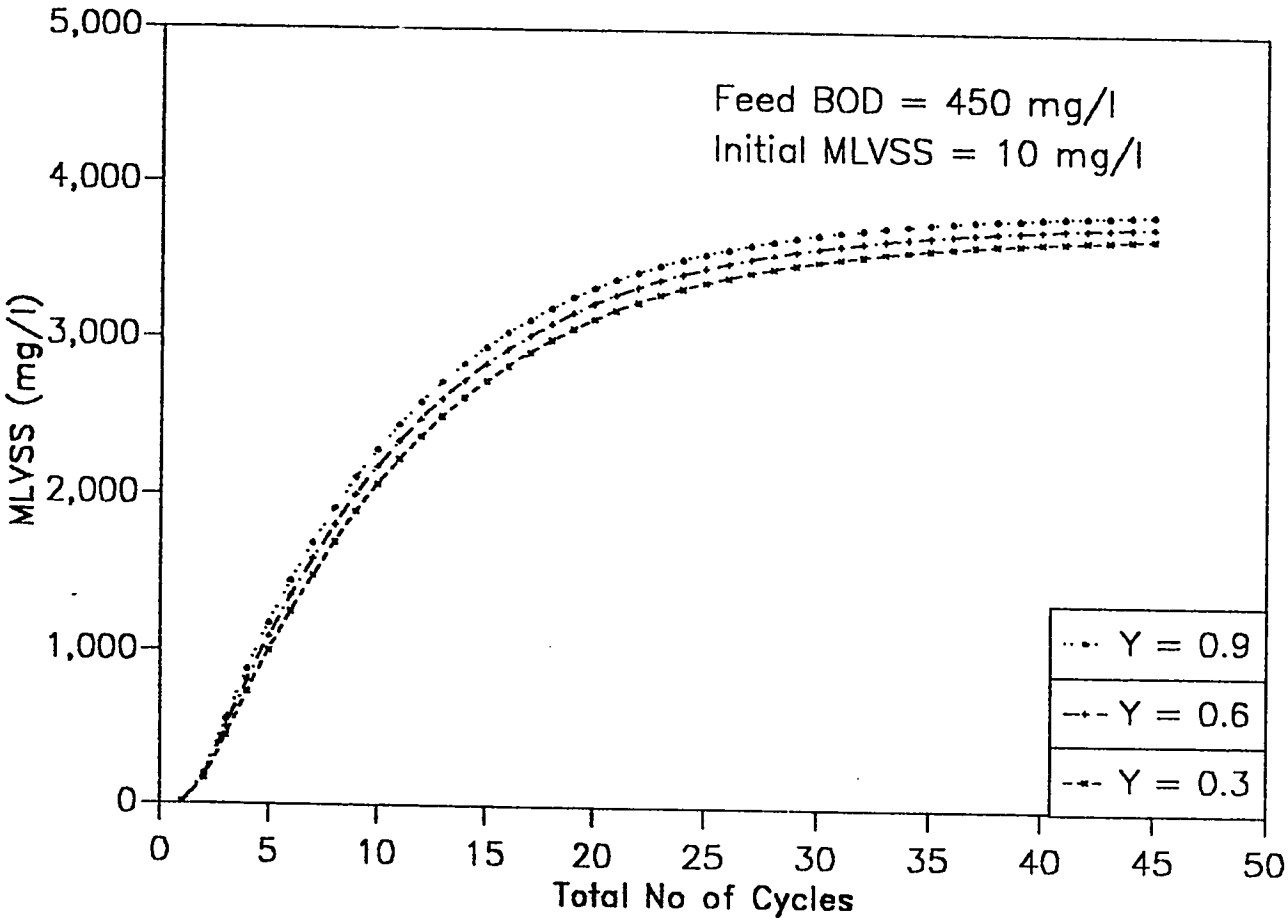


Figure 5.26: Effect of Variation of Yield Ceofficient (Y)

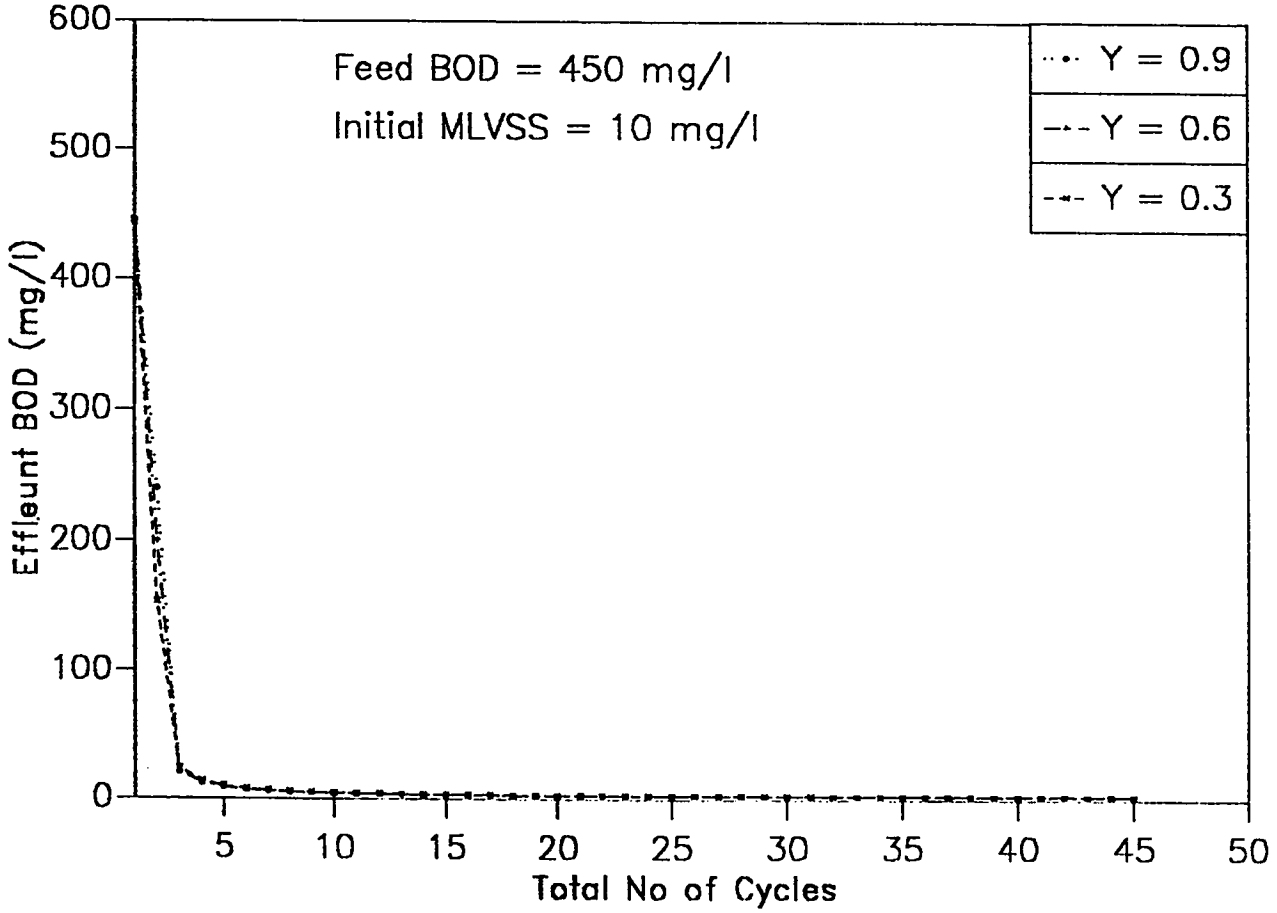


Figure 5.27: Effect of Variation of Yield Coefficient (Y)

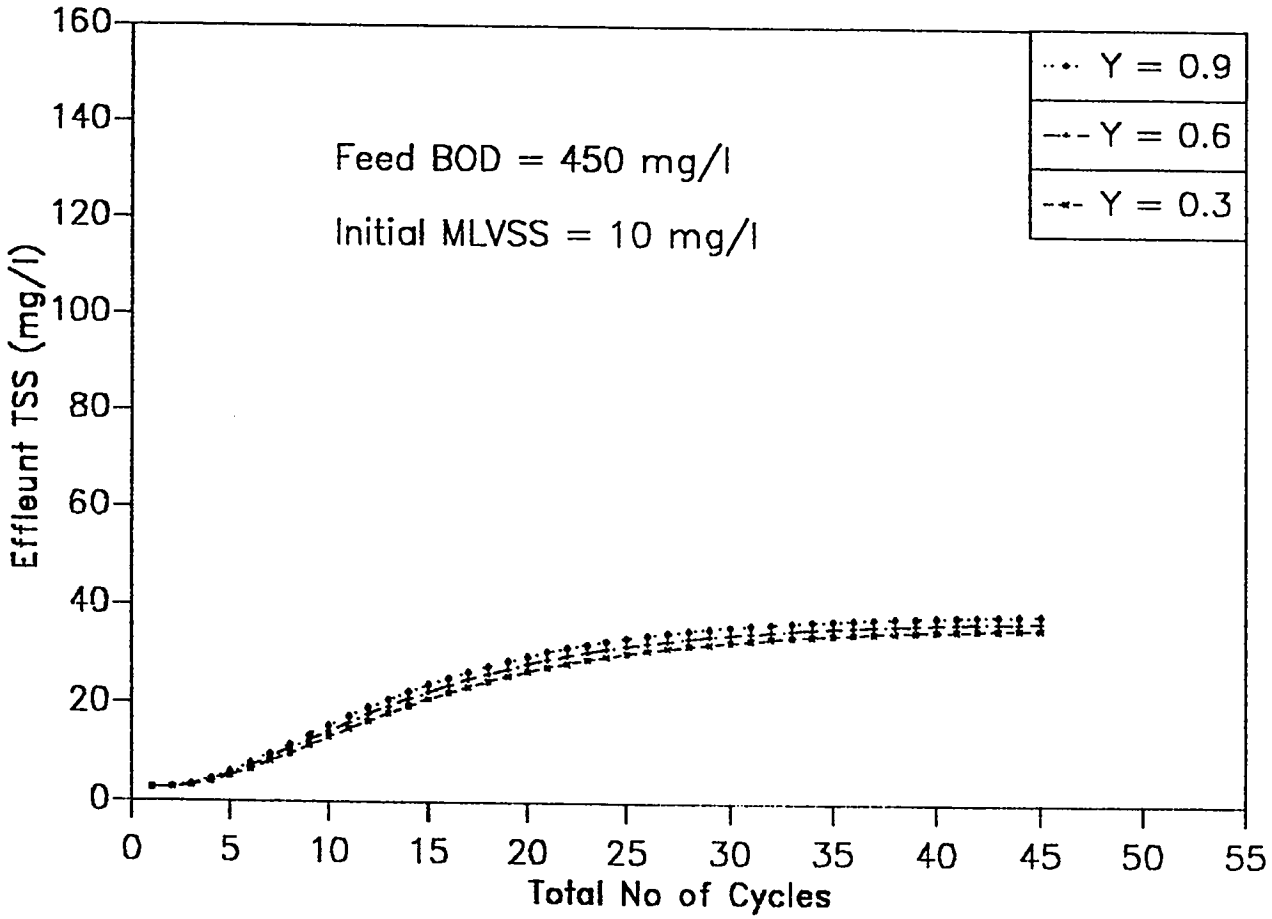


Figure 5.28: Effect of Variation of Yield Coefficient (Y)

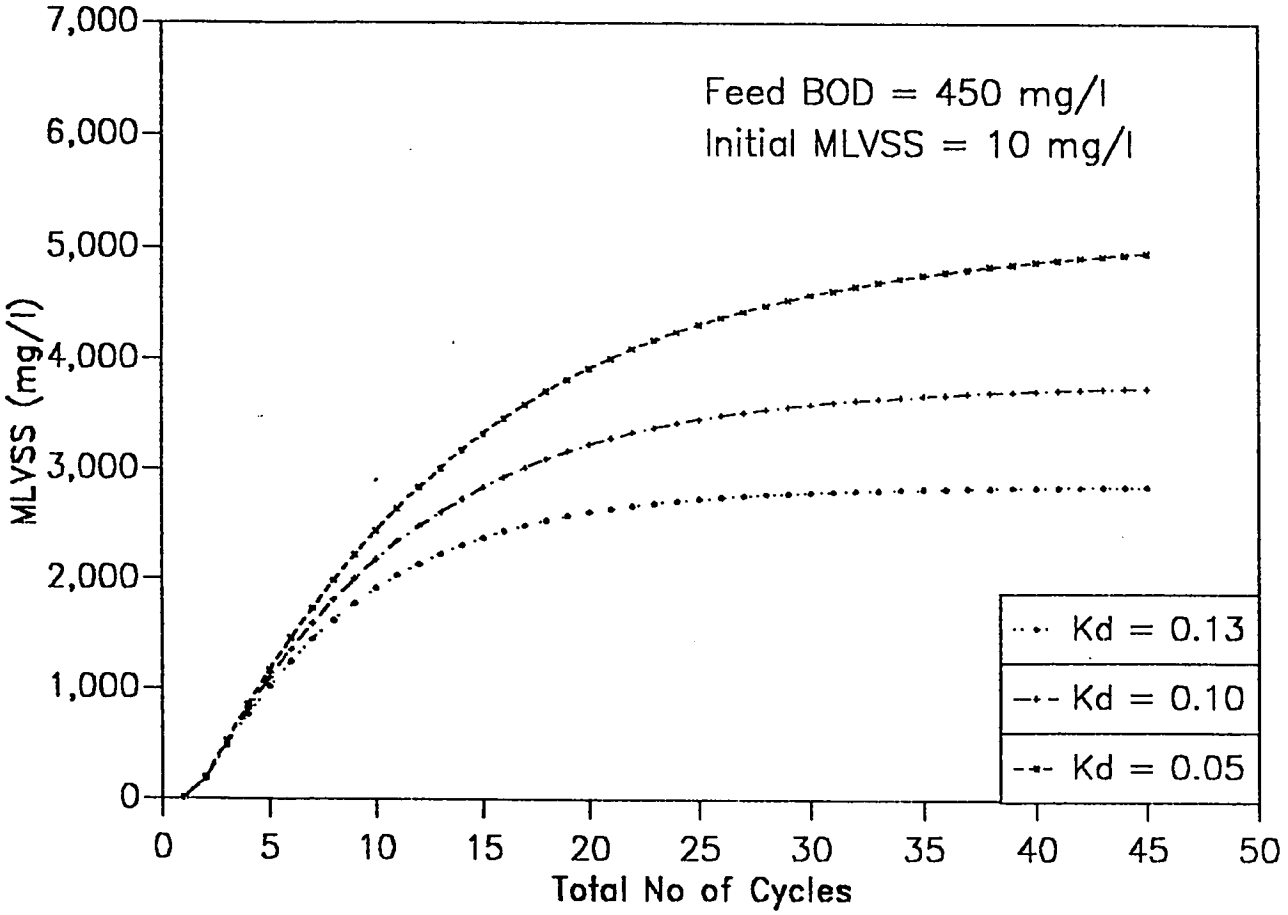


Figure 5.29: Effect of Variation of Decay Coefficient (Kd)

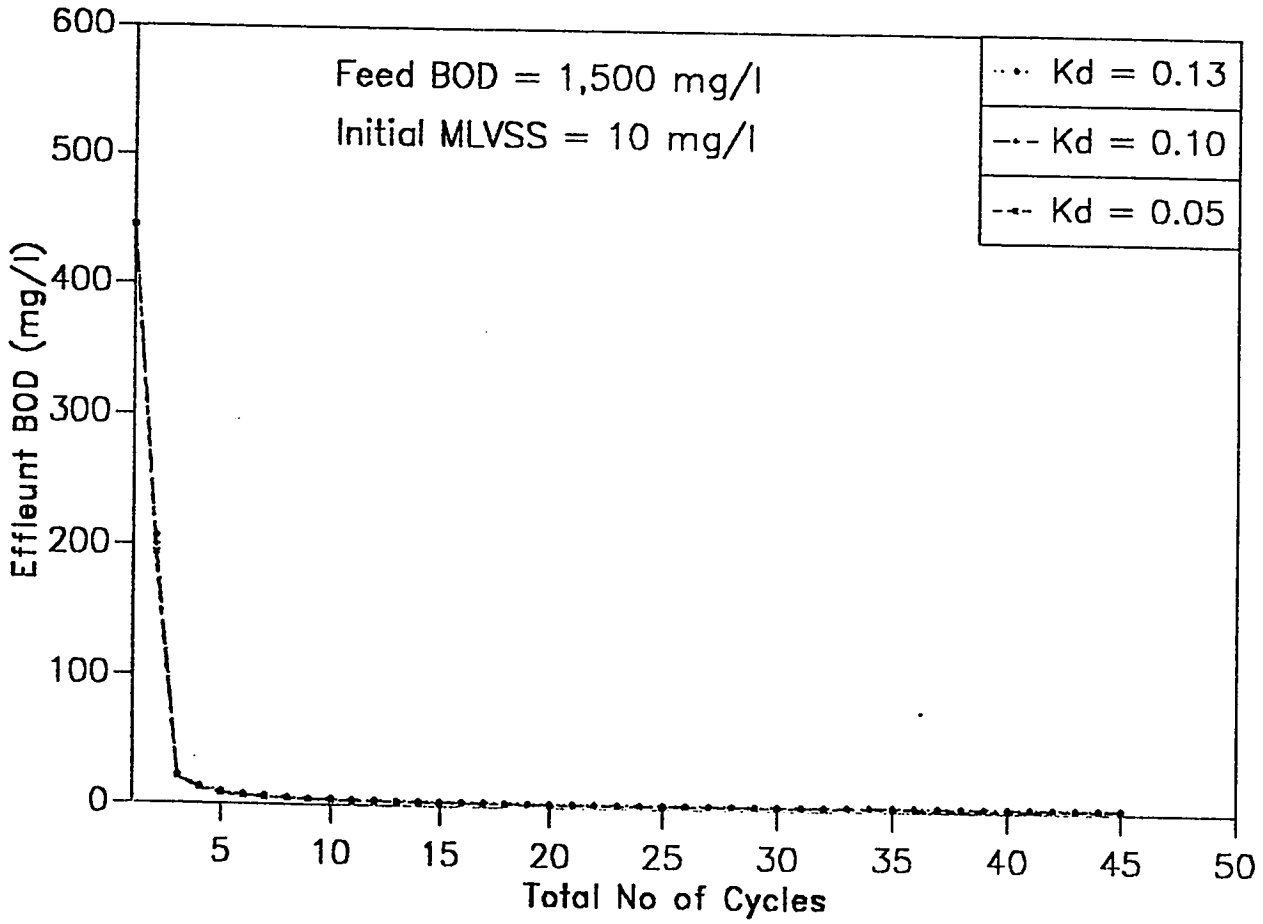


Figure 5.30: Effect of Variation o f Decay Coefficient (Kd)

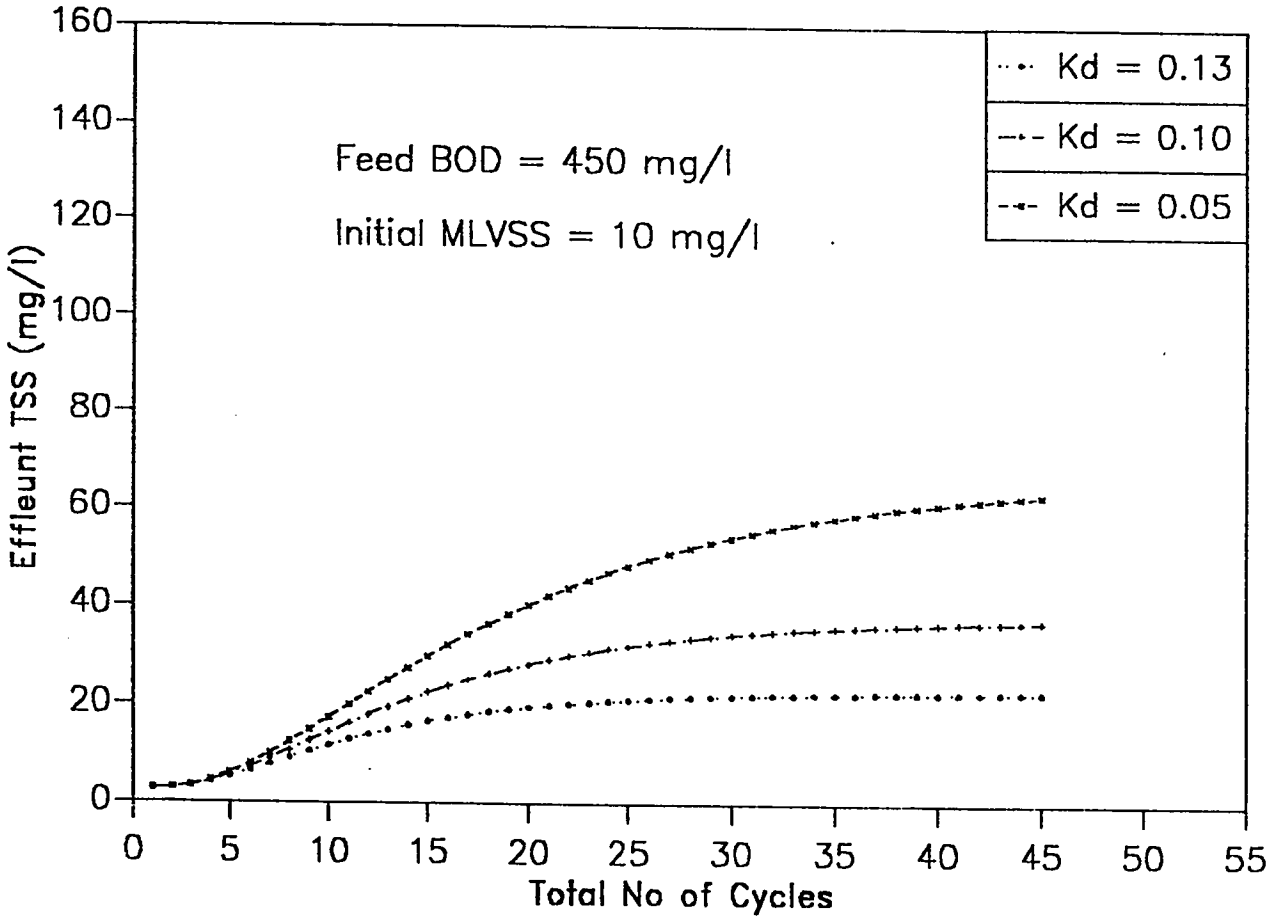


Figure 5.31: Effect of Variation of Decay Coefficient (Kd)

tion. The variation of K_d do affect also the effluent TSS concentration as it can be seen from Figure 5.31.

In summary, the variation of the magnitude of the kinetic coefficients affect the model predictions. The results from the sensitivity analysis revealed that for MLVSS build-up and effluent TSS, K_d and μ_{max} are the most influential parameters, while Y is the least affect one and K_s is in between. The variation of μ_{max} and K_s also affects effluent BOD. Therefore, careful selection of the values for these parameters, based on the type of the waste, is of prime importance for accurate predictions in any kinetic model.

5.6 Effect of Fill-React Ratio

As it has been mentioned earlier, Fill and React are the most important periods of the SBR treatment from operational point of view. Both growth of microorganisms as well as substrate removal takes place during these two periods (Irvine and Ketchum, 1989). The duration of each period depends on the total time of the cycle, the system or plant capacity, and the wastewater flow rate and its strength. The duration of fill relative to react affects the SBR treatment efficiency (Dennis and Irvine, 1979). Dennis and Irvine (1979) studied experimentally, the effect of fill:react ratio on SBR treatment using a bench scale system. They reported that high substrate concentrations occur during relatively shorter fill periods, which sometimes causes an overloading of the system, and affects the

sludge settleability.

Most of the bench-scale studies reported in the literature, a relatively short fill time, (5 to 120 minutes) followed by a longer react period (8 hours to 7 days) were used (Hsu, 1986; Al-Harazin et al., 1991; Manning and Irvine, 1985; Alleman and Irvine, 1980; Misbahuddin and Farooq, 1990). In some cases, fill time from 4 to 10 hours were reported (Herzburn et al. 1985, Dennis and Irvine 1979). Regarding full-scale SBR treatment facilities, a fill time variation from 1.3 to 3.1 hours and a react time from 0.4 to to 22 hours have been reported (Irvine et al. 1983). With the above in mind, it was interesting to simulate the effect of variations of fill and react periods on the SBR treatment efficiency.

In the present simulations, three scenarios of fill-react ratio (FRR), which are, 0.1, 0.5, and 0.8 and each has a cycle time of 11 hours to allow for 1-hr settling, i.e, 2 cycles/day were adopted. Two levels of initial MLVSS were adopted, a MLVSS of 10 mg/l (to simulate conditions during start-up) and MLVSS of 1500 mg/l (to represent operating conditions), and two feed concentrations of 450 and 1000 mg/l were employed. For each scenario considered, the MLVSS, effluent BOD and TSS were simulated to see the effect of FRR variation on these parameters.

5.6.1 Effect of Fill-React Ratio on MLVSS Build-up

During acclimatization, a rapid MLVSS growth is essential for

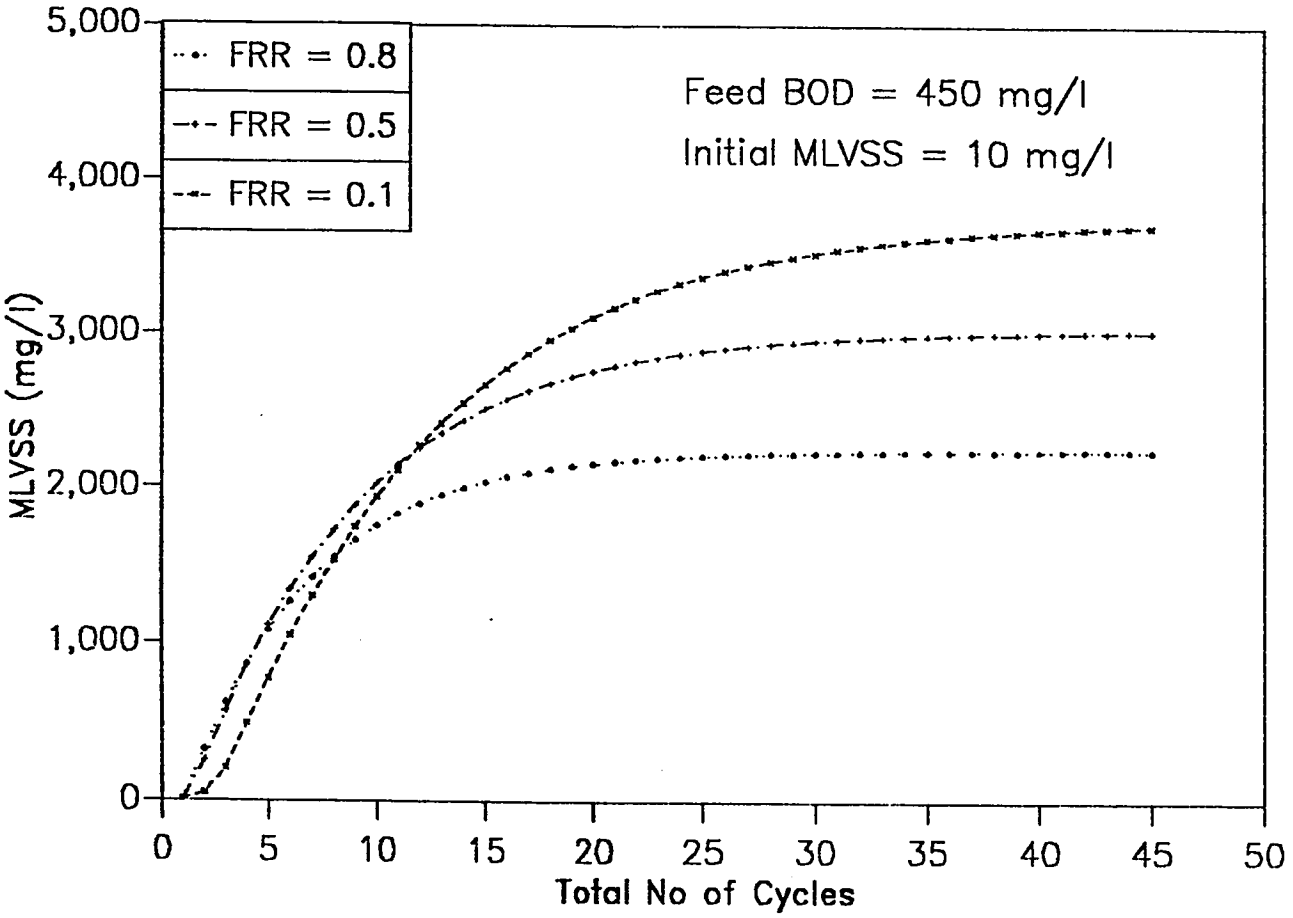


Figure 5.32: Simulation of Fill–React Ratio

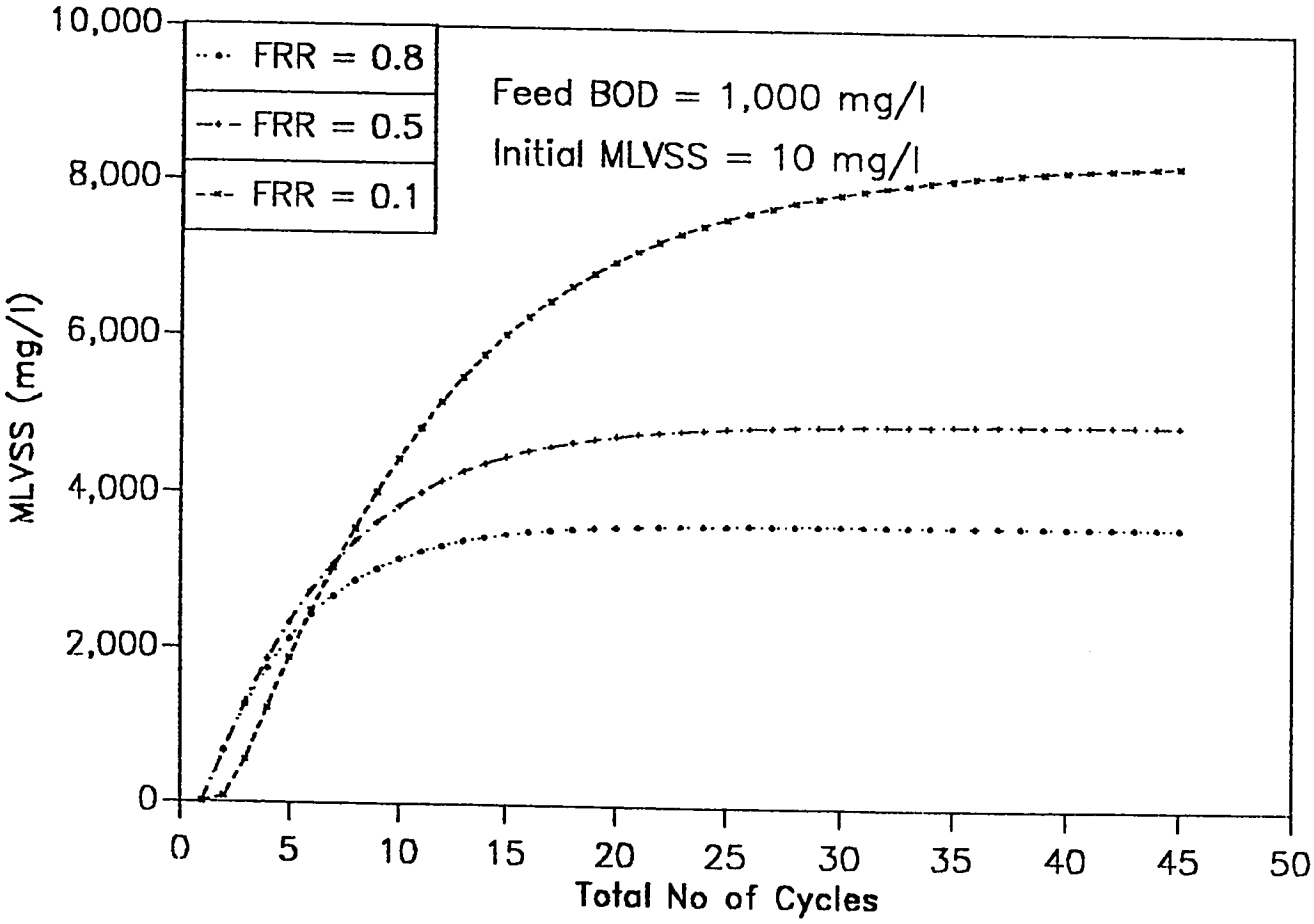


Figure 5.33: Simulation of Fill–React Ratio

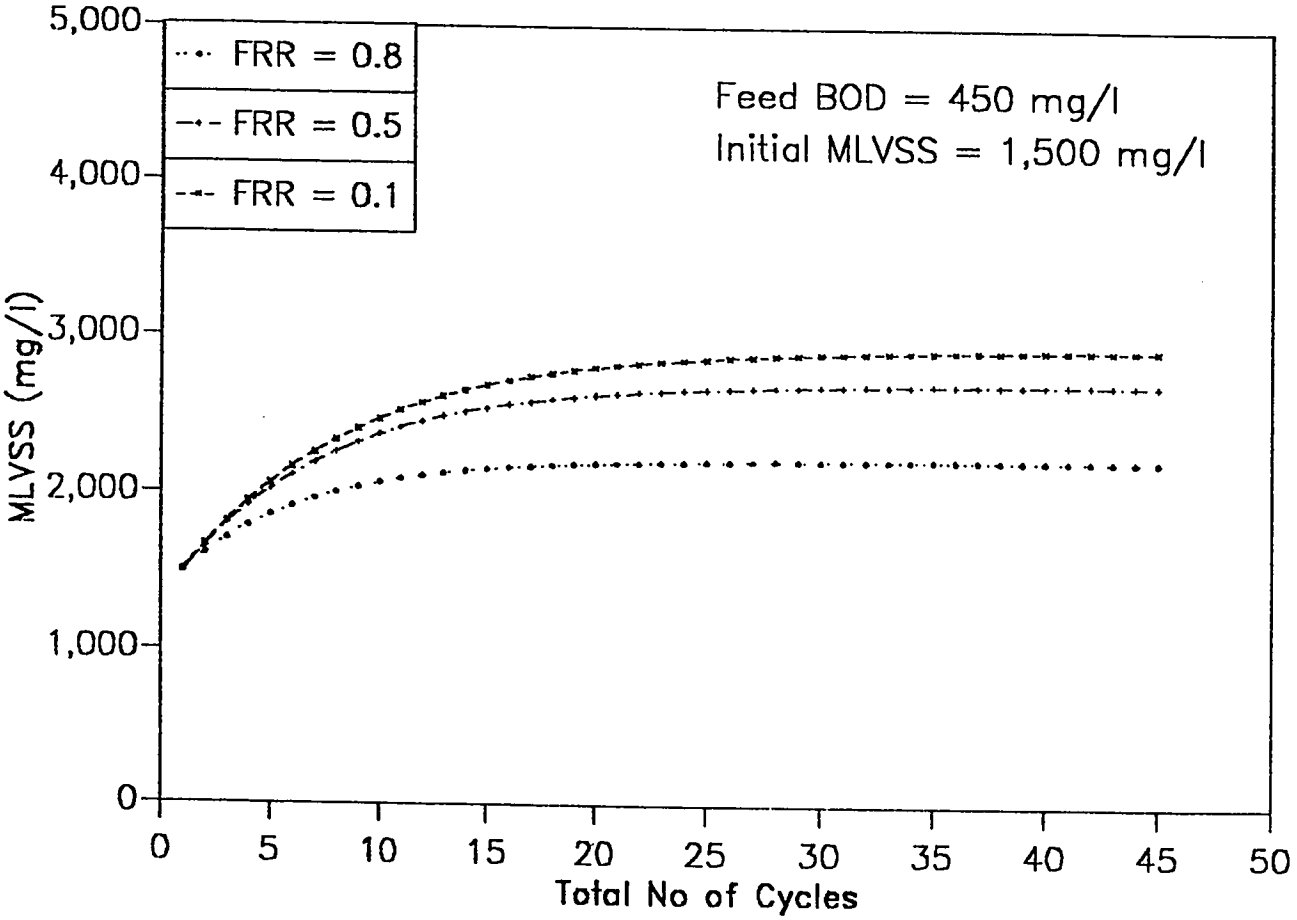


Figure 5.34: Simulation of Fill–React Ratio

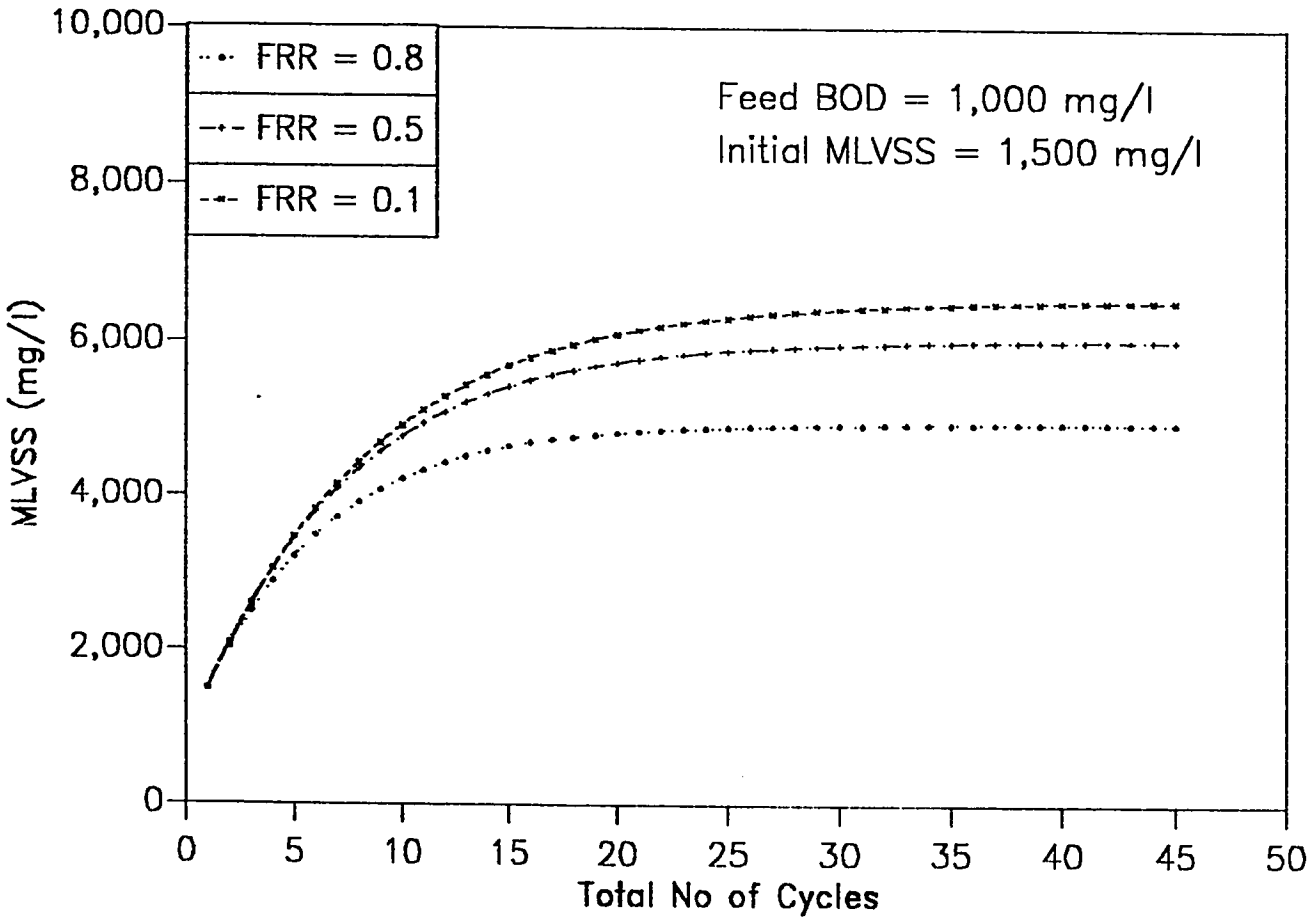


Figure 5.35: Simulation of Fill–React Ratio

waste treatment and improves the effluent quality. Figures 5.32 - 5.35 show the theoretical profile of MLVSS during acclimatization under different initial condition. From these simulations, it was found that the MLVSS build-up is affected very much by the variation of fill-react ratio. This is due to the fact that extending the fill period will limit the microbial growth and the decay effect will dominate. Therefore, in all scenarios investigated, the lower FRR is the higher MLVSS build-up rate.

5.6.2 Effect of Fill-React Ratio on Effluent BOD

The effluent BOD is an important parameter for evaluation of the performance of any treatment plant. The present simulations revealed that, the lower FRR is the lower effluent BOD (Figures 5.36 - 5.39). Even in the case of higher FRR, the effluent BOD is less than 5 mg/l after 10 cycles of operation. Lower value of FRR means a relatively shorter fill followed by an extended react which alows more time for waste biodegradation. The findings of Misbahuddin and Farooq (1991) supports this.

5.6.3 Effect of Fill-React Ratio on Effluent TSS

During the present simulation, the effluent TSS also was monitored to see the general trend of this parameter. The effluent TSS decreased with increasing FRR value, e.i the higher the FRR the lower was effluent TSS and vice versa for all scenarios considered (Figures 5.40 - 5.43).

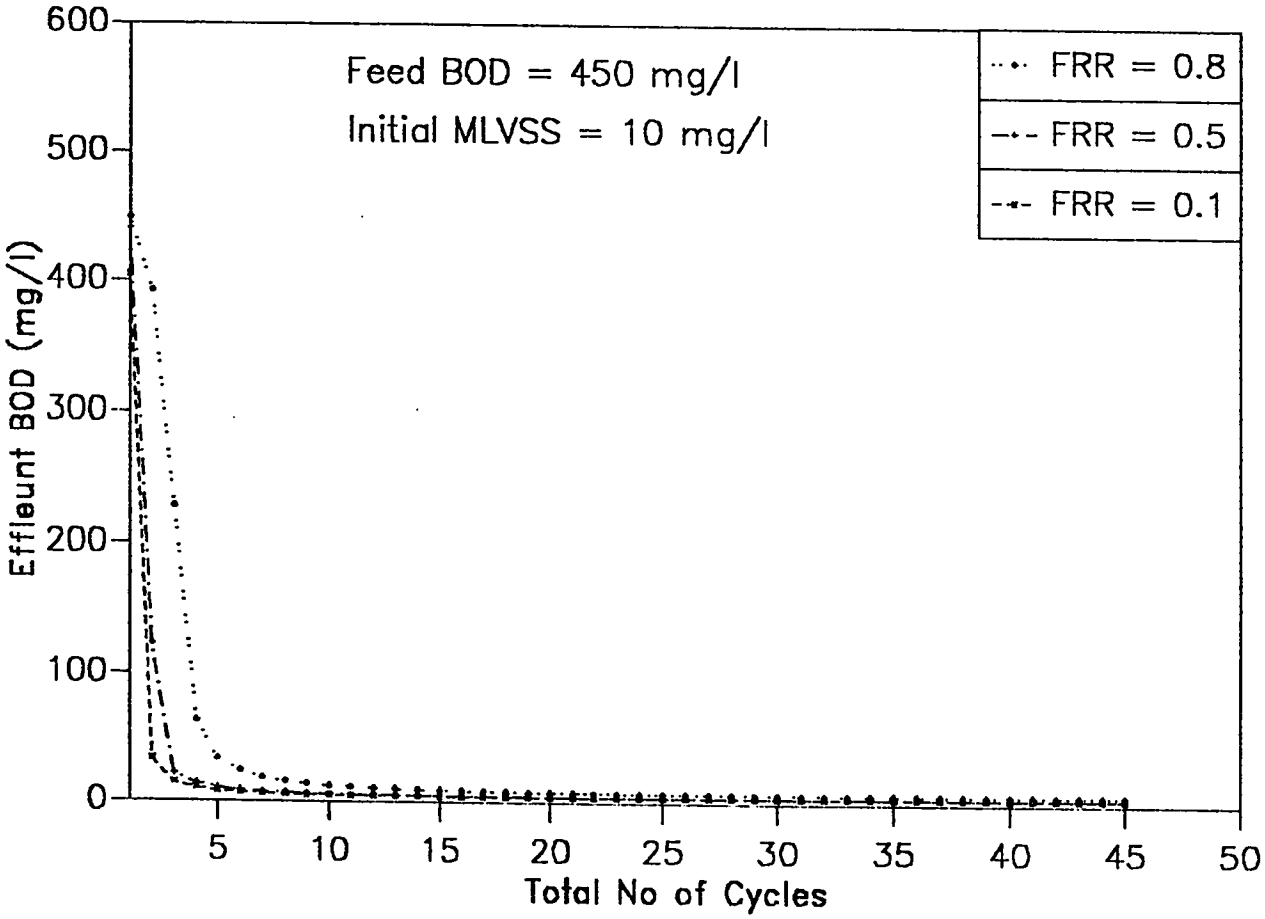


Figure 5.36: Simualtion of Fill–React Ratio

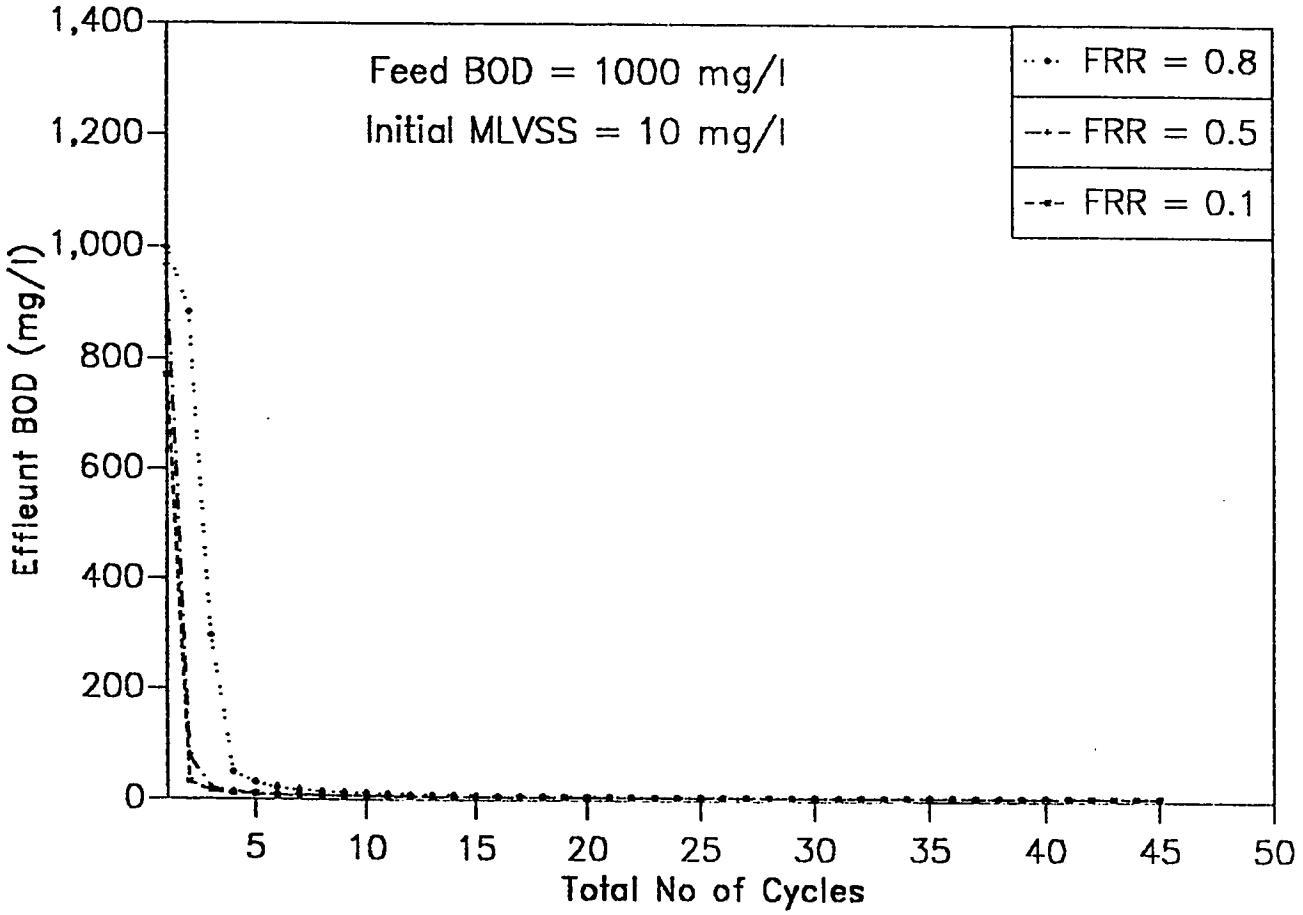


Figure 5.37: Simulation of Fill–React Ratio

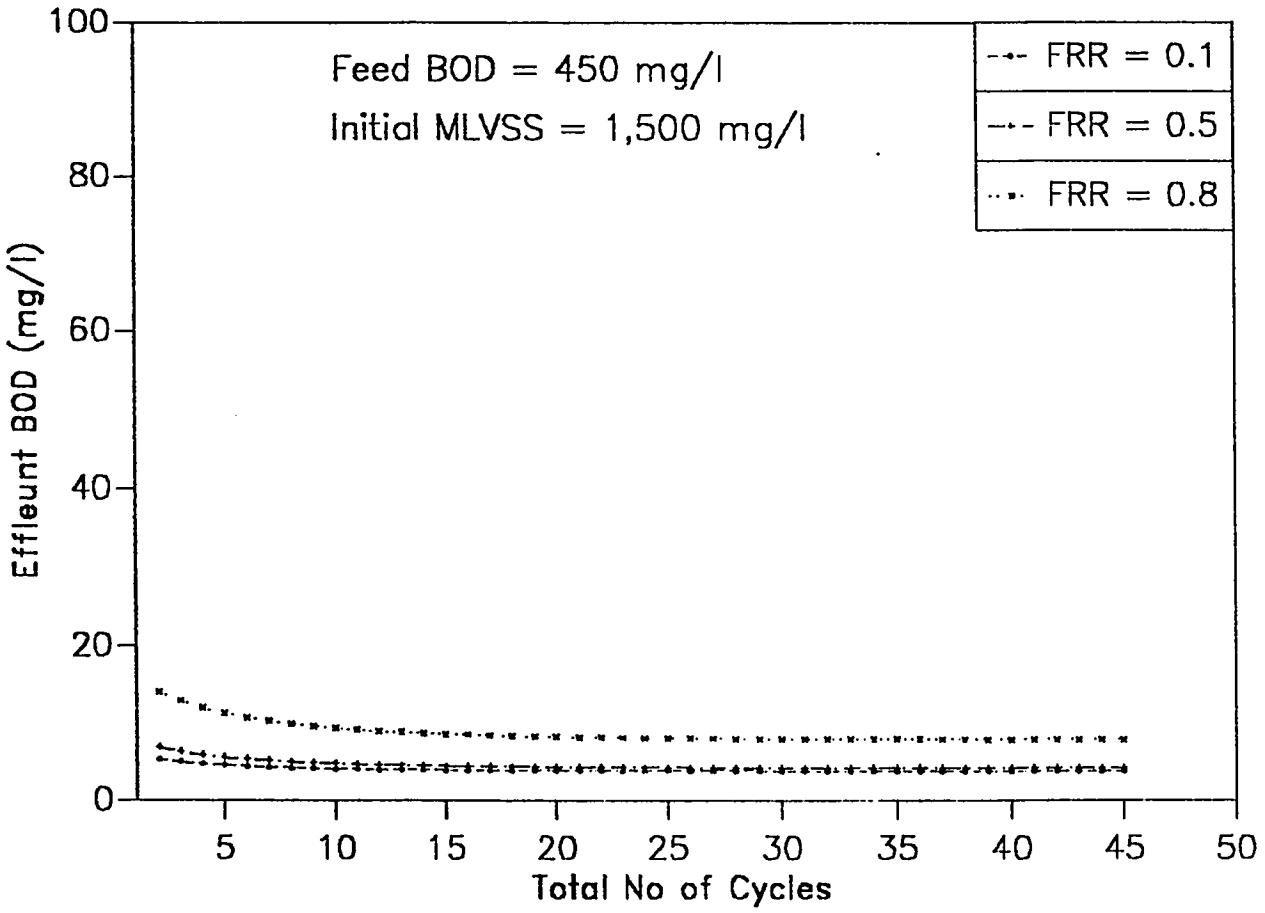


Figure 5.38: Simulation of Fill–React Ratio

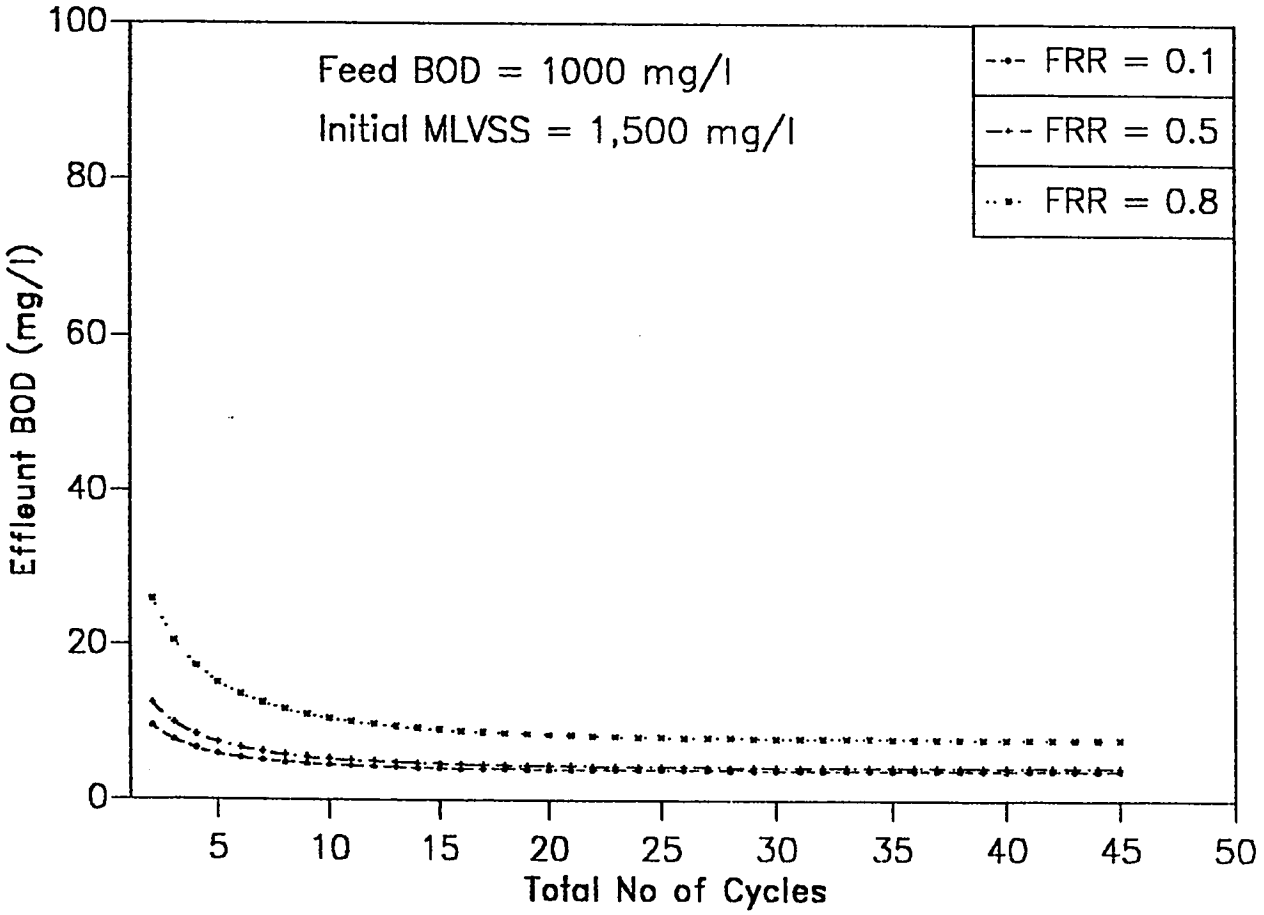


Figure 5.39: Simulation of Fill–React Ratio

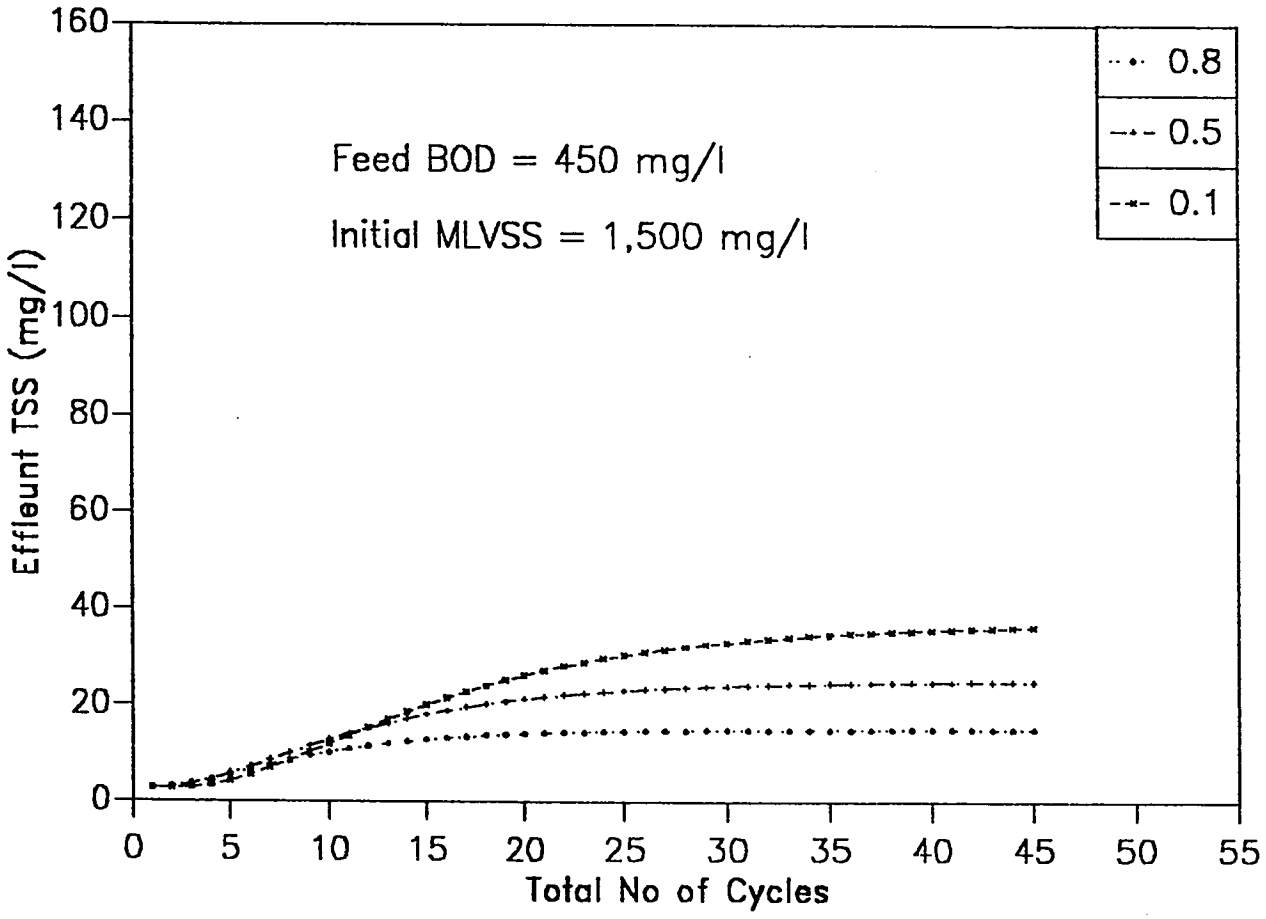


Figure 5.40: Simulation of Fill–React Ratio

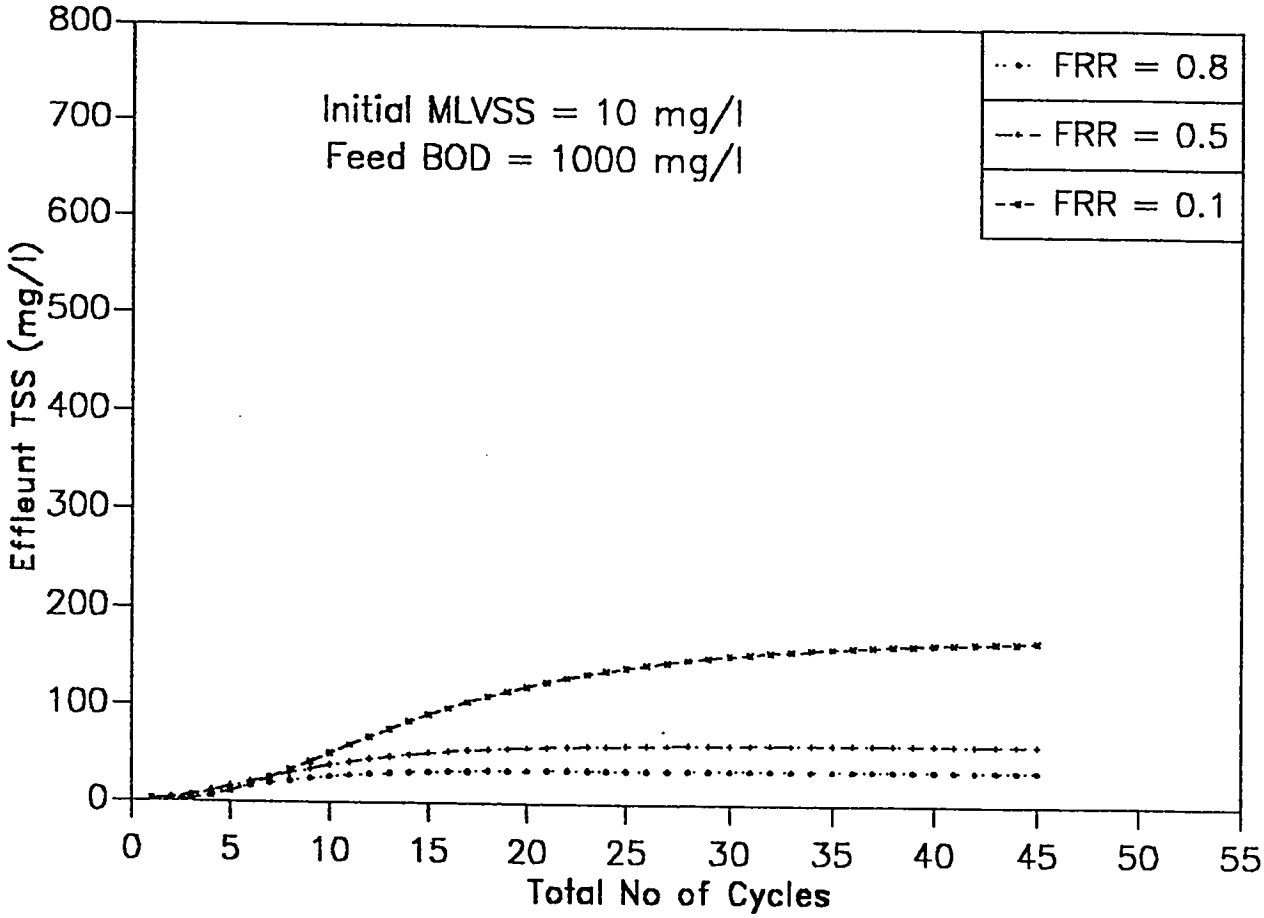


Figure 5.41: Simulation of Fill–React Ratio

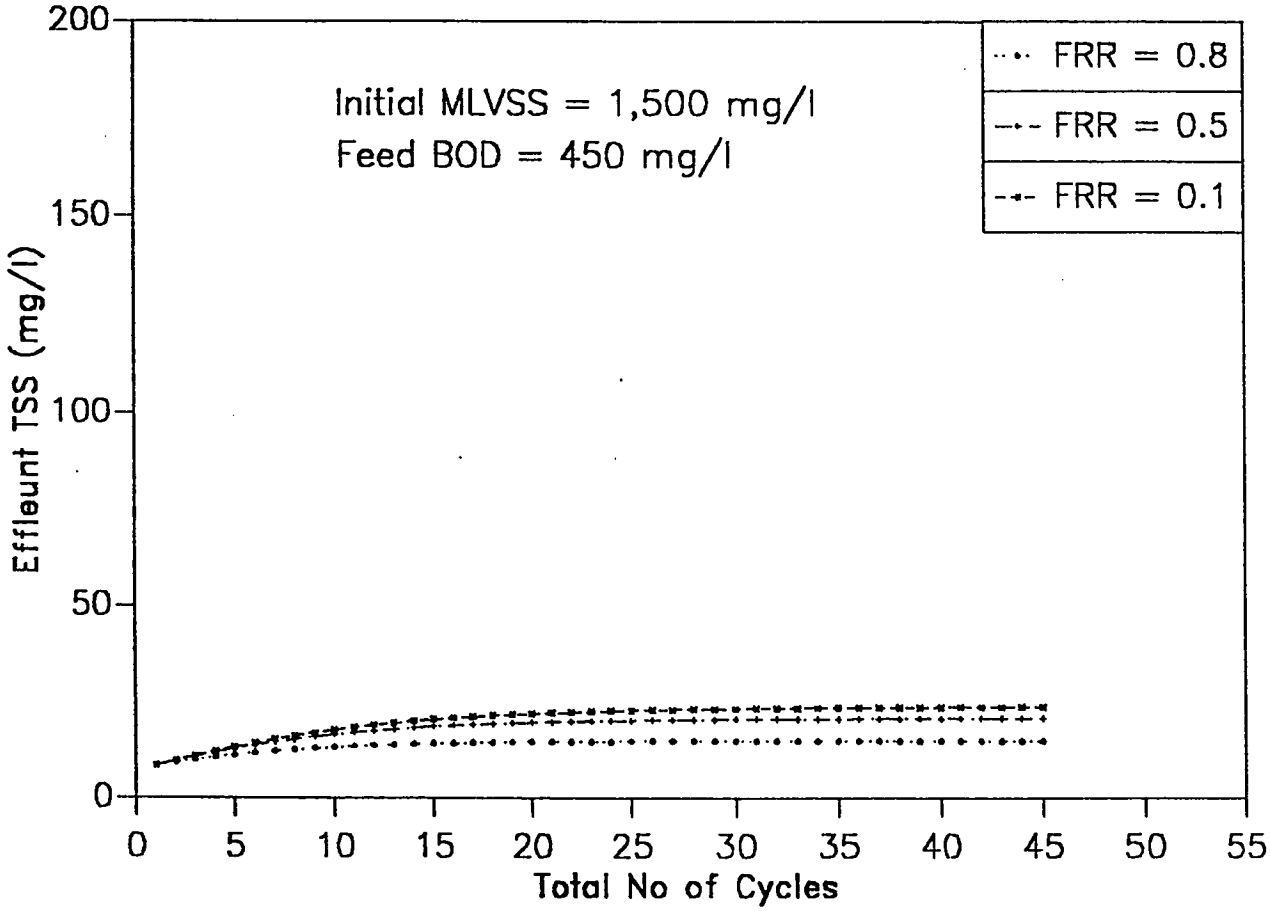


Figure 5.42: Simulation of Fill–React Ratio

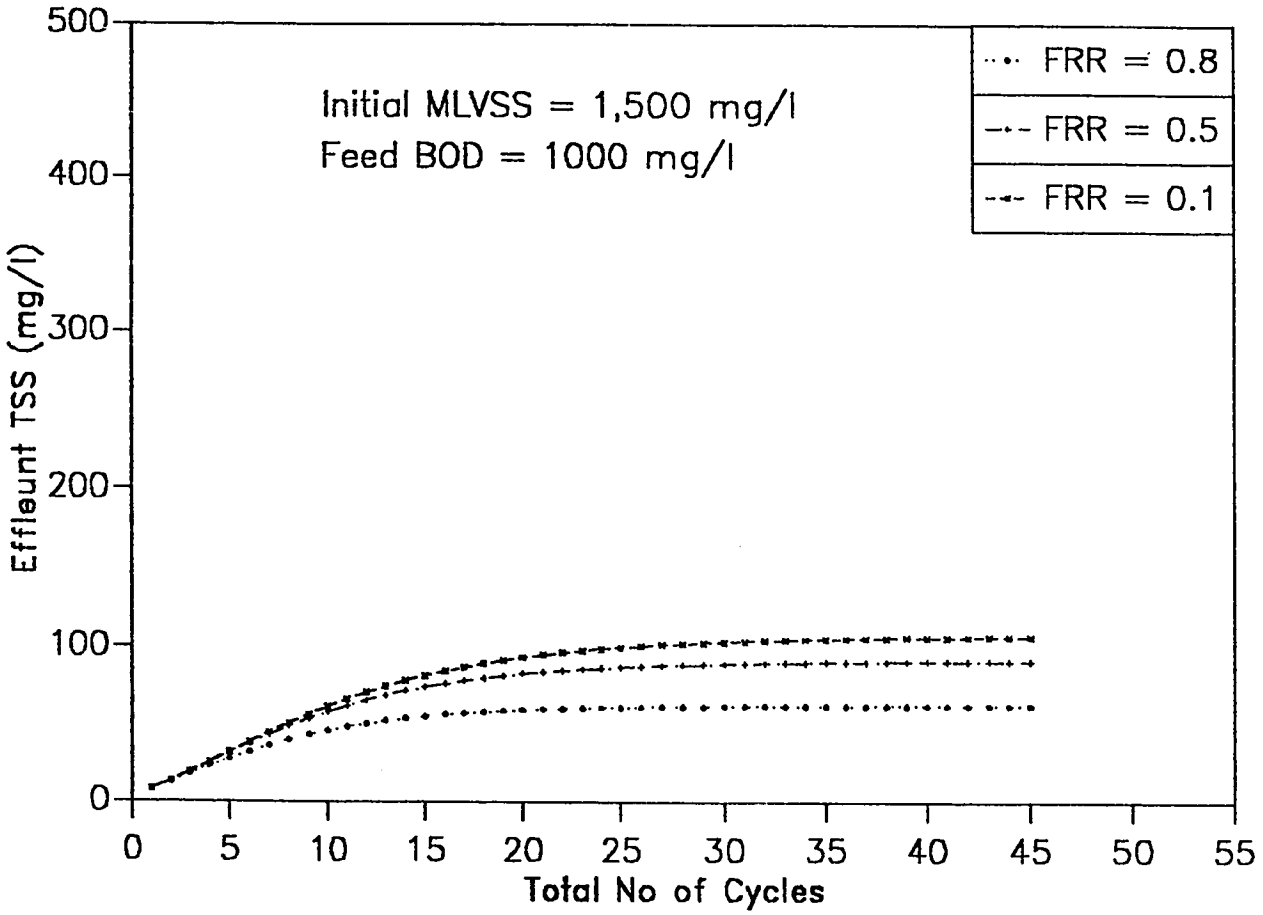


Figure 5.43: Simulation of Fill–React Ratio

In summary, it must be concluded from these analysis that significant substrate removal can be achieved during extended react period and the choice between an extended fill followed by a shortened react period on one hand and a shorter fill followed by an extended react period is primarily governed by the waste characteristics. For low strength readily biodegradable wastes there is no advantage to using an extended fill. However, for high strength biodegradable wastes and toxic wastes an extended fill safeguards against organic overloading and toxicity.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions can be drawn based on the modelling of biological wastewater treatment in sequencing batch reactors.

(a) A model has been developed and validated with experimental data from the literature. The predictions closely matched the experimental data in most cases, although some, discrepancies have been occasionally observed.

(b) Simulation results have indicated that an extended fill period is beneficial to the treatment of toxic and high-strength wastes as it mitigates inhibition and organic overloading effects.

(c) Overdesign of the react time beyond that required for organic removal results in significant loss of biosolids and hinders efficient treatment.

(d) Results from sensitivity analysis showed that the impact of magnitude of the kinetic parameters such as μ_{max}, K_s, Y, and K_d, on the microbial growth rate and substrate removal is quite remarkable. Therefore, the appropriate values of these parame-

ters must be used to get accurate predictions.

(e) Finally, it should be recognized that modelling is an essential part of research in each scientific field.

6.2 Recommendations

At the end of this work, we propose the following recommendations for further research:

(a) Incorporate the present model into other kinetic models which will account for toxicity and inhibition phenomena.

(b) Extend this model for multiple species model with respective multiple growth limiting substrates.

(c) Improve the equation for settling period in the model and validate against experimental data.

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