SHOCK LOADINGS OF LAGOONS AND SEQUENCING BATCH REACTORS TREATING BLEACHED KRAFT MILL WASTEWATER

BY

BJÖRN WEEKS

A Thesis

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ABSTRACT

Biological treatment systems used in the pulp and paper industry are subject to shock loadings with concentrated waste. These shock loadings may reduce or eliminate the treatment capacity of the biological system. An experimental shock loading study of aerated lagoons and sequencing batch reactors treating wastewater from an integrated bleached Kraft process pulp and paper mill was undertaken. Under moderate shock loading conditions, systems with low solids retention times (SRT) recovered faster than systems with higher SRTs. Sequencing batch reactors (SBRs) with SRTs from 5 to 40 days were studied experimentally. A more severe shock disrupted treatment similarly in all SBRs, without regard for pre-shock growth conditions. Under both moderate and severe shocks, SBRs can recover more rapidly than lagoons.

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DEDICATION

To my friends and family; too numerous to list, but too important to be forgotten.

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LIST OF ABBREVIATIONS

AOX	-Adsorbable Organic Halides
BOD_5	-5 day Biological Oxygen Demand
COD	-Chemical Oxygen Demand
E	-Process Efficiency
F/M	-Food to Microorganism Ratio
HRT	-Hydraulic Retention Time
MLSS	-Mixed Liquor Suspended Solids
MLVSS	-Mixed Liquor Volatile Suspended Solids
RAS	-Recycled Activated Sludge
RNA	-Ribose Nucleic Acid
SBR	-Sequencing Batch Reactor
SOC	-Soluble Organic Carbon
SRT	-Solids Retention Time
TOC	-Total Organic Carbon
t50	-Time Needed for 50% Recovery
t90	-Time Needed for 90% Recovery
TSS	-Total Suspended Solids
U	-Specific Substrate Utilization Ratio
WAS	-Wasted Activated Sludge

LIST OF EQUATIONS

CHAPTER 1: INTRODUCTION

Shock loadings of biological treatment systems occur in many industries. Shocks are sudden increases in the mass loading administered to a treatment system. Surges in the concentration or volume of waste administered to the treatment system can result in shock loads. Typically, shock loads are caused by spills or process upsets within a plant. Shock loads have the potential to decrease or eliminate the treatment capacity of a biological system. This study examines the effects of shock loading biological treatment systems with highly concentrated industrial waste.

Shock loadings of two distinct types of treatment system, sequencing batch reactors (SBRs) and aerated lagoons, are examined. SBRs are a type of activated sludge treatment that has been successfully used in a variety of industrial applications. Past industrial applications include situations where the systems were subject to unsteady loadings. SBRs are a potential upgrade for an aerated lagoon, which is the most common form of biological treatment in the North American pulp and paper industry.

The laboratory scale reactors used to study the effects of shock loads were fed with waste from an integrated bleached Kraft pulp and paper mill. Shock loadings were administered using concentrated waste from the same mill. The intent was to study the effect of complex and poorly defined shocks, such as would be found in an industrial situation. Laboratory studies reported in the literature focus on well defined, synthetic shocks, using simple substrates such as glucose or sorbitol, rather than the less well defined combinations of substrates found in industrial wastes. These substrates may include toxic or inhibitory compounds. Results from the lab studies with simple compounds may not be applicable to field conditions. Throughout the experiment, four SBRs were operated at different solids retention times (SRTs), in order to evaluate the impact of SRT on shock load recovery. A lagoon was operated simultaneously for comparison.

This document consists of four main sections. The first section reviews the relevant literature and background material on the treatment of pulp and paper wastewater, describes the SBR process, and gives an overview of shock loadings of biological treatment systems. The following section covers the objectives of the experimental work, and the methodology used to achieve these objectives. The experimental results of each experimental run are then reported and discussed. The final section summarizes the main experimental findings, and lists the conclusions drawn from the findings and the literature review.

CHAPTER 2: BACKGROUND AND REVIEW OF THE LITERATURE

The background for this work has been broken down into three main sections. The first section, 2.1, deals with characterization of bleached Kraft pulp mill waste. The second section, 2.2, covers the sequencing batch reactor process for biological treatment and its industrial applications. The final section, 2.3, covers past research into shock loading conditions with biological treatment.

2.1 Kraft Pulp Mill Wastewater

This thesis is concerned with the biological treatment of the wastes produced through paper making using the bleached Kraft integrated pulp and paper mill process. It is therefore important to understand the sources of this waste, its prime constituents, and the treatment strategies currently in use.

2.1.1 Sources of Kraft Pulp and Paper Mill Wastewater

The bleached Kraft process is one of the most common methods used in the production of high grade paper. Mills using the bleached kraft process are in place throughout North America and Europe. This section outlines a typical Kraft process. Liquid wastes from the Fort Francis Boise Cascade integrated Kraft process pulp and paper mill in Ontario were used in this study.

The production of paper by the Kraft process begins with the debarking of logs and processing them into wood chips.

The chips, roughly two centimetres long, are sorted and mixed before being blown into digesters. The digesters are large steel vessels, containing the chemicals that turn the wood chips into pulp. The chemicals used form a strong alkaline liquor that dissolves the lignin in the wood. Lignin can be considered an organic glue that holds the cellulose wood fibres together. It also contributes the brown colour to unbleached pulp. Digestion releases the cellulose fibres that form the pulp.

The pulp is screened and washed after digestion. This turns it into a watery substance which requires dewatering and thickening. If extended delignification is used, it will be done at this point in the process. The pulping and washing produces a waste stream, made up of spent alkaline cooking liquor and dissolved wood lignin. Much of the alkaline liquor is recovered inside the plant and returned to the digester. The liquid waste from the chemical pulping and dewatering can be treated effectively using existing technology. The potential pollutants found in the waste can be recovered for re-use, or used as fuel (Gullichsen, 1991). Unbleached pulp can be produced virtually free of contaminated liquid effluents (Ibid).

After the pulp has been thickened, it is bleached to the desired degree of whiteness. This can be done with chlorine (the traditional agent), chlorine dioxide, or some combination of the two. Since the use of chlorine as a bleaching agent creates chlorinated organics, chlorine dioxide substitution is becoming common practice in the industry. Substituting chlorine dioxide reduces considerably the amount of chlorinated organics produced during bleaching (Gullichsen, 1991). The amount of bleaching needed can also be reduced by removing lignin from the pulp prior to bleaching in a process called delignification. Since bleaching is done to remove the brown colour in the pulp caused by the lignin, delignification reduces the amount of bleach needed to achieve the desired paper brightness. However, despite the possible process modifications, the pollutants in the liquid waste stream produced during bleaching still are of great concern, and make treatment necessary. The nature of the pollutants in the bleach plant effluent is the topic of the following section.

After bleaching, the pulp may be dried and baled for sale elsewhere. It may alternatively be formed and finished into paper at an on-site paper mill.

2.1.2 Composition of Waste

The liquid waste stream from a pulp and paper mill includes many different compounds. A variety of parameters have been used to gauge the strength of the waste. These parameters have been used to monitor the performance of treatment systems in pulp and paper mills, to set regulations, and to establish permit limits.

The traditional regulatory focus has been on the total suspended solids (TSS) in the waste stream, and the 5 day biological oxygen demand (BOD_5). Because of this, most modern plants provide high removals of TSS and BOD_5 from their waste. TSS and BOD_5 are both seen as measurements of the ability of the waste to degrade water quality in the receiving body. TSS degrades quality through the deposition of sediment, and BOD_5 measures oxygen demand on the water body. Despite the recent focus on various priority pollutants, these parameters are still important. Due to the long period of time needed to get results from the BOD test it has been supplanted in recent times by the total organic carbon (TOC) and chemical oxygen demand (COD) tests. These tests provide similar information more rapidly, and are well suited to in-line application.

Pulp and paper mill effluents contain pollutants that are not characterised by either the BOD_5 or TSS tests. A recent survey of effluents from 13 mills in Quebec, including 6 Kraft mills, provided a characterization of the substances found in mill effluents (Lavallée, et al. 1993). All of the wastes contained resins and fatty acids, which are implicated in the toxicity of mill wastes. The wastes also all included a variety of chlorinated organics, including dioxins and furans. The dioxin discharges were in the range of 56 to 197 mg/a. Adsorbable Organic Halide (AOX) measurements, which are a popular inclusive measure of chlorinated organics, were in the range of 2.8 to 4.7 kg/t.

The parameters of chlorinated organics and effluent toxicity are becoming the focus of public and legislative attention. Chlorinated organics have become particularly important since the discovery of dioxins and furans in pulp mill wastes. Chlorinated organics are produced as a byproduct in the bleaching process by the action of chlorine on organic compounds. Chlorine acts as both a substituting and oxidizing agent, creating chlorinated organics (Bryant et al., 1987). Some of the compounds created include: chlorophenols, chloroatecols, chloroguaiacols, chloro-resin acids, chloroform (a halogenated volatile compound), and chlorolignins (a large group of molecules with an apparent molecular weight greater than 1000).

Chlorinated organics are considered pollutants as many are persistent, toxic, and bioaccumulative. In general, the toxicity of the compound is related to the degree to which it is chlorinated. Highly toxic compounds such as dioxins and PCBs are 40 to 79% chlorine by weight. Many of the less chlorinated organic compounds are non-toxic. Some are commonly used in food and drugs (Fleming, 1992).

The most accepted method for the characterisation of the chlorinated organics in a waste is the AOX test. This test non-specifically measures the spectrum of chlorinated organics. It has been suggested that because of its broad nature, the AOX test is inappropriate, and that tests such as "flow field-flow fractionation", which characterise the distribution of molecular weights should be applied (Dixon et al., 1992). However, research has show that the distribution of molecular weights is quite broad in effluents from both Kraft and Sulfite mills (Beckett et al., 1992). This suggests that a general characterisation such as the AOX test, while inherently limited, provides representative results. As of 1993, virtually all current and upcoming regulations for chlorinated organics are based on either the AOX test or some measure of dioxins and furans (McCubbin and Folke, 1993).

The AOX test should not be considered a measure of toxicity. While chlorinated organics have been implicated in the toxicity of bleached Kraft effluents (Walden and Howard 1981), AOX is a poor predictor of either acute or chronic toxicity (O'Connor et al., 1993). O'Connor also showed that bleached and unbleached mill effluents posses a similar level of chronic toxicity. This supports findings that mill effluent toxicity is mainly due to the resin acids and unsaturated fatty acids found in the wastewater (Walden and Howard 1981). The survey of Quebec mills also found a strong correlation between mill effluent toxicity and resin acid content (Lavallée et al., 1993).

The modern treatment of Kraft mill wastes should remove several important waste constituents. Waste treatment must provide removal of suspended solids and organic carbon. The modern treatment system should also offer significant reductions in chlorinated organics, measured either as AOX, or other parameters. The system should also reduce or eliminate effluent toxicity, through the control of resin and fatty acids.

2.1.3 Waste Treatment

Many pulp and paper mills have applied internal controls to help reduce the waste loads produced by daily operations. Upgrades such as in-plant recycling and various process changes are common. However, external treatment systems are still needed. In the past, external treatment has been limited to primary treatment, such as a clarifier. To meet current and future regulations, mills will require some form of secondary treatment. In Canada, all pulp mills should have both primary and secondary treatment by December 31, 1995 (Odendahl, 1993).

The advantages of biological secondary treatment for pulp and paper waste have been well documented. Walden and Howard (1981) cite the detoxification of mill effluents as a major reason for the installation of secondary treatment systems in Canada. Of 13 mills surveyed in Quebec, only the lone mill with secondary treatment had a non-toxic effluent (Lavallée et al., 1993). Secondary biological treatment has been shown to eliminate the acute toxicity of pulp mill effluent, and reduce chronic toxicity (O'Connor et al., 1993). Some removal of AOX has also been found during biological treatment for the reduction of oxygen demand (Bryant et al. 1987).

Despite the demonstrated advantages, not all mills employ secondary treatment, as can be seen from the Quebec survey (Lavallée et al., 1993). Due to regulations, these mills will soon have to adopt secondary treatment. Without secondary treatment stricter regulations for parameters such as AOX will be difficult to meet. In North America, aerated lagoons are the most common form of secondary treatment used by the industry (Oleszkiewicz et al., 1992). Based on the Finnish experience, lagoons are likely to be supplanted by activated sludge systems. In a survey of pulp and paper mills in Finland, Junna and Ruonal (1991) point out that of the plants surveyed, 22 used activated sludge systems for secondary treatment, and only 5 still used lagoons. New lagoons had not been constructed for pulp and paper mills in Finland since the 1970's. Further, none of the lagoons that were still in use were used for the treatment of wastes from Kraft mills. Similarly, in Russia, the activated sludge plant is the most common method used for the treatment of pulp and paper wastes. Most of the existing lagoons have been converted to polishing basins for new activated sludge plants (Kenny et al., 1993).

Lagoons have several shortcomings compared to activated sludge. The performance of a lagoon under transient loadings is questionable. While lagoons can provide good treatment and a high degree of detoxification for wastes under steady loading conditions, they are vulnerable to poor performance after spills and other upsets in mill operation (Walden and

Howard, 1981). A study of aerated lagoons (Bryant et al. 1987) showed that the concentration of both organic carbon and chlorinated organics in the lagoon effluent was closely linked to the concentration of those substances in the influent. This also points to the vulnerability of lagoons after treatment upsets.

The increasing strictness of the regulations governing pulp and paper mill effluents is making secondary treatment systems essential. Aerated lagoons have been proven effective for the removal of biodegradable organics, toxic compounds and suspended solids. However, they are vulnerable to the variations that can be expected in pulp and paper mill wastes. Activated sludge systems are considered the standard in countries that have strict regulations of the sort that are developing in North America. Many Canadian mills are now investigating activated sludge systems for secondary treatment.

2.2 The Sequencing Batch Reactor Process

The Sequencing Batch Reactor (SBR) process is a viable method for the biological treatment of a variety of industrial wastes, as well as municipal wastes. As an alternative to treatment with traditional, continuously-mixed activated sludge, it has grown in popularity throughout the 1980's. Since laboratory scale SBRs were used in the experimental part of this thesis, a description of the SBR process is included in the following section. This discussion will show how the process relates to other forms of activated sludge treatment, and its particular advantages for treating industrial wastes under non-steady state conditions.

2.2.1 Process Description

The SBR process is a type of activated sludge system. All of the processes that are normally associated with an activated sludge system still take place in the SBR. However, the mixing of fresh waste with activated sludge, the period of reaction, the settling out of the sludge, and the decanting of the treated waste all take place in a single basin. The treatment processes are separated in time rather than space. Figure 1 (adapted from US EPA 1986) illustrates the basic treatment process. A reactor is initially filled with waste under conditions that may or may not involve aeration (this depends on the process strategy). The waste is then treated during some period of mixing and aeration.

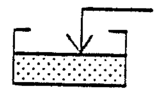
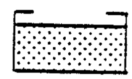
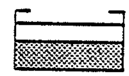
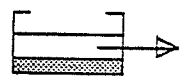
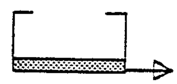
Percent of Maximum Volume:	Percent of Cycle Time:	Operation	Purpose:		
25 to 100	25	Air On/Off	Add Substrate		FILL
100	35	Air On/Cycle	Reaction Time		REACT
100	20	Air Off	Clarify		SETTLE
100 to 35	15	Air Off	Remove Effluent		DRAW
35 to 25	5	Air On/Off	Waste Sludge		IDLE

Figure 1: Typical Operation Details for a Sequencing Batch Reactor (US EPA 1986).

Following the desired treatment period, mixers and aerators are shut off for a period of time. This allows the biomass to settle out. The clarified effluent is then drained off before the next batch of influent is brought in. Since the solids are retained in the basin, the desired solids retention time is maintained by wasting solids directly from the SBR basin. This can be accomplished at several different points in the cycle, most commonly during the idle period.

While the SBR has found wide acceptance in recent times, the basic idea of batch wastewater treatment is quite old. The experimental work of Arden and Lockett in 1914 is often cited as the originator of both activated sludge and batch treatment. They demonstrated the advantage of retaining the sludge accumulated in batch reactors while aerating municipal waste water. However, the technology of the time was not up to the operation of large scale batch operation systems. In relatively recent times, the availability of sophisticated measurement and computer control devices has made batch operations viable and attractive (Arora et al. 1985).

Batch operated systems can handle continuous flows in several possible ways. If multiple reactors are in place, operation can be staggered such that one of the reactors is always receiving waste. If a single reactor is in place, a basin can be used prior to the reactor for the storage of waste between cycles. For the large wastewater flows associated with the pulp and paper industry, the continuous influent, intermittent decant (CI-ID) modification of the SBR process may be most practical way to handle continuous flows. These systems are continuously fed, as in traditional activated sludge treatment, but decanted intermittently as in an SBR.(Arora et al. 1985) This gives the system many of the advantages of the SBR. The main sacrifice in operating an SBR with continuous inflow is the loss of perfect settling conditions prior to decanting. Baffles are used to minimize this disturbance.(Irvine et al. 1985)

Operationally, it is relatively simple to control the cycles of aerobic, anoxic and anaerobic conditions to which the waste is exposed during the treatment cycle. This makes it possible to operate the SBR for the removal of nitrogen and phosphorus, as well as organic carbon (Irvine and Busch 1979). Further, anoxic periods can be used to control the growth of filamentous bacteria. The SBR process also allows simple control of sludge age. Combined with the flexibility of the dissolved oxygen control, the operation of the SBR can be tailored to both the conditions of the influent, and the required effluent.

The SBR has several other advantages that are a function of the batch process of operation. The SBR has no need for Recycled Activated Sludge (RAS) pumping, as the sludge is retained in the basin. Also, the conditions for solid/liquid separation in the basin are ideal, as the SBR basin is completely quiescent during the settling phase, unlike traditional settling basins that must mitigate flow effects. With all processes taking place in a single basin, construction costs are also reduced. In selecting a treatment system for a highly concentrated meat processing waste water, Mikkelson and Lowery (1992) noted the low cost of an SBR system. They found that SBRs had lower capital costs than comparable flow-through systems, partly due to lesser land requirements. Simplicity of operation also leads to lower operating and maintenance costs. A survey of 8 municipal SBRs (Arora et al. 1985) found that costs were significantly lower for SBRs, and that operators found the systems much easier to operate than the previously used continuous-flow systems. The only operational difficulty that turned up commonly was due to poor decanter design. At the time of the survey (1985), proven decanters were available.

While SBRs and traditional activated sludge systems are comparable to a degree, it has been pointed out that experimental findings with an SBR should not be directly extrapolated to continuous activated sludge operations (Benefied et al., 1989). While a steady state can exist in an SBR as an average across several cycles, there is a pronounced transient effect within each cycle. This creates a selection pressure upon the micro-organisms in the reactor, and causes a much different ecosystem to develop than would be found in an equivalent continuous activated sludge system. Chiesa et al. (1985) examined the effects of intermittent high substrate conditions, and found that such conditions created a population with high peak rates of both oxygen and substrate uptake. The populations created by such pressures had several operational advantages such as good settling characteristics, and resistance to starvation. Part of the reason for the good settling characteristics noted was that filamentous bacteria do not possess the needed characteristics for survival under such conditions (Stokes et al. 1968). While filamentous organisms may be well adapted for either high initial loadings or low food conditions, they do not stand up well to the cyclic nature of these conditions in an SBR.

2.2.2 Operation Under Non-Ideal Conditions

As a process, the SBR is well suited to operation under non-ideal situations. SBRs have been used in many different non-ideal applications, including very strong or inhibitory loadings. Data has also been presented that suggests SBRs are well suited for unsteady loading situations.

The SBR has been used to treat very strong wastes. Norcoss et al. (1987) reported on an SBR that was satisfactorily treating meat processing wastewater with a strength of 10,000 mg/L BOD_5. Mikkelson and Lowery (1992) reported over 99% removals treating a meat packaging waste water with an initial concentration of from over 1000 mg/L BOD_5. A continuously fed batch reactor treating munitions waste with a COD of 2500 mg/L was reported to give good results for both COD removal and nitrification/denitrification.

The treatment of inhibitory wastes such as phenolic compounds in SBRs has also been examined. In general, SBRs appear to be less prone to inhibition than comparable flow-through reactors. In the examination of a high strength waste with mixed phenolic compounds, Brenner et al. (1992) found an SBR system to give efficient treatment, and to operate with less inhibition than was expected. A study for a hazardous waste treatment plant (Herzbrun et al. 1984) evaluated the degradation of organic carbon and phenol in an SBR. At retention times varying from 1.5 to 10 days, the system gave excellent result for the degradation of phenol. However, at the lower retention times, organic carbon in the effluent increased noticeably, suggesting the onset of inhibition. Not surprisingly, lower F/M ratios provide protection against inhibition in SBRs. However, it has been shown that an SBR can operate at a relatively high food to microorganism (F/M) ratio for inhibitory compounds. Nakhla (1993) showed that even at relatively high toxicant loadings, the degradation of other compounds was not inhibited. Varying the F/M ratio from 0.12 to 0.46 mg phenol/ mg MLVSS·d had little effect on either the suspended solids or the organic carbon in the SBR effluent. Nakhla also noted that the onset of inhibition was linked to the F/M ratio. Other researchers have noted that lower loadings also improve the performance of SBRs when treating non-inhibitory substrates (Irvine et al., 1985; Oleszkiewicz et al., 1990).

There is evidence to suggest that under various non-steady load conditions, including shock loads, the SBR will provide better performance than a flow-through system. Arora (1985) pointed out four important advantages of the SBR during unsteady loads. First, because the mixed liquor suspended solids can be held in the tank as long as necessary, they cannot be lost through hydraulic shock loads. (If loading conditions cause the solids to become non-settleable, they will be lost.) Secondly, when flows are much lower than the design flow, design operation conditions can still be maintained by operating the basin at a lower level. Third, during the period of filling, the aeration basin is effectively an equalization basin, mitigating any short term spikes. Finally, it is possible to monitor the waste in the basin, and not discharge it until it meets effluent requirements. This capacity is limited, and depends greatly on the design of the plant and flow conditions.

SBRs have generally been shown to be quite hardy under variable conditions. Mikkelson and Lowery (1992) reported that for a meat packing waste stream with highly variable flows and organic loads, the plant's original flow-through system could not cope. The SBR that was installed as a replacement produced consistently good effluent under the same loading conditions. Similarly, Norcoss et al. (1987) found that extreme variations in flow rate and pH had little effect on the effluent quality from their SBR treating meat processing wastes. In a study of a SBR treating high strength industrial waste, Bell and Hardcastle (1984) noted that the system was very tolerant of a number of operational mishaps, including power outages, mixer failure, and accidental overfeeds (shock loads). Unfortunately, they did not discuss in detail the effects of these upsets.

The most direct study of the effect of loading SBRs in an unsteady manner was conducted by Pisano et al.(1989). This study looked at the effects of organic shocks on sequencing batch reactors treating synthetic wastewater. The SBR study was conducted with 15 litre laboratory scale reactors. The reactors were acclimatized to a synthetic waste, and then shocked with a priority pollutant, toluene. The shock solution and the regular feed both had concentrations in the range of 300 to 500 mg/L BOD; the shock was qualitative in nature. The shock was administered by replacing 6 litres of clarified reactor contents with 6 litres of the shock solution in two reactors, and 6 litres of the regular feed in the control reactor. All reactors were then monitored after the shock. The shock loading had virtually no effect on the effluent.

In another study, Herzburn et al., (1984) took sludge from phenol-acclimatized SBRs, and subjected them to "spiking studies". In these studies, the sludge was dosed with various quantities of a phenol based substrate, and the oxygen uptake rate measured. At lower dosages, the oxygen uptake rate increased with the increase in substrate. However, as the dosage increased, the rate of change in the oxygen uptake rate decreased in an asymptotic fashion. The results of this study suggest that the sludge had a reserve capacity for uptake. This allows the sludge to consume more substrate than normal under a shock loading condition. The results also suggest that this reserve capacity is limited, and that shocks above a certain mass loading will overwhelm the reserve.

Some of the advantages presented for the SBR system under shock loadings are based in what are essentially mechanical benefits of batch systems, such as perfect settling and the capacity of the basin. However, the SBR has advantages on a microbiological level for coping with unsteady loadings. An SBR operates under a condition of continual low-level transient loadings. This creates environmental pressures that select certain types of microorganisms over others.

It has been shown that SBRs breed microorganisms with a high peak substrate uptake rate (Chiesa et al., 1985). This study also showed that organisms selected in an SBR have a high peak oxygen uptake rate, and rapid settling qualities. Irvine (1985) looked at the RNA content of microorganisms in activated sludge. In his study, he found that the microorganisms in an SBR had RNA levels three to four times what would be expected from microorganisms in comparable continuous flow situations. The growth rate of a microorganism depends largely on its RNA content. This means that the bacteria in an SBR can be expected to grow and process substrate much faster than the bacteria in a continuous flow system.

The specific character and adaptions of microorganisms in a SBR are developed as a result of their continual exposure to low level transient conditions in batch operation. It appears that the attributes selected by these conditions are also ideal for coping with shock loads.

The SBR process is an activated sludge system, operated as a fill and draw process. SBRs are capable of treating many wastes, including waste streams that have a variable nature, or contain toxic or inhibitory substrates. Batch operation selects microorganisms that are well suited to variable conditions. Batch operation also gives considerable operational flexibility.

2.3 Response of Biological Treatment Systems to Shock Loads

2.3.1 Shock Loads

Few biological treatment systems operate without experiencing some shock loadings. In the pulp and paper industry, shock loads to treatment systems are fairly common, and may occur in a variety of ways. The literature to date on the characterisation of shock loads and recovery from shock loads is covered in this section.

Shock loads are normally divided into two main groups: quantitative shocks and qualitative shocks. Quantitative shocks include any change in the mass loading of substrate administered to a treatment system. Qualitative shocks involve a change in the nature of the substrate. The substrate may become toxic or inhibitory in a qualitative shock.

A strict qualitative shock may be applied in a variety of ways. An increase in the concentration of substrate that is fed to the reactor can cause the same change in mass loading as an increase in flow at a constant concentration. The two effects can also be combined. In theory, equivalent increases in mass loading will have equivalent effects on treatment systems, regardless of the method of application. This was shown by Grady (1971) in a study using mathematical modelling of the activated sludge process. However, experimental work (Manickam and Gaudy, 1985) has shown this not to be the case.

They found that a concentration shock produced a much greater increase in the effluent COD than an equivalent mass load applied with an increase in hydraulic loading. However, the hydraulic shock was more disruptive in terms of the leakage of suspended solids. In this study, they found that equations based on Monod-style kinetics did not accurately predict the performance of the treatment system. They suggest that because the complex biological changes caused by a shock load affect kinetic parameters, it may not be possible to model shock load responses accurately with kinetic equations.

The intensity of a quantitative shock load is often characterised by the change in mass loading. However, Krishnan and Gaudy (1976) found that the intensity of the shock, measured as a percentage increase in mass loading, is more important in describing the event than the absolute magnitude of the shock load.

In many industries, shock loads to treatment systems may include a wide variety of qualitative loads. Qualitative shock loads require special consideration, as they stress the treatment system much more than straight quantitative shock loads. This was found by Manickam and Gaudy (1979) in a simple laboratory study, with glucose-acclimatized activated sludge shocked with sorbitol. Other researchers have looked at more complex qualitative shock loads. Santiago and Grady (1990) performed a simulation study on the effects of shock loads with phenol, an inhibitory chemical. Lange et al.

(1989) looked at toxic inhibition with 2-chlorophenol in a laboratory study.

A review of the literature has shown that several different kinds of shock load events are used by researchers. A shock load may be applied as a "pulse" loading. This is a short duration increase in loading, followed by a resumption of the normal (pre-shock) loading. The reactor undergoes a single disruptive event, and then returns to pre-shock operation over time. Also common in the literature is a "step-up" shock load. This is a rapid or instantaneous change to a more concentrated feed, which then becomes the normal feed for the reactor. The system must then adjust to a new steady state, different from pre-shock conditions. The final kind of shock loading found in the literature is the "step-up and step-down" shock load. The first part of this shock load is like the "step-up" shock load. The concentrated feed is maintained for a period of time which is long enough for the system to react to the change. The feed is then returned to pre-shock levels, and system recovery is to pre-shock conditions as in the pulse load, but after having experienced two disruptive events.

How to quantify the response of a system to a shock load is an important problem. One of the most useful and practical approaches to this problem was given by Gaudy and Gaudy (1980). The effects of shock loads were characterised by the substrate found in the reactor effluent. Both the magnitude of the substrate in the effluent, and the time taken for it to return to normal were considered. This was done with the removal efficiency, E (%), defined in the following equation:

$$E = [\frac{S_i - S_e}{S_e}] * 100 \qquad (1)$$

The substrate concentration in the reactor effluent is S_e, and the feed concentration is S_i. Assuming the system was functioning well prior to the shock, the response to the shock load can be characterised by both the time taken to return to pre-shock efficiency, and the maximum substrate in the effluent (S_e). The indicators of an unsuccessful response include prolonged periods of high substrate in the effluent, a permanent breakdown of substrate removal efficiency, and an increase in effluent suspended solids.

These criteria are used in some form by most researchers for the comparison of various treatment systems, and to define what gives a better response. However, in order to gain a better understanding of what is happening in the system during shock loading and recovery, some characterisation of biomass and growth are common. Most often, the suspended solids or volatile suspended solids are monitored for this purpose. Some studies have also monitored protein and carbohydrate to observe changes in biomass composition (Krishnan and Gaudy 1976, Manickam and Gaudy 1979).

2.3.2 Minimizing Shock Load Effects

It is generally accepted that the best way to minimize the disruptive effects of a shock load is to provide sufficient equalization prior to biological treatment. However, there are practical limitations to how much equalization is possible. Therefore, biological treatment systems should be designed to minimize the effects of shocks (Santiago and Grady, 1990).

A shock load by definition creates a rapid change in the environment within a treatment system. Under normal treatment conditions, a complex ecological balance exists within the treatment system. The shock load upsets this balance dramatically. This upset has been noted as the main source of operational difficulty after a shock load (Gaudy and Gaudy, 1980). The microorganisms that are well suited to the normal operating conditions may be very poorly suited to the transient conditions. Therefore, microorganisms that could have functioned very well in both the pre- and post-shock environment may be diluted out of the system due to their inability to compete during the transient. This means that after a shock load, there may be a drastic change in the environment. The ecological upset after a shock load can result in prolonged instability of the treatment system. In a study of phenol-acclimated activated sludge systems, Rozich and Gaudy (1983) noted dramatic ecological changes after shock loading, coupled with prolonged instability. Instability after a shock was also noted by Manickam and Gaudy (1985) in their experimental work with non-toxic shock loads.

Considerable research has been undertaken to determine what parameters affect shock load response. Research includes mathematical studies, using combinations of standard kinetic equations and computer modelling to predict the response of various systems to shock loads. These studies often look at varying parameters such as hydraulic retention time and sludge age. Many experimental studies have also been reported in the literature. These form the basis for our current understanding of shock loadings.

Experimental work studying the effects of shock loads on activated sludge have been undertaken by several researchers. The largest single body of work is that of Gaudy and his associates. His experimental work has typically involved laboratory scale reactors treating synthetic, defined wastes. In a summary of his published and unpublished findings, it is stated that "slower growing, higher aged, more mature populations are better poised to respond to a variety of changes in the environmental conditions" (Manickam and Gaudy, 1979). In this paper, three explanations for the benefits of older sludge are postulated. Firstly, in an older system, more autodigestion is occurring. The death and lysis of older cells means that pre-formed organic co-factors will be more available in an older system than they would be in a younger system. This would presumably aid in growth. Secondly, in an older system, there is a greater diversity of species. This is thought to make more cells available that are well suited to the new environment created by the shock load. Finally, as a function of the longer solids retention time, the total number of cells available will be greater. This means that even if large numbers of cells are killed off in the shock event, there will still be a good number remaining for digestion. Taken together, these factors are characterised as a more "balanced" ecosystem, which is more difficult to disturb from its normal operation.

Considerable support for the benefits of longer solids retention times and the inherent older populations exists in the literature. A mathematical simulation study of shock loads conducted by Grady (1971) concluded that the lower the growth rate (that is, the higher the solids retention time) prior to the shock load, the better the response of the system. McLellan and Busch (1969) concluded that the mass of substrate in the treatment system effluent after a shock can be reduced through operation with increased solids concentrations in the reactor. This is equivalent to a greater sludge age. In another experimental study Lawrence and Sherrard (1975) found that poor sludge settling occurred after shocks at low SRT. They also found that changes in the solids retention time were far more important in the mitigation of shock disturbances than were changes in the hydraulic retention time. In a theoretical study of the biodegradation of shock loads using inhibitory substances, Santiago and Grady (1991) found that higher solids retention times reduced the maximum concentration of soluble substrate discharged after a shock load, and also reduced the total mass of substrate discharged. The authors found that in general, solids retention times were far more important than hydraulic retention times. From this, they concluded that greater solids retention provided more biomass to act against the shock, whereas hydraulic effects only provided more dilution. In experimental work with a toxic, inhibitory substrate, Lange et al. (1989) found that elevated biomass moderated toxic inhibition. They noted that increasing the mean cell retention time is the most common method of damping transitory inhibitions.

The general consensus in the papers discussed so far is that a higher sludge age or greater biomass concentration confers a better response to shock loads. However, some benefits of lower sludge ages have been reported. Particularly interesting are the results of Selna and Schroeder (1978). They conducted experimental work with activated sludge treating a complex waste. They operated the system at solids retention times of 5 and 10 days. Administering shock loads with intensities between 2.85 and 7.25 times the regular feed concentration, they found that doubling the solids retention time to 10 days provided no obvious benefit compared to the 5 day retention time. From the data presented in their paper, it appears that at the lower shock loads (approximately three times the regular influent concentration), the system with the 10 day solids retention time shows less leakage of COD in the effluent. However, as the magnitude of the shock increases towards seven times the regular influent, the systems operated at the lower retention time are disturbed a slight but noticeable amount less than those at the longer retention.

While the work of Gaudy generally showed the advantages of higher sludge ages, his study with Krishnan (1976) showed some benefits of low sludge age. Looking at simple quantitative shock loads, they found that slow growth rates (equivalent to high sludge ages) may lessen the total shock mass loading capability of the system, measured as unit mass of substrate per day, per unit of reactor capacity. They found that the higher growth rate of young sludge would give it a greater capacity to consume substrate per unit mass. They expected this advantage to be outweighed by the greater concentration of biomass in an older system.

In a later study (Krishnan and Gaudy, 1985), it was observed that systems with low biomass depend on microbial growth to respond to a shock load. Older systems exhibited a growth rate hysteresis, also termed a kinetic lag. This meant that the system did not immediately respond to a change in the substrate availability with a change in growth. However, in the systems with high biomass studied, the response to the shock load was even better than was predicted for a system where growth rate was immediately affected by substrate. This was ascribed to the "immediate oxidative assimilation of substrate by the biomass, and its conversion to storage products rather than growth", or biosorption.

At young sludge ages, the amount of biomass present in the reactor is less than at older ages. There is, therefore less biomass available for immediate biosorption of the shock load. However, at high sludge ages, more of the biomass will be dead or dying, and it will be poised to respond to the shock in a more sluggish manner (Gaudy and Gaudy, 1980).

Experimental and theoretical work studies often show that the advantages of high sludge ages for a shock load outweigh the advantages of low ages. However, experimental and theoretical studies may not accurately reflect industrial conditions. Some evidence suggests that in industrial applications, treatment systems with faster growth rates are better suited to shock loads. This has been found by Sullivan (1992), over eight years of experience with biological treatment systems used in a wide variety of American industries. His experience repeatedly showed that problems with shock loadings could be mitigated through operation with faster growth rates in the biological systems. Fast growth in a treatment system was established by operating at lower SRT, with a high F/M ratio. While this does increase the production of sludge, it results in improved response to shock loads.

Shock loads of various types are a part of industrial and municipal treatment conditions. Mitigation of these shock loads is best done through equalization. However, design of treatment systems should also consider biological factors that may mitigate the effects of shock loads. Much experimental and theoretical work points to the advantages of high sludge ages for the mitigation of shock effects. However, some experiments and industrial experience suggest that lower sludge ages and the inherent faster growth rates may be better.

2.4 SUMMARY

The Kraft process of pulp and paper production produces a liquid waste stream. The waste includes toxic compounds, suspended solids, biodegradable organics and chlorinated organics from the bleaching process. This waste can be successfully treated biologically, using aerated lagoons or activated sludge.

The SBR process is a flexible type of activated sludge treatment. It has been used in a variety of industrial applications, including the treatment of strong, inhibitory, or highly variable wastes. SBR operation selects microorganisms better suited to variable conditions. Batch operation also provides greater flexibility for the control of the process. These attributes make SBRs attractive for the treatment of pulp and paper waste.

Most treatment systems are subjected to shock loads during their operation. Shock loads may be qualitative or quantitative. Shock loads may include combinations of hydraulic or concentration changes, and substrates of a toxic or inhibitory nature. Research into the effects of shock loads on biological treatment systems has been done, through both laboratory and computer simulation studies. Simulation studies cannot account for the environmental upset that is found after a shock load. Experimental studies of simple shock loading situations have generally found that longer solids retention times mitigate the effects of shock loads.

Some experimental work and industrial experience suggests that under more intense shock loadings, the demonstrated faster growth and greater efficiency of younger sludge leads to better recovery.

The experimental work in this study was designed to look at the treatment of waste from an integrated bleached Kraft pulp and paper mill, under shock loading conditions. Both aerated lagoons and activated sludge were studied. The activated sludge system used was an SBR, due to the demonstrated advantages of the SBR under shock loadings, and its potential for application in the pulp and paper industry. The study looked at the responses of treatment systems shocked several times at different intensities with wastes from a pulp and paper mill, as opposed to the synthetic wastes used in the typical studies by other researchers. In view of the literature, biological system recovery was studied with particular attention to the effects of SRT on shock response.

CHAPTER 3: EXPERIMENTAL OBJECTIVES AND METHODOLOGY

3.1 Experimental Objectives

The main objective of this study was to look at the response to shock loads in aerated lagoons and sequencing batch reactors, treating an industrial waste. Many industrial wastes tend to have a complex or poorly defined composition. This contrasts to the synthetic wastes used in past studies of shock loadings. The study was designed to investigate:

1. The effect of SRTs varied from 5 to 40 days on the recovery from shocks.
2. How the performance of lagoons compared to that of sequencing batch reactors after shock loads.
3. The effect of multiple shocks on treatment systems.
4. The effects of shocks of moderate and severe intensity.

The objectives of this study were developed with respect to the conditions found in the pulp and paper industry. Waste from an integrated Kraft pulp and paper mill was used in the experimental work. Since aerated lagoons are the most common form of secondary treatment in the North American pulp and paper industry, their response to shock loads are studied along with those of activated sludge. Due to changes in regulations, many mills are now looking at treating waste with activated sludge systems. Sequencing batch reactors are particularly well suited to unsteady loadings, and also have the potential to be used as upgrades for existing aerated lagoons. They are therefore the activated sludge system studied.

3.2 Experimental Methods

To meet the aims of this study, laboratory scale reactors were used to study the shock load responses of various treatment systems. Over a period of roughly eight months, four sequencing batch reactors and one lagoon were operated continuously. These treatment systems were acclimatized over a period of several weeks to typical Kraft mill waste water. After acclimation, the systems were subject to shock loadings with stronger waste from the same Kraft mill. The recovery of each treatment system was monitored. After steady state operation had been reestablished, the reactors were shocked again under different conditions. Four different shocks were applied over the course of the experiment.

3.2.1. Apparatus

Illustrated in Figure 2 is a typical reactor used in the experimental work as either a sequencing batch reactor or a lagoon. The plexiglass cylinders that made up the reactors were 6 mm thick, with an outside diameter of 119 mm, and an interior height of roughly 425 mm. This made for a total possible volume of about 4 liters. The effluent line was located at the two liter level in the cylinder. Each cylinder rested on a Can-Lab variable speed magnetic stirrer. The stirrer was adjusted to run just fast enough to ensure complete mixing of the reactor contents. Excessive speed would result in shearing of the flocs.

Each cylinder was aerated with a porus stone air diffuser. The diffusers were connected to a pressurized laboratory air supply. A filter/dust trap was added to the air supply. This prevented dust from entering the air lines to the reactor, and potentially clogging the aeration stones. Some clogging of the aeration stones occurred due to biomass growth. Because of this growth, the stones had to be cleaned regularly by hand scrubbing, or occasionally by soaking with acid. Each air supply was individually controllable, to allow

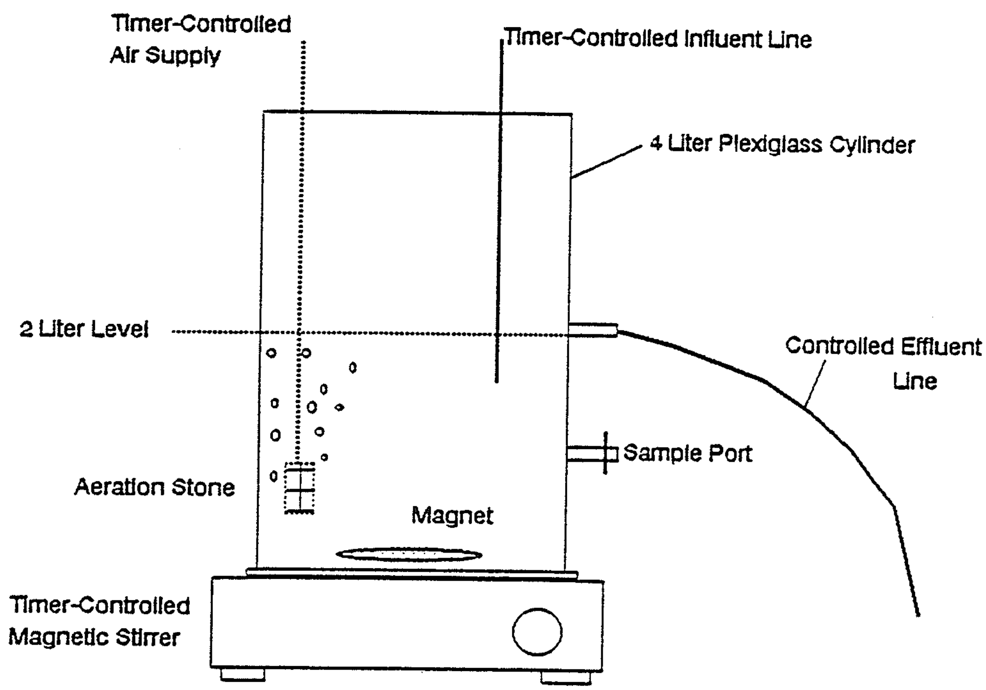


Figure 2: Typical SBR or Lagoon Reactor

fine tuning of air delivery to the reactors, based on dissolved oxygen readings.

Two temperature controlled Econair environmental chambers were used in this experiment. The first was kept at 4° C, and was used to store the Kraft Mill effluent used for the shock loads and regular feeding. The low temperature prevented degradation of the waste strength during storage (Standard Methods; APHA et al. 1992). The second environmental chamber was kept between 20 and 23° C, and housed most of the experimental apparatus, including the reactors. Raw waste was transported from the cold chamber to the reactors by means of Cole-Parmer peristaltic pumps with Masterflex heads and variable speed controllers. One pump was used for the lagoon, and another pump, with four heads, was used for the remaining four reactors. The variable speed controllers were calibrated to deliver the desired amount of waste to the reactors. It was not possible to control this amount exactly throughout the experiment, as growth would occur within the lines and impede flow. The lines were cleaned or replaced whenever such obstruction was noticed.

Reactor effluent was removed through a port at the 2 liter level of each cylinder. A multi-head pump, of the same type used for the feed of influent, controlled effluent removal. Effluent from each day's operation was stored in individual containers. This effluent was kept for analysis. A timer was used to control the operation of all air supplies, pumps, and mixers. Timer-controlled operation was needed to maintain the desired operating cycles. These cycles are discussed later.

3.2.2. Experimental Media

The Boise Cascade bleached Kraft pulp and paper mill in Fort Frances Ontario provided the raw waste used in the experimental work. Composite samples of mill effluents and settling pond effluents were collected in twenty litre pails, and shipped to the University of Manitoba. A shipment was received at the start of each experimental run. Each shipment consisted of typical mill waste, with an SOC concentration of 300 to 500 mg/L, and a bucket of particularly strong mill effluent, with a concentration 3 or more times higher. During the first experimental run, the stronger effluent was used to shock the reactors, and the normal waste was used for the regular feed. After the first experiment, all buckets of regular feed waste were mixed together in a single large container, to help ensure a more even concentration of regular feed.

Pulp and paper mill wastes normally have quite low concentrations of nitrogen and phosphorus. These elements are essential nutrients for the microorganisms used to degrade the waste. Since a nutrient deficiency could interfere with the operation of the reactors, and thus our study, nutrients were added to the waste prior to treatment. According to Eckenfelder and O'Conner (1966), at a BOD:N:P ratio of 100:5:1

nutrients is sufficient. As the waste had a BOD typically in the range of 200 mg/L, roughly 3 mg/L phosphorus was added in the form of orthophosphate. Ammonium nitrogen was added at about 10 to 12 mg/L.

The initial microorganism seed for the five reactors used in this experiment came from previously operated batch reactors in the same laboratory. These reactors had been used in other studies on activated sludge treating Kraft mill wastes.

3.3. Experiment Operation

3.3.1. Experimental Plan

Figure 3 shows in schematic form the overall layout used throughout the experiment, with the influent stored in the 4° C chamber, and the 5 reactors operated in parallel. Reactor 1 was operated as a lagoon throughout the experiment, while the remaining reactors were operated as SBRs. After the initial acclimation of the sludge, there were four separate experimental runs, each consisting of a shock load followed by a period of recovery. The nominal operating conditions in each reactor during the shock loads are summarized in the table below. The first three shock loads were all moderate shocks, approximately three time the concentration of the regular feed, while the fourth was a severe shock load, eight times the regular feed concentration.

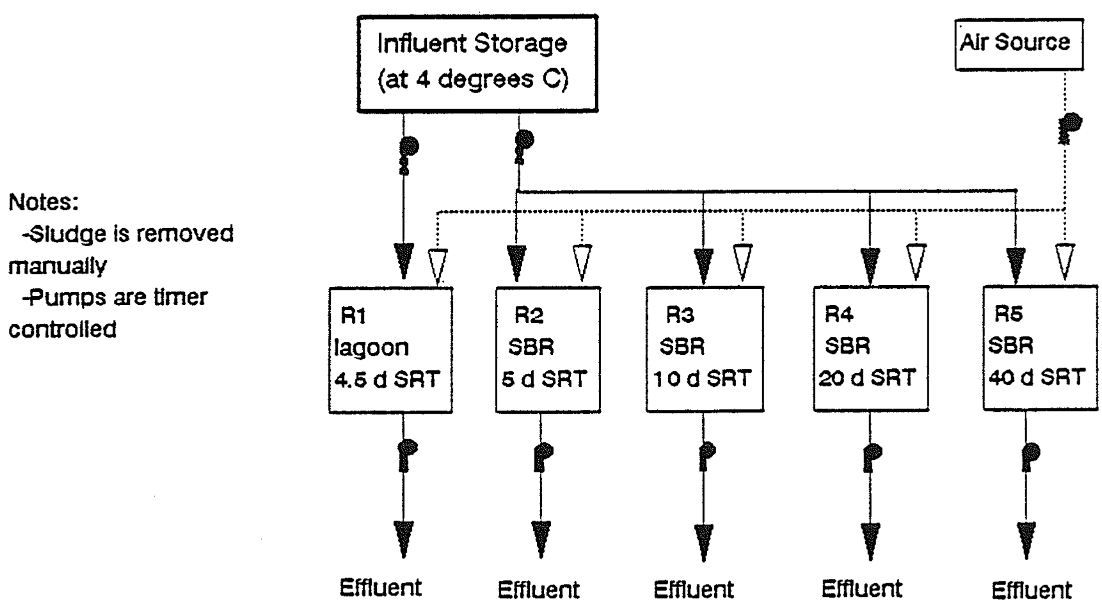


Figure 3: Schematic of the Experimental Setup

Table 1: Nominal Operating Conditions During Shock Loads.

Shock Load (Concentration Change)	I (3x)	II (3x)	III (3x)	IV (8x)
Reactor (SRT)	HRT	HRT	HRT	HRT
Lagoon R1 (4.5 d)	4.5 d	4.5 d	4.5 d	4.5 d
SBR R2 (5 d)	4.5 d	1.5 d	1.5 d	1.5 d
SBR R3 (10 d)	4.5 d	1.5 d	1.5 d	1.5 d
SBR R4 (20 d)	4.5 d	1.5 d	1.5 d	1.5 d
SBR R5 (40 d)	4.5 d	1.5 d	1.5 d	1.5 d

As can be seen in the table, the initial shock load occurred at a hydraulic retention time (HRT) of 4.5 days in all of the reactors. This HRT was changed to 1.5 days in all of the SBRs for subsequent tests. Each reactor was operated at the same nominal SRT throughout the study.

3.3.2. Automatic SBR and Lagoon Operations

The SBR cycle used in reactors 2 through 4 is shown in Figure 4. Each cycle was eight hours in duration, and commenced when the raw waste was pumped from the cool chamber into the reactor. Once the appropriate amount (depending on the desired HRT) had been added, the timer shut off the pumps and switched on the aeration and mixing devices for 6 hours. During this time, the waste mixed and reacted with the biomass. At the end of the mixing period, the timer switched off the aerator and mixer, and the contents of the reactor were allowed to settle. This separated the biomass from the

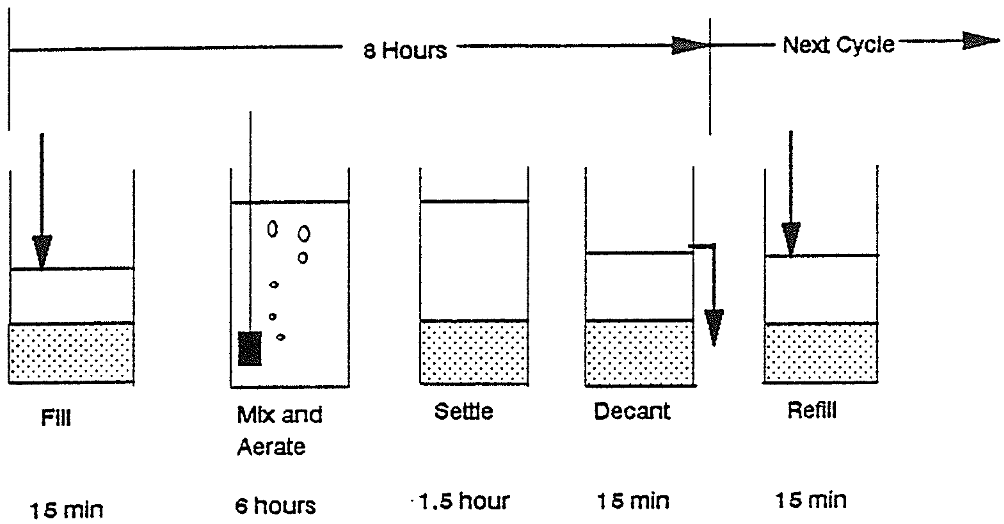


Figure 4: The Sequencing Batch Reactor (SBR) Cycle

treated supernatant. At the end of the 1.5 hour settling period, the effluent pump started, and the clarified supernatant was decanted out to the effluent bottles. The effluent pumps were then deactivated by the timer, and the influent pumps were turned on, completing the cycle.

The lagoon was operated in a similar manner to the SBRs, but was continuously mixed, so that the HRT and SRT were identical. Operating the lagoon with cyclic feeding and aeration in parallel with the SBR was done to make the results more comparable. For instance, at a HRT of 4.5 days, the lagoon will provided sludge with an average age of 4.5 days, whereas one SBR may provide 20 day old sludge. However, both systems will have been fed in the same manner, and have been oxygenated for the same duration.

3.3.3. Solid and Hydraulic Retention Time Control

As discussed, the Solids Retention Time (SRT), or mean sludge age, is an important factor affecting the response of treatment systems to a shock load. The SRT is a measure of the average age of microorganism in the reactor. Since part of the experimental aim was to observe the influence of SRT on shock load recovery, it was important to establish and control the desired SRT in each reactor. The basic principle of maintaining the desired SRT is quite simple. To keep the sludge age at, for example 40 days, one ensures that 1/40th of the biomass is removed each day. Monitoring the solids entering and leaving the reactor, as well as the solids in the reactor, allows such a determination to be made. For this experiment, wasting of solids was done manually. Every day a volume of completely mixed reactor contents, containing the desired amount of solids, would be removed from each reactor and allowed to settle for at least a half hour. The clarified supernatant would then be returned to the reactor, and the settled solids disposed of. The formula used to determine the volume of mixed contents to be removed for settling each day is shown in equation (2).

$$V_W = \frac{\frac{V_R(C_R) + V_T(C_i)}{SRT} - V_T(C_E)}{C_R} \qquad (2)$$

Where:

SRT= Solids Retention Time (days)

C_R= Solids concentration in the reactor (mg/L)

C_E= Solids concentration in the reactor effluent (mg/L)

C_i= Solids concentration in the influent (mg/L)

V_R= Volume of the reactor (L)

V_T= Volume passing through reactor (influent/effluent) (L/d)

V_w= Volume to be removed from fully mixed reactor each day for desired SRT to be achieved (L/d).

The term $V_w \cdot C_R$ gives the amount of biomass wasted each day in mg/d. This calculation and the subsequent waste removal was made on a daily basis, with the most recent data available. The relevant data were collected daily or every other day, depending on operating conditions.

Occasionally, the calculation gave a negative value for V_w. The physical interpretation of this was that more solids were being removed from the system than can be removed while maintaining the desired SRT. This loss of reactor solids in the effluent typically reflected some upset within the reactor. Under such conditions, reactors were left to recover while being monitored. Once solids retention in excess of the targeted solids retention resumed, the daily wasting also resumed.

The hydraulic retention time was adjusted through control of the influent pumps. The pumps were calibrated to deliver the appropriate amount of waste each eight hour cycle to obtain the desired HRT. For a 4.5 day HRT with a 2000 ml reactor, the design daily influent volume was 444 ml, or 148 ml per cycle. Similarly for the 1.5 day HRT used in the SBRs during the second third and fourth shock loads, the design feed volume per reactor was 1333 ml per day, or 444 ml per cycle. In practice, control of the HRT was less precise because of perpetual problems with biomass growth in the feed lines interfering with flow. The actual HRTs, based on the daily effluent volumes, are included in the results section.

3.3.4. Shock Load Application

In the experimental study, shock loads were applied as a pulse increase in feed concentration, measured as SOC. This increase was applied in essentially an instantaneous fashion, although due to the nature of the SBR process, it could also be considered a short term step-up and step-down loading.

The shock solution was culled from a reserved supply of strong mill effluent, similar to that which would cause a shock to a treatment system in an actual mill. To administer the shock, the regular feed was disconnected, and after the treated supernatant from the previous cycle had been removed, the reactor was refilled with the strong mill waste. The actual application of the shock is therefore essentially instantaneous. However, since no new feed enters the reactor until the next cycle eight hours later (when regular feed resumes), the shock can also be considered a step increase in loading with an eight hour duration.

3.3.5. Testing Procedures and Schedule

3.3.5.1 Total Suspended Solids and Effluent Volumes

Total Suspended Solids (TSS) were normally determined every other day, although at some parts of the experiment they were monitored daily. The TSS was determined for the fully mixed reactor contents, as well as the feed and effluent. Determination was carried out in accordance with Standard Methods (APHA et al., 1992) ,sections 2540 A and D (total suspended solids dried at 103-105° C), using Gooch crucibles, and glass fibre microfilters with a 0.45 μm pore size. Every day, the total daily effluent volume from each reactor was measured, prior to testing for suspended solids. The daily effluent volume and the most recent suspended solids data was then used in sludge wasting calculations.

3.3.5.2 Soluble Organic Carbon

Soluble Organic Carbon (SOC) was the main parameter used in characterising waste strength. Organic carbon removal based on the effluent SOC was used to describe the efficiency and recovery of the reactors. SOC was checked at the same time as TSS (daily or every other day), using a Dohrmann Carbon Analyzer. Filtered samples of both the raw waste (influent) and treated waste (effluent) were analyzed.

Some experimentation was needed to get consistent results in the carbon analysis. Initially, testing was done on samples filtered during the determination of TSS. Later, a combination of a syringe and a 0.45 μL disposable screw-on filter was felt to give better samples, and a more flexible sampling procedure. These samples were then acidified with phosphoric acid (H_3PO_4) immediately prior to a 2 minute aeration period. Following this, the aerated samples were immediately injected in 200 uL samples to the carbon analyzer.

It was found that adding acid to the samples (part of the standard procedure with the carbon analyzer) caused a visible precipitation of particulate matter. Within about five minutes of acidification, a film of particles could clearly be observed on the surface of the sample, and the previously uniform sample showed a distinct darkening in the lower half, and lightening in the upper half. After some experimentation, it was found that aerating the sample immediately after acidification prevented visible coagulation of the colloidal material in the sample. Injection of the sample immediately after aeration then provided the most consistent results.

3.3.5.3 Microscopic Examination

Microscopic examinations were made on mixed samples from each reactor throughout the experiment. These examinations gave a qualitative understanding of reactor conditions. Some of the information gained included the nature of the bacterial flocs present, the presence of filamentous growth, and the higher organisms present. For the higher organisms, it was possible to determine the type of organism(s) present, and the general size and diversity of the microbial population. The examinations were carried out on live, wet mount slides, under a light microscope at a magnification of 600x. The information obtained is included in Appendix A.

3.3.5.4 Operating Tests

Several times per shock load, the Sludge Volume Index (SVI) was determined. This was done on fully mixed samples of the reactor contents, as per Standard Methods section 2710 D (APHA, 1992).

To ensure that the aeration system was supplying sufficient oxygen to meet the demands of the shock loaded system, dissolved oxygen was tested approximately weekly. The test was carried out during the aeration phase of the SBR cycle, using a calibrated YSI model 51B oxygen meter. Temperature was checked at the same time dissolved oxygen was measured, using a good quality mercury filled thermometer, as per Standard Methods 2550 B (APHA, 1992).

Monitoring of the pH was done typically once a week. The pH of the influent was tested, along with that of mixed samples of the reactor contents, and of treated effluent, using a Corning Scientific Instruments Model 5 pH meter.

3.4 Analytical Methods

Under non-steady loading conditions, much of the traditional analysis for activated sludge becomes more difficult. Many of the parameters that can be used to characterise a steady state system, such as the food to microorganism (F:M) ratio, or the specific substrate utilization rate (U), keep changing over time. Many of the parameters can still be found or estimated, by applying an understanding of the kinetics of the shock load.

One of the most basic characteristics of a biological reactor's performance is the removal of substrate by biological consumption. Under non-shock loading circumstances, this is simply the difference between the substrate concentration in the influent (S_o), and the effluent concentration, S. After a shock loading situation, this is no longer true. Instead, the term (S_o-S), must be replaced by a term that indicates the difference between the effluent concentration that would be expected if no biological consumption occurs, and that which actually occurs. Figure 5 illustrates this point, showing the dilution curve that represents the expected effluent concentration after the shock without consumption, much as S_o did prior to the shock load. The difference between this dilution curve and the actual effluent concentration is the biological consumption that is represented by S_o-S in equations.

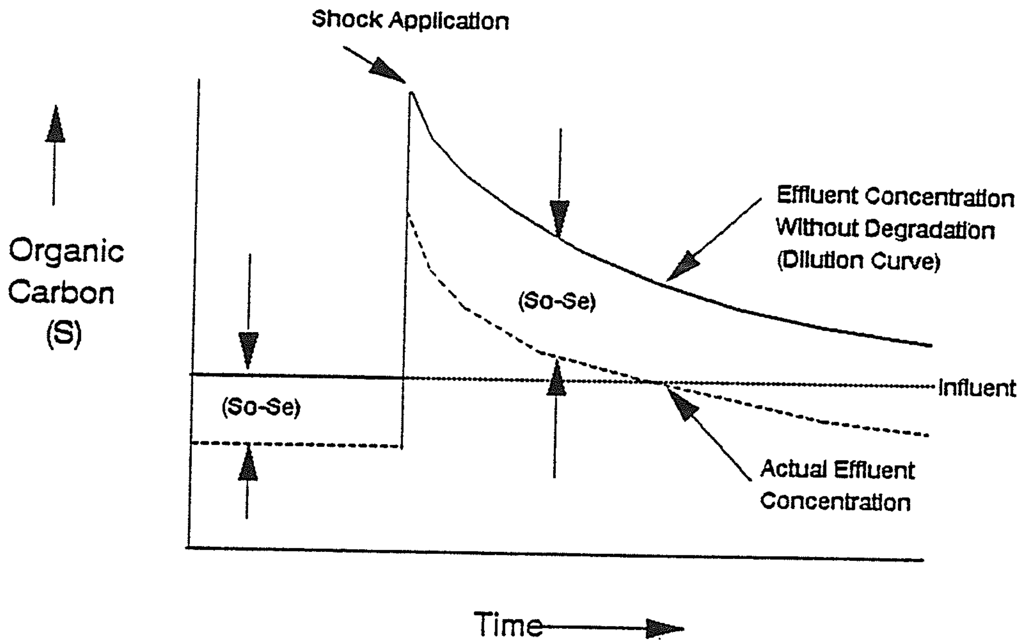


Figure 5: Substrate Consumption After Shock Loading

Returning to parameters such as U, and E (the process efficiency), it can be seen from the equations below that in order to determine these parameters, a dilution model is needed.

$$U = \frac{S_o - S}{(HRT)\ X} \qquad (3)$$

Where X is the concentration of biomass in mg/L

$$E = \frac{S_o - S}{S_o} \times 100 \qquad (4)$$

What is needed is an accurate model of dilution in a sequencing batch process such as our reactors. With such a model, and information on the initial SOC concentration in the reactors, the biological consumption can be determined. With the addition of data for S, X and HRT, the process design and control relationships such U can be determined.

3.4.1 The Dilution Model

The dilution model is a straight forward recursive formula, which considers the reactor to be fully mixed, and the effluent concentration to be a function of the mass of substrate currently in the reactor, the mass removed in the effluent, and the mass added in the influent. The formula derived from this approach is shown below.

$$S_{n+1} = \frac{S_n V_R + S_{o_n} V_{n+1}}{V_R + V_{n+1}} \tag{5}$$

Where;

V_R= Volume of the reactor [L].

V_{n+1}= Volume of effluent from the reactor on day n+1 [L], which is the same as the influent to the reactor on day n.

S_{on}= The concentration of the influent on day n [mg/L].

S_n= The concentration in the reactor on day n [mg/L].

In order to verify this model, a tracer study was run with one of the SBRs, using methylene blue as a tracer. The reactor was initially filled with water having a methylene blue concentration of 2.5 mg/L. The reactor was then fed automatically with deionized water, using the same equipment set-up and cycle as was used during the main experiment. Samples were kept from the effluent jug each day, and the volume of effluent recorded. The initial concentration and the daily effluent volumes were used to predict concentrations in the effluent jug each day. The predicted values showed excellent agreement with the values obtained in the testing. The concentration of methylene blue was determined using a Bausch & Lomb Spectronic 20 spectrophotometer. Detailed results from the tracer study are included in the appendix.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter covers all major results from the experimental work done in this study. A complete listing of the experimental data is included in the appendix. This chapter is divided into three main sections. The first section (4.1) looks at the results from shock load I, the second (4.2) at results from shock loads II and III, and the third (4.3) at the results from shock load IV.

4.1 Shock Load I

In this section, the results from the first shock loading of the treatment systems are reported and discussed. During this phase of the experiment, the normal influent to the reactors had an average strength of 459 mg/L, measured as SOC. The sample standard deviation of the samples' concentration was 55 mg/L, which shows that the regular influent was fairly consistent. The concentration of the strong mill waste used to shock the treatment systems was 1228 mg/L SOC. The shock was administered on November 6 1992. The shock was applied by removing one liter of supernatant after a settling phase, and replacing it with one liter of the strong effluent. This translates into a mass load on the day of the shock that averaged 7.17 times the mass load on a normal day. The standard deviation of this average was 0.69. This reflects slightly different pre-shock mass loads in each of the reactors, due to the small variance of hydraulic retention times. The change in concentration from the regular feed to the shock feed was 2.7 times. Data characterizing the shocks is included in the appendix. The intended HRT and SRT for this trial are shown in Table 1 in the Methods section. The following table shows the actual operating conditions obtained during the run, including the mixed-liquor suspended solids (MLSS) prior to the shock.

Table 2: Experimental Operating Conditions for the First Shock Load.

Reactor	HRT (Days)	SRT (Days)	MLSS (mg/L) Pre-Shock
Lagoon R1	5.1	5.1	508
SBR R2	4.6	5	542
SBR R3	4.2	10	1026
SBR R4	4.8	20	1581
SBR R5	5.6	40	2270

The variation of the HRT from the nominal HRT of 4.5 days was due to the difficulty in accurately controlling the peristaltic feed pumps. Despite monthly cleaning, bacterial growth in the feed lines caused the flow to change over time. The pre-shock solids levels represent averages for several days prior to the shock.

4.1.1. Rate of Recovery to Pre-shock Treatment Efficiency.

Following the recommendations of Gaudy and Gaudy (1980), the rate of recovery to pre-shock treatment levels was used as one of the main parameters to characterise shock load response. The recovery time was considered the time taken by the system to return to its pre-shock removal efficiency. Using this as a criteria had several advantages. It provided practical information, as the time a reactor would be functioning poorly after a shock load would be of great importance from an operational point of view. It also provided a useful relative characterization of the degree to which the ecosystem in a biological reactor had been disrupted. Prolonged instability of operation after a shock load had been described by several researchers (Rozich and Gaudy 1985, Manickam and Gaudy 1985). The time taken to recover indicated how long the biological upset lasted.

Recovery was characterized through two time intervals, the time to 50 % recovery (t50) and the time to 90 % recovery (t90). Both of these were calculated on the basis of the mass removal of SOC. Figure 6 summarizes this data for all reactors after shock load I. Graphs of effluent SOC versus time were used to develop this figure. These graphs are included in the appendix. The first column on the left of Figure 6 shows the 50 and 90 % recovery times for the lagoon, with its nominal SRT of 4.5 days. The remaining columns show the recovery times for the SBR's, operating at solids retention times from 5 to 40 days.

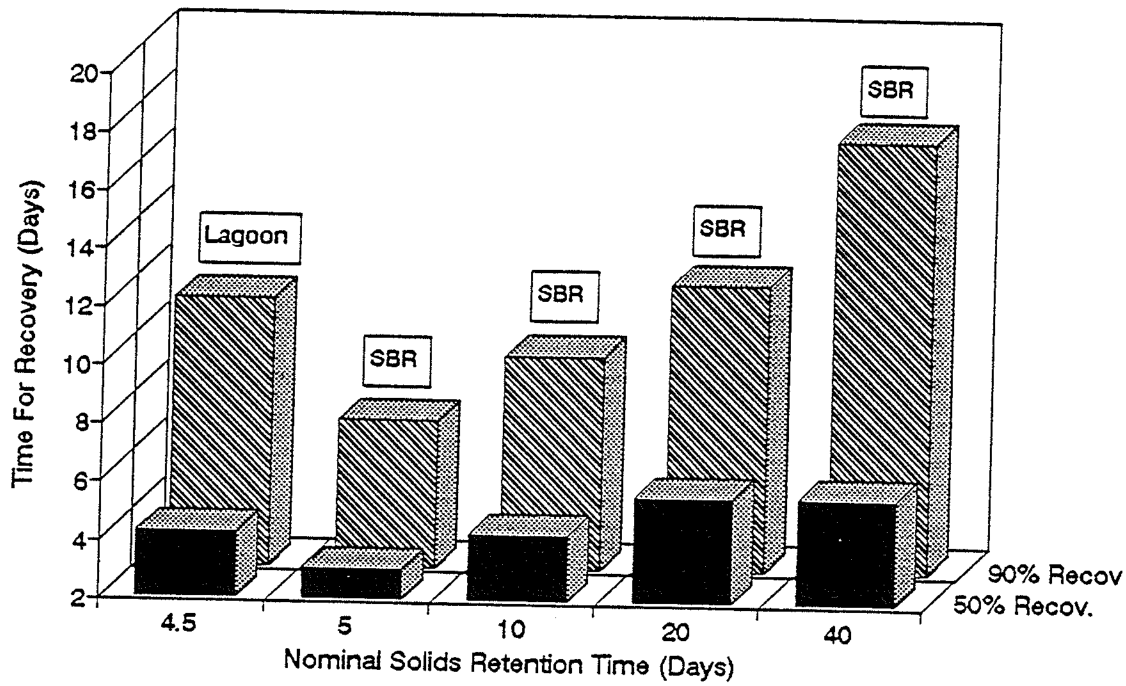


Figure 6: Illustration of the Time Taken for Recovery From A Moderate Shock Load at HRT=4.5 Days

Looking at the SBR's in Figure 6, one can see that there was a tendency for longer recovery times as SRT increased. This trend emerged at 50 % recovery, and became more explicit at 90% recovery. At a low SRT, the microorganisms in the reactor were by definition younger and faster growing than at a higher SRT. This fast growth results in rapid response to changing conditions, such as those due to a shock load.

Virtually the same amount of time was required for 50% recovery for reactors operating at SRTs of 20 and 40 days. It took considerably longer, however, for the reactor with the longer SRT to reach the point of 90 % recovery. This suggests that the initial recovery came about through the actions of the fast growers in the system. More complete recovery required the recovery of the slow growers. This necessarily took longer.

Comparing the lagoon to the SBR, it can be seen that even at very similar operating conditions with respect to HRT and SRT, the SBR recovered from the shock significantly faster. Except for the mode of operation, all other parameters were quite similar (reactor solids, dissolved oxygen, pH, etcetera). The advantage in terms of rate of recovery seemed to be a function of the mode of operation. As discussed in the literature review, the SBR mode of operation has been shown to have certain advantages under shock load conditions. Micro-organisms selected by the SBR had a higher concentration of RNA (Irvine, 1985), and were thus prepared for faster growth and recovery. The micro-organisms retained in an SBR were accustomed to low-level transients, part of typical operation for the SBR. The organisms thus selected may then be better suited to the high level transient of a shock load.

4.1.2. Maximum Organic Carbon in Effluent

Knowledge of the extent of maximum leakage of organic carbon to the effluent is important in describing the effect the shock load has on the treatment system. This parameter gives some idea of the instantaneous effect of the shock load on the treatment system. Depending on regulatory limits, it may be very important operationally to limit peak discharges. Gaudy and Gaudy (1980) suggest that maximum leakage may be used as well as time to recovery for the characterisation of shock load response. Note that in the experiment, the lagoon was operated in a sequencing batch mode, in parallel with the SBRs. Peak effluents from the SBR can therefore be compared to those of the lagoon.

Figure 7 shows the peak SOC recorded in the effluent for each reactor after the shock load. This figure shows that in the SBRs, the greatest effluent leakage (811 mg/L SOC) occurred from the SBR with the lowest SRT, 5 days. The leakage steadily decreased with increases in SRT, to a low of 554 mg/L SOC at a SRT of 40 days.

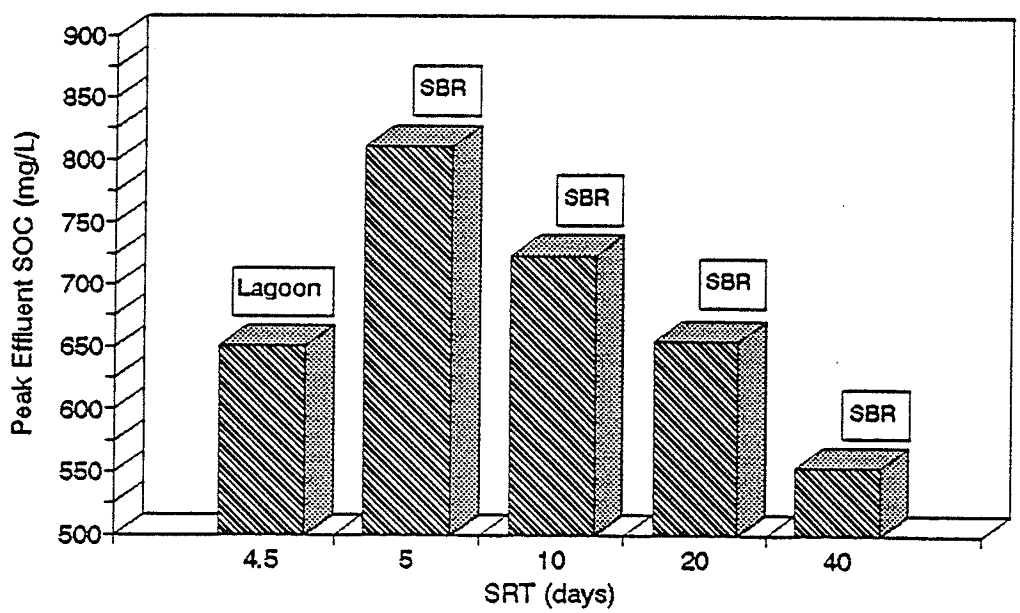


Figure 7: SOC Leakage the Day After the First Shock Load

A partial explanation for this trend may be the effect of biomass concentration. Immediate, non-digestive uptake by the biomass has been demonstrated as a part of shock load response (Manickam and Gaudy, 1985). Since initial leakage was less in reactors with a higher biomass, this may be partly due to such uptake by the biomass. However, this does not explain lower leakage in the lagoon when compared to the SBR operated at similar solids levels. The effect of pre-shock treatment efficiencies may also be a factor, as the lagoon provided slightly better effluent than the comparable SBR prior to the shock (by about 50 mg/L). The differences in pre-shock treatment efficiencies did not seem to be large enough to explain the differences in substrate leakage.

In the laboratory system, mixing was virtually ideal. As a result, even with a 4.5 day hydraulic retention time, peaks in effluent concentration were seen the day after the shock. In contrast, a full scale treatment system in a pulp and paper mill would be treating a very large volume of wastewater. In this case, mixing would be incomplete, and peaks would take a longer time to work through the system. Despite this difference, the effect of non-digestive uptake of substrate on biomass should still be evident in the larger system. Greater biomass concentrations would still result in greater uptake and less immediate substrate leakage.

4.1.3. Effect of Shock on Mixed Liquor Suspended Solids

Examination of the response of the mixed liquor suspended solids (MLSS) after the shock indicates the effect of the shock on the reactor contents. Figure 8 shows the behaviour of the solids over time before and after the first shock load. The relative solids levels were about what would be expected based on SRT, where the highest solids levels corresponded to the longest SRT. The data from this graph is given a brief statistical analysis in Table 3.

Table 3: Statistical analysis of MLSS for the first shock load.

Reactor	Pre - Shock			Post - Shock		
	Average (mg/L)	Std.Dev.	n	Average (mg/L)	Std. Dev.	n
R1	508.8	127.6	8	618.3	127.4	18
R2	542.5	124.9	8	488.3	83.3	18
R3	1026.3	160.4	8	885.6	126.3	18
R4	1581.3	237.3	8	1243.9	272.7	18
R5	2270.0	162.4	8	1923.9	258.2	18

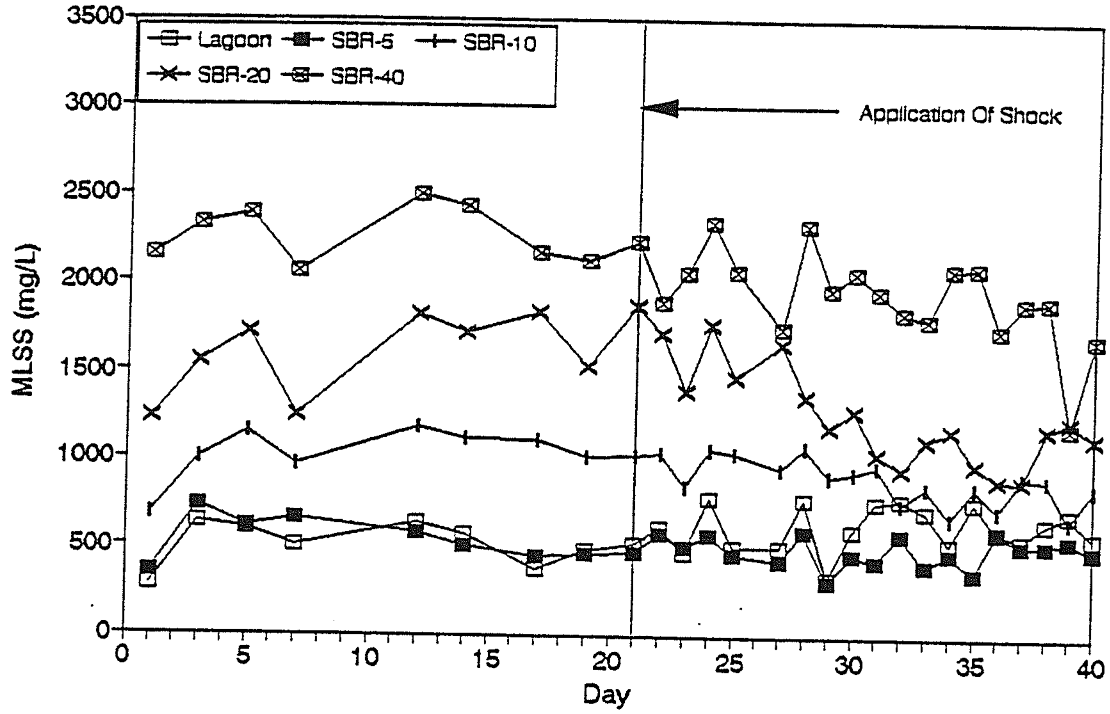


Figure 8: MLSS Before and After First Shock Load

Figure 8 shows that the solids had achieved a roughly steady state in the reactor prior to the shock load application. After the application of the shock, it is clear that the solids in several of the SBRs decreased. Data in Table 3 showed that for each SBR, the average post-shock solids level was lower than that of the average pre-shock solids. In contrast, the lagoon underwent a small but noticeable increase in MLSS, when the period from day 1 to 21 is compared to the period from day 21 to 40.

4.1.4. Effect of Shock on Effluent Suspended Solids

The effect of the shock load on the suspended solids in the effluent also characterizes the response of the reactor. Figure 9 shows the erratic behaviour of the total suspended solids leaked into the effluent. Table 4 reports the statistical analysis of the data shown in this graph.

Table 4: Statistical analysis of effluent suspended solids for the first shock load.

Reactor	Pre - Shock			Post - Shock		
	Average (mg/L)	Std.Dev.	n	Average (mg/L)	Std. Dev.	n
R1	328.0	112.7	8	317.6	126.7	18
R2	146.1	86.1	8	113.1	57.2	18
R3	131.8	91.3	8	181.3	70.5	18
R4	269.0	111.4	8	353.1	170.0	18
R5	111.5	49.4	8	212.0	93.3	18

The statistical analysis of the data showed several interesting points. In terms of operation, the SBR with the lowest SRT provided the best effluent. Both the average suspended solids in the effluent (113 mg/L), and the variability (57.2) were lowest among the reactors in the post-shock operation.

Both before and after the shock load, the effluent suspended solids were highly variable, as is shown by the high standard deviation. The variability did not appear to be closely related to SRT. In reactors 2, 3, and 4 (SRT=10, 20, and 40 days), there was a considerable increase in the effluent solids after the shock load. This increase of solids in the effluent reflected the previously shown result that these reactors underwent a loss of MLSS in post-shock operation.

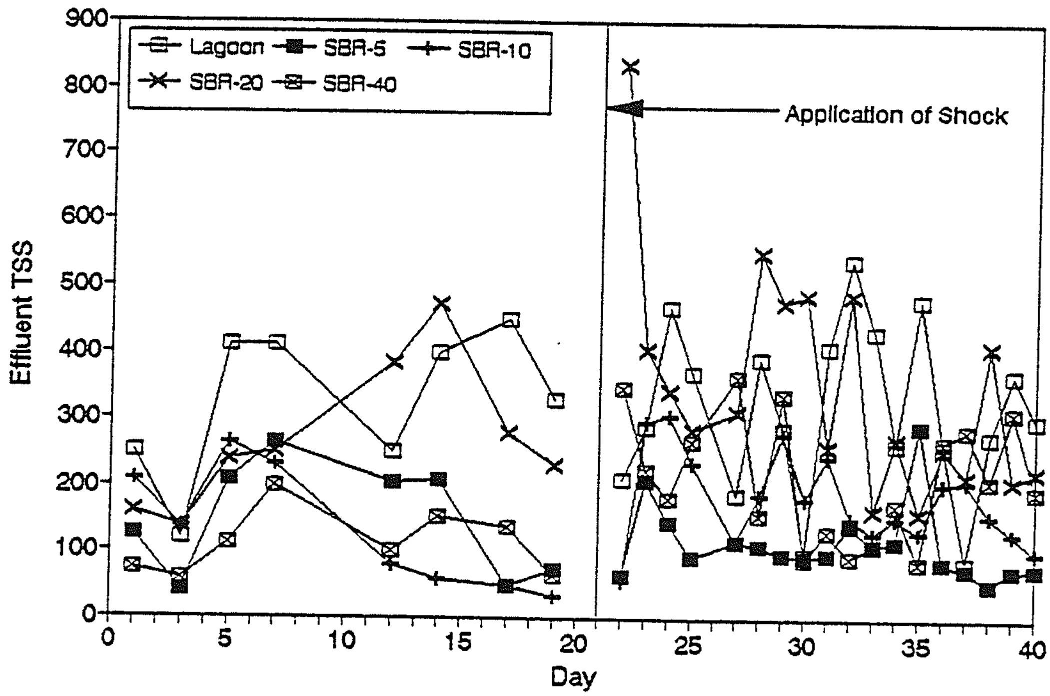


Figure 9: Effluent TSS Before and After First Shock Load

4.1.5. The Specific Substrate Utilization Ratio (U)

Figure 10 plots the specific substrate utilization ratio (U) for all of the SBR's after the shock load. The parameter U was calculated from the experimental data and the dilution model, as described in the methods section. This parameter gave an indication of the per unit mass efficiency of the reactor contents, for the consumption of the substrate. The substrate measure used was SOC.

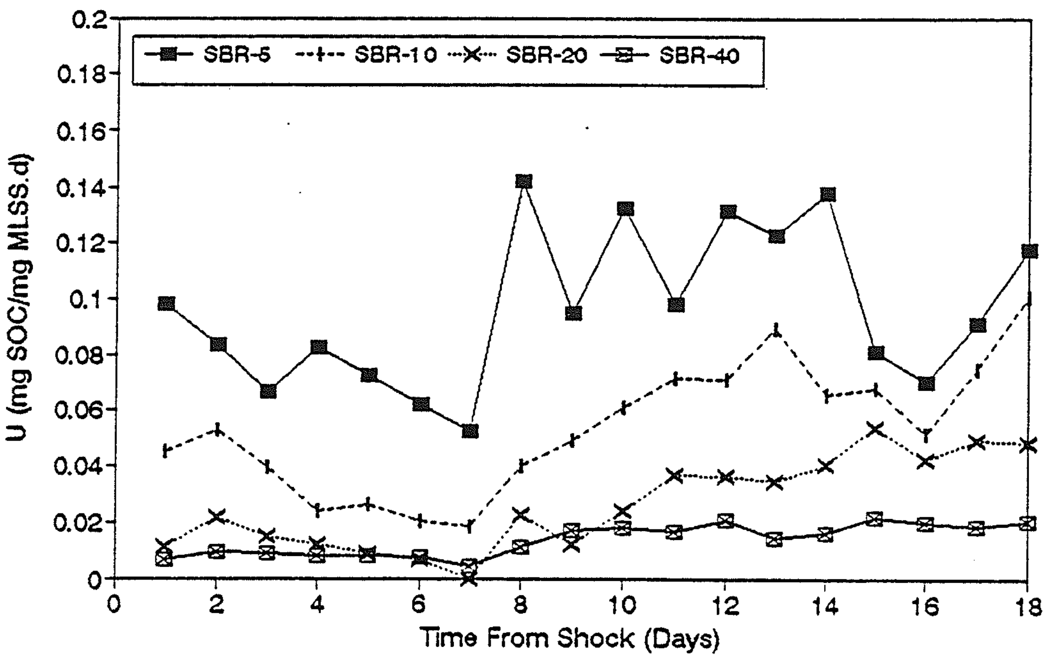


Figure 10: Effect of SRT on U for The First Shock Load

It can be seen in the graph that the lower the SRT, the higher the per unit mass efficiency in the reactor. There appeared to be an inverse correlation between the sludge age, and its efficiency on a per unit mass basis. The greater efficiency of youthful, active sludge at least partially compensated for the lesser concentrations of sludge found in a reactor at low SRT. Krishnan and Gaudy (1976) also found that younger sludge was more efficient at the removal of substrate on a per unit mass basis. However, they felt that this greater efficiency would be outweighed by the greater concentration of biomass found in older systems.

Examination of the graph showed that there was a tendency for the specific substrate utilization ratio to increase after several days. This may have reflected the decrease in reactor solids that also occurred at this point. The figure also showed that while the reactor at a lower SRT operated with a higher specific substrate utilization ratio, this parameter was more unstable at lower SRTs. Instability after a change in loading had been noted elsewhere (Manickam and Gaudy, 1985), and particulary in faster growing (low SRT) systems, (noted by Thabaraj and Gaudy 1969).

4.1.6. The System Response to a Shock Load

The picture that emerged from the results was one of systems greatly disturbed by a shock load. In contrast to the study of Pisano et al. (1989) with SBRs under shock loads, all systems were measurably disrupted and took several times the HRT to return to pre-shock operation. Microscopic examinations of sludge samples from reactor before an after the shock loads suggested that the ecological balance had been disrupted. In general, populations appeared smaller, and predominant species had changed after the shock load. The SBR systems operated at lower SRT showed faster recovery to pre-shock treatment levels. It appeared that in a shock of this severity, the fast growth of young sludge was most important in mitigating the effects of the shock. The advantages of older sludge, related to the greater mass present and the greater capacity for sorption did not appear sufficient to counter balance their slow growth. The greater mass in older systems may have played a role in mitigating the peak substrate leaked into the effluent. Older systems also exhibited a small but significant leakage of reactor solids into the effluent after the shock event. Microscopic study suggests that this was due the floc becoming poorly settleable, and not to the development of filamentous growth.

4.1.7. Summary

A shock load of pulp and paper waste with a mass loading approximately 7.2 times that of the regular feed was administered to five parallel biological treatment systems. The systems were all functioning well prior to the shock. For all treatment systems, the shock caused biological upset. The rate of recovery was highest in the SBR with the lowest SRT of 5 days. Recovery rates worsened as SRTs increased to 40 days. A lagoon recovered slower than an SBR at a comparable SRT.

Peak SOC in the effluent from the SBRs tended to decrease as SRT increased. This trend, shown in Figure 7, was linked to the concentration of biomass in the reactors. In terms of the mass-load of substrate applied, all reactors were shocked equally, and operated under similar hydraulic conditions. The difference in leakage appeared to be caused by non-digestive uptake of substrate onto the biomass. Systems with greater concentrations of biomass (those operated at a longer SRT) had greater capacity for this uptake.

After the shock, MLSS decreased in all of the SBRs, and increased slightly in the lagoons. Effluent suspended solids were lowest in the SBR with the lowest SRT. The decrease in MLSS was reflected in the increase in effluent TSS. The per unit mass efficiency of the biomass increased in the SBRs as the SRT decreased. This greater efficiency, in combination with the faster growth at low SRT, may have been the reason for the faster recovery in reactors with lower SRT.

The results from the first shock load showed that younger sludge recovered from shock loads faster than did older. Shock load II was administered to observe the effects of a similar shock to batch reactors operating at a lower HRT.

4.2 Shock Loads II and III

During shock load I, all treatment systems were operated at a nominal hydraulic retention time of 4.5 days. The main finding was that the speed of recovery worsened in the SBRs as the solids retention time increased. Shock load II was planned to investigate this effect at a different hydraulic retention time. It was decided to keep the lagoon at an HRT of 4.5 days, while the SBRs were switched to a 1.5 day HRT. The intention was to compare the effect of the greater dilution between the lagoon with HRT=SRT= 4.5 days, and the SBR with HRT = 1.5 days and SRT = 5 days. Note that operation at a different HRT created a different mass loading under normal conditions. Shocks of equal mass would therefore cause a different relative change in the mass load.

Shock loads II and III are considered together as they were very similar experimental runs. Shock load III was also administered quite soon after shock load II. This gave an opportunity to investigate the effects of multiple shock loadings. Nominal operating conditions and the approximate magnitude of the shock were the same for both tests. Because of variations in the mill effluent received, it was not possible to hold conditions identical for both shock loads. The average influent concentration was 398 mg/L (standard deviation= 43.6 mg/L) in the period after and a week before shock load II. The concentration was 272.3 mg/L (standard deviation= 25.2 mg/L) for the period before and after shock load III. The shock loads were administered in the same manner as shock load I. The shock feed concentration for shock load II was 1200 mg/L SOC (3.0 times the normal feed concentration), while shock III was 980 mg/L, for a shock 3.6 times the regular feed concentration. The ratio of mass fed (mg SOC/day) to the SBRs on the day of shock load II to the mass fed on a normal day was 3.3, with a standard deviation of 0.15. For the lagoon after shock load II, the ratio was 7.6. Note that both the lagoon and the SBR were being fed the same mass of substrate, but that the normal mass loading in the lagoon was much lower because of the high HRT, hence the difference in mass loading ratio. For the SBRs in shock load III, the ratio was 4.0 with a standard deviation of 0.11. For the lagoon in this shock, the ratio was 9.1. The actual HRT's obtained during these two shock loads are shown in the table below.

Table 5: Hydraulic retention times for shock loads II and III.

Reactor	Nominal HRT (Days)	Shock II HRT (days)	Shock III HRT (Days)
Lagoon R1	4.5	4.6	4.7
SBR R2	1.5	1.8	1.9
SBR R3	1.5	1.6	1.9
SBR R4	1.5	1.8	1.8
SBR R5	1.5	1.8	1.8

Shock load II took place on February 8, 1993 after adjustment of the HRT in the SBRs from 4.5 days to 1.5 days.

Operational difficulties were experienced during shock load II. To check the results of shock load II, shock load III was administered under conditions as similar as possible to those of shock load II. Shock load III took place on March 9, 1993, after the system had recovered from the previous shock.

4.2.1. Rate of Recovery to Pre-Shock Treatment Efficiencies.

As with shock I, the time taken for recovery to pre-shock treatment efficiency was of prime importance in characterising the response of the system to a shock. Figure 11 illustrates in the form of a bar graph the time it took for 50 % recovery from both shocks II and III. Figure 12 shows the time it took for 90 % recovery from the same shocks.

Examination of the graphs initially appeared partly at odds with the results from shock load I. For the SBR's after shock load II, the rate of recovery worsened as SRT increased (as per shock load I), until SRT reached 40 days, at which point the performance improved dramatically. After shock load III, all SBRs performed much better than in the course of shock load II, even though the relative magnitude of the shock load was somewhat higher (mass loading 4.0 times the regular feed mass load, versus 3.31 times). Further, after shock III there was very little of the SRT-linked differentiation of performance seen in the previous shock loads. Shock load III was administered within about 3 weeks after the recovery from shock load II.

It appeared from analysis of the MLSS data (given in section 4.2.3.) that reactor 5, with SRT=40 days, had not yet acclimatized to the change in hydraulic retention time in the weeks prior to shock II. At the time of shock loading, the MLSS in reactor 5 was in the range of 1500 mg/L, while at the end of the roughly 2 weeks needed for recovery, it had grown to 4000 mg/L. The reactor was essentially functioning as a much younger reactor. This resulted in the faster recovery than would be expected from previous trends.

Prior to the application of shock load II, the effluent SOC and MLSS in the reactor appeared to have stabilized after the change in HRT. Zaloum (1992) performed studies monitoring a variety of transient conditions, including changes in HRT, SRT and organic feed. From this work he advised that "monitoring the MLVSS until a steady level is attained will coincide with the establishment of equilibrium conditions." In the case of changes in HRT, he found an initial lag of the MLSS response, followed by a period of growth and then a new equilibrium. For a change from HRT= 5 days to HRT=3 days, this lag period was 10 days long, followed by roughly 11 days of growth to the new equilibrium level. It appeared that for our SBR with the 40 day SRT, the lag period was mistaken for a steady state. When shock load II was applied, the reactor 5 had entered a period of rapid growth caused by the earlier change in HRT. This period of growth coincided with the shock

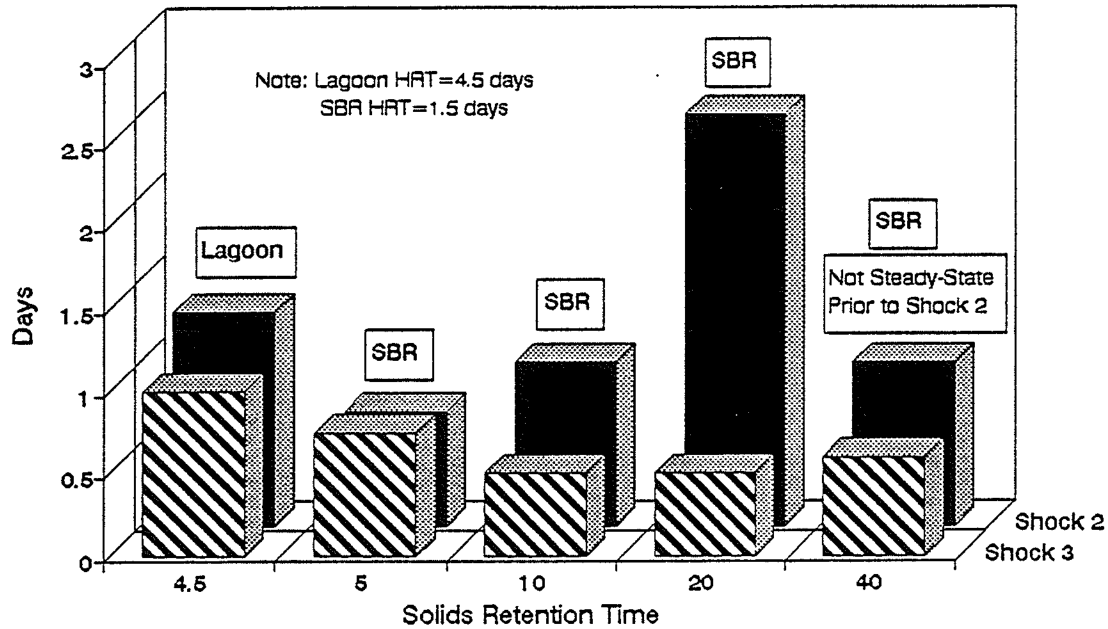


Figure 11: Illustration of the Time Taken for 50 % Recovery From Shock Loads 2 and 3

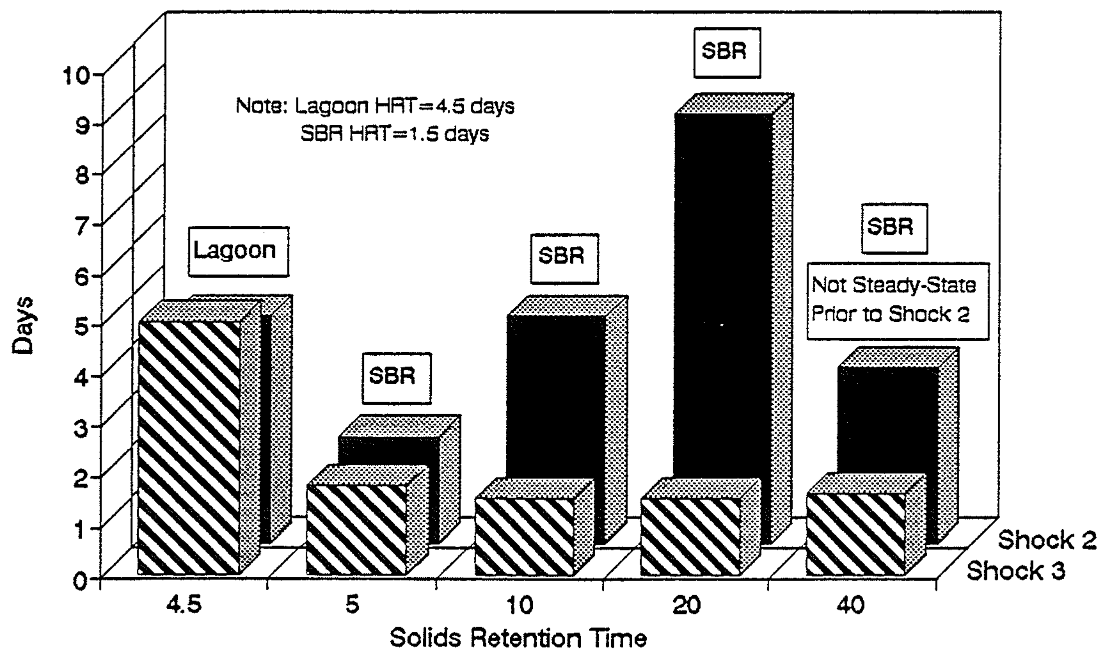


Figure 12: Illustration of the Time Taken for 90 % Recovery From Shock Loads 2 and 3.

load, and resulted in the rapid recovery of the system.

The far faster recovery (40 % or more) after shock load III for the SBRs operating at SRTs of 10 to 40 days, was unexpected and not immediately explicable. It appears that older sludge may have developed a type of memory or acclimatization to transient loadings. In the case of repeated shock loads with similar constituents, older systems may offer substantially more rapid recovery than in a single shock situation. Past work by Templeton and Grady (1988) has shown that the biodegradation kinetics of pure bacterial cultures were affected by cell history. They have shown that the levels of RNA, proteins, and other macromolecules in the cell depend on past growth conditions, and are part of the cell's physiological adaption to environmental conditions. Their study looked at cell history in steady state (constant rate of substrate administration) situations. Further study is needed to determine the effects of unsteady state cell history (i.e. previous shock loadings) on the performance of microorganisms in shock loading situations. The data from this experiment suggests that in the case of closely repeated shock loads (ie, with the span of the solids retention time), acclimation to shock loading may be possible.

4.2.2. Maximum Organic Carbon in Effluent

Unlike shock load I, the maximum organic carbon in the effluent did not show a distinct trend related to operating conditions in the reactors. Table 6 shows the maximum substrate concentration found in the effluent from each reactor after shock loads II and III.

Table 6: Maximum concentration of SOC in the effluent, the day after shock loads II and III.

Reactor	Shock II (mg/L SOC)	Shock III (mg/L SOC)
R1	792	434
R2	754	376
R3	715	313
R4	790	340
R5	709	379

Little significant variation between the reactors after shock load II is shown from the mean leakage of 752 mg/L of organic carbon. Similarly, for shock load III, no particular trend is visible in the initial substrate leakages. For shock load III, the mean maximum post-shock effluent concentration was 369 mg/L. This is 38 % of the shock feed concentration of 980 mg/L. In contrast, for shock load II, the leakage of 752 mg/L was 63 % of the 1200 mg/L shock load. This is indicative of the better performance noted for all reactors during the third shock load. Even though shock load III was slightly greater as a relative mass loading to regular feed, it had a much less disruptive effect than the similar shock previously applied. It should also be considered that the concentration of the solution for shock load III was 20 % less than that for shock II. Furthermore, for all reactors except R2 (SBR, SRT=5 d), the MLSS was higher at the start of shock III than at the start of shock II. While the mass loading ratio administered to the lagoons was more than double the ratio administered to the SBRs, the initial leakage of SOC was only slightly greater than that from the SBRs. After shock load I, where the loading change was identical, the lagoon offered slightly better mitigation of the peak SOC than the comparable SBR.

4.2.3. Effect of Shocks on Mixed liquor Suspended Solids.

Figure 13 illustrates the MLSS in all of the reactors after the application of shock load II, while Figure 14 shows the same information for shock load III. A statistical breakdown of solids information for the duration of the post-shock recovery period is shown in Table 7.

Table 7: Statistical information about MLSS during the recovery from the second and third shock loads.

Reactor	Shock II			Shock III		
	Average (mg/L)	Std. Dev. (mg/L)	n	Average (mg/L)	Std.Dev. (mg/L)	n
R1	515.0	55.8	8	577.8	118.5	9
R2	881.3	428.9	8	581.1	153.3	9
R3	1228.8	337.4	8	1768.9	165.8	9
R4	1191.3	140.6	8	1725.6	123.1	9
R5	2517.5	713.4	8	3635.6	674.4	9

Examination of Figure 13 for shock load II shows several trends in the post shock performance. As noted in section 4.2.1., the reactor solids for R5 (SRT=40 days) had not yet stabilized at the time of shock load application, and climbed

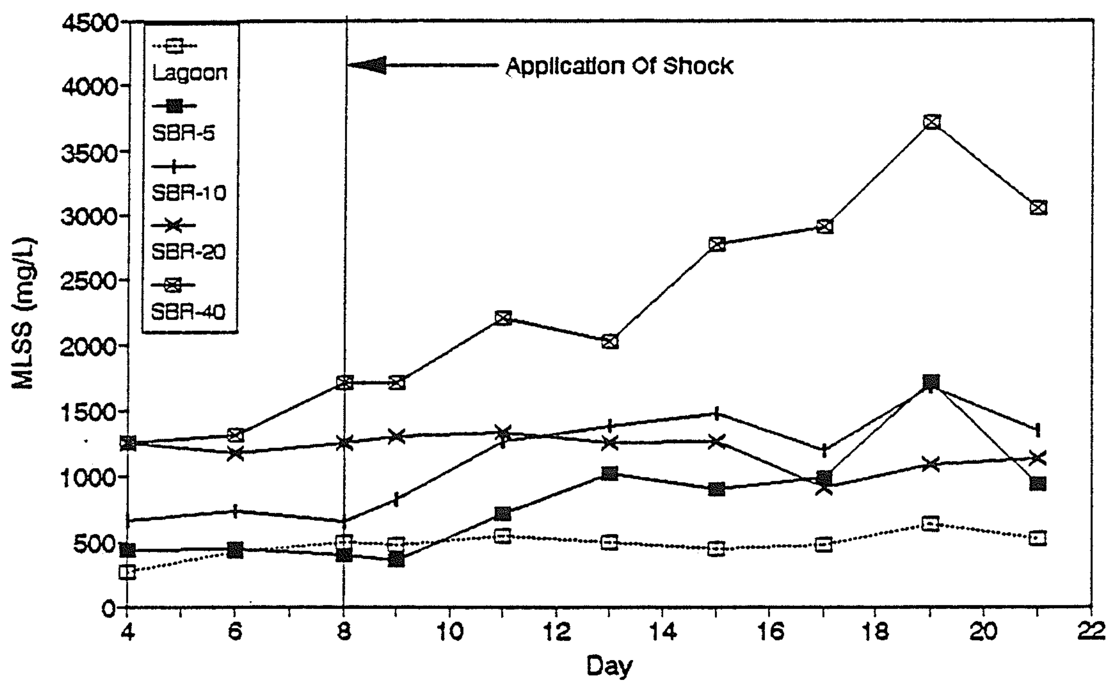


Figure 13: MLSS Before and After the Second Shock Load

steadily after the shock load. This steady and rapid climb was also the reason for the large standard deviation shown for the average solids in this reactor (Table 7). Reactors 2 and 3 also exhibited an increase in solids after the shock. This growth may have been related to the increase in substrate due to the shock load. More likely, however, is that it was related to the establishment of a new HRT. This is supported by the fact that after shock load III, no similar increase was noted, and the reactors in question operated at a MLSS close to that observed at the end of the period considered in shock II (see Figure 14).

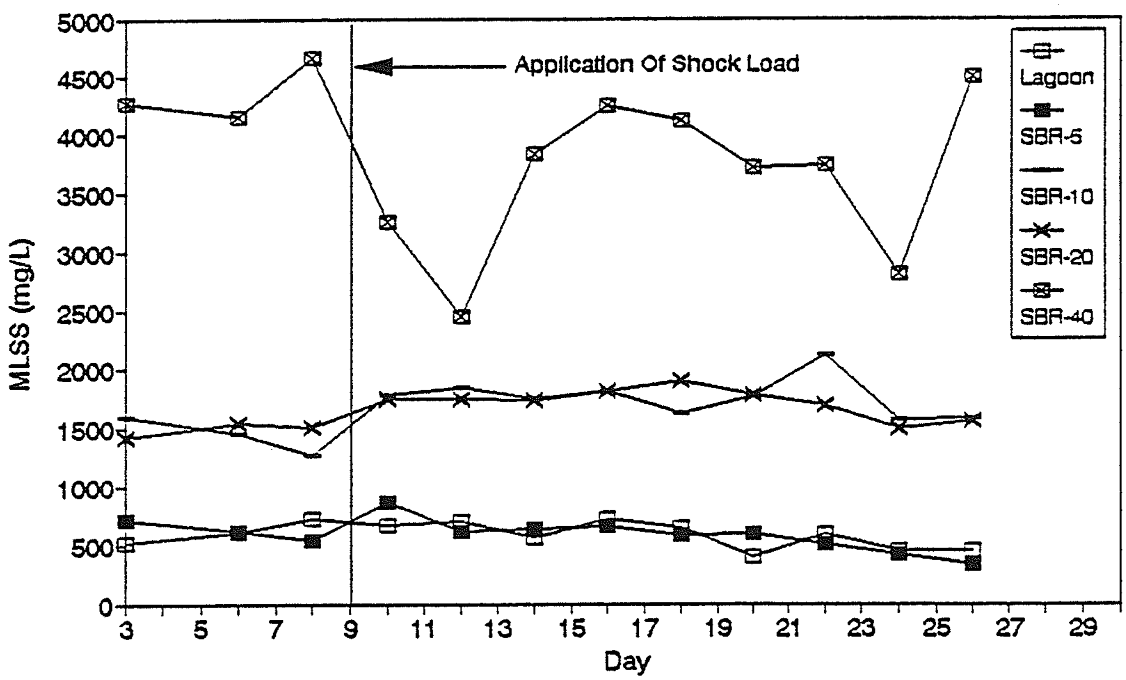


Figure 14: MLSS Before and After the Third Shock Load

In reactor 4, a decrease can be seen in the reactor solids nearly a week after the shock load. This was likely due to low dissolved oxygen in this reactor during this period. The low dissolved oxygen was due to the aeration system malfunctioning and failing to deliver sufficient air to the reactor. The lagoon, reactor 1, operated at a fairly steady MLSS throughout the shock loading period, near its pre-shock MLSS. This was comparable to the performance it gave after shock load III, shown in Figure 14.

After shock load III, the MLSS in reactor 5 (SRT=40 days) remained at a high level, but was somewhat erratic. Immediately after the application of the shock load, the MLSS dropped significantly, and did not recover for 5 days. Reactors 1 and 2 both operated at consistent and nearly identical MLSS both before and after the shock. This was not unexpected, as both had a 5 day SRT, but different HRT. More oddly, reactors 3 and 4 operated at very similar MLSS both before and after the shock load, despite being operated at different SRT. Figure 13 shows that the solids levels in these reactors began to converge after the system had mostly recovered from shock load II. As mentioned, the drop in solids in reactor 4 may have been due to problems with low dissolved oxygen in the reactor. The aeration system was fixed prior to the start of shock load III.

4.2.4. Effect of Shocks on Effluent Suspended Solids.

The behaviour of the reactors in terms of effluent solids is summarized in Figure 15 (effluent TSS after shock load II), Figure 16 (effluent TSS after shock load III), and Table 8, which presents a statistical information about the effluent suspended solids.

Table 8: Statistical information about effluent suspended solids for shock loads II and III.

Reactor	Shock II			Shock III		
	Average (mg/L)	Std. Dev. (mg/L)	n	Average (mg/L)	Std. Dev. (mg/L)	n
R1	311.5	190.5	8	267.6	103.9	9
R2	50.0	46.4	8	35.3	31.2	9
R3	70.1	52.6	8	42.9	23.1	9
R4	161.0	62.4	8	55.1	31.8	9
R5	79.3	82.3	8	26.4	14.2	9

As expected, the highest effluent total suspended solids came from reactor 1, the completely mixed lagoon. This effluent total suspended solids was also the most variable. Figures 15 and 16 show the relative magnitude of the suspended solids from the lagoon effluent versus the SBR effluent. All SBRs provided quite comparable effluent solids. Reactor 4 gave the highest effluent suspended solids among the SBRs after both shock loads. This may be related to the dissolved oxygen problems previously noted.

Figures 15 and 16 show that the effluent suspended solids from the lagoon behaved in an erratic and unpredictable manner. Immediately after shock load II, the solids showed a dramatic rise, and then fell in the first 5 days after the shock load. This period corresponds roughly to the period needed for the 90% recovery of this reactor after the shock. In contrast, after shock III, in the same 90% recovery period, the effluent solids dropped dramatically and then rebounded. None of this had an impact on the MLSS in the reactor, which remained fairly consistent throughout this period. These peaks and dips were also reflected in the effluent of the SBRs, albeit to a much lesser degree. This suggests that the change in effluent solids may be due to the solids in the shock loading solutions. While visual examination of the shock load solutions suggests that they were quite high in solids, the solutions were not tested for suspended solids concentrations, and this suggestion cannot be confirmed.

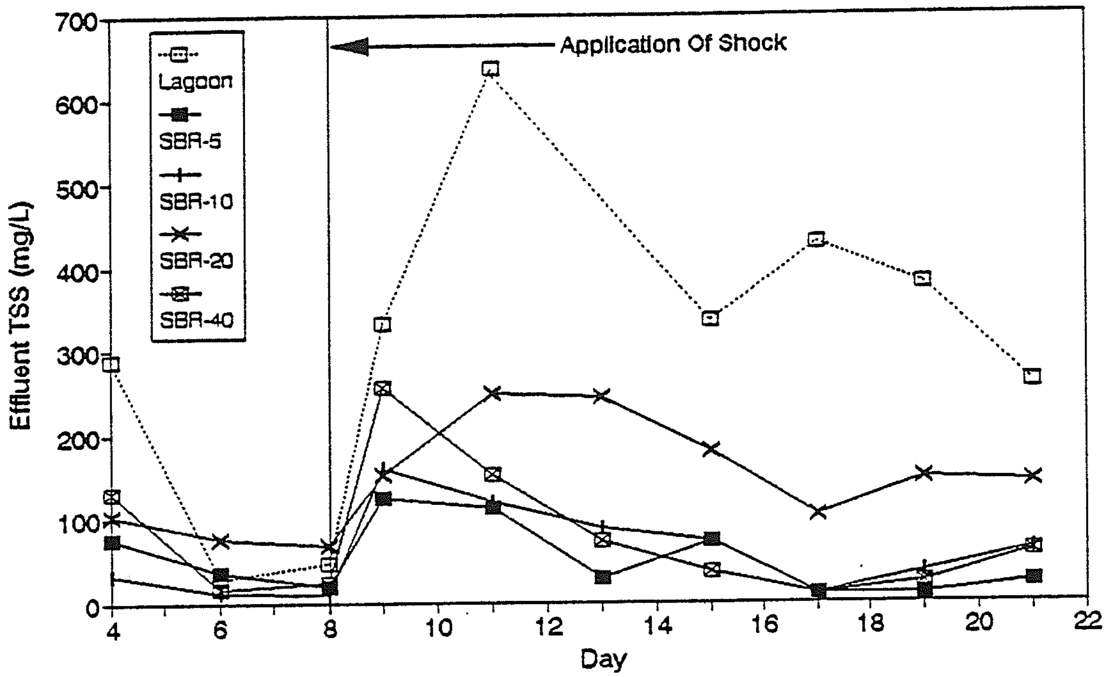


Figure 15: Effluent TSS Before and After the Second Shock Load

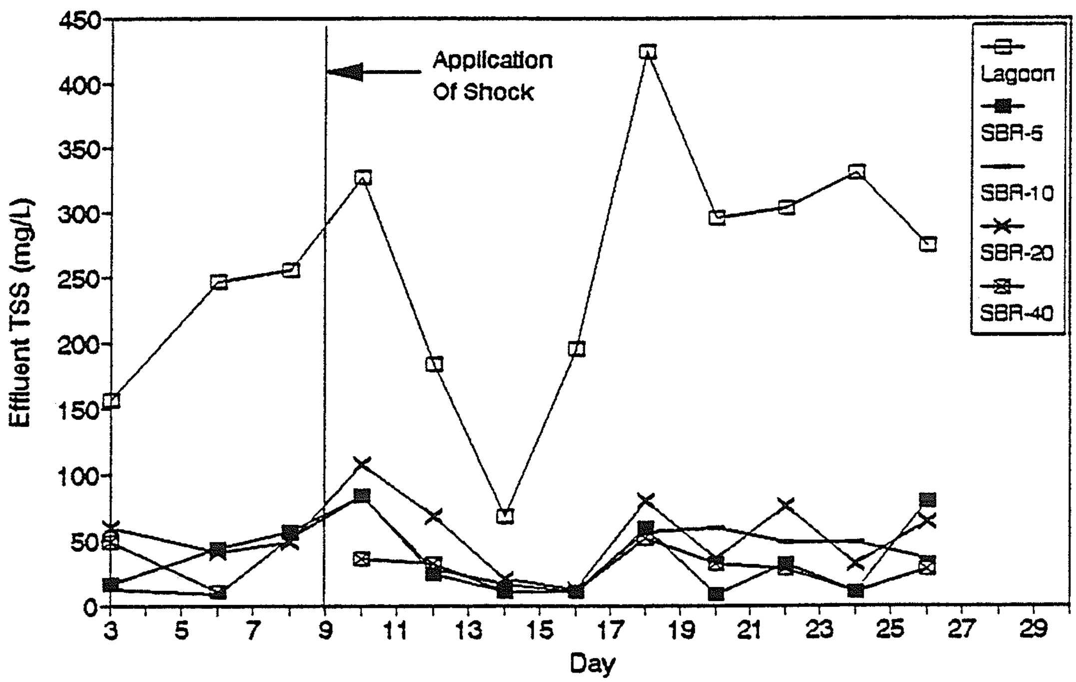


Figure 16: Effluent TSS Before and After the Third Shock Load

4.2.5. The Specific Substrate Utilization Ratio (U)

As mentioned in section 4.1.5., the specific substrate utilization ratio allows characterization of the per unit mass efficiency of the reactor contents. Figures 17 and 18 show how this parameter varied over time for each reactor after shock loads II and III, respectively.

In Figure 17, the results for shock load II show that for the most part, the reactors with longer solids retention time exhibited a poorer efficiency on a per unit mass basis. This agrees well with what was found in shock load I. However, in contrast to shock load I, there was no tendency for the ratio to increase over time. Instead , it remained fairly steady, or even decreased (reactor 2, SRT=5 days) over time. It is worth noting that while the solids levels in reactor 2 increased slightly after the shock load, the solids' efficiency on a unit mass basis decreased. Meanwhile in reactor 5 (SRT=40 days), where it has already been noted that the MLSS increased dramatically in the period after the second shock load, the per unit mass efficiency remains quite constant, despite the increase in mass. Previously, a higher mass was associated with a lower efficiency, per unit mass. However, since the biomass in this reactor appeared to be actively growing at the time of the shock load, its efficiency remained constant. Presumably, when the new equilibrium was established the growth of the biomass would slow to a level of maintenance rather than active growth. The substrate

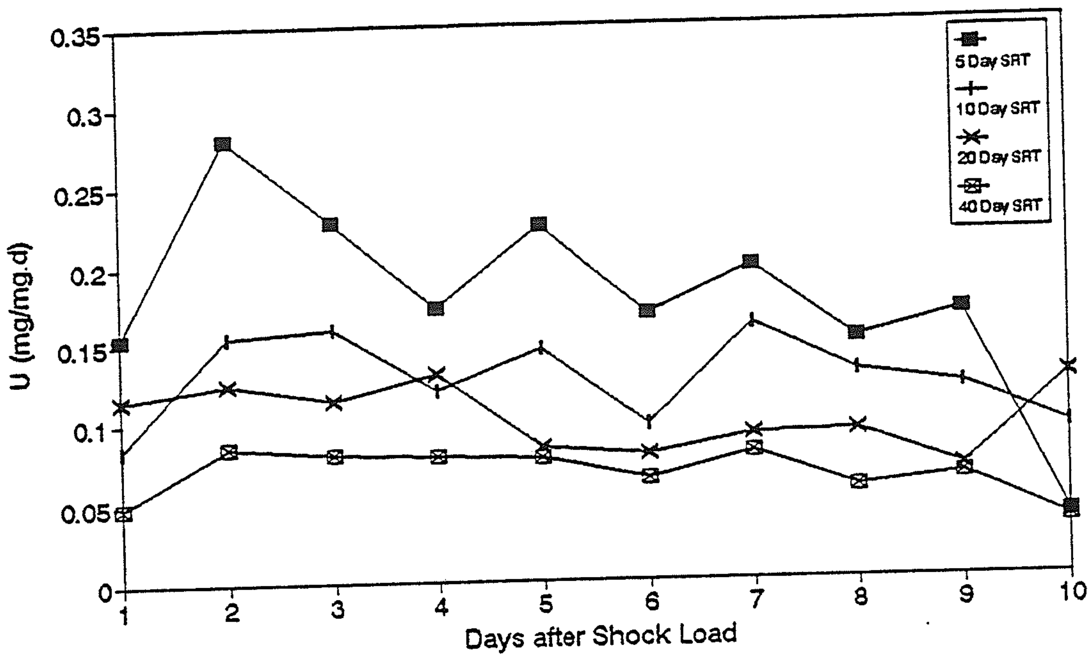


Figure 17: Effect of SRT on U for the Second Shock Load

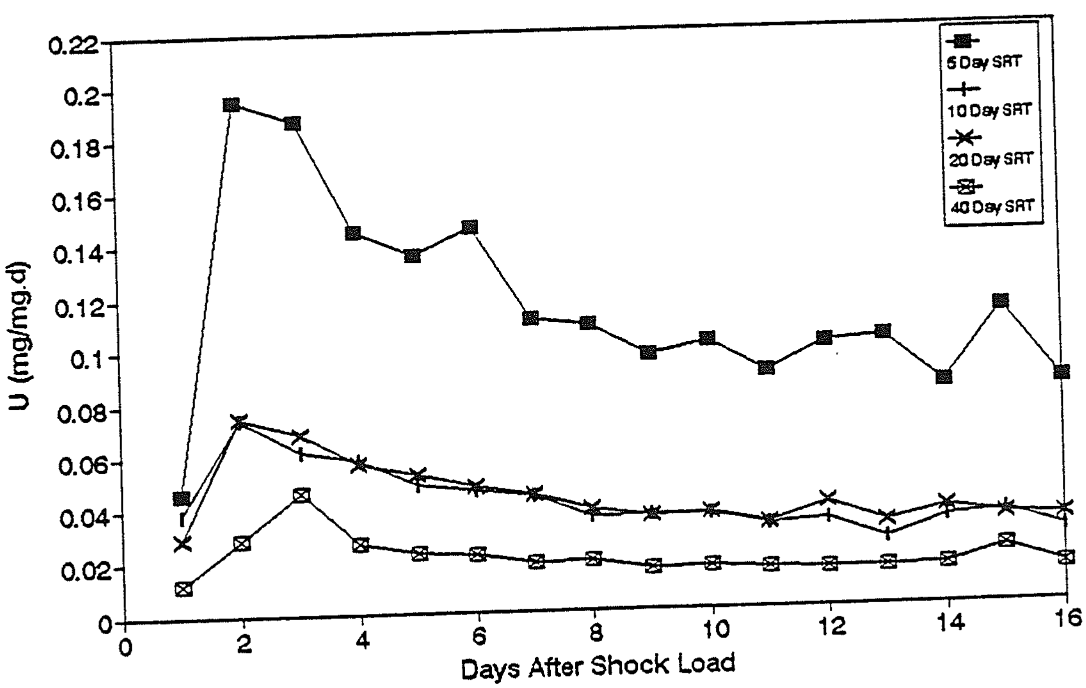


Figure 18: Effect of SRT on U for the Third Shock Load

utilization ratio is a function of the rate of growth rather than the concentration of biomass. However, high concentrations of biomass are normally associated with slow growth rates. Figure 17 also shows that after shock load II, the values for the substrate utilization ratio tended to be more unsteady at lower SRT. This is in agreement with the results for shock load I.

The unit mass efficiencies shown for each of the reactors after the third shock load in Figure 4 reflect in part the unusual operating conditions during this shock load. As noted, during this part of the experiment, reactors 3 and 4 (10 and 20 day SRT respectively) were operating at near identical solids levels. This resulted in very similar performance, including the specific substrate utilization ratio, which was almost identical for both reactors, throughout the experiment. The reactor at a 5 day SRT showed a much higher specific utilization ratio, while the one at 40 days showed a lower ratio. In the first 3 days after the shock load, the utilization ratio increased noticeably in all reactors, followed by a gradual decrease in the days after. However, this change was not reflected in a change of the MLSS within the reactors. This may have reflected the occurrence of substrate uptake that was not directly related to growth of the micro-organisms. Assimilation and storage of substrate after a shock load, rather than the usage of that substrate for growth, has been noted by Krishnan and Gaudy (1985).

4.2.6. The System Response To Shock Loads

Comparison of the results from shocks II and III suggest that the past shock history of the sludge is important in determining the response to a shock. The system recovered rapidly from shock III, which was carried out within weeks of the recovery from shock II. It is also apparent that the age of the sludge and its growth conditions prior to the shock are of great importance to how the system will respond to the shock.

Reference to the growth of bacteria suggests how the pre-shock operation can affect shock load response. The growth curve for bacteria in a batch culture is shown in Figure 19. The growth includes several distinct phases, labelled on the graph. Of particular importance is the log-growth phase. During this phase, bacteria are growing and multiplying rapidly, and food is in excess. This corresponds to a high F/M ratio and a low SRT in a continuously fed system. As the F/M ratio declines and the average sludge age increase, the rate of growth slows, until the bacteria enter the endogenous phase. This corresponds to many cells being very slow growing or dead, and a higher average sludge age. Bacteria that are in the log-growth phase prior to the shock are poised to respond more rapidly to the shock. Operation at a low sludge age gives faster growth.

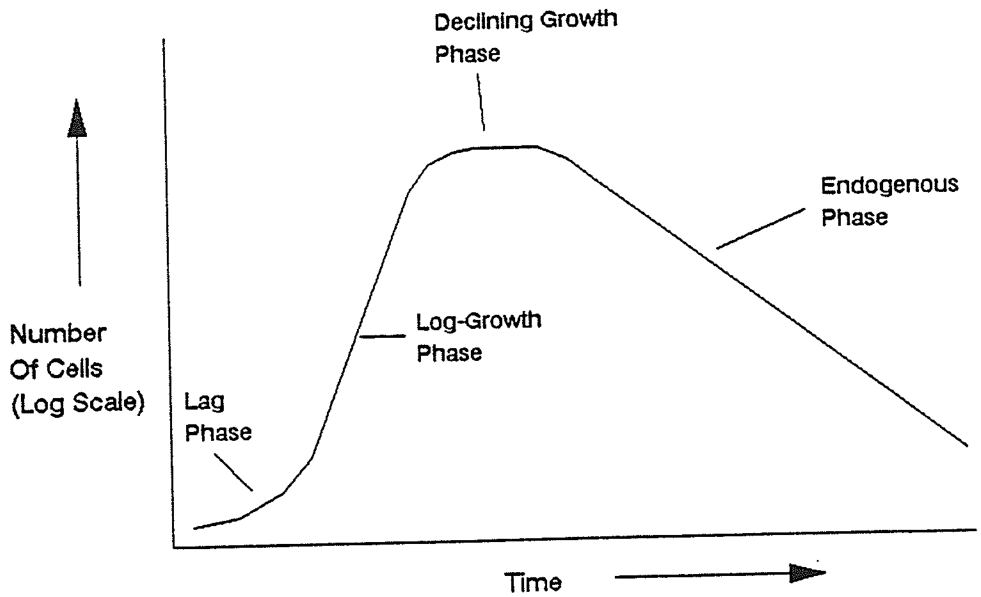


Figure 19: The Bacterial Growth Curve (Metcalf and Eddy, 1991)

The greater efficiency of younger sludge has been noted several times in the experimental results. In the work of Chudoba et al. (1989) the relationship between the maximum specific removal rate of a substrate and the maximum volumetric removal rate was studied. Similar to our study, they found the maximum specific rate to increase at lower SRT, although this was offset by a decrease in volumetric rate. The study showed younger members of the species responsible for degradation are more active than older ones in terms of substrate removal. Further, at lower SRTs, other slower growing microorganisms are washed out of the reactor leading to an enrichment of the media with the organisms responsible for degrading the substrate entering the reactor. However, they found a critical SRT, different from the minimum SRT, and dependant on loading rate. Below the critical SRT, the micro-organisms cannot grow and reproduce fast enough to degrade all of the substrate, even though the SRT is above the minimum for degradation. In the range between minimum and critical SRT, the system is only capable of partial degradation of the substrate.

The implication of these findings is that the choice of SRT must be balanced against several factors. A low SRT will provide micro-organisms well suited to coping with shock loads. However, if the SRT is too low, the degradation of substrate will suffer. Older systems are unlikely to run into problems with substrate becoming partly degradable, but react sluggishly to larger or more complex shocks. Findings in the literature suggest that older systems may be able to mitigate smaller shocks through immediate non-digestive uptake onto the biomass. At higher SRTs, the greater biomass allows for more uptake. Figure 20 shows a hypothetical relationship between the factors discussed. This graph shows how greater shocks may be needed to disturb the operation of older systems, but once disturbed, the systems take longer to recover.

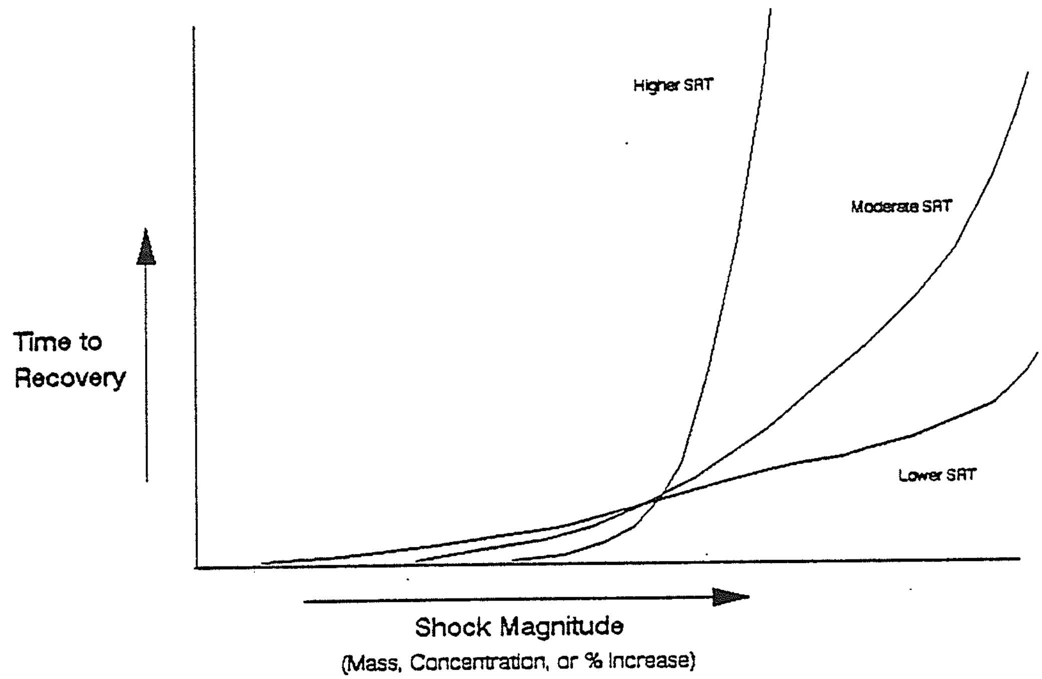


Figure 20: Postulated Relationship Between SRT, Shock Magnitude, and Time Needed to Recovery

4.2.7 Summary

For shock loads II and III, the SBRs were operated at an HRT of 1.5 days, and the lagoon was operated at an HRT of 4.5 days. The ratio of the shock mass loading to the normal mass loading for the lagoon was 7.6 and 9.1 for shocks II and III respectively. For the SBRs, the shocks were correspondingly 3.3 and 4.0 times the regular mass loading.

It has been found initially that recovery from the shocks was related to prior growth conditions, with fast growth allowing faster recovery from the shocks. SBRs recovered faster than comparable lagoons. This may be due to the nature of the SBR process, as suggested by shock load I. It may also be related to the difference in the relative mass loading caused by the differences in HRT. SBRs with SRT greater or equal to 10 days recovered from shock load III much more rapidly than from the similar shock load II. Acclimatization of the older sludge to the transient conditions may have taken place. Maximum organic carbon in the effluent did not seem related to SRT or solids in the reactor.

MLSS in the reactors was not greatly affected by the shock loads. An insufficient transition period after the change in HRT and poor aeration caused problems with MLSS in two reactors during shock load II. Effluent suspended solids were consistently low from the SBR with the lowest SRT. As found after shock load I, higher concentrations of solids in reactors corresponded to lower efficiencies per unit mass of solids.

Shock load II showed that the growth conditions prior to the shock load affect the response of the treatment system. Fast growth prior to the shock load was equivalent to faster recovery. Recovery after shock III was much more rapid in the older reactors, suggesting some acclimation to shock loads. Since all of the shock loads to this point caused a similar level of disturbance, shock load IV was planned to observe the effects of a much more intense shock.

4.3 Shock Load IV

Shock load IV took place under similar operating conditions to shock loads II and III, with respect to HRT and SRT. The difference with shock load IV was in the magnitude of the shock. The shock load solution had a SOC concentration of 2765 mg/L. The shock was applied in the same manner as previous shocks (replacing one liter of supernatant with the shock load solution). Since the regular feed before and after the shock load had a concentration of 355 mg/L SOC (standard deviation = 71.9 mg/L), this made for a shock roughly 7.8 times the regular feed. This compares to shocks in the range of 2.7 to 3.6 times the regular feed concentration in shocks I through III. In terms of mass loading, the loading on the shock day was an average of 8.55 times the normal mass loading to the SBRs. The loading to the lagoon was 20 times the normal mass loading. The greater intensity of shock IV caused substantially different responses within the system compared to the previous shocks. Table 9 shows the operating conditions for this shock. Note that after the shock, it was not possible to maintain the desired SRT, so that the SRT given for each reactor reflects only the pre-shock conditions. Shock load IV was applied on April 2, 1993. It was the final run for the experiment, which concluded on April 23,1993.

Table 9: Experimental operating conditions for shock load IV.

Reactor	Nominal SRT (days)	HRT (days)	MLSS (mg/L) (pre-shock)
R1	4.5	4.9	550
R2	5	1.7	377
R3	10	1.6	1527
R4	20	2.6	1543
R5	40	2.2	4390

4.3.1 Effect of shock IV on effluent SOC

In the previous sections, the effects of shock loads were characterised by the time taken for the systems to recover to their pre-shock removal efficiencies. This criteria was abandoned for shock load IV, as none of the systems tested truly recovered from the shock load. In place of recovery rate analysis, the post shock performance of each reactor was examined individually. To help characterise the recovery, or lack of it, the removal of SOC in each reactor was graphically compared to the removal that would be predicted by the calibrated dilution model. This analysis generated Figures 21 through 25, for reactors 1 through 5, respectively.

Figure 21 shows the post-shock performance of reactor 1, the completely mixed lagoon. This figure shows that 11 days after the application of the strong shock, the concentration of SOC in the effluent from the lagoon was roughly equal to the concentration of the influent to it. No removal was occurring, and the reactor was essentially dead. No sign of renewed activity was present 18 days after the shock event.

The dilution curve shown (discussed in the methods section 3.4.1) provided a reasonable approximation of the lagoon's effluent after the shock load. However, the effluent concentration became equal to the influent concentration somewhat faster than predicted by the curve. Comparison of the effluent with the dilution curve suggested that immediately after the shock load, some of the organic carbon from the shock load is removed through effects other than dilution. This removal may be due to the effects of the biomass, such as initial sorption.

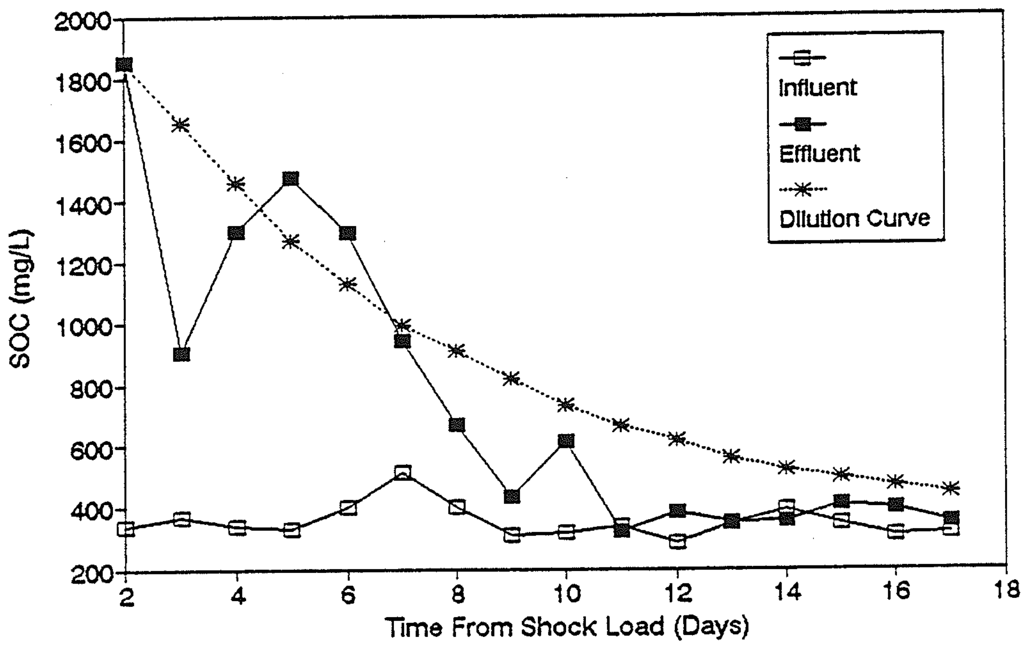


Figure 21: Comparison of SOC Removal in Lagoon To SOC Decrease Due to Dilution After Shock IV

For the SBR reactor 2, Figure 22 shows that partial recovery from the shock load eventually occurs. Approximately six days after the shock load, the concentration of organic carbon in the effluent was equal to the concentration in the influent. After 12 days, the effluent concentration began to dip below the influent concentration, suggesting some active biomass was now present. Comparison of the actual effluent concentrations with those predicted by the dilution curve showed that the shape of both curves was quite similar. However, the actual effluent underwent an initial decline in concentration more rapid than that predicted, similar to that noted in the lagoon. Approximately ten days after the shock load, a second decline occurred, suggesting biological consumption had resumed.

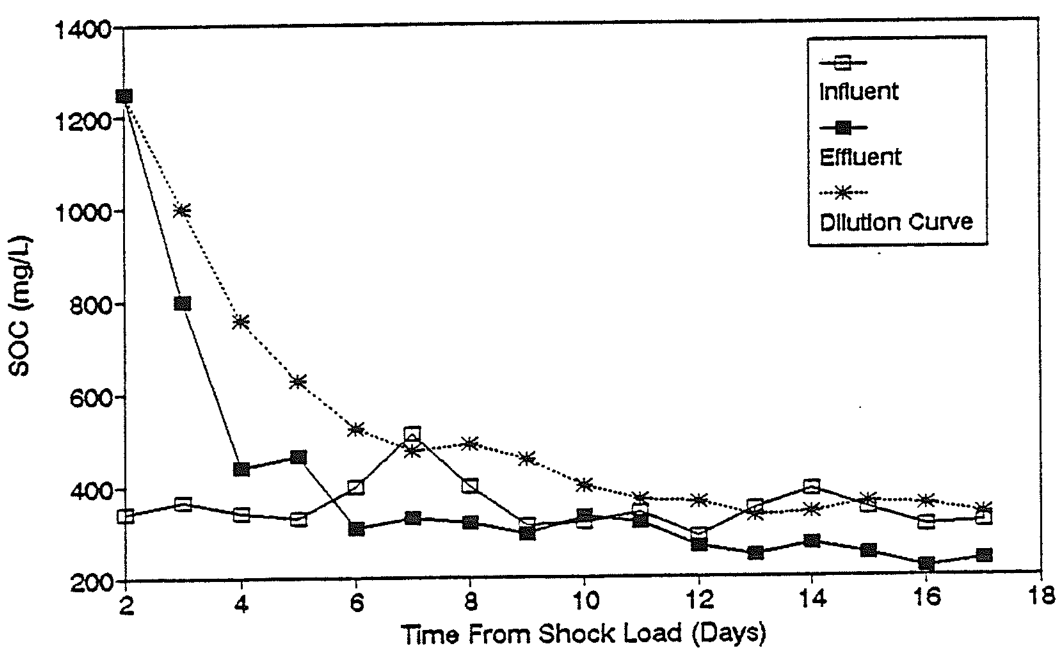


Figure 22 : Comparison of SOC Removal in SBR with SRT=5 days To SOC Decrease Due to Dilution After Shock IV

Reactor 3 (Figure 23) showed particularly good performance during this shock load. After a low initial leakage (discussed later), it showed distinct signs of recovery a few days after the effluent concentration reached the influent concentration. By 12 days after the shock load, the effluent SOC concentration was significantly lower than the influent, and showed continued to decrease.

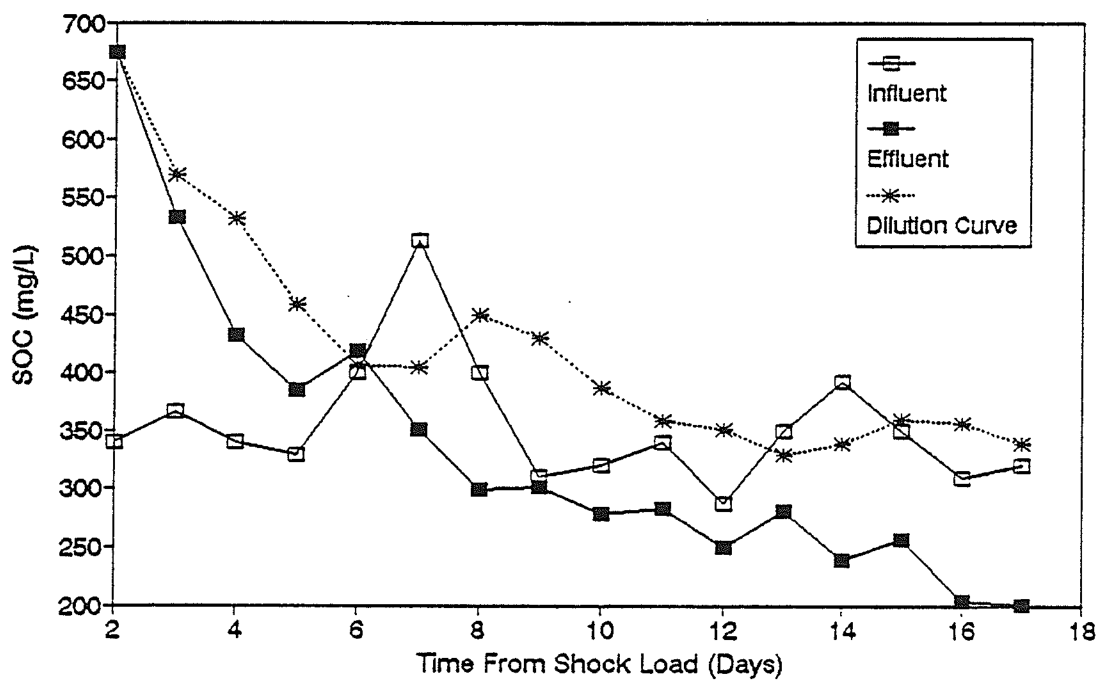


Figure 23:Comparison of SOC Removal in SBR with SRT=10 days To SOC Decrease Due to Dilution After Shock IV.

The post shock performance of reactor 4, shown in Figure 24, more closely resembled the performance of reactor 2 than reactor 3. Effluent concentration reached influent concentration after about 6 days, and showed no signs of further decrease until 13 days after the shock load. This reactor exhibited a substantially faster initial removal of waste than would be predicted by the dilution curve.

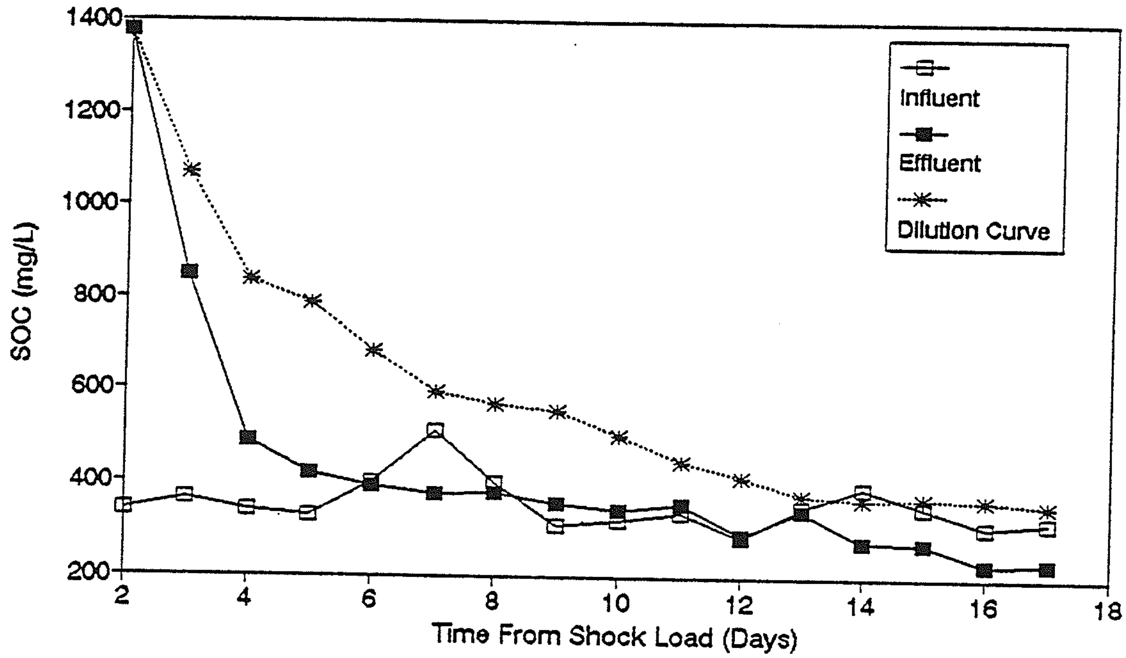


Figure 24: Comparison of SOC Removal in SBR with SRT = 20 days To SOC Decrease Due to Dilution After Shock IV

Operation with the higher pre-shock solids levels and longer SRT in reactor 5 did not seem to differentiate its performance from that of the other reactors. As shown in Figure 25, 6 days was again needed for the organic carbon in the effluent to match the levels found in the regular influent. No recovery seemed to occur until 13 days after the shock load. Reactor 5 does not appear to recover as well as the other reactors within this time frame, although this is difficult to quantify.

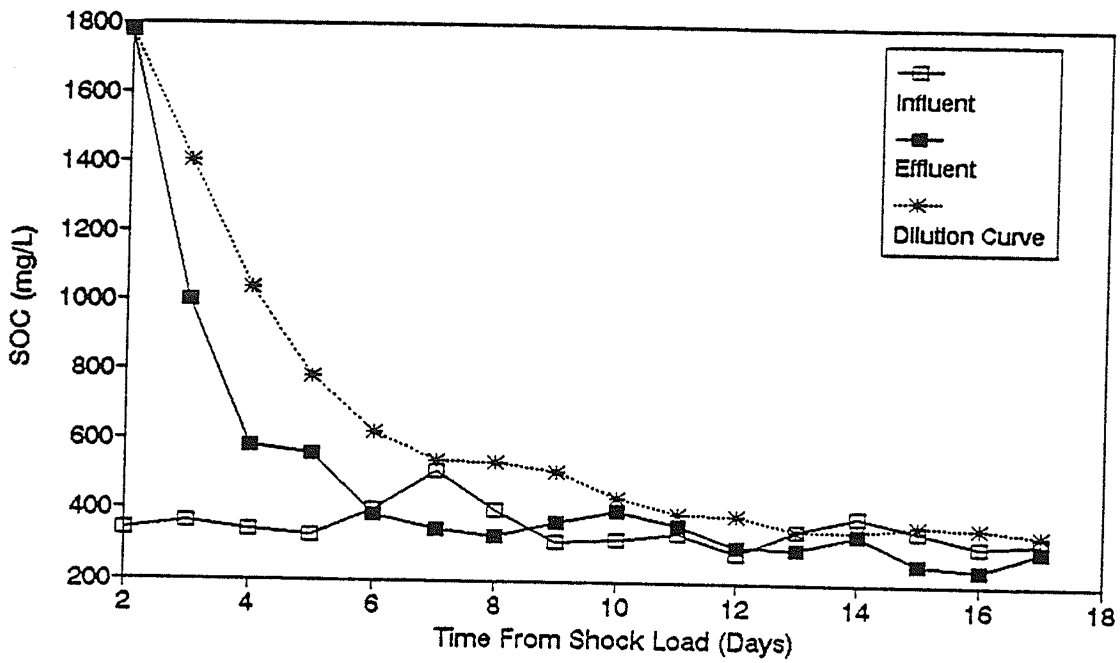


Figure 25: Comparison of SOC Removal in SBR with SRT = 40 days To SOC Decrease Due to Dilution After Shock IV

Peak effluent SOC concentrations the day after the shock load showed considerable variability, from a low of 673.5 mg/L in the effluent of reactor 3 (SBR, SRT=10 days), to a high of 1857.5 mg/L in from the lagoon. These concentrations did not correspond to the SRT or MLSS in the reactors. On the other hand, they did correspond very closely to the suspended solids initially leaked from the each reactor immediately after the shock loads. Figure 26 shows these parallel trends. This strong correlation did not appear after the other, less severe shock loads. The correlation is likely related to the high strength of the shock.

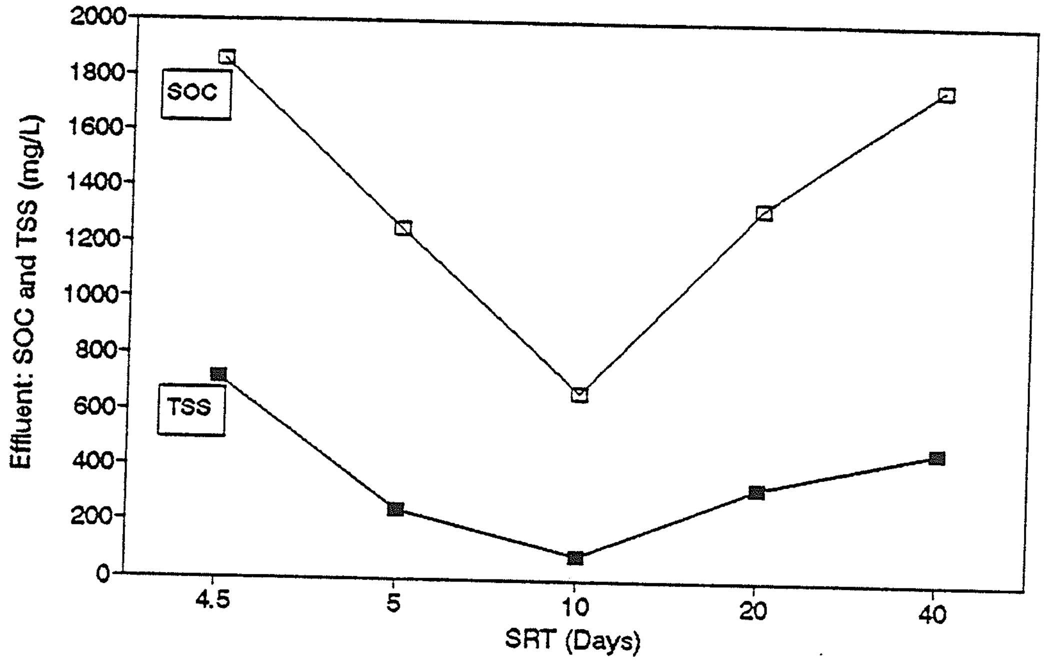


Figure 26: Relationship Between Initial SOC Leakage, and Effluent TSS for the Severe Shock Load.

4.3.2 Effect of shock IV on MLSS

Figure 27 shows the MLSS of each reactor before and after the shock loads. Reactor 5, operated with the highest initial solids concentration, showed a slight initial drop in solids, followed by a period of rapid washout to a solids concentration below 500 mg/L. All other reactors showed an initial increase in solids (presumably due to a high concentration of solids in the shock feed), followed by a drop over 5 to 10 days to a lower level. Reactors 3 and 5, which operated at pre-shock MLSS in the range of 1500 mg/L showed a decrease to below 500 mg/L by the end of the experiment.

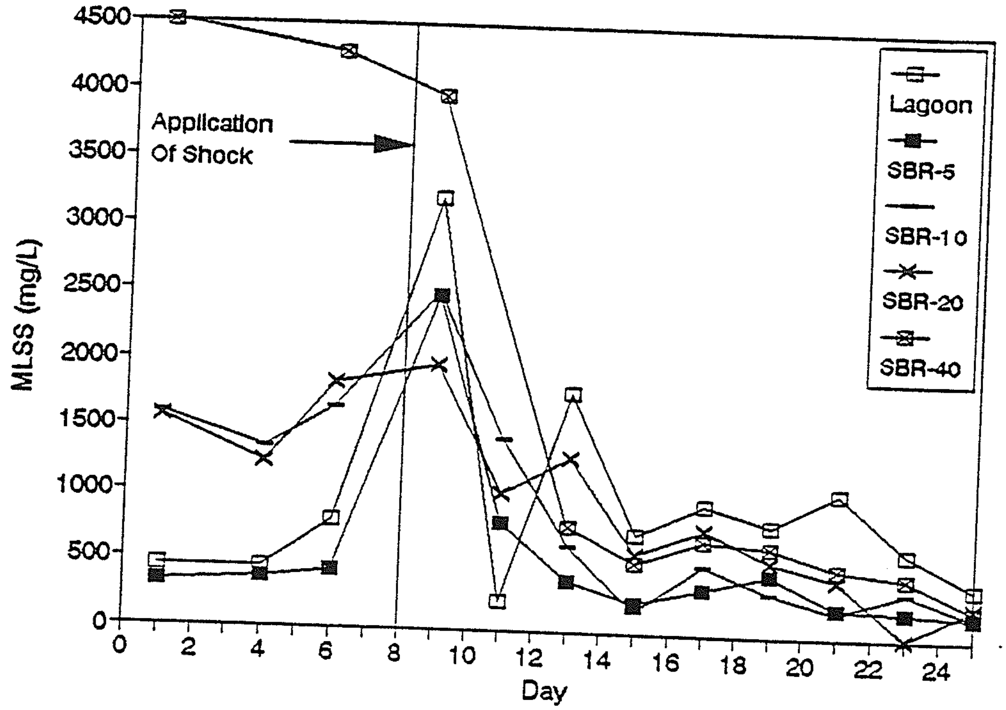


Figure 27: MLSS Before and After Fourth Shock Load

By the end of the experiment, none of the reactors showed signs of increasing biomass. Visual examinations, with and without the microscope, revealed poorly settleable pin floc in the reactors. After the shock load, it was not possible to settle biomass for the recycling of sludge. While all SBRs provided some removal of substrate 20 days after the shock loads, none of them showed signs of developing healthy biomass. Microscopic examinations at the end of the experimental run showed almost no active higher micro-organisms, such as protozoa or rotifers.

4.3.3 Effect of shock IV on effluent TSS

Figure 28 shows the effluent TSS for all the reactors before and after the shock load. As can be seen in the figure, all reactors underwent a large initial jump in effluent solids after the shock load. The magnitude of the jump varied between the reactors, but did not seem dependant on pre-shock solids levels, either in the reactors, or in the reactor effluents. The increase in solids likely reflected several factors, including the TSS in the shock load, and the washout of reactor contents shown in the previous section. This period of washout seemed to continue for roughly 10 days before the effluent suspended solids appeared to stabilize somewhat. Effluent suspended solids stabilized at a higher concentration than was typical of pre-shock operation.

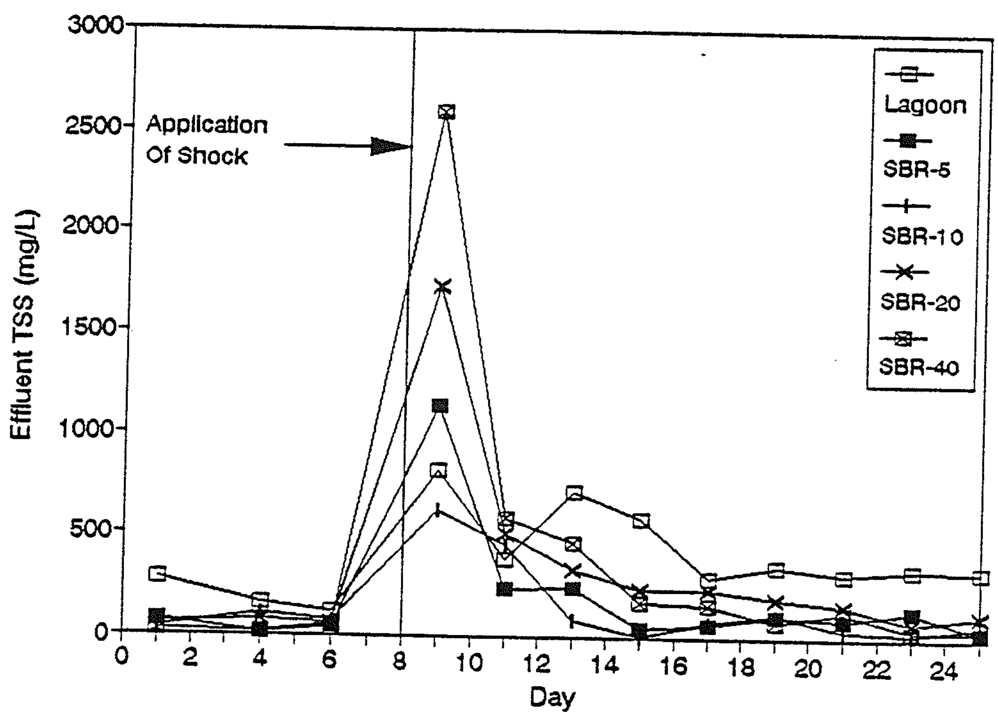


Figure 28: Effluent TSS Before and After Fourth Shock Load

4.3.4 Response of system to shock load.

It can be seen from these results that for this system, a shock load 7.8 times the regular feed concentration had a severe effect on all treatment systems used. The severity of the response was such that criteria used for previous shock loads, such as the time to recovery, were not possible to apply within the time frame of the experiment. The effect of the shock on the settleability of the solids was such that SRT control was no longer possible after the shock. From an operational point of view, all systems failed after the shock load, with a loss of treatment capacity and a massive loss of biomass.

From a biological standpoint, the systems showed several interesting traits. For all of the activated sludge systems (R2 to R5), there was evidence of some initial response to the new substrate load prior to failure. Failure included a considerable loss of mixed liquor suspended solids. The activated sludge systems generally reached null operation (influent concentration=effluent concentration) around six days after the application of the shock load. The systems also showed signs of recovery roughly twelve days after the shock load application. This recovery included only slight removal of substrate. The settling characteristics of the post-shock biomass did not improve within the span of the experiment; nor did there appear to be any re-development of a microlife population in the reactors within two weeks of the shock load. Also, no signs of any recovery were seen in the lagoon.

4.3.5 Summary

A shock load equivalent to an increase in mass loading (kg/m^3d) by a factor of 8.55 times in the SBRs and 20 times in the lagoon severely disrupted the operation of all treatment systems. The lagoon was more severely affected than the SBRs. Unlike the previous shock loads, pre-shock growth conditions did not seem to influence the response to the shock load.

All reactors lost solids after the shock loads. The solids that remained were poorly settleable and prevented re-establishment of the pre-shock SRT within the span of the experiment. None of the reactors approached pre-shock treatment levels 20 days after the application of the shock.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary

The liquid waste stream from a pulp and paper mill generally requires biological treatment. The use of aerated lagoons or activated sludge systems can provide the needed removal of biodegradable organics and toxic compounds. In many industries using biological treatment, including the pulp and paper industry, occasional spills to the treatment system are possible. The spills constitute shock loadings which may disrupt or destroy the treatment capacity of the system.

Treatment systems subject to shock loads should be designed to mitigate the detrimental effects of the shocks. A review of the literature generally suggested that this can be accomplished through the use of longer solids retention times. However, some studies and industrial experience suggested that lower solids retention times would be better. For this work, shock loads of laboratory scale lagoons and sequencing batch reactors (SBRs) treating effluent from an integrated pulp and paper mill were studied. The shock loads were drawn from strong mill effluent, to approximate real shock loads, as opposed to the synthetic feeds typically used in past laboratory studies.

Four separate experimental trials were carried out, using a lagoon with HRT=SRT= 4.5 days, and four SBRs, with SRTs from 5 to 40 days. The first three runs examined the recovery from moderate shock loads, and the last looked at the effects of a severe shock.

During shock load I, all reactors were operated with an HRT of 4.5 days. In the SBRs, the time for 90 % recovery increased with SRT from 7 days at SRT=5 days, to 17 days at SRT=40 days. The efficiency per unit mass of reactor solids (MLSS) decreased as the MLSS increased with SRT. All SBRs showed a slight decrease in solids after the shock load. The lagoon took almost twice as long for recovery as did the SBR at the same SRT. Solids increased slightly in the lagoon after the shock load.

For shock load II, the HRT was changed to 1.5 days in the SBRs. As with shock load I, fast growth prior to the shock load resulted in faster recovery. The reactor with a 40 day SRT had not recovered from the change in HRT prior to the application of the shock load. It was therefore in a period of rapid growth at the time of shock load application; this resulted in much faster than anticipated recovery in this reactor, equivalent to the recovery of a reactor with a 10 day SRT in this run. As per shock I, the per unit mass efficiency of reactor solids decreased as MLSS increased. Shock loading did not seem to greatly affect MLSS. The SBRs again out-performed the equivalent lagoon, recovering roughly twice as fast. However, since the same mass load was applied to systems operating at different HRT, the relative change in mass load to the lagoon was much greater than the relative change in the SBR (7.6 times normal mass, versus 3.3 times).

Shock load III was administered under operating conditions almost identical to shock load II. SBRs operating at SRTs of 10 days or more all recovered from shock III at least 50 % faster than for shock load II. MLSS was not greatly affected by the shock in any of the reactors. As in the previous two shocks, the unit mass efficiency was tied to the concentration of mass. The lagoon was again outperformed by the comparable SBR, but with the same caution about the relative change in mass loading.

Operating conditions prior to shock IV were similar to those of shocks II and III. The intensity of shock IV was more than twice that of any of the previous shocks. This shock overwhelmed all systems, and caused a massive loss of solids from each reactor. Solids remaining were poorly settleable, and did not allow for the reestablishment of SRT, even 20 days after the shock event. Regardless of the pre-shock SRT, all SBRs performed similarly. Some removal of substrate in the SBRs resumed 10 to 12 days after the shock event. The lagoon showed no signs of recovery after the shock.

5.2 Conclusions

1. Under moderate shock loading conditions, the SBR recovered 30 to 50% faster than a lagoon operating at a comparable SRT. This was true when both systems operated at

a 4.5 day HRT, and when the SBR operated at an HRT of 1.5 days. Other researchers have shown that microorganisms in SBRs have more RNA than microorganisms in comparable continuous flow systems. This may lead to faster growth and may explain better recovery under shock loading situations for SBRs.

2. Longer SRT was generally detrimental to the rate of recovery from the shock loads. This is in contrast to much of what has been shown in the literature, but agrees with industrial experience, and some experimental studies with complex feeds.

3. For repeated moderate shocks, older sludge (10 day or greater SRT) showed an approximately 50 percent faster recovery to the second shock. This suggests that older sludge may be able to develop improved resistance to repeated shocks.

4. A severe shock to the lagoon, with a mass loading 20 times the normal mass loading, destroyed the treatment capacity of the lagoon. The lagoon showed no signs of recovery within 20 days of the shock load.

5. While the treatment capacity of the lagoon was overwhelmed by the severe shock, initial removal of substrate was better than predicted by the dilution curve, suggesting an initial uptake of substrate by the biomass prior to washout.

6. After a severe shock, the SBRs responded better than the lagoon to shocks delivering the same mass load, showing signs of recovery within 10 to 12 days. This may be due to

the inherent benefits of the SBR system. The shorter HRT in the SBR may also have contributed to the better performance. Shorter HRT resulted in a higher mass loading of the system prior to the shock, so that the change in loading due to the shock was lower in the SBRs. All SBRs performed similarly, regardless of pre-shock SRT.

7. Experiments with moderate shock loads suggest that recovery from a shock load is dependant on growth conditions prior to the application of the shock. The rapidly changing environmental conditions associated with a shock load tend to favour faster growing, more efficient young sludge. The benefits of younger sludge tend to outweigh the benefits of older sludge that have been put forward in many previous studies. One can speculate that this difference may be due to the fact that studies indicating the benefits of longer SRT for resistance to shock loads considered relatively simple shocks, made up of single substrates such as glucose. In this experiment, shock loads were made up of mill waste. This waste is a complex mix of compounds, some of which may be difficult to degrade. The changes in the ecological balance within a reactor caused by complex shock loads are more dramatic than those caused by simple shocks (shocks with single, well defined compounds). This creates conditions where the rapid growth and high efficiency associated with younger sludge allow for the fastest recovery.

CHAPTER 6: SUGGESTIONS FOR FURTHER STUDY

The work contained within this thesis suggests several possible avenues of future research to develop the understanding of how biological treatment systems will respond to shock loads in an industrial setting. Possible further study includes:

1. The relationship between SRT, shock intensity, and rate of recovery should be clarified. This could be done through laboratory scale studies using carefully controlled shock loads, and examining the effect of various shock intensities on the rate of recovery.

2. Results obtained in this work suggest that systems may acclimate to multiple shocks within the span of the solids retention time. A study could be undertaken to investigate this possibility.

3. Information found in the literature suggest that SBRs may be better suited to operation under shock loadings than conventional activated sludge. This should be tested experimentally, with a shock loading study that includes careful monitoring of microbiological conditions, oxygen uptake rates and cellular RNA differences.

4. For a system greatly disrupted by a shock, the recovery rate may be improved by re-seeding the system. This could be investigated experimentally.

CHAPTER 7: ENGINEERING SIGNIFICANCE

If a biological treatment system will be subject to shock loadings, its design should take into account factors that will help mitigate the effects of the shock load. From this study, it appears that lower SRTs in activated sludge system will result in faster recovery from larger shock loads. This must be balanced against the advantages associated with higher SRTs, such as better resistance to minor shocks, less excess sludge production, and potentially better treatment under steady-state conditions.

The results of shock load IV highlight the importance of equalization prior to biological treatment. Without equalization, it is easier shock the system such that all biological treatment capacity will be overwhelmed.

Finally, this study has shown that for a system subject to shock loads, an SBR would be superior to a lagoon.

REFERENCES

APHA, AWWA, WPCF (1992). Standard methods for the examination of water and wastewater, 19th Edition. APHA, Washington, DC, U.S.A.

Ardern E. and Lockett W.T., (1914) Experiments on the oxidation of sewage without the aid of filters. *J. Soc. Chem. Ind.* **33**, pp. 523.

Arora M.L., Barth E.F., and Umphreg M.B. (1985) Technology evaluation of sequencing batch reactors. *Jour. W.P.C.F.*, **57**, pp. 867-875.

Beckett R., Wood F.J., and Dixon D.R. (1992) Size and chemical characterization of pulp and paper mill effluents by flow field-flow fractionation and resin adsorption techniques. *Environmental Tech.*, **13**, pp. 1129-1140.

Bell B.A. and Hardcastle G.J. (1984) Treatment of a high-strength industrial waste in a continuously fed, intermittently operated, activated sludge system. *Jour. W.P.C.F.*, **56**, pp. 1160-1164.

Benefield L., Kim S., and Randall C. (1989) The effect of Pentachlorophenol on enhanced biological phosphorus removal in

SBR systems. Proceedings of the 44th Industrial Waste Conference, Purdue University, pp. 141-147.

Brenner A., Chozick R., and Irvine R.L. (1992) Treatment of a high strength mixed phenolic waste in a SBR. *Water Env. Res.*, **64**, pp. 128-133.

Bryant C.W., Amy G.L., and Alleman B.C. (1987) Organic halide and organic carbon distribution and removal in a pulp and paper wastewater lagoon. *Jour. W.P.C.F.* **59**, pp. 890-896.

Bryant C.W., Amy G.L., and Alleman B.C. (1988) Biosorption of organic halide in a kraft mill generated lagoon. *Jour. W.P.C.F.* **60**, pp. 1445-1453.

Cheisa S.C., Irvine R.L., and Manning J.F. Jr. (1985) Feast/famine growth environments and activated sludge population selection. *Biotech. and Bioeng.*, **27**, pp. 562-569.

Chudoba J., Aboková J., and Cech J.S. (1989) Determination of kinetic constants of activated sludge microorganisms responsible for degradation of xenobiotics. *Wat.Res.* **23**, pp. 1431-1438.

Dixon D.R., Wood F.J., and Beckett R. (1992) Size and chemical characterization of pulp and paper mill effluents by flow field-flow fractionation and resin and resin adsorption techniques. *Environmental Tech.*, **13**, pp. 1129-1140.

Eckenfelder W.W. and O'Connor D.J. (1966) Biological Waste Treatment. Pergammon Press, New York

Fleming B.I. (1992) The organochlorine spectrum. *Pulp and Paper.*, **66**(4), pp. 59-62.

Gaudy A.F. and Gaudy E.T. (1980) Microbiology for Environmental Engineers and Scientists. McGraw-Hill Book Co., New York.

Grady C.P.L. Jr. (1971) A theoretical study of activated sludge transient response. Proceedings of the 26th Industrial Waste Conference, Purdue University. **26**, pp. 318

Gullichsen, J. (1991) Means to reduce effluent pollution of kraft pulp mills. Proceedings of the 1991 Tappi Conference, Atlanta Georgia, pp. 185-190.

Herzbrun P.A., Hanchak M.J., and Irvine R.L. (1984) Treatment of hazardous wastes in a sequencing batch reactor. Proceedings of the 39th Industrial Waste Conference, Purdue University, pp. 385-393.

Irvine R.L., (1985) Structured models for biological waste treatment systems. Research Grant, National Science Foundation.

Irvine R.L. and Busch A.W. (1979) Sequencing batch biological reactors - an overview. *Jour. W.P.C.F.*, **51**, pp. 235-243

Irvine R.L., Kectchum L.H., Arora M.L., and Barth E.F., (1985) An organic loading study of full-scale sequencing batch reactors. *Jour. W.P.C.F.*, **57**, pp. 847-853.

Junna J. and Ruonala S. (1991) Trends and guidelines in water pollution control in the Finnish pulp and paper industry. *Tappi Jour.*, **74**, pp. 105-110.

Kenny R., Yampolsky M., Volsky O., and Naumov A. (1993) A general review of Russian pulp and paper treatment technology. Pre-print of the Canadian Pulp and Paper Association's 1993 Environmental Conference Proceedings. pp.127-131.

Krishnan P. and Gaudy A.F. Jr. (1976) Response of activated sludge process to quantitative shock loading. *Jour. W.P.C.F.* **48**, pp. 906-919.

Lange C.R., Weber A.S., and Matsumoto M.R. (1989) Mitigation of biological process upsets caused by biological inhibitors. *Jour. Env. Eng. ASCE.*, **115**, pp. 1061-1065.

Lavallée H.C., Rouisse L., and Paradis R. (1993) A comprehensive study of the Quebec pulp and paper mill effluents as an instrument to define a strategy for abatement. *Pulp and Paper Canada*, **94**, pp. T393-T399.

Lawrence A.W. and Sherrard J.H. (1975) Response of activated sludge to step increase in loading. *Jour. W.P.C.F.* **47**, pp. 1848-1856.

Manickam T. and Gaudy A.F. Jr. (1979) Qualitative-quantitative shock of activated sludge, *Jour. W.P.C.F.* **51**, pp. 2033-2043.

Manickam T.S. and Gaudy A.F. Jr. (1985) Comparison of activated sludge response to quantitative, hydraulic and combined shock for the same increase in mass loading, *Jour. W.P.C.F.* **57**, pp. 241-252.

McCubbin N. and Folke J. (1993) Significance of AOX versus unchlorinated organics. Pre-print of the Canadian Pulp and Paper Association's 1993 Environmental Conference Proceedings. pp. 21-29.

McLellan J.C. and Busch A.W. (1969) Hydraulic and process aspects of reactor design II-response to variations. Proceedings of the 24th Industrial Waste Conference, Purdue University, pp. 493.

Mikkelson K.A. and Lowery K.W. (1992) Designing a sequencing batch reactor system for the treatment of high strength meat processing wastewaster. Proceedings of the 47th Industrial Waste Conference, Purdue University, pp. 765.

Nakhla G.F. (1993) SBR biotreatment of Phenolic Wastes. 1993 Joint CSCE-ASCE National Conference on Environmental Engineering. pp. 1891-1898.

Norcoss K.L., Petrie S., Bair R., and Beaushaw G. (1987) Startup and operating results from an SBR treating meat processing wastewater. Proceedings of the 42nd Industrial Waste Conference, Purdue University, pp. 475-481.

O'Conner B.I, Kovacs T.G., Voss R.H., and Martel P.H. (1993) A study of the relationship between laboratory bioassay response and AOX content for pulp mill effluents. *Jour. of Pulp and Paper Sci.*, **19**, pp. J33-J39.

Odenhal S. (1993) Environmental protection and consumer demands: a review of trends and impacts. Preprint of the

Canadian Pulp and Paper Association's 1993 Environmental Conference Proceedings. pp. 49-56.

Oleszkiewicz J.A., Mateja S., and Hutchison J.E. (1990) Treatment of food industry wastewater in sequencing batch reactors. *Environ. Technol.*, **11**, pp. 499-508.

Oleszkiewicz J.A., Trebacz W, and Thompson D. (1992) Biological treatment of Kraft mill wastewater. *Wat. Env. Res.*, **64**, pp. 805-810.

Pisano S.L., O'Shaughnessy J.C., LaMarre D., Gray C., Pederson S., and Sykes M. (1989) Toxic organic shock loading of rotating biological contactors and sequencing batch reactors. Proceedings of the 44th Industrial Waste Conference, Purdue University, pp.125-140.

Rozich A.F. and Gaudy A.F. Jr. (1983) Response of phenol-acclimated activated sludge process to quantitative shock loading, Proceedings of the 45th Industrial Waste Conference, Purdue University. **26**, pp. 725-736.

Rozich A.F. and Gaudy A.F. Jr. (1984) Critical point analysis for toxic waste treatment, *Jour. Env. Eng. ASCE* **110**, pp. 562-572.

Santiago I. and Grady C.P.L. Jr. (1990) Simulation studies of the transient response of activated sludge systems to biodegradable inhibitory shock loads. Proceedings of the 44th Industrial Waste Conference, Purdue University. pp. 191-198.

Selna M.W. and Schroeder E.D. (1978) Response of activated sludge processes to organic transients - kinetics. *Jour. W.P.C.F.* **56**, pp. 944-969.

Sherrard J.H. and Lawrence A.W. (1975) Response of activated sludge to step increase in loading. *Jour. W.P.C.F.* **47**, pp. 1848-1857.

Stokes J.L. and Parson W.L., (1968) Role of poly-ß-hydroxybutyrate in survival of *Sphaerotilus discophorus* during starvation. *Canadian J. Microbiol.*, **14**, pp. 785.

Sullivan D., (1992) Personal communication. G. D. Searle Pharmacuetical, Chicago Illinois.

Templeton L.L. and Grady C.P.L. Jr. (1988) Effect of culture history on the determination of biodegradation kinetics by batch and fed batch techniques. *Jour. W.P.C.F.* **60**, pp. 651-658.

Thabaraj G.J. and Gaudy A.F. Jr. (1969) Effect of dissolved oxygen concentration on the metabolic response of completely mixed activated sludge. *Jour. W.P.C.F.* **41**, pp. 322-335.

U.S. Environmental Protection Agency (1986) Sequencing Batch Reactors, EPA/625/8-86/011, Cincinnati, OH.

Walden C.C. and Howard T.E. (1981) Toxicity of pulp and paper mill effluents - a review. *Pulp & Paper Canada*, **82**, T143-T148.

Zaloum R. (1992) Significance and establishment of adequate transition periods in wastewater experimentation. *Environmental Technol.*, **13**, pp. 605-619.

APPENDIX A

Experimental Data

Data for the start-up

Date		SOC (mg/L) Inf	E1	E2	E3	E4	E5
Oct.	5	417.9	161.9	189.5	162.6	164.2	156.9
	7	398.4	154	158.5	170.1	162.3	184.1
	9	393.8	162.4	190.1	179.1		188.3
	14	685.8	207.9	218.8	214.1	181.9	217.6
	16	683.4	257.5	271.5	257	235.4	194.2
	19	549	267.1	310.21	221	269.4	173.5
	21	535.9	239.1	302.4	267.5	262.3	191.6
	23	572	236.5	275	254	247.1	150
	28	383.9	190.5	264.5	225	186.3	166.8
	30	343	224.1	213.2	203.4	187.7	178.4
Jan.	6	280.2	225.8	173.4	241.4	223.5	373.7

Total suspended solids data

Date	(mg/L) Inf	E1	E2	E3	E4	E5	R1	R2	R3	R4	R5
Sept. 30							490	280	1040	1160	2370
Oct. 1		40	64	64	124	120					
5	30	44	60	144	128	52	150	370	640	840	2100
7	16	48	64	148	124	76	670	890	960	1230	1220
9	44	48	40	128		88	1140	880	920	1430	1980
14	108	368	72	192	124	88	310	540	890	1330	2290
16	20	252	124	208	160	72	280	350	680	1230	2150
19	56	120	40	136	136	56	630	730	1000	1550	2330
21	28	412	208	264	240	112	600	610	1150	1720	2390
23	32	410	264	230	250	200	510	660	960	1250	2060
28	32	250	205	80	384	100	630	580	1180	1820	2500
30	32	400	208	56	472	152	570	500	1120	1720	2430

Data for Start-up period

Effluent and Waste Data

Date	Volume (ml)					Wasted (mg)				
	E1	E2	E3	E4	E5	R1	R2	R3	R4	R5
1	300	325	280	350	80	215	100	195	75	110
5	450	450	450	450	450	50	124	65	27	81
6	320	375	425	350	360	55	128	68	39	86
7	400	400	400	400	400	280	314	133	73	30
8	400	425	440	380	420	280	341	128	76	29
9	420	440	500	0	440	531	338	122	143	61
13	450	450	500	450	450	lagoon	338	122	91	61
14	440	450	500	425	440		193	87	83	77
15	400	440	500	410	270		194	87	84	92
16	430	175	420	370	280		119	49.5	64	88
19	1250	1300	1300	1600	700		254	30	-58	77
20	400	440	510	425	150		279	133	98	108
21	410	440	510	420	290		161	115	50	87
22	410	445	490	410	350		154	102	74	81
23	200	570	510	440	390		117	76	16	25.3
27	425	460	550	500	440		145	67	1	15
28	420	450	520	440	400		149	201	14	85
29	410	440	475	420	400		144	199.5	21.4	85
30	375	460	500	450	225		107	198	-40	88

First Shock Loading of Reactor System
Shock Load on November 6, 1992

		SOC (mg/L)					
Date	Day	Inf	E1	E2	E3	E4	E5
2	1	399.8	186.9	252	196.8	192.4	169.5
3	2						
4	3	363.5	217.3	250.2	192.3	183.8	192.6
5	4						
6	5	1228					
7	6	558.6	650.9	811	723.9	654.9	553.6
8	7	399	503	505.2	495	545.6	482.9
9	8		466.5	503.6	442.9	449.3	417.3
10	9		426.6	470.5	409.2	436.2	388.7
11	10		459	424.5	442	443	395
12	11		431	415.7	407	441.6	390
13	12	456.4	377.1	412.5	413.1	435.7	394.3
14	13	547.6	354.9	376.7	402.4	483.9	403.7
15	14	449.5	520.5	321.7	345.5	364.2	358.1
16	15	428.8	279	309.2	297.7	408.1	275.4
17	16	432.3	230.2	239.1	230.9	357.5	266.7
18	17	449.8	297.9	224.1	243.4	302.4	287.8
19	18	438.3	222.7	237.4	210.4	271.2	248.8
20	19	449.4	209.2	206.5	208.2	266.4	288.8
21	20		250.5	239.5	222.7	268.5	265
22	21		229	244.8	251.3	227.1	240.5
23	22	503.7	273.7	293.7	257.9	276.7	246
24	23	507.5	184.9	249.9	185.4	185.4	263.8
25	24	499.9	179.1	178.1	193.7	188.4	250.5

Shock Load 1

Total Suspended Solids Data

		Effluent (mg/L)					Reactor Contents (mg/L)				
Day	Inf	E1	E2	E3	E4	E5	R1	R2	R3	R4	R5
2	48	450	48	48	280	136	370	450	1110	1830	2170
4	20	330	72	32	230	64	480	460	1010	1530	2130
6	64						520	470	1020	1870	2240
7	68	210	64	55	836	348	610	580	1030	1720	1890
8	120	290	208	296	404	224	470	510	850	1390	2060
9	120	470	144	308	344	180	780	570	1060	1770	2340
10	72	370	92	236	284	268	500	460	1040	1470	2070
12	56	188	116	116	312	364	500	420	950	1660	1750
13	76	392	108	188	552	156	770	590	1070	1360	2330
14	64	288	96	280	476	336	330	310	910	1190	1960
15	24	96	92	180	488	88	600	460	930	1280	2060
16	56	408	96	244	260	132	760	420	960	1030	1950
17	100	540	140	152	488	92	770	580	750	950	1840
18	84	432	112	128	164	108	710	400	850	1120	1800
19	108	264	116	152	272	172	530	470	670	1170	2080
20	80	480	292	132	160	84	760	360	850	980	2090
21	88	260	84	204	256	268	600	590	720	890	1740
22	48	84	76	208	216	284	550	520	910	880	1890
23	80	276	52	156	412	208	640	520	890	1180	1900
24	104	368	72	128	208	312	690	550	660	1220	1190
25	76	300	76	100	224	192	560	480	840	1130	1690
Avg	74.09524	324.8	107.8	167.15	343.3	200.8	595.2381	484.2857	908.5714	1315.238	1960.476

Shock Load 1

Effluent and Waste Data

Date	Volume (ml)					Wasted (mg)			
Nov.	E1	E2	E3	E4	E5	R2	R3	R4	R5
3	100	440	475	440	400	163	202	61	55
4	400	450	475	430	400	153	188	55	81
5	400	440	475	430	400	154	188	55	81
7	200	325	340	300	250	216	190	-78	8
8	400	425	500	425	400	91	72	16	-14.2
9	400	450	500	415	400	174	64	37	46
10	410	440	510	425	400	150	91	28	-3
11	400	460	500	440	400				
12	420	460	510	450	400	76	79	-109	-202
13	410	450	510	450	150	194	122	-110	93
14	400	450	500	440	350	75	39	-92	-20
15	410	450	510	425	390	145	95	-79	69
16	410	450	510	430	390	130	70	-7.6	47
17	410	450	490	410	360	178	80	-103	60
18	350	375	440	350	300	124	117	56.1	58
19	400	440	460	425	350	146	69	3.7	45
20	400	440	480	400	360	23	111	36	75
21	400	440	475	410	350	206	51	-14	-6
22	400	430	475	410	360	180	85	0.424	-7.3
23	400	425	475	410	360	193	108	-49	21
24	400	400	500	410	360	200	73	39	-51
25	400	425	475	410	360	166	124	22.7	16
26	400	410	475	410	350	167	124	22.7	18
Avg	391.8182	431.1364	481.1364	413.8636	356.3636	149.5714	101.9048	-12.856	19.7381
HRT	5.104408	4.638904	4.156826	4.83251	5.612245				

Data for period between shocks 1 and 2

Total Suspended Solids Data

Date	(mg/L) Inf	E1	E2	E3	E4	E5	R1	R2	R3	R4	R5
Nov. 27	60	212	28	72	288	200	560	440	860	1100	1650
Dec. 1	60	184	68	76	196	172	460	560	670	1080	1990
14	40	64	24	20	112	228	500	332	580	620	1360
Jan. 6	20	68	52	112	228	452	690	910	490	860	1810
8	20	320	36	40	48	148	640	740	580	1220	1010
11	28	880	20	32	96	92	760	720	840	970	1220
13	16	572	72	16	144	140	550	310	520	800	1400
15	24	376	24	32	212	200	540	290	590	830	700
18	20	560	10	32	16	96	420	340	600	980	810
20	40	252	48	64	124	68	330	340	540	750	1310
22	52	136	36	56	228	160	400	350	580	940	1080
28	28	148	80	80	124	108	370	36	850	950	1390
31	52	320	56	72	180	100	260	260	590	880	1280

Data for the period between shocks 1 and 2
Effluent and waste data

Date	Volume (ml)					Wasted (mg)			
	E1	E2	E3	E4	E5	R2	R3	R4	R5
Nov. 27	425	450	500	430	380	169	139	-13	7
30	200	1300	1450	1230	1100	155	76	-240	-136
Dec. 1	400	450	500	425	380	199	99	26	35
2	400	430	475	400	380	200	101	31	35
3	425	450	480	420	390	199	100	27	33
4	400	440	480	410	375	200	100	29	35
7	1240	1320	1300	1260	1120	150	43	-135	-91
8	400	450	500	410	380	199	99	29	35
9	400	450	475	420	375	199	101	27	35
10	400	450	490	425	390	199	101	26	35
11	410	450	475	400	355	199	101	29	35
14	1060	1160	1180	1100	1000	113	97	-59	-220.5
15	350	400	450	375	350	125	109	20	-11
16	400	450	475	425	375	125	108	15	-17
17	400	450	475	425	375	125	108	15	-17
18	400	425	475	425	375	125	108	15	-17
21	120	1250	1490	1220	1100	115	100	--	--
Jan. 6	2900	3800	4000	3600	1900				
7	375	0	450	400	340	364	48.5	-5	-63
8	400	970	450	400	350	265	99	103	-1
11	1160	1220	1160	1120	1020	503	233	39	-10
12	375	400	425	375	350	350	191	78	37
13	400	425	450	375	360	95	97	26	20
14	375	400	440	360	340	97	97	28	23
15	475	425	440	375	375	108	105	4	-40
18	1120	1200	1360	1020	1000	129	79	-19	-5
19	360	400	430	325	340	134	107	60.6	8
20	350	400	450	350	340	120	81	32	42
21	600	640	475	700	450	110	80	-10	35
22	700	760	800	500	500	120	75	-19	-25
23	775	700	825	150	150				
24	800	700	860	0	250				
25	750	700	850	125	600				
26	520	0	0	0	500				
27	800	1000	500	575	675	350	150	40	0
28	800	650	750	900	700	96	12	-15	-5.6
29	800	600	710	900	675	99	115	-15	-3.9
30	800	650	725	900	675				
31	800	650	725	900	700				

Second Shock Loading of Reactors
Administered on February 8, 1993
SOC Data (mg/L)

	Date	Inf	E1	E2	E3	E4	E5
Feb.	4	256	158	164	144	132	136
	5	341	145	148	141	122	120
	6	385	143	146	132	129	122
	8	362	151	148		130	143
	8.5	1200	752	772	794	770	780
	9	464	792	754	715	790	709
	10	463.1	453	425	467	421	431
	11		273	217	240	291	231
	12	410	229	195	217	281	191
	13		267.9	163	202	192	190
	14		185	136	182	277	143
	15	415	197	174	199	270	127
	16		151	153	137	249	113
	17	372	166	150	164	276	125
	18		166	159	175	257	142
	19	370	171	268	127	150	158

Shock Load 2

Total Suspended Solids Data

Date Nov.	Inf	E1	E2	E3	E4	E5	R1	R2	R3	R4	R5
4	24	288	76	32	104	132	270	440	670	1250	1250
6	40	280	36	12	76	16	430	450	730	1180	1310
8	110	480	20	10	68	24	500	400	660	1250	1720
9	108	332	124	160	152	256	480	360	820	1300	1720
11	112	636	112	120	248	152	550	710	1260	1330	2210
13	120		28	89	244	72	500	1020	1380	1250	2030
15	132	336	72	72	180	36	450	900	1480	1270	2770
17	108	428	10	10	104	10	480	990	1200	910	2910
19	152	380	10	36	148	24	630	1730	1680	1080	3720
21	156	260	24	64	144	60	530	940	1350	1140	3060
Average	106.2	380	51.2	60.5	146.8	78.2	482	794	1123	1196	2270

Effluent Volumes and waste

Date	Volume (ml)					Wasted (mg)			
Feb.	E1	E2	E3	E4	E5	R2	R3	R4	R5
1	800	650	750	900	650	74	68	-70	0
2	800	650	750	90	650	74	68	-70	0
4	800	650	700	920	650	130	107	30	-22
5	525	905	960	300	970	112	100	94	-65
6	450	1100	1150	760	1200	142.6	136	62	47
7	425	1080	1160	1200	1140	150	137	29	48
8	450	1080	1160	1100	1140	162	133	56	61
9	300	670	720	760	670	175			-83
10	450	1100	1170	1280	1120	31	-10	-58	-197
11	440	1160	1220	1350	1180	180	119	-194	-66
12	440	1120	1220	1340	1180	183	119	-194	-66
13	450	1120	1200	1320	1200	354	196	-189	18.7
14	440	900	1200	1250	1180	364	196	-173	18.7
15	450	600	1220	440	1200	333	224	200	24.26
16	450	680	380	440	400	329	274	200	50
17	450	1460	1320	1340	1180	412	241	-41	137
18	440	1380	1580	1440	1340	412	243	-50	136
19	440	1300	1520	1520	1340	718	304	-77	160
20	425	1240	1460	1280	1220	717	305	-71	161
21	450	1240	1480	1290	1240	385	198	-61	83
22	440	1210	1450	1250	1220	384	200	-56	84
	434.7059	1084.706	1212.353	1138.824	1126.471				
HRT (d):	4.600812	1.843818	1.649685	1.756198	1.775457				

Third Shock Loading of The System
Administered on March 9, 1993
SOC Data (mg/L)

	Date	Inf	Effluent (mg/L) E1	E2	E3	E4	E5
March	6	310.5	137.8	116.2	111.8	113.5	124.6
	7		160.8	172.5	132.8	135.3	147.5
	8	279.9	124.4	137	129	131	164.3
	9	980	553.4	537.4	514.5	506.1	535
	10	298.7	434	375.8	313.1	340.4	379.4
	11		255	182.5	158.5	158.9	198.5
	12	298.4	192	142	147	142	153
	13		176	180.4	155.3	165.6	153.7
	14		191.3	160.7	163.3	157.8	160.8
	15		171.9	147.2	162.8	164	157.1
	16	264.7	169.4	155.7	147.7	151	149.1
	17		183	164.4	172.4	169.8	153.8
	18	251.7	169	166.7	166.1	154.7	157.8
	19		155.1	154.7	153.2	157.5	156.7
	20	254.5	159.5	159.2	158.2	159.6	159
	21		160.8	148.6	156.5	142.3	158.8
	22	245.7	158.5	156.9	158.9	161	156.4
	23		163.9	159.3	149.3	143.1	151.2
	24	246.6	162.2	160.3	148.8	161.5	141.4
	25		165.8	155.5	161.8	151.4	151.8

Shock Load 3

Total Suspended Solids Data

Date		Effluent (mg/L)					Reactor Contents (mg/L)				
March	Inf	E1	E2	E3	E4	E5	R1	R2	R3	R4	R5
6	16	248	44	8	40	10	610	620	1450	1540	4160
8	56	256	56	52	48	268	720	540	1270	1510	4670
10	28	328	84	84	108	36	670	870	1790	1760	3260
12	108	184	24	28	68	32	700	620	1850	1750	2460
14	60	68	10	16	20	10	570	630	1760	1740	3840
16	60	196	10	10	12	10	720	660	1820	1820	4260
18	64	424	60	56	80	52	640	590	1630	1900	4120
20	132	296	8	60	36	32	400	600	1780	1790	3720
22	20	304	32	48	76	28	600	510	2120	1700	3750
24	24	332	10	48	32	10	450	420	1580	1500	2810
26	12	276	80	36	64	28	450	330	1590	1570	4500
Avg:	52.73	264.73	38.00	40.55	53.09	46.91	593.64	580.91	1694.55	1689.09	3777.27

Shock Load 3
Effluent Volume And Solids Wasted

Date	Volume (ml)					Wasted (mg)			
March	E1	E2	E3	E4	E5	R2	R3	R4	R5
6	450	1120	1080	1100	980	202	283	111	198
7	440	1100	1020	1120	1080	203	282	110	198
8	440	1040	1100	1180	1100	169	203	98	-60
10	425	1130	1100	1180	1140	259	269	50	123
11	450	1080	1060	1160	1080	263	272	52	125
12	450	1120	1060	1120	1140	245	352	105	90
13	450	1060	1080	1110	1120	245	352	105	95
14	450	1080	1080	1070	1120	254	341	155	182
15	450	1080	1060	1040	1100	254	340	154	183
16	450	1100	1100	1080	1140	266	360	172	203
17	450	1080	1120	1200	1120	260	360	171	203
18	450	1080	1140	1200	1100	185	270	97	150
19	400	1060	1120	1200	1100	185	270	97	150
20	400	1060	1140	1200	1100	260	303	144	154
21	400	1080	1200	1200	1100	260	303	144	154
22	400	1020	1100	1180	1100	175	289	124	157
23	400	980	1080	1180	1100	175	289	124	157
24	400	1120	1100	1180	1120	162	265	114	130
25	300	670	780	800	760	164	280	125	133
26	425	1020	1060	1170	1120	538	282	83	194
Avg:	424	1054	1079	1133.5	1086				
HRT (d):	4.72	1.90	1.85	1.76	1.84				

Fourth Shock Loading of the System
Administered on April 2, 1993
SOC Data (mg/L)

Date	Inf	E1	E2	E3	E4	E5
1		158.7	182.5	157.1	165.6	174.5
2	2765	183.7	197.5	176.2	173.7	183.3
4		1857.5	1253	673.5	1377	1774.5
5	365.4	906.6	799.8	533	850.2	
6		1302	438.4	432	491	583.8
7	328.1	1475	464	384.4	420.2	562.4
8		1296.5	306	417.4	392.4	386.4
9	512.5	941.2	330	351	375.4	347.4
10		666.4	319.5	299.7	378.1	329
11	310.3	435.1	293.3	301.7	356	367.7
12		612.8	330.4	277.2	343.2	401
13	338.7	320.5	320.2	282.9	356.8	361.5
15	286.2	385.2	265.9	249.8	290.5	303
16		351.1	246.7	280.1	342.4	297
17	392.4	354	272.6	239	275.1	338.4
18		409.3	247.6	256.2	273.4	258.5
19	309	395.3	218.6	203.7	228.1	240.6
20		353.6	232.9	200.9	232.7	298.7

Shock Load Four
Suspended Solids Data

Date	Inf	Effluent (mg/L) E1	E2	E3	E4	E5	Reactor Contents (mg/L) R1	R2	R3	R4	R5
3	72	820	1136	624	1724	2590	3210	2490	2520	1970	3960
5	80	380	240	452	504	584	220	800	1430	1020	
7		720	244	84	328	468	1780	380	640	1290	780
9	80	584	44	10	236	176	730	230	180	590	530
11	40	292	68	80	236	160	970	340	520	780	700
13	92	352	104	112	192	80	820	460	320	550	660
15	40	312	88	40	156	128	1070	220	190	430	500
17	44	336	136	24	76	36	630	200	350	10	450
19		332	32	68	120	40	384	172	168	244	220

Shock Load 4

Daily Effluent Volume (ml)

Date April	E1	E2	E3	E4	E5
1	450	1120	1140	1200	1140
3	400	1400	1260	1270	400
4	450	1280	1420	1300	1120
5	300	780	920	840	700
6	360	1230	440	990	1090
7	400	890	1260	210	1130
8	360	1060	1320	600	1080
9	450	1260	1320	880	1160
10	425	1240	1480	850	380
11	450	1240	1470	200	450
12	400	1240	1140	560	1200
13	400	1200	1480	820	1100
15	310	820	1300	870	100
16	450	1220	1000	900	1200
17	425	1220	1340	880	1000
18	450	1500	1280	400	1040
19	400	1550	1200	540	1020
Avg	404.71	1191.18	1221.76	782.94	900.59
HRT(d)	4.94	1.68	1.64	2.55	2.22

Temperature, Dissolved Oxygen
And Sludge Volume Index (SVI)

Temperature (C)

Month	Day	R1	R2	R3	R4	R5
October	14	24.5	24.0	23.5	23.0	23.0
	21	26.0	25.5	25.0	25.0	25.0
	28	24.5	24.0	23.0	23.0	23.0
Novembe	4	24.5	23.5	23.0	23.0	23.0
	9	26.0	26.0	25.5	25.5	25.0
	18	25.5	25.0	25.0	24.5	24.0
	25	27.0	26.0	26.0	25.0	25.0

Dissolved Oxygen (mg/L)

Month	Day	R1	R2	R3	R4	R5
October	14	3.0	7.2	7.2	7.4	4.8
	21	4.3	4.6	5.4	6.6	2.9
	28	3.2	6.2	2.4	2.4	4.8
Novembe	4	5.7	6.7	3.2	3.3	5.9
	18	2.2	4.4	1.0	4.6	3.7
	25	7.0	10.2	3.3	8.6	3.6
February	19	4.7	5.5	1.7	2.2	2.5

Note: Though February to April, DO was adjusted based on experience with the system, and spot checks with the DO meter.

SVI Data (mL/g)

Month	Day	R1	R2	R3	R4	R5
October	9	41	68	54	56	91
	14	226	74	45	60	78
	21	200	66	52	58	105
	28	95	43	68	77	296
Novembe	4	104	109	79	105	263
	9	64	18	28	62	77
	18	70	75	47	45	100
	25	36	21	60	62	89
February	19	79	41	77	83	83

pH Data for Experiment

Month	Date	Effluent pH E1	E2	E3	E4	E5	pH Influent
October	9	8.2	8.5	8.3	N/A	8.3	7.2
	14	8.1	8.4	8.3	8.3	8.2	6.6
	21	7.6	7.8	7.7	7.9	8.3	6.3
	28	7.7	7.6	7.6	7.6	8.0	6.4
Nov.	4	8.0	8.1	7.9	7.9	7.9	7.4
	9	8.8	8.9	8.9	8.8	8.7	10.5
	18	8.8	8.8	8.9	8.8	8.9	10.4
	25	8.9	8.9	8.8	9.0	8.7	10.4

pH of Reactor contents

Month	Date	R1	R2	R3	R4	R5
October	9	8.1	8.5	8.4	8.5	7.9
	14	8.0	8.2	8.1	8.1	7.9
	21	7.7	7.1	7.9	8.1	8.0
	28	7.7	7.8	7.3	7.5	7.6
Nov.	4	8.1	8.0	7.7	7.7	7.9
	9	9.1	9.1	9.1	9.0	8.8
	18	9.1	9.0	9.1	9.0	9.0
	25	9.0	9.1	9.0	9.1	8.9

Microbiological Examinations

Date	Reactor	Description
		Start-up Period
Oct. 9	R1	Little higher organism activity, considerable filamentous growth.
	R2	Little activity, less filamentous growth.
	R3	Rotifers, nematodes, paramecium, ciliated protozoa observe; as well as some filamentous growth.
	R4	Low activity, some amoebas, rotifers and stalked ciliated protozoa present.
	R5	Little activity, some protozoa; some filamentous growth.
Oct.16	R1	Some flagellated protozoa, noticeable filamentous growth.
	R2	Less activity than R1, and noticeably less filament.
	R3	Many smaller microorganisms, flagellated protozoa, and some rotifers observed.
	R4	Good population of rotifers, some protozoa, and some filamentous growth.
	R5	Rotifers, protozoa, and smaller organisms observed.
Oct.23	R1	Some protozoa and filamentous growth.
	R2	Some variety, less filamentous growth.
	R3	Stalked ciliated protozoa, some other life forms.
	R4	Good variety - rotifers, several types of protozoa present.
	R5	Rotifers, various protozoa, and paramecium all observed.

Microbiological Examinations, continued

Date	Reactor	Description
		Start-up period, continued
Oct.30	R1	Mostly ciliated of protozoa, some filamentous growth.
	R2	Some ciliated protozoa, less filamentous growth.
	R3	Stalked and ciliated protozoa dominant, nematodes and rotifers also present.
	R4	Mostly ciliated protozoa present.
	R5	Ciliated protozoa and rotifers, some filamentous growth.
		First shock load, Nov. 6.
Nov.9	R1	Few higher organisms, many lower. Low levels of filament.
	R2	Very little activity, some lower organisms.
	R3	Some ciliated protozoa, moderate activity, mostly lower organisms.
	R4	Very little activity, some lower organisms.
	R5	Some ciliated protozoa and filamentous growth, fairly low activity.
Nov.20	R1	Good population of flagellated and ciliated protozoa, as well as other microorganisms. Some filamentous growth.
	R2	Mostly ciliated protozoa and some other organisms, less filament.
	R3	Rotifers and ciliated protozoa dominate, almost no filament.
	R4	Good populations of flagellated and ciliated protozoa; some filament.
	R5	Some protozoa present, low levels of filament.

Microbiological Examinations, continued

Date	Reactor	Descriptions
		First shock load, continued.
Nov.27	R1	Very little activity or filamentous growth.
	R2	High numbers of ciliated protozoa, rotifers present, no filamentous growth.
	R3	Some rotifers, relatively little activity.
	R4	High numbers of ciliated and stalked ciliated protozoa, highly active.
	R5	Similar to R4.
		Second shock load, Feb. 8.
Feb.10	R1	No activity, several inactive protozoa and rotifers observed.
	R2	Same as R1.
	R3	Same as R1.
	R4	Some activity, including active rotifers.
	R5	Some organisms, mostly inactive.
Feb.17	R1	Good population of ciliated protozoa.
	R2	High activity, mostly protozoa and some stalked ciliated protozoa.
	R3	Very active, good variety, including paramecium.
	R4	Similar to R3
	R5	Stalked protozoa, many ciliated protozoa, good variety of lower organisms.

Microbiological Examinations, continued.

Date	Reactor	Description
		Third shock load 3, March 9
March 10	R1	Little activity.
	R2	No activity observed.
	R3	Little activity.
	R4	Some active higher organisms, more active lower ones.
	R5	Similar to R4, but with fewer higher organisms.
		Fourth shock load, April 2
April 5	R1	Poor floc, no activity observed.
	R2	Slightly better floc, some activity observed.
	R3	Similar to R2.
	R4	Similar to R2, with inactive or dead protozoa observed.
	R5	Similar to R4.
April 23	R1	Poor floc and no activity observed.
	R2	Slightly better floc, also no activity.
	R3	Same as R2.
	R4	Pin floc, no activity observed.
	R5	Some larger floc, mostly pin floc. No activity observed.

Summary of Calculated Shock Loading Ratios

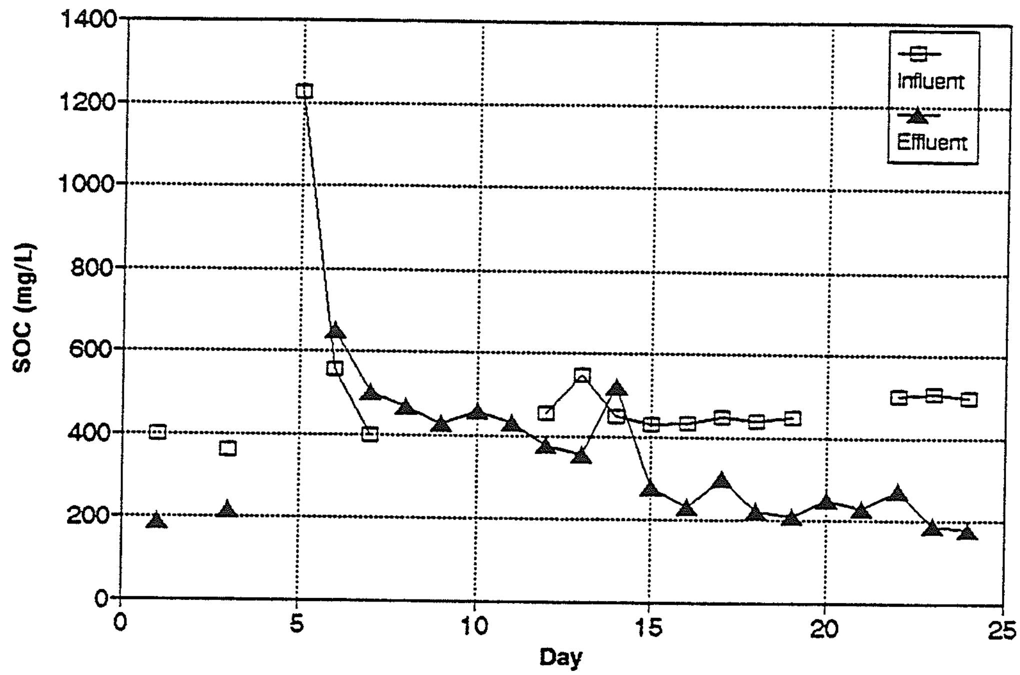
Ratio of Mass Loading of Substrate on the Day of The Shock Loading to the Mass Loading of Substrate on a Normal Day (mg/d:mg/d).

	Shock I	Shock II	Shock III	Shock IV
Lagoon R1	7.49	7.6	9.1	20
SBR 5 (R2)	6.8	3.38	4.1	7.3
SBR 10 (R3)	6.33	3.08	4.1	6.9
SBR 20 (R4)	7.09	3.38	3.9	10.8
SBR 40 (R5)	8.15	3.38	3.9	9.2

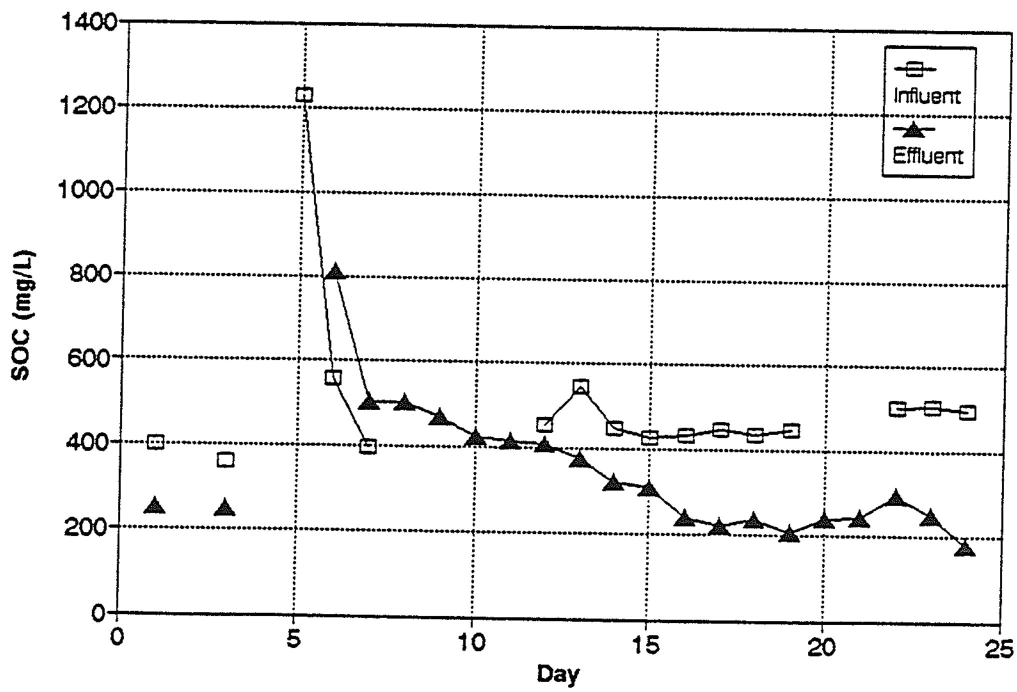
Ratio of the Mass Load of Substrate on the Day of Shock Loading to the Mass of Solids Present in the Reactor on the Shock Day (mg:mg).

	Shock I	Shock II	Shock III	Shock IV
Lagoon R1	2.65	3.13	1.58	5.2
SBR 5 (R2)	2.51	3.62	2.02	8.1
SBR 10 (R3)	1.34	2.12	0.86	2.0
SBR 20 (R4)	0.86	1.20	0.78	1.9
SBR 40 (R5)	0.59	1.00	0.27	0.68

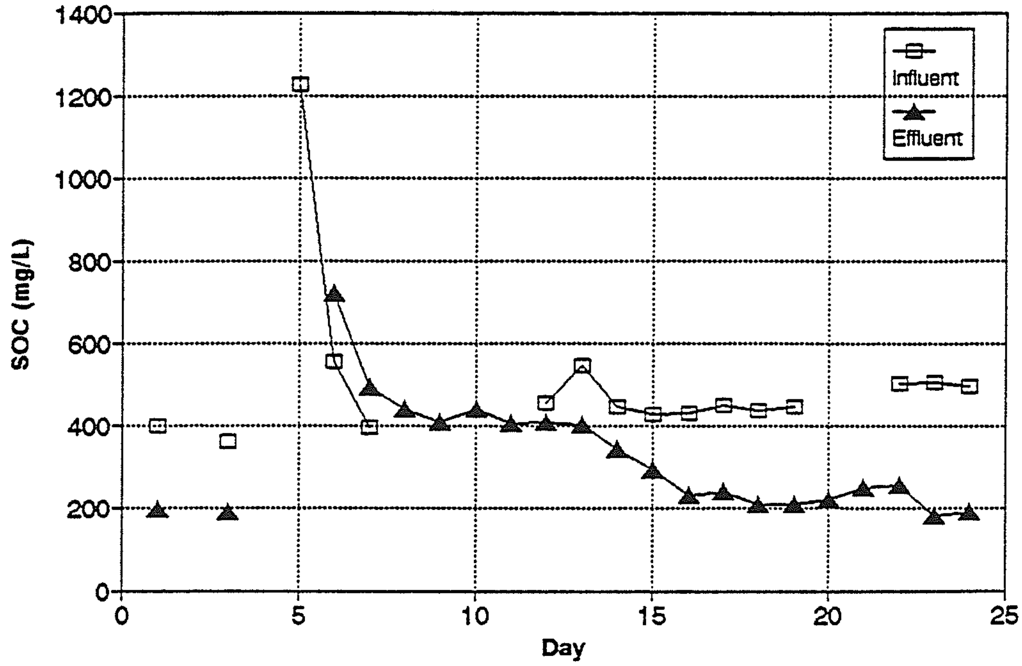
APPENDIX B
Histographs of Organic Carbon Data



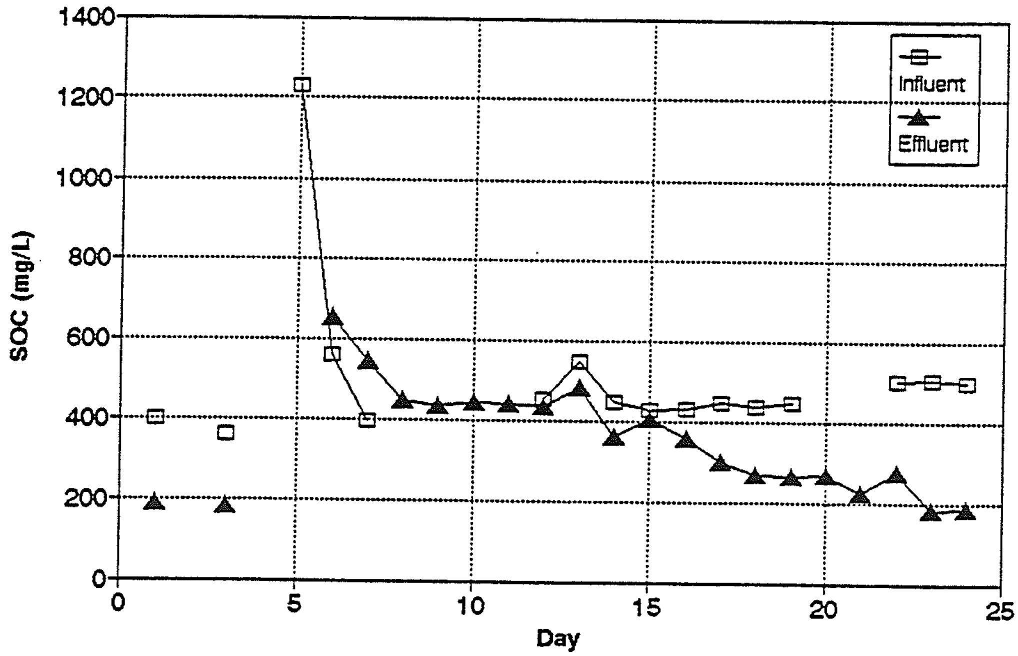
Organic carbon Sock Load I, Reactor 1, Lagoon
with nominal HRT=SRT=4.5 days



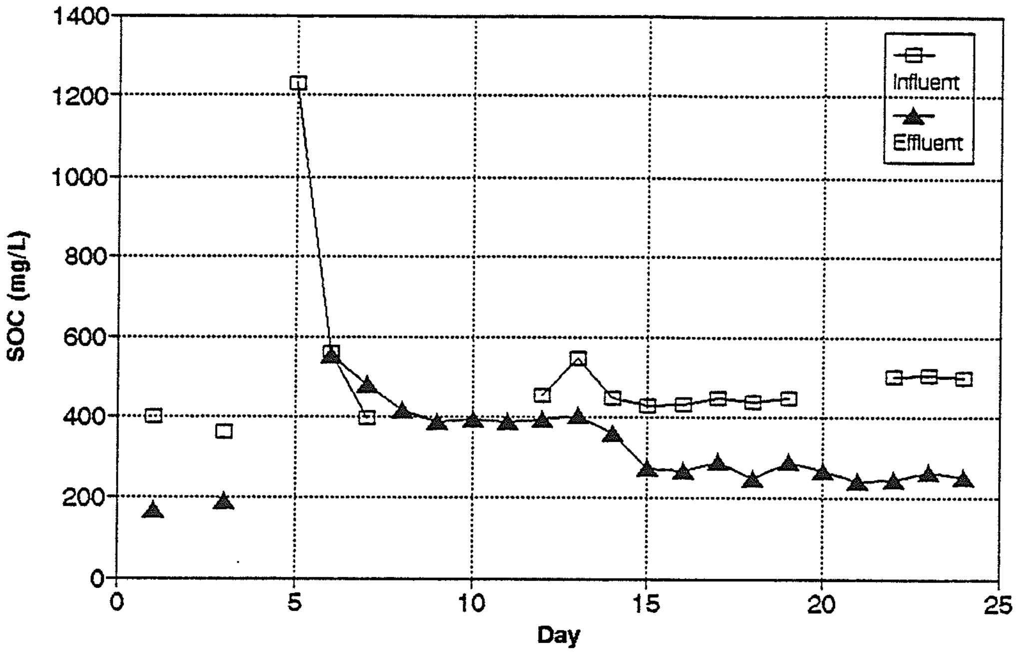
Organic carbon for Shock Load 1, Reactor 2, SBR
with nominal HRT =4.5 days, SRT=5 days



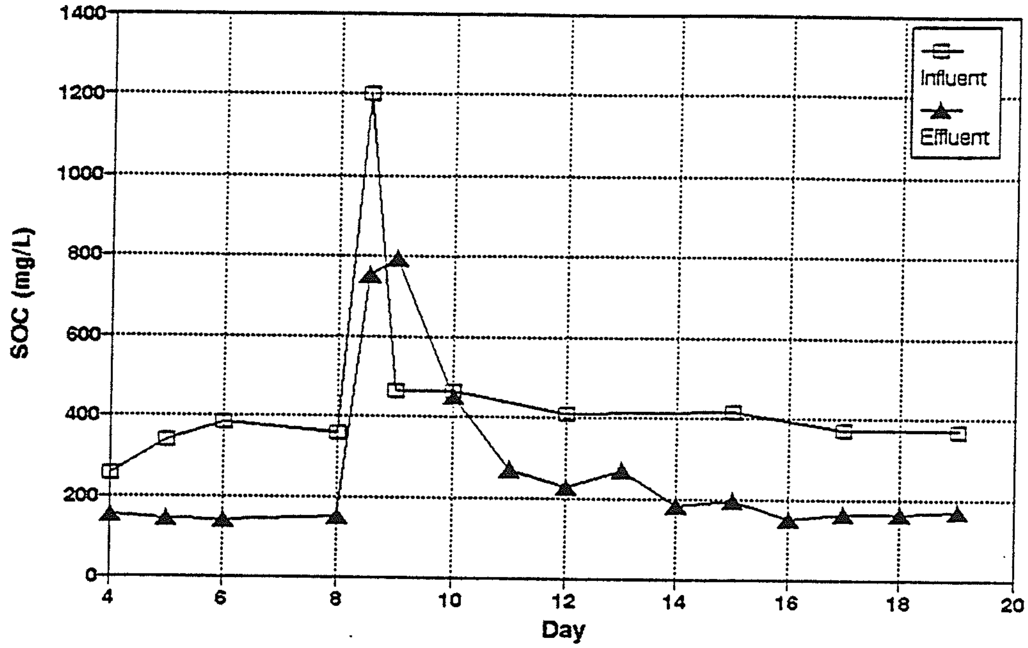
Organic carbon, Shock Load 1, Reactor 3, SBR
with nominal HRT=4.5 days, SRT=10 days



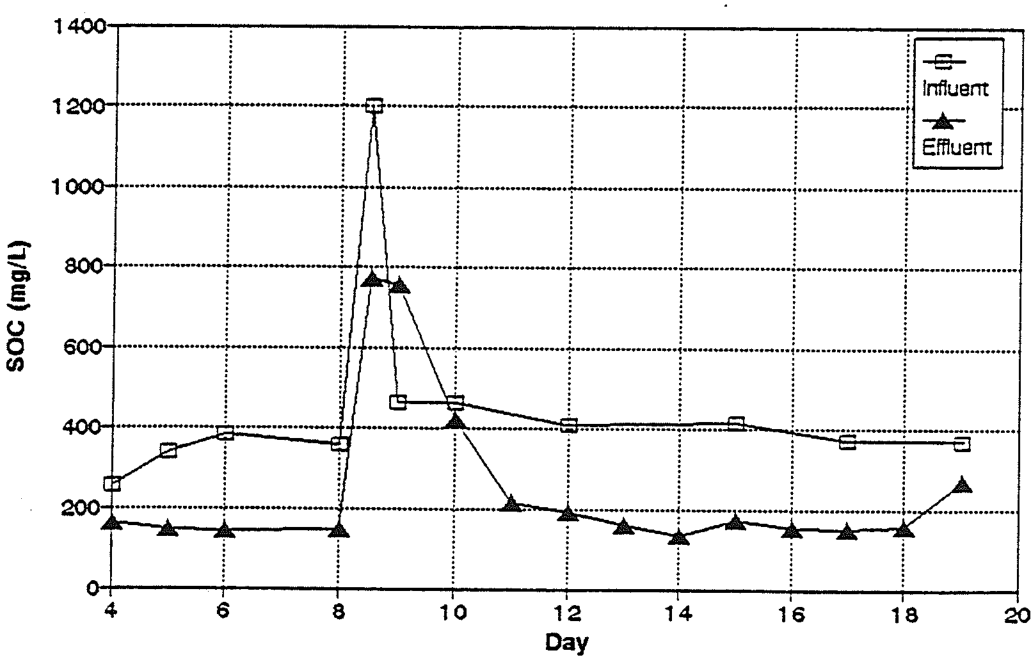
Organic carbon, Shock Load 1, Reactor 4, SBR
with nominal HRT=4.5 days, SRT=20 days



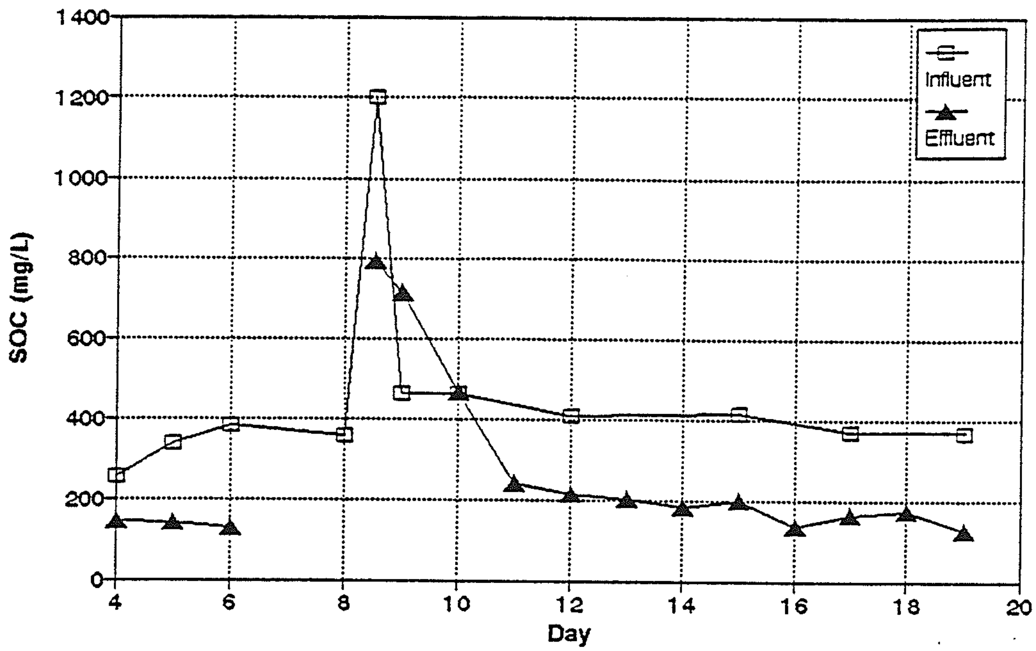
Organic carbon, Shock Load 1, Reactor 5, SBR
with nominal HRT=4.5 days, SRT=40 days



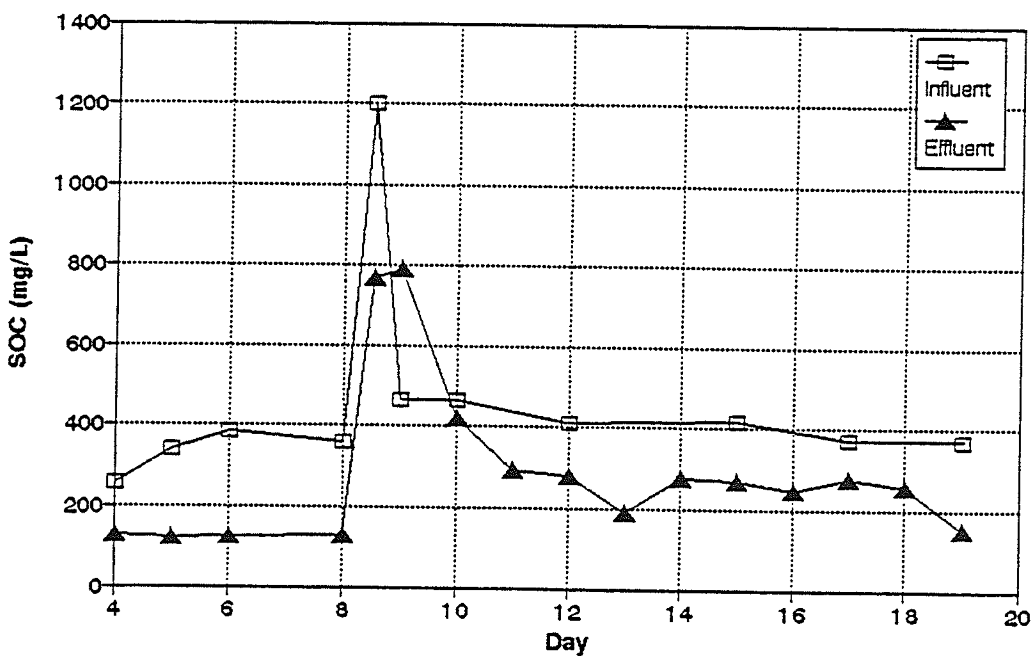
Organic carbon, Shock Load 2, Reactor 1, Lagoon
with nominal HRT=SRT=4.5 days



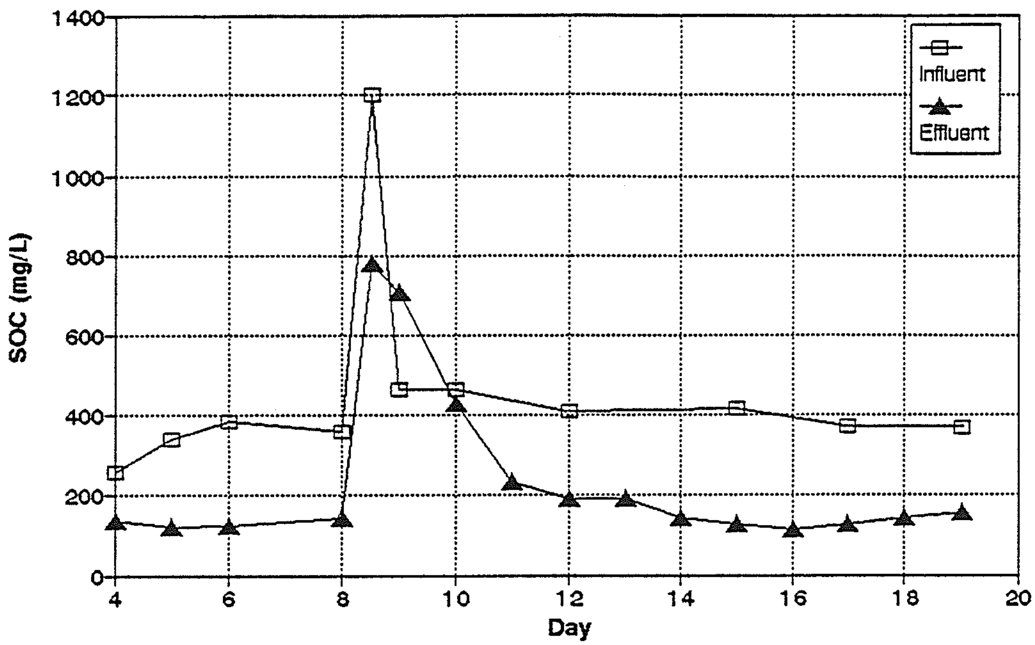
Organic carbon, Shock Load 2, Reactor 2, SBR
with nominal HRT=1.5 days, SRT=5 days



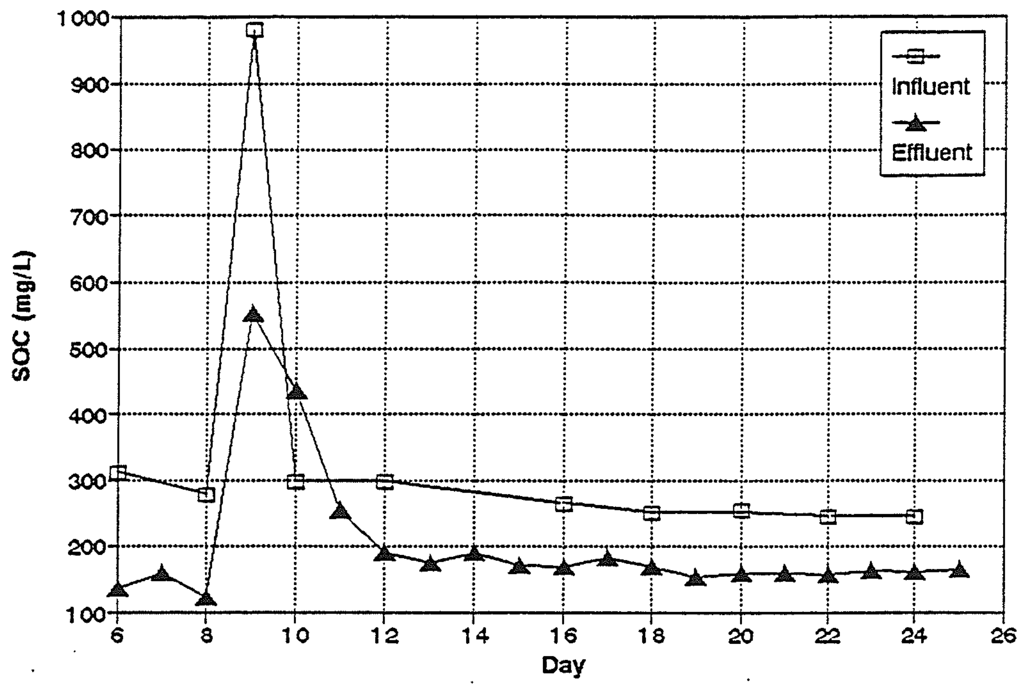
Organic carbon, Shock Load 2, Reactor 3, SBR
with nominal HRT=1.5 days, SRT=10 days



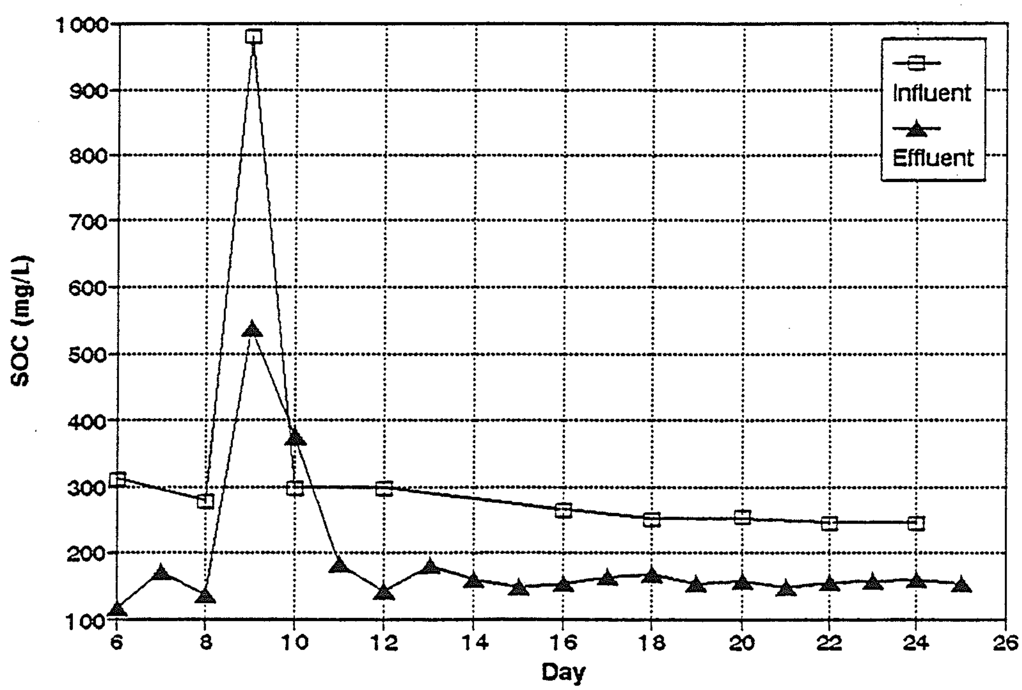
Organic carbon, Shock Load 2, Reactor 4, SBR
with nominal HRT=1.5 days, SRT=20 days



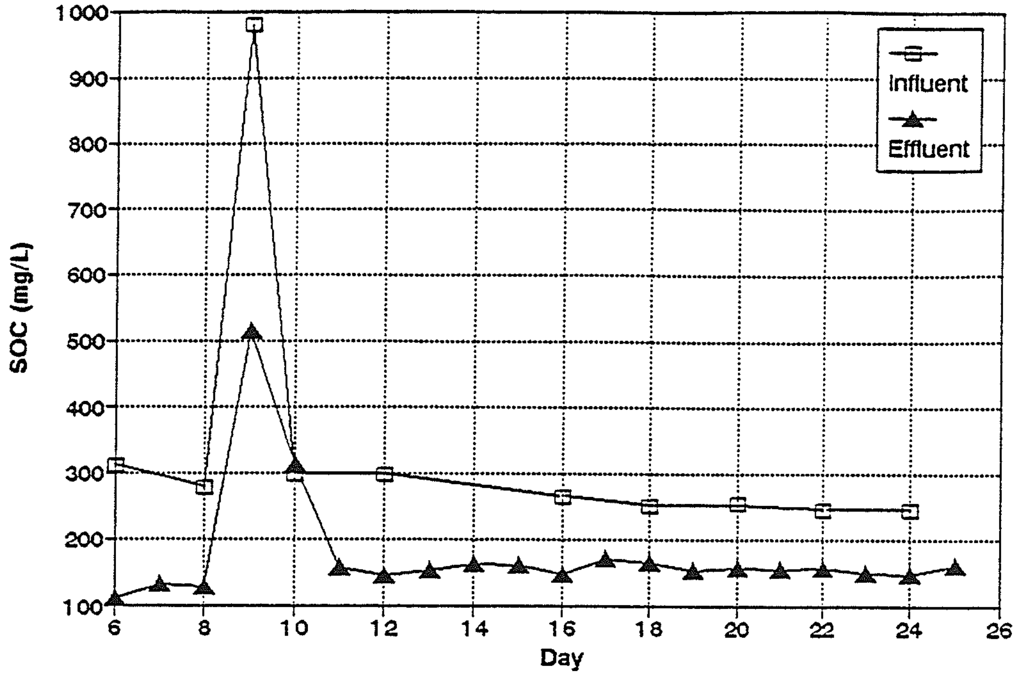
Organic carbon, Shock Load 2, Reactor 5, SBR
with nominal HRT=1.5 days, SRT=40 days



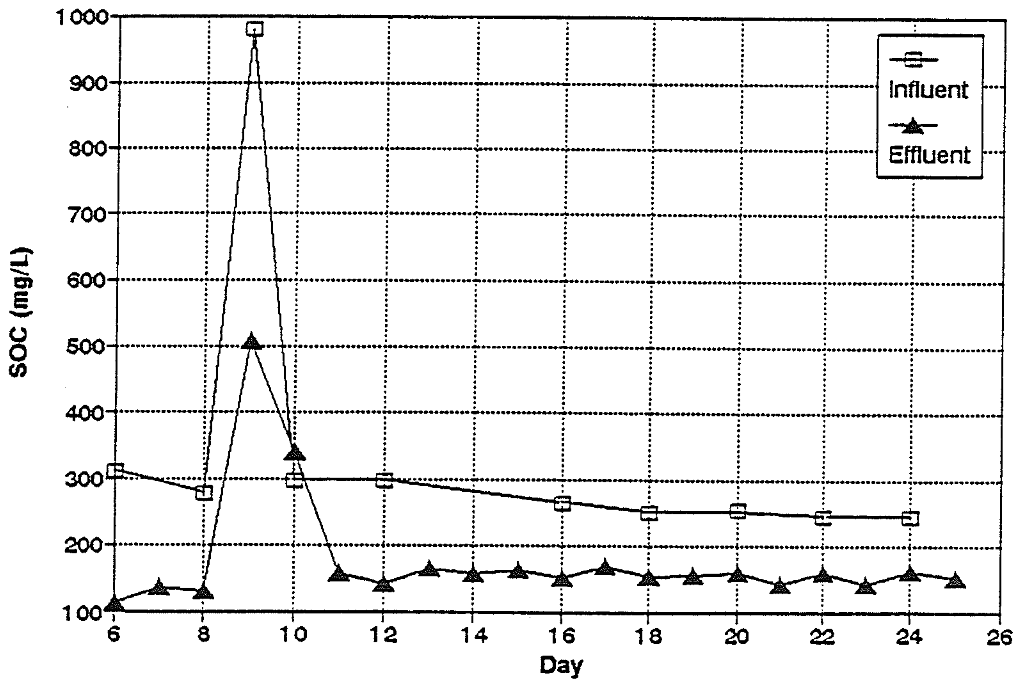
Organic carbon, Shock Load 3, Reactor 1, Lagoon
with nominal HRT=SRT=4.5 days



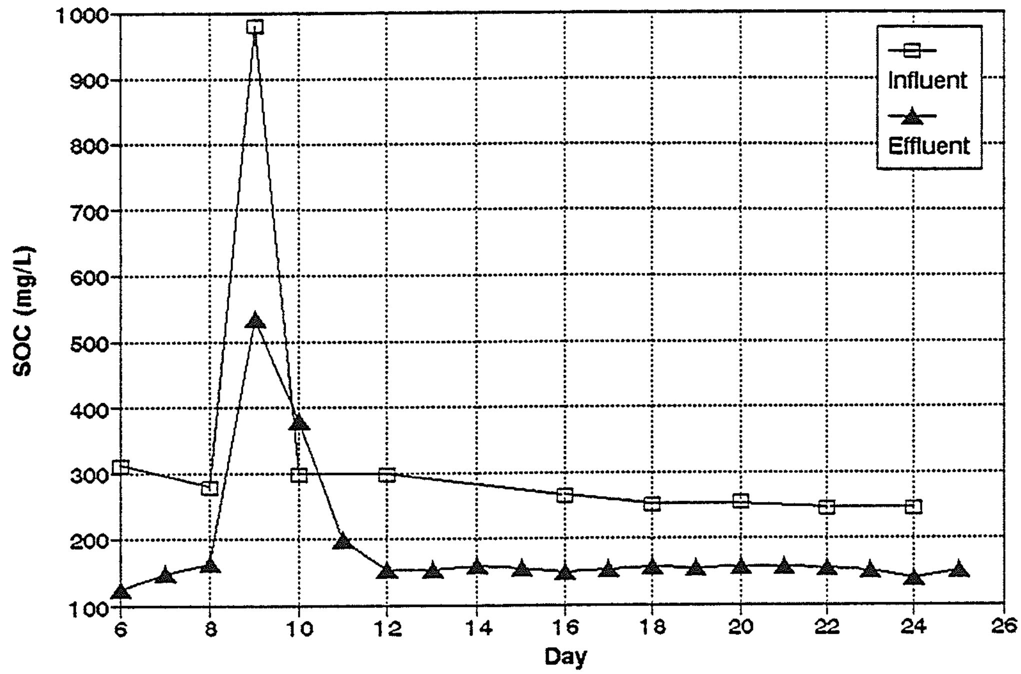
Organic carbon, Shock Load 3, Reactor 2, SBR
with nominal HRT=1.5 days, SRT=5 days



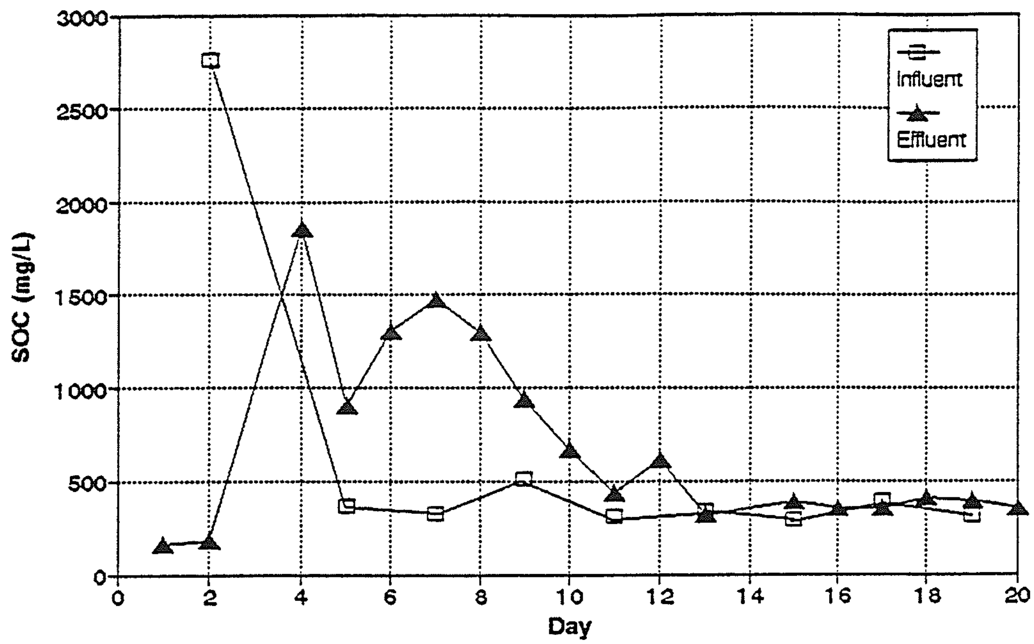
Organic carbon, Shock Load 3, Reactor 3, SBR
with nominal HRT=1.5 days, SRT=10 days



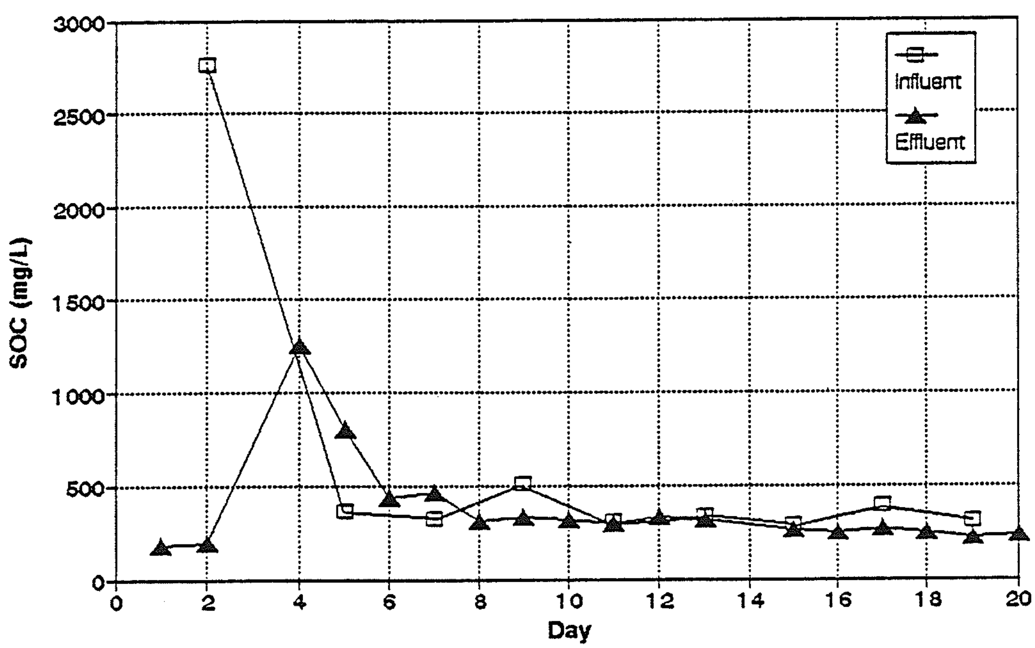
Organic carbon, Shock Load 3, Reactor 4, SBR
with nominal HRT=1.5 days, SRT=20 days



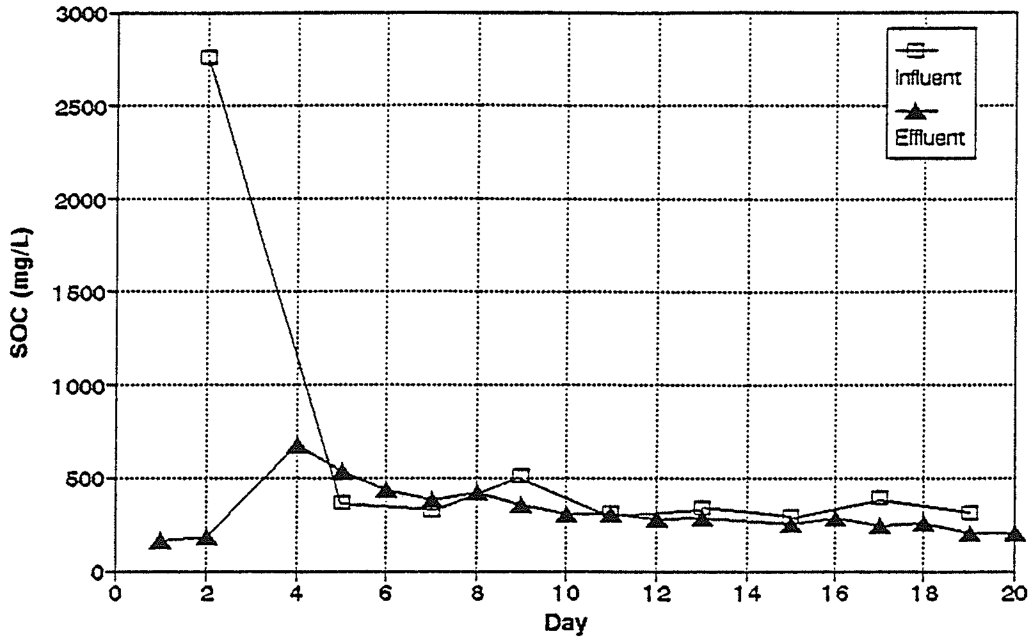
Organic carbon, Shock Load 3, Reactor 5, SBR
with nominal HRT=1.5 days, SRT=40 days



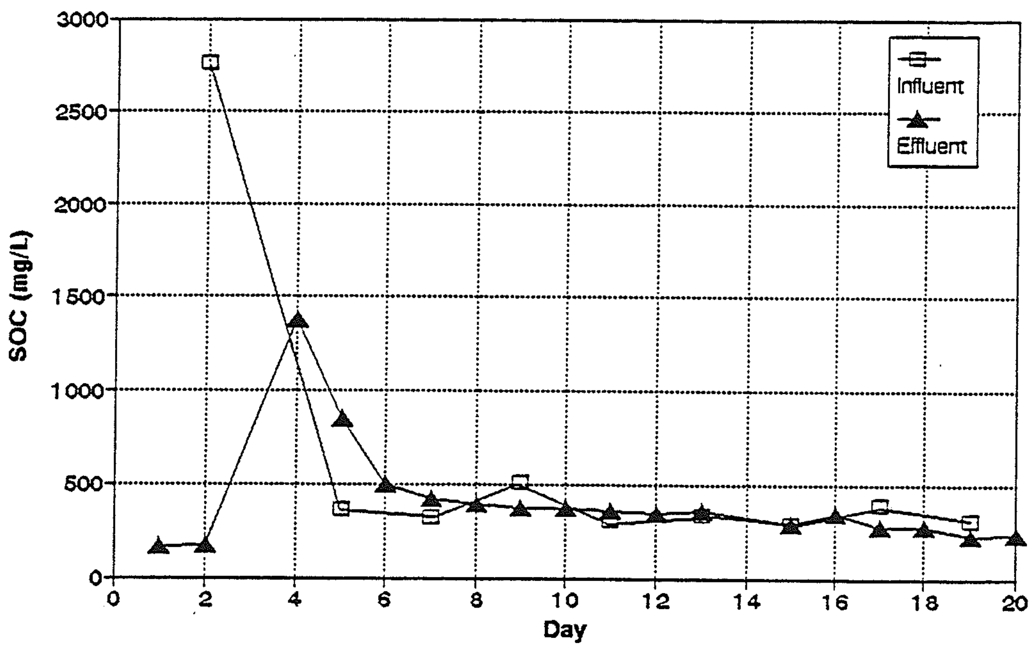
Organic carbon, Shock 4, Reactor 1, Lagoon
with nominal HRT=SRT= 4.5 days



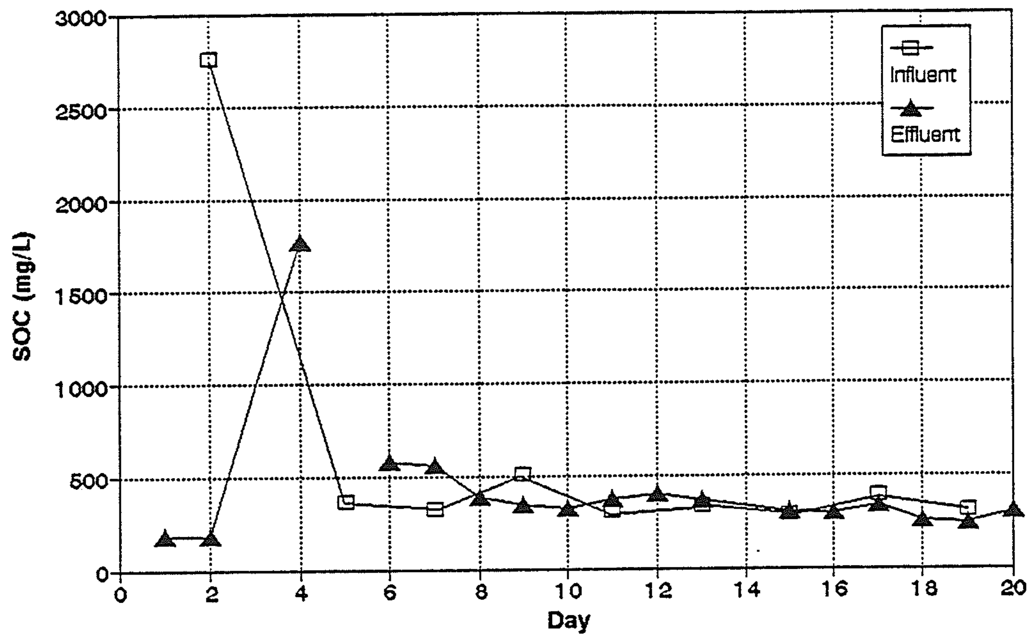
Organic carbon, Shock 4, Reactor 2, SBR
with nominal HRT=1.5 days, SRT= 5 days



Organic carbon, Shock 4, Reactor 3, SBR
with nominal HRT=1.5 days, SRT= 10 days



Organic carbon, Shock 4, Reactor 4, SBR
with nominal HRT=1.5 days, SRT= 20 days



Organic carbon, Shock 4, Reactor 5, SBR
with nominal HRT=1.5 days, SRT= 40 days

APPENDIX C
Dilution Model and Calculation of U

Dilution Model Verification --- Tracer Study

The dilution model discussed in section 3.4 of the Methodology chapter was verified experimentally using a tracer study. Initially, a calibration curve was established for concentrations of methylene blue with concentrations of 0 to 2.5 mg/L. These concentrations were correlated to the percentage transmittance of light using a Bausch & Lomb Spectronic 20 spectrophotometer. This data and the calibration curve established are shown on the following pages.

The dilution model discussed in the methods was used to predict the concentration of methylene blue in the reactor effluent, based on the initial concentration in the reactor on day 1, and the effluent volumes on subsequent days. The predicted and actual values are reported on the following pages, in both a table and a graph. The graph shows excellent agreement between the predicted and actual values.

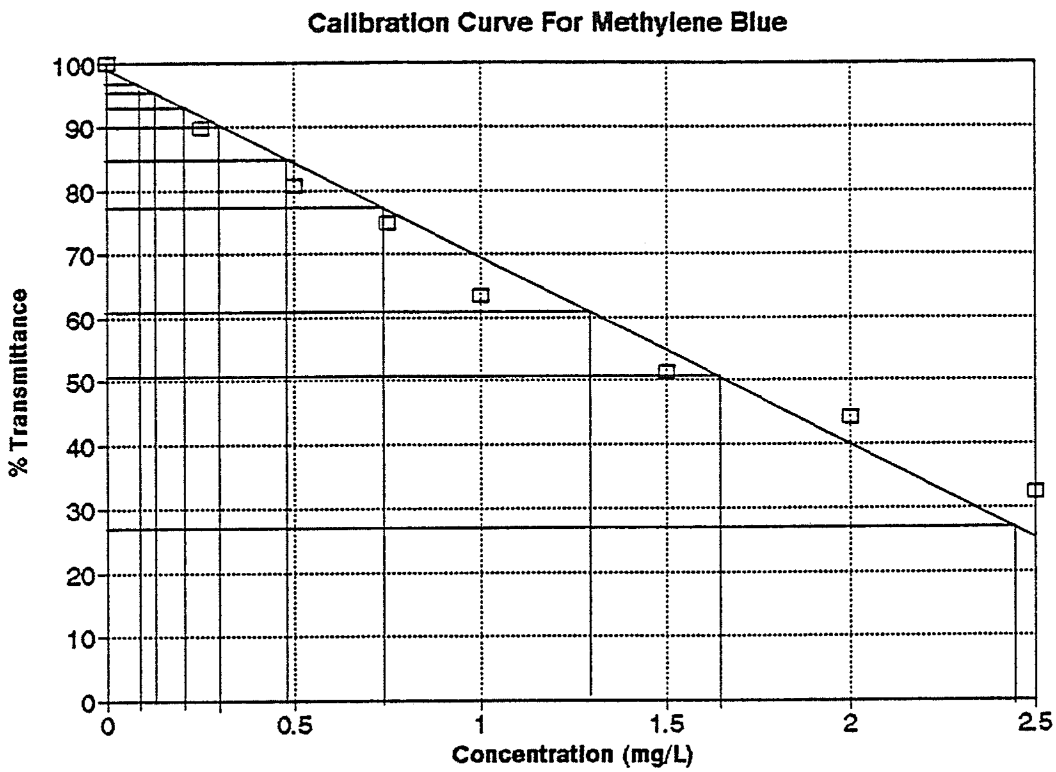
Dilution Model -- Tracer Study

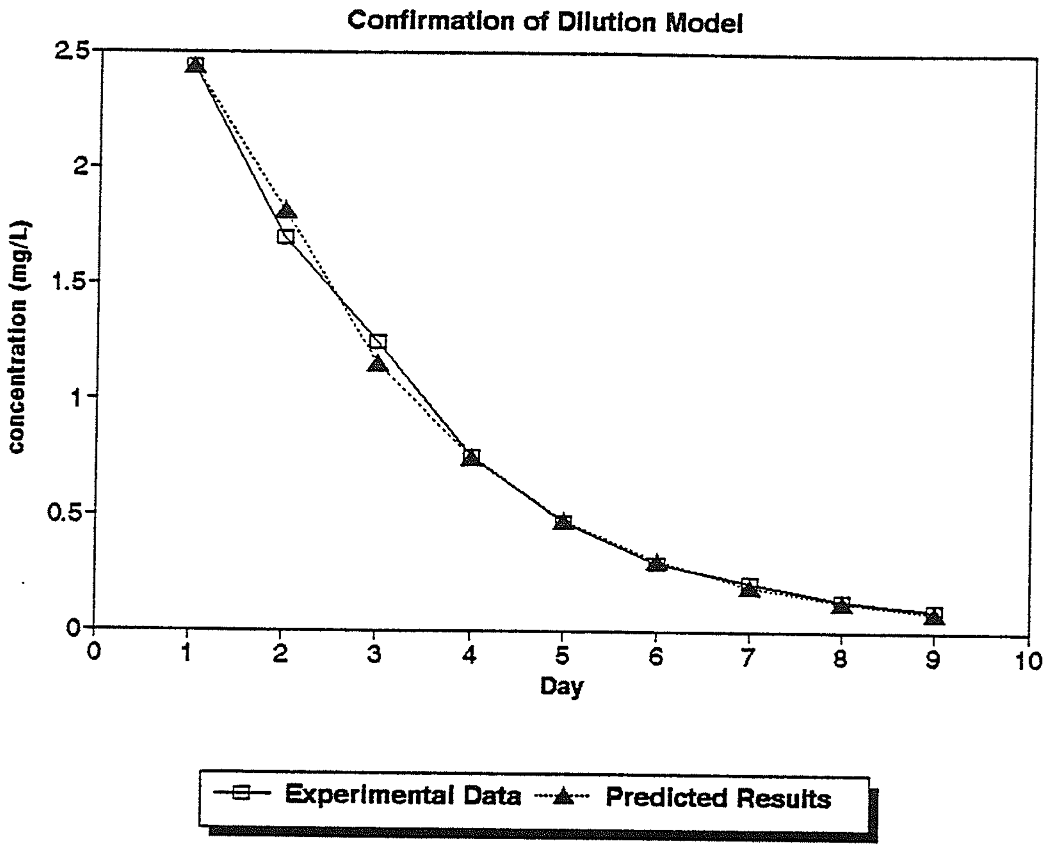
Calibration Curve
For Methylene Blue

Concentration (mg/L)	% Trans
0	100
0.25	89.75
0.5	80.75
0.75	75
1	63.5
1.5	51.25
2	44.25
2.5	32.5

Test Results and
Model Confirmation

Day	%trans.	Actual Concen. (mg/L)	Effluent Volume (ml)	Concentration Predicted by Model (mg/L)
1	27	2.44		2.44
2	50.5	1.7	685	1.817505
3	61	1.25	1150	1.153971
4	78	0.75	1115	0.740912
5	85	0.47	1125	0.474184
6	90	0.29	1140	0.302028
7	93	0.21	1145	0.192069
8	95	0.13	1135	0.122532
9	97	0.09	1140	0.078046


Calibration Curve For Methylene Blue
% Transmittance
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
Concentration (mg/L)


Confirmation of Dilution Model
concentration (mg/L)
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Day
Experimental Data
Predicted Results

Determination of U for first shock Load
Reactor 1

Day	Son SOC Inf	Sn E1	Vn Volume (ml) E1	model	Soc Dif	Rsu	X R1	Rsu/X
1	399.8	186.9						
2							370	
3	363.5	217.3	100					
4			400				480	
5	1228		400				500	
6	558.6	650.9	200	650	0	0	520	0
7	399	503	400	634.7667	131.7667	25.8366	610	0.042355
8	400	466.5	400	595.4722	128.9722	25.28867	470	0.053806
9	400	426.6	410	562.2176	135.6176	26.59169	780	0.034092
10	400	459	400	535.1813	76.18134	14.93752	500	0.029875
11	400	431	420	511.7201	80.72012	15.82747	500	0.031655
12	456.4	377.1	410	492.7138	115.6138	22.66937	500	0.045339
13	547.6	354.9	400	486.6615	131.7615	25.83559	770	0.033553
14	449.5	520.5	410	497.0286	-23.4714	-4.60223	330	-0.01395
15	428.8	279	410	488.9428	209.9428	41.16526	600	0.068609
16	432.3	230.2	410	478.7111	248.5111	48.72766	760	0.064115
17	449.8	297.9	350	471.7988	173.8988	34.0978	770	0.044283
18	438.3	222.7	400	468.1323	245.4323	48.12398	710	0.06778
19	449.4	209.2	400	463.1603	253.9603	49.79613	530	0.093955
20	450	250.5	400	460.8669	210.3669	41.24841	760	0.054274
21	450	229	400	459.0557	230.0557	45.10897	600	0.075182
22	503.7	273.7	400	457.5465	183.8465	36.04832	550	0.065542
23	507.5	184.9	400	465.2387	280.3387	54.96837	640	0.085888
24	499.9	179.1	400	472.2823	293.1823	57.48672	690	0.083314
			400				560	

Determination of U for first shock Load

Reactor 2

Sn E2	Vn Volume E2	model	SOC Dif	Rsu	X R2	Rsu/X
252						
					450	
250.2	440					
	450				460	
	440					
811	325	811	0	0	470	0
505.2	425	766.7649	261.5649	56.86195	580	0.098038
503.6	450	699.2163	195.6163	42.52528	510	0.083383
470.5	440	645.2592	174.7592	37.99114	570	0.066651
424.5	460	599.3978	174.8978	38.02125	460	0.082655
415.7	460	562.112	146.412	31.8287	440	0.072338
412.5	450	532.3363	119.8363	26.05138	420	0.062027
376.7	450	518.3888	141.6888	30.80192	590	0.052207
321.7	450	523.7542	202.0542	43.92482	310	0.141693
309.2	450	510.1156	200.9156	43.67731	460	0.094951
239.1	450	495.1801	256.0801	55.66959	420	0.132547
224.1	375	485.2517	261.1517	56.7721	580	0.097883
237.4	440	478.8587	241.4587	52.49103	400	0.131228
206.5	440	471.5449	265.0449	57.61845	470	0.122592
239.5	440	467.5515	228.0515	49.57642	360	0.137712
244.8	430	464.4457	219.6457	47.74907	590	0.080931
293.7	425	461.914	168.214	36.56826	520	0.070324
249.9	400	468.8783	218.9783	47.60398	520	0.091546
178.1	425	475.6471	297.5471	64.68415	550	0.117608
	410				480	

Determination of U for first shock Load
Reactor 3

Sn E3	Vn Volume E3	model	SOC dif	Rsu	X R3	Rsu/X
196.8						
					1110	
192.3	475					
	475				1010	
	475					
723.9	340	723	0	0	1020	0
495	500	690.12	195.12	46.45714	1030	0.045104
442.9	500	631.896	188.996	44.99905	850	0.05294
409.2	510	584.7777	175.5777	41.80421	1060	0.039438
442	500	547.8222	105.8222	25.19575	1040	0.024227
407	510	517.7866	110.7866	26.37776	1000	0.026378
413.1	510	493.8538	80.75384	19.22711	950	0.020239
402.4	500	486.3631	83.96308	19.99121	1070	0.018683
345.5	510	498.8056	153.3056	36.50134	910	0.040111
297.7	510	488.7874	191.0874	45.49699	930	0.048921
230.9	490	476.9826	246.0826	58.5911	960	0.061032
243.4	440	468.9251	225.5251	53.69645	750	0.071595
210.4	460	465.3489	254.9489	60.70211	850	0.071414
208.2	480	460.1136	251.9136	59.97943	670	0.089522
222.7	475	458.0575	235.3575	56.03749	850	0.065926
251.3	475	456.5111	205.2111	48.85978	720	0.067861
257.9	475	455.2615	197.3615	46.99083	910	0.051638
185.4	500	464.9492	279.5492	66.55933	890	0.074786
193.7	475	473.1155	279.4155	66.5275	660	0.100799
	475				840	

Determination of U for first shock Load

Reactor 4

Sn	Vn Volume	Model	SOC dif	Rsu	X R4	Rsu/X
E4	E4					
192.4						
					1830	
183.8	440					
	430				1530	
	430					
654.9	300	654	0	0	1870	0
545.6	425	637.2804	91.68041	19.10009	1720	0.011105
449.3	415	596.3337	147.0337	30.63202	1390	0.022037
436.2	425	561.9247	125.7247	26.19264	1770	0.014798
443	440	532.7251	89.72515	18.69274	1470	0.012716
441.6	450	508.3471	66.74706	13.90564	1530	0.009089
435.7	450	488.4466	52.74658	10.98887	1660	0.00662
483.9	440	482.6677	-1.23231	-0.25673	1360	-0.00019
364.2	425	494.0476	129.8476	27.05158	1190	0.022732
408.1	430	486.1647	78.06467	16.26347	1280	0.012706
357.5	410	476.4055	118.9055	24.77199	1030	0.02405
302.4	350	469.8366	167.4366	34.88263	950	0.036719
271.2	425	466.3251	195.1251	40.65105	1120	0.036296
266.4	400	461.6542	195.2542	40.67796	1170	0.034767
268.5	410	459.5695	191.0695	39.80614	980	0.040619
227.1	410	457.9415	230.8415	48.09197	890	0.054036
276.7	410	456.5904	179.8904	37.47717	880	0.042588
185.4	410	464.6049	279.2049	58.16769	1180	0.049295
188.4	410	471.9024	283.5024	59.06301	1220	0.048412
	410				1130	

Determination of U for first shock Load

Reactor 5

Sn E5	Vn Volume E5	Model	SOC dif	Rsu	X R5	Day	Rsu/X
169.5							
					2170	2	
192.6	400						
	400				2130	4	
	400						
553.6	250	553.6	0	0	2240	6	0
482.9	400	554.4333	71.53333	12.77381	1890	7	0.006759
417.3	400	528.5278	111.2278	19.8621	2060	8	0.009642
388.7	400	507.1065	118.4065	21.14401	2340	9	0.009036
395	400	489.2554	94.2554	16.83132	2070	10	0.008131
390	400	474.3795	84.3795	15.06777	1800		0.008371
394.3	150	469.1902	74.89023	13.37326	1750	12	0.007642
403.7	350	467.2853	63.58531	11.35452	2330	13	0.004873
358.1	390	480.3911	122.2911	21.83769	1960	14	0.011142
275.4	390	475.3503	199.9503	35.7054	2060	15	0.017333
266.7	360	468.2494	201.5494	35.99096	1950	16	0.018457
287.8	300	463.5603	175.7603	31.38577	1840	17	0.017057
248.8	350	461.5109	212.7109	37.98409	1800	18	0.021102
288.8	360	457.9703	169.1703	30.20898	2080	19	0.014524
265	350	456.6938	191.6938	34.23104	2090	20	0.016378
240.5	360	455.6727	215.1727	38.4237	1740	21	0.022083
246	360	454.8074	208.8074	37.28704	1890	22	0.019729
263.8	360	462.2656	198.4656	35.44029	1900	23	0.018653
250.5	360	469.1658	218.6658	39.04746	1900	24	0.020551
	350				1690	25	

Determination of U for the second shock load

Reactor 1

HRT act=4.6

	Son	Sn	Vn				X	
feb.	SOC		Volume (ml)					
Date	Inf	E1	E1	model	SOC Dif	Rsu	R1	Rsu/X
4	256	158	800				270	
5	341	145	525				430	
6	385	143	450				500	
8	362	151	450					
8.5	1200	752						
9	464	792	300	792	0	0	480	0
10	463.1	453	450	731.7551	278.7551	60.59894	482	0.125724
11	430	273	440	683.3091	410.3091	89.19763	550	0.162178
12	410	229	440	637.6304	408.6304	88.8327	482	0.1843
13	412	267.9	450	595.8207	327.9207	71.28712	500	0.142574
14	413	185	440	562.6727	377.6727	82.10277	482	0.170338
15	415	197	450	535.1818	338.1818	73.51779	450	0.163373
16	400	151	450	513.1076	362.1076	78.71905	482	0.163318
17	372	166	450	492.3327	326.3327	70.9419	480	0.147796
18	371	166	440	470.6334	304.6334	66.22465	482	0.137396
19	370	171	440	452.6667	281.6667	61.2319	630	0.097193

Reactor 2

HRT act=1.84

Sn	Vn				X	
	Volume (ml)					
E2	E2	model	SOC Dif	Rsu	R2	Rsu/X
164	650				440	
148	905				450	
146	1100				400	
148	1080					
772						
754	670	754	0	0	360	0
425	1100	651.0968	226.0968	122.8787	794	0.154759
217	1160	582.0853	365.0853	198.4159	710	0.279459
195	1120	527.4906	332.4906	180.7014	794	0.227584
163	1120	485.3145	322.3145	175.1709	1020	0.171736
136	900	462.5617	326.5617	177.4792	794	0.223525
174	600	451.1244	277.1244	150.6111	900	0.167346
153	680	441.9585	288.9585	157.0427	794	0.197787
150	1460	424.2535	274.2535	149.0508	990	0.150556
159	1380	402.9192	243.9192	132.5648	794	0.166958
268	1300	390.345	122.345	66.49184	1730	0.038435

Determination of U for the second shock load

Reactor 3

HRT act=1.65

Sn	Vn				X	
	Volume (ml)					
E3	E3	model	SOC Dif	Rsu	R3	Rsu/X
144	700				670	
141	960				730	
132	1150				660	
	1160					
794						
715	720	715	0	0	820	0
467	1170	622.3596	155.3596	94.15735	1123	0.083844
240	1220	562.019	322.019	195.163	1260	0.154891
217	1220	511.9994	294.9994	178.7875	1123	0.159205
202	1200	473.7496	271.7496	164.6967	1380	0.119345
182	1200	450.5935	268.5935	162.7839	1123	0.144955
199	1220	436.35	237.35	143.8485	1480	0.097195
137	380	432.9412	295.9412	179.3583	1123	0.159714
164	1320	419.8441	255.8441	155.057	1200	0.129214
175	1580	398.7285	223.7285	135.5931	1123	0.120742
127	1520	386.7549	259.7549	157.4272	1680	0.093707

Reactor 4

HRT act=1.76

Sn	Vn				X	
	Volume (ml)					
E4	E4	model	SOC Dif	Rsu	R4	Rsu/X
132	920				1250	
122	300				1180	
129	760				1250	
130	1100					
770						
790	760	790	0	0	1300	0
421	1280	662.7805	241.7805	137.3753	1196	0.114862
291	1350	582.3122	291.3122	165.5183	1330	0.12445
281	1340	521.2049	240.2049	136.4801	1196	0.114114
192	1320	476.9909	284.9909	161.9267	1250	0.129541
277	1250	451.9944	174.9944	99.42864	1196	0.083134
270	440	444.9626	174.9626	99.41059	1270	0.078276
249	440	439.5595	190.5595	108.2725	1196	0.090529
276	1340	423.6883	147.6883	83.91383	910	0.092213
257	1440	402.0514	145.0514	82.41555	1196	0.068909
150	1520	388.6428	238.6428	135.5925	1080	0.125549

Determination of U for the second shock load
Reactor 5
HRT act=1.77

Sn	Vn				X	
	Volume (ml)					
E5	E5	model	SOC Dif	Rsu	R5	Rsu/X
136	650				1250	
120	970				1310	
122	1200				1720	
143	1140					
780						
709	670	709	0	0	1720	0
431	1120	621.0513	190.0513	107.3736	2270	0.047301
231	1180	562.4404	331.4404	187.2545	2210	0.084731
191	1180	513.2959	322.2959	182.0881	2270	0.080215
190	1200	474.5599	284.5599	160.7683	2030	0.079196
143	1180	451.3459	308.3459	174.2067	2270	0.076743
127	1200	436.9662	309.9662	175.1221	2770	0.063221
113	400	433.3051	320.3051	180.9634	2270	0.07972
125	1180	420.9466	295.9466	167.2015	2910	0.057458
142	1340	401.3094	259.3094	146.5025	2270	0.064539
158	1340	389.1493	231.1493	130.5928	3720	0.035106

Summary of Utilization ratios determined
Shock Load 2

		R1	R2	R3	R4	R5
Date	Day	Rsu/X	Rsu/X	Rsu/X	Rsu/X	Rsu/X
9	0	0.0000	0.0000	0.0000	0.0000	0.0000
10	1	0.1257	0.1548	0.0838	0.1149	0.0473
11	2	0.1622	0.2795	0.1549	0.1244	0.0847
12	3	0.1843	0.2276	0.1592	0.1141	0.0802
13	4	0.1426	0.1717	0.1193	0.1295	0.0792
14	5	0.1703	0.2235	0.1450	0.0831	0.0767
15	6	0.1634	0.1673	0.0972	0.0783	0.0632
16	7	0.1633	0.1978	0.1597	0.0905	0.0797
17	8	0.1478	0.1506	0.1292	0.0922	0.0575
18	9	0.1374	0.1670	0.1207	0.0689	0.0645
19	10	0.0972	0.0384	0.0937	0.1255	0.0351

Determination of U for the Third Shock Load
Reactor 1 HRT act=4.72

March Date	Son SOC Inf	Sn E1	Vn Volume (ml) E1	model	SOC dif	Rsu	X R1	Rsu/X
6	310.5	137.8	450				610	
7		160.8	440					
8	279.9	124.4	440				720	
9	980	553.4		553.4	0	0		0
10	298.7	434	425	508.762	74.7619	15.8394	670	0.02364
11	298	255	450	470.179	215.179	45.5888	593	0.07688
12	298.4	192	450	438.554	246.554	52.2361	700	0.07462
13	290	176	450	412.812	236.812	50.172	593	0.08461
14	280	191.3	450	390.254	198.954	42.1514	570	0.07395
15	270	171.9	450	370.004	198.104	41.9711	593	0.07078
16	264.7	169.4	450	351.636	182.236	38.6092	720	0.05362
17	257	183	450	335.668	152.668	32.3449	593	0.05454
18	251.7	169	450	321.219	152.219	32.2497	640	0.05039
19	252	155.1	400	309.632	154.532	32.7399	593	0.05521
20	254.5	159.5	400	300.027	140.527	29.7726	400	0.07443
21	250	160.8	400	292.439	131.639	27.8896	593	0.04703
22	245.7	158.5	400	285.366	126.866	26.8784	600	0.0448
23	245	163.9	400	278.755	114.855	24.3337	593	0.04103
24	246.6	162.2	400	273.129	110.929	23.5019	450	0.05223
25	246	165.8	300	269.669	103.869	22.0061	593	0.03711

Reactor 2 HRT act=1.9

Sn E2	Vn Volume (ml) E2	model	SOC dif	Rsu	X R2	Rsu/X
116.2	1120				620	
172.5	1100					
137	1040				540	
537.4		537.4	0	0		0
375.8	1130	451.224	75.424	39.6968	870	0.04563
182.5	1080	397.742	215.242	113.285	581	0.19498
142	1120	361.937	219.937	115.756	620	0.1867
180.4	1060	339.927	159.527	83.9618	581	0.14451
160.7	1080	322.42	161.72	85.116	630	0.1351
147.2	1080	307.546	160.346	84.3925	581	0.14525
155.7	1100	294.223	138.523	72.9069	660	0.11046
164.4	1080	283.871	119.471	62.8794	581	0.10823
166.7	1080	274.449	107.749	56.7098	590	0.09612
154.7	1060	266.568	111.868	58.8781	581	0.10134
159.2	1060	261.522	102.322	53.8536	600	0.08976
148.6	1080	259.06	110.46	58.1366	581	0.10006
156.9	1020	256	99.0997	52.1578	510	0.10227
159.3	980	252.613	93.3126	49.1119	581	0.08453
160.3	1120	249.88	89.5799	47.1473	420	0.11226
155.5	670	249.057	93.5568	49.2404	581	0.08475

Determination of U for the Third Shock Load
Reactor 3 HRT act=1.85

Sn	Vn				X	
	Volume (ml)					
E3	E3	model	SOC dif	Rsu	R3	Rsu/X
111.8	1080				1450	
132.8	1020					
129	1100				1270	
514.5		514.5	0	0		0
313.1	1100	437.926	124.826	67.4734	1790	0.03769
158.5	1060	389.697	231.197	124.971	1695	0.07373
147	1060	357.933	210.933	114.018	1850	0.06163
155.3	1080	337.058	181.758	98.2474	1695	0.05796
163.3	1080	320.557	157.257	85.0038	1760	0.0483
162.8	1060	306.508	143.708	77.6799	1695	0.04583
147.7	1100	293.553	145.853	78.8397	1820	0.04332
172.4	1120	283.196	110.796	59.8896	1695	0.03533
166.1	1140	273.685	107.585	58.1542	1630	0.03568
153.2	1120	265.793	112.593	60.8611	1695	0.03591
158.2	1140	260.785	102.585	55.4516	1780	0.03115
156.5	1200	258.428	101.928	55.0964	1695	0.03251
158.9	1100	255.438	96.5377	52.1825	2120	0.02461
149.3	1080	252.023	102.723	55.526	1695	0.03276
148.8	1100	249.531	100.731	54.4492	1580	0.03446
161.8	780	248.709	86.9087	46.9777	1695	0.02772

Reactor 4 HRT act=1.76

Sn	Vn				X	
	Volume (ml)					
E4	E4	model	SOC dif	Rsu	R4	Rsu/X
113.5	1100				1540	
135.3	1120					
131	1180				1510	
506.1		506.1	0	0		0
340.4	1180	429.14	88.7403	50.4206	1760	0.02865
158.9	1160	381.257	222.357	126.339	1690	0.07476
142	1120	351.37	209.37	118.96	1750	0.06798
165.6	1110	332.464	166.864	94.8092	1690	0.0561
157.8	1070	317.664	159.864	90.8318	1740	0.0522
164	1040	304.779	140.779	79.988	1690	0.04733
151	1080	292.584	141.584	80.4453	1820	0.0442
169.8	1200	282.127	112.327	63.8224	1690	0.03776
154.7	1200	272.705	118.005	67.0481	1900	0.03529
157.5	1200	264.828	107.328	60.9817	1690	0.03608
159.6	1200	260.017	100.417	57.0554	1790	0.03187
142.3	1200	257.948	115.648	65.7093	1690	0.03888
161	1180	254.999	93.999	53.4085	1700	0.03142
143.1	1180	251.548	108.448	61.6184	1690	0.03646
161.5	1180	249.119	87.6185	49.7832	1500	0.03319
151.4	800	248.399	96.9989	55.113	1690	0.03261

Determination of U for the Third Shock Load
Reactor 5 HRT act=1.84

Sn	Vn				X	
	Volume (ml)					
E5	E5	model	SOC dif	Rsu	R5	Rsu/X
124.6	980				4160	
147.5	1080					
164.3	1100				4670	
535		535	0	0	0	0
379.4	1140	449.21	69.8096	37.94	3260	0.01164
198.5	1080	396.433	197.933	107.573	3777	0.02848
153	1140	360.696	207.696	112.879	2460	0.04589
153.7	1120	338.334	184.634	100.344	3777	0.02657
160.8	1120	320.983	160.183	87.056	3840	0.02267
157.1	1100	306.441	149.341	81.1634	3777	0.02149
149.1	1140	293.211	144.111	78.321	4260	0.01839
153.8	1120	282.976	129.176	70.2044	3777	0.01859
157.8	1100	273.759	115.959	63.0211	4120	0.0153
156.7	1100	265.931	109.231	59.3649	3777	0.01572
159	1100	260.988	101.988	55.4283	3720	0.0149
158.8	1100	258.686	99.8858	54.2858	3777	0.01437
156.4	1100	255.604	99.2038	53.9151	3750	0.01438
151.2	1100	252.09	100.89	54.8313	3777	0.01452
141.4	1120	249.545	108.145	58.7742	2810	0.02092
151.8	760	248.734	96.9337	52.6814	3777	0.01395

Summary of Data To Be Fitted To Consumption Model
Shock Load 3

		R1	R2	R3	R4	R5
Date	Day	Rsu/X	Rsu/X	Rsu/X	Rsu/X	Rsu/X
9	0	0.0000	0.0000	0.0000	0.0000	0.0000
10	1	0.0236	0.0456	0.0377	0.0286	0.0116
11	2	0.0769	0.1950	0.0737	0.0748	0.0285
12	3	0.0746	0.1867	0.0616	0.0680	0.0459
13	4	0.0846	0.1445	0.0580	0.0561	0.0266
14	5	0.0739	0.1351	0.0483	0.0522	0.0227
15	6	0.0708	0.1453	0.0458	0.0473	0.0215
16	7	0.0536	0.1105	0.0433	0.0442	0.0184
17	8	0.0545	0.1082	0.0353	0.0378	0.0186
18	9	0.0504	0.0961	0.0357	0.0353	0.0153
19	10	0.0552	0.1013	0.0359	0.0361	0.0157
20	11	0.0744	0.0898	0.0312	0.0319	0.0149
21	12	0.0470	0.1001	0.0325	0.0389	0.0144
22	13	0.0448	0.1023	0.0246	0.0314	0.0144
23	14	0.0410	0.0845	0.0328	0.0365	0.0145
24	15	0.0522	0.1123	0.0345	0.0332	0.0209
25	16	0.0371	0.0848	0.0277	0.0326	0.0139

Summary of effluent SOC concentrations expected after shock IV based on the dilution model.

Date	R1	R2	R3	R4	R5
April 1					
2					
4	1850.00	1253.00	673.50	1377.00	1774.50
5	1653.04	996.83	568.42	1070.28	1402.59
6	1456.62	756.38	531.81	836.89	1036.72
7	1270.52	628.15	457.68	789.68	785.19
8	1126.76	524.21	406.16	683.16	624.91
9	993.27	476.20	403.71	596.64	542.35
10	909.01	490.10	449.98	571.54	537.58
11	815.52	455.61	428.81	555.95	512.31
12	731.32	400.00	385.78	502.21	436.56
13	662.77	370.00	357.81	449.23	395.20
15	619.28	360.90	350.28	415.72	392.51
16	558.10	332.60	328.92	375.53	352.64
17	521.63	339.19	337.38	367.73	351.76
18	497.89	361.99	358.85	371.84	365.66
19	473.24	356.76	355.53	367.20	360.37
20	445.87	335.91	338.08	354.82	343.02