ABSTRACT

RICHARD P. McCOY. Biological Treatment of Wastewater from
the Production of p-Nitrosophenol. (Under the Direction of
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The biological treatability of p-nitrosophenol

wastewater was investigated using Sequencing Batch

Reactors (SBRs). Two 2.5 l SBRs were operated for more

than six months and were fed both a raw waste and a

synthetic feed. Removal of phenol was greater than 93% and

soluble COD removal was 75% or greater. The inhibitory

effects of the phenolic waste were partially overcome by

increasing the number of treatment cycles per day.

Significant loading rates were sustained throughout the

study, the highest being achieved at two cycles per day.

Loss of soluble COD by abiotic means was ruled out. The

use of SBRs for treatment of p-nitrosophenol wastewaters

will result in significant savings over present chemical

oxidation processes.

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I. INTRODUCTION

The purpose of this research project was to determine the feasibility of biologically treating an industrial wastewater using sequencing batch reactors (SBRs). This project was funded by Sandoz Chemicals of Mt. Holly, NC.

Sandoz Chemicals, located 6 miles west of Charlotte, NC, is one of the largest manufacturers of textile dyes and dye intermediates in the United States. The plant employs approximately 350 people and its products are distributed throughout the US and overseas. The textile manufacturing processes at the Mt. Holly plant are all batch processes. The most common reactions used to produce dyes are sulfonation, chlorination, nitration and nitrosation of phenol and chlorobenzene. These batch processes result in a waste stream with varying concentrations of a wide variety of organic and inorganic constituents. The plant currently treats the majority of its wastewater on site by means of chemical neutralization and biological treatment. Sludges resulting from precipitation of neutralized chemicals are disposed of on-site by landfilling.

One particular wastestream that the company is concerned about is the wastewater resulting from the production of p-nitrosophenol. p-Nitrosophenol ($C_6H_5NO_2$, 1,4-benzoquinone monoxime) is an important stock chemical used in the synthesis of dyes by Sandoz and other dye manufacturers. Nitrosophenol (as p-nitrosophenol will be referred to in the rest of this report) is produced by the nitrosation of phenol using sodium nitrite in a concentrated sulfuric acid medium. 4-Nitrophenol is a byproduct of this reaction.

After the reaction is complete, the liquid (approximately 50,000 gallons) is drained from the reaction vessel and put through a centrifuge. Since nitrosophenol is a relatively insoluble compound at acid pH, the majority of the nitrosophenol produced in the reaction is captured in the centrifuge cake.

The centrate that remains consists of dissolved and suspended nitrosophenol, 4-nitrophenol, phenol, sodium nitrite, and sulfuric acid. The organic content of the wastestream, on average, consists of 1340 mg/l nitrosophenol, 1140 mg/l phenol and 190 mg/l 4-nitrophenol. However, there is considerable variability in these concentrations from batch to batch.

Though the activated sludge system at the Sandoz plant

currently treats the majority of the wastewaters generated, the nitrosophenol process wastewater is not sent to the activated sludge system. The discharge permit issued to Sandoz Chemicals has a very strict mass limit on phenol, so that it is prudent for them to pre-treat wastes that have a high phenol content, such as the nitrosophenol wastewater. The current treatment method for this wastestream is chemical oxidation in a batch system using hydrogen peroxide in the presence of iron (the Fenton Reaction):

$$\text{p-Nitrosophenol + Phenol + 4-Nitrophenol + } H_2O_2 \xrightarrow{Fe(III)}$$

$$CO_2 + H_2O + NO_3^- + \text{other products}$$
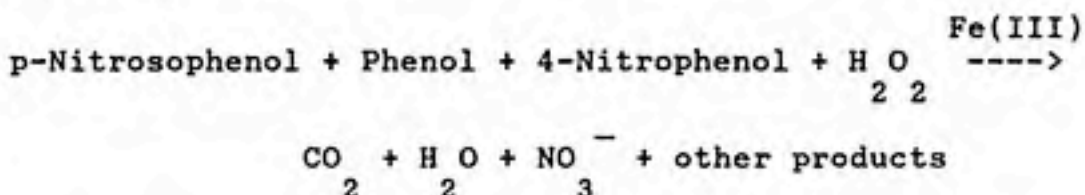
The optimum pH for the reaction has been found to be between 3.5 and 4.3. This is achieved by adding sodium hydroxide to the centrate. The theoretical molar ratio of peroxide to phenol is 14:1. Personnel at the plant use considerably more than the theoretical ratio. The current cost of treatment with this system is very high.

Ferric sulfate is used as the catalyst at 50 lb per 50,000 gallon batch. The oxidation reaction is highly exothermic and foaming is used as an indication of reaction rate. The reaction is performed at very low initial temperatures ($5\ ^{o}F$). Analyses of effluent concentrations of

nitrosophenol, 4-nitrophenol, and phenol after peroxide oxidation showed virtually complete elimination of all three chemicals in 60 individual batches. Data on reaction products from the chemical oxidation process are not available.

Because of the hazard and expense of using hydrogen peroxide (50% reagent is used), Sandoz is very interested in converting its nitrosophenol filtrate treatment process to a biological system. In addition, the current production rate of nitrosophenol is restricted by the limited capacity of the chemical oxidation treatment process.

Sequencing batch biological reactors pose significant advantages to Sandoz in the treatment of this waste stream. Sequencing batch reactors are essentially a set of tanks that operate on a fill and draw basis. Each tank in the SBR system is filled during a discrete period of time and then operated as a batch reactor. After desired treatment, the mixed liquor is allowed to settle and the clarified supernatant is drawn from the tank. Sequencing batch biological reactor design and operation was recently reviewed (Irvine and Ketchum, 1989), and the following description of SBRs is from that article.

The essential difference between the SBR and a

conventional continuous-flow activated sludge system is that each SBR tank carries out functions such as equalization, aeration, and sedimentation in a time, rather than a space sequence. One advantage of the time orientation is the flexibility of operation. The total time in the SBR is used to establish the size of the system and can be related to the total volume of a conventional continuous-flow facility.

The cycle for each tank in a typical SBR is divided into five discrete time periods: Fill, React, Settle, Draw, and Idle.

During Fill, the influent wastewater is added to the biomass which remained in the tank from the previous cycle. The Fill period may be either a Static Fill (no mixing or aerating), Mixed Fill (mixing without aerating), or Aerated Fill. Fill is typically terminated when the tank is full or when the next tank in the sequence is ready to receive influent.

Reactions that may have been initiated during the Fill period are completed during React. React is characterized by a high concentration of substrate at the beginning of the period. By the end of React, most, if not all, of the substrate has been degraded. The exposure to wide

differences in substrate concentration thus achieved can be an important aspect in selection of the microbial community in the reactor, and can lead to the development of a culture adapted to transient loading conditions.

After the React period is over, aeration (and sometimes mixing) is stopped and quiescent conditions are maintained in the reactor during a Settle period to allow settling of the biomass. The Settle period is usually between 1 and 2 hours. After Settle, the supernatant is drawn off during Draw. Supernatant can be drawn by either a floating pump or adjustable weir or a pipe at a fixed position in the side of the reactor. Draw typically only takes 5-30% of the total cycle time. After drawing off the effluent, the SBR may go into an Idle period or it may immediately begin a new Fill period.

At the Sandoz plant, three tanks are available near the nitrosophenol treatment area and would be ideal for use as SBRs. With a minimum of retrofitting, a two tank SBR system, using the third tank as an equalization/storage tank could be set up with a minimal amount of capital equipment.

One of the objectives of this study was to determine whether the existing tank volume would be sufficient to treat the average daily volume of nitrosophenol wastewater.

This required an evaluation of treatment efficiency as a function of loading rate. In addition, Sandoz gave a stated objective that the biological process should remove phenol to below 10 mg/l consistently. Specific objectives of the study included:

     1.   evaluate the biodegradability of nitrosophenol wastewater constituents and the treatability of the waste in a bench-scale SBR;

     2.   determine nutrient requirements for optimum degradation;

     3.   evaluate treatment performance as a function of reactor operating conditions; and

     4.   draw conclusions as to the biological treatability of the waste and develop a conceptual process design if treatment appeared to be feasible.

II.   LITERATURE REVIEW

Sequencing Batch Reactors

The historical perspective, advantages of SBRs over conventional biological treatment systems, and design considerations for using multiple tanks (since it is proposed that two or three tanks at the Sandoz plant be reconfigured as SBRs) are discussed below. This information has been excerpted from Irvine and Ketchum (1989).

1. Historical Perspective: Sequencing Batch Biological Reactors were initially studied and placed into actual service in the early 1900s. Good removal of suspended solids and BOD was observed in the treatment of domestic sewage as early as 1914. However, in the 1920s, research and development efforts switched to continuous flow treatment systems due to the high discharge flow rate relative to that of the influent when one tank is employed, clogging of diffusers because of periodic settling of the sludge, and increased operator attention resulting from the need to switch valves and clean diffusers. The use of a

multiple tank strategy alleviates the first objection and
vast improvements made since the 1920s in aeration devices
and control systems obviate the second and third
objections. Today, applications of SBR technology can
focus more on process advantages over continuous systems,
rather than on factors associated with hardware and
operating labor.

2.   Advantages of the SBRs:

a.   Equalization and Dilution: SBRs have two
distinct advantages over conventional biological treatment
systems when employed in the degradation of high strength,
variable composition waste. These are its ability to
equalize and dilute wastes. When a significant amount of
the total reactor liquid volume is removed during Draw, and
no aeration is provided during Fill, the SBR acts like a
stepwise equalization system. Wastewater with a highly
variable concentration is equalized over the period of
Fill. When a relatively small amount of effluent is
withdrawn during Draw, and the liquid level in the reactor
is high at the beginning of Fill, the effect is to dilute
the influent wastewater. Thus, the SBR provides a
buffering action against rapid changes in concentration of
any component in the reactor that could result from a
sudden increase in the strength of influent wastewater.

b. Population Selection: The power of an unsteady-state SBR comes from its ability to provide the microbial consortium with a controlled environment which will select for organisms that have advantageous characteristics in treating the wastewater. For instance, Static Fill is frequently used to establish feast conditions (high instantaneous substrate concentratations) in the SBR. Famine conditions naturally result during React, when the substrates are being utilized without the input of raw waste. Organisms that are able to compete best for the food supplied under alternating conditions of feast and famine will be enriched in the system.

In another example, Mixed Fill conveniently allows alternative electron acceptors such as nitrite and nitrate to be utilized. Thus if oxidized forms of nitrogen are generated by nitrification in the SBR during Aerated Fill or React, denitrification will take place during unaerated periods.

3. Design Considerations Involved with Using Multiple-Tank SBRs:

a. In multiple tank systems, the time available for React, Settle, Draw, and Idle must equal the

sum of the Fill periods for all other tanks. Therefore as the number of tanks increases, the fraction of time devoted to Fill in any one tank decreases, and an increased fraction of time during a cycle is available for React, Settle, and Idle.

b. For a given total tank volume, the load that can be handled increases as the number of tanks is increased.

Because of the unsteady-state nature of Fill and React, a kinetic-based definition of sludge age, an important operating parameter in conventional activated sludge systems, is not possible. However, an evaluation of the kinetics and stoichiometry of the treatment system is vital (Irvine, et al., 1977). A mathematical method of describing the kinetic relationships of multiple reactions involved in an SBR has been presented (Irvine, et al., 1980). The rates of various reactions help determine the relative importance of each reaction in a reaction scheme.

Because the SBR has five nonaeration-oriented functions (Static Fill, Mixed Fill, Settle, Draw, and Idle), the definition of mass loading rate is also obscured. A useful definition of mass loading rate in an SBR adjusts the time factor appearing in the denominator of the term by

including only the fraction of time the mixed liquor is under aeration each day.

The effect of the organic loading rate on the operation of an SBR treating municipal waste has been reported (Irvine, et al., 1985). The study was done at the Culver, IN, Wastewater Treatment Plant. Two SBRs had been retrofitted at the plant. During the two month study, one tank was operated at an organic loading rate (adjusted for aeration time) of 0.16 kg BOD5/kg MLVSS-d, and the other was operated at an organic loading rate of 0.42. The performance of the SBR at the low loading rate was found to be better than the SBR at high loading rate in terms of effluent BOD5, and suspended solids (SS). However, both SBRs maintained effluent qualities that were quite good. It was found that the highly loaded reactor was more difficult to operate.

The effect of the loading rate on effluent quality in an SBR treating domestic sewage was evaluated (Hoepker and Schroeder, 1979). Because bioflocculation has been associated with extracellular polymer production occurring under low growth rate conditions, the effluent turbidity was thought to be related to the maximum growth rate experienced during the feed cycle. In this study effluent SS and TOC were measured as functions of loading rate. Effluent TOC concentrations varied with influent TOC

concentration. No relationship was found between effluent quality and growth rate in the reactor. The lower feed strength and lower growth rate systems were found to have lower suspended solids concentrations.

A study was performed to determine the effect of the Fill:React ratio on SBR performance (Dennis and Irvine, 1979). In this study Fill and React times were varied to determine the effect on settleability of the mixed liquor. A loading rate of 0.3 g BOD5/g MLSS-d was used. It was found that employing short Fill periods, and consequently long React periods, settleability was markedly better than for long Fill and short React periods.

Treatment of Hazardous Waste Using Sequencing Batch Biological Reactors

The treatment of an industrial wastewater with SBRs has been evaluated at bench scale (Murthy, et al., 1988). In this study the wastewater from the production of Roundup (TM), an agricultural pesticide, was treated using batch flasks and with SBRs. The target compound for removal in the wastewater was glyphosate (N-phosphono-methyl glycine, $COOH-CH2-NH-CH2-H2PO3$). The feed to the reactors had a soluble COD of 3600 mg/l and a glyphosate concentration of 1600 mg/l.

Complete removal of glyphosate was achieved in preliminary studies using SBRs up to an initial concentration of 3000 mg/l. Denitrification was found to be an important mechanism in glyphosate removal, so the Fill period was changed from an Aerated Fill to a Mixed Fill. When this occurred, better removal rates were observed.

The results of bench scale and initial operation of a full scale SBR system to treat landfill leachate, water from a groundwater remediation program, and bulk hazardous waste has been reported (Herzbrun, et al., 1985). The plant is operated by CECOS International at Niagara Falls, NY. Prior to the SBR study, removal of organics in the wastewater was accomplished by adsorption onto activated carbon.

Preliminary studies had confirmed the treatability of the wastewater (Herzbrun, et al., 1984). Total Organic Carbon degradation ranged from 55 to 81% and phenol degradation ranged from 96.8 to 99.2%. Foaming was observed during the treatment of the waste on several occasions, but was easily controlled with a bubble breaking compound. A study to determine the effect of a power failure or mechanical problems showed that with no air supplied to a reactor for as long as 48 hours, no short-

term or long term effects were observed.

During the bench scale testing, the waste treated had an influent TOC of 1620 mg/l and influent phenol of approximately 40 mg/l. Two reactors were operated over a nine-week period. One reactor operated at room temperature (21 - 25 degrees C) and the other operated below room temperature (5 - 17 degrees C) to simulate cold weather operation. Total Organic Carbon (TOC) removal averaged 79% for the room temperature reactor and 75% for the cold weather reactor. Overall effluent phenol concentrations averaged 0.4 mg/l throughout the bench scale study for both reactors.

Phenol augmentation was evaluated in both reactors to evaluate reactor performance at increasing levels of influent phenol. The weekly average concentration of phenol was increased from 40 mg/l to 570 mg/l over a six week period. The room temperature reactor maintained an effluent phenol concentration of 0.4 mg/l and the simulated cold-weather reactor experienced two weekly average spikes of 55 mg/l and 63 mg/l.

Results of the second through the fifth week of full scale SBR operation were reported. The one 1900 m^3 SBR constructed at the site treated an average of 220m^3/d at

an eight to nine day retention time. Phenol degradation in
the SBR averaged 99% and average TOC removal was 72%.
These reductions in phenol and TOC by biological methods
resulted in significant cost savings over carbon adsorption
alone. Carbon adsorption was retained, though, as a
polishing step for the effluent.

The treatment of soils and leachate from a landfill
containing typical coal gasification wastes such as
polynuclear aromatic hydrocarbons (PNAs), phenols, coal
tars and oils, and cyanide- and sulfate-containing wastes
was reported (Brenner, et al., 1987). In this study the
overall goal was to develop a "specialized bacteria" to be
used in a land farming technique to remediate the soil.
The SBR was chosen to develop the specialized bacteria
because of the unique activities that can occur during its
Settle period.

During the Settle period, the microorganisms have an
opportunity to perform plasmid exchange, in which general
enrichment of genetic information is achieved. This was
thought to be an excellent way to develop a population of
organisms that would be adapted to coal conversion gas by-
product degradation. Once the population was developed,
the SBR would be used to culture organisms to be applied to
the surface of the contaminated site to maximize the rate
of soil detoxification.

A population of organisms was isolated from soils at the site and were confirmed to degrade phenol, naphthalene, and acenaphthene by plating and respirometry methods. Two initial SBRs were operated using a soil/leachate mixture as the feed to one reactor and the low COD (100 mg/l soluble COD) leachate as the feed to the other reactor. Performance of these screening test reactors showed good removal of soluble COD and good oxygen uptake rates.

Four bench scale SBRs were then operated. Two of the four reactors were fed a soil/leachate mixture which had a soluble COD of 30 to 75 mg/l and a total COD of 350 to 900 mg/l. Phenol concentrations in the feed mixture averaged 13.1 ug/l. The other two reactors received this same feed supplemented with glucose (5 mg/l as COD).

Effluent soluble COD ranged from 15 to 40 mg/l. Effluent phenol concentrations were 0.5 ug/l in one reactor not supplemented with glucose and less than 0.14 ug/l in the other three reactors. Moderate wasting of sludge resulted in higher MLSS. The reactors fed glucose-augmented feed had higher yields of solids, though all reactors achieved high removal efficiencies for most of the feed constituents. The effluents from the reactors were turbid and this was thought to be due to the oily nature of the feed.

Treatment of another landfill leachate in Niagara, NY was also evaluated using SBRs (Ying, et al., 1986). The leachate was mixed with a small amount of chemical manufacturing wastewaters before treatment. The leachate accounted for about 60% of the combined wastewater volume, but 80% of the total organic loading to the existing adsorption system. The combined waste feed had an average phenol concentration of 780 mg/l, COD concentration of 9200 mg/l, and total dissolved solids averaged 22,000 mg/l.

Previous treatment consisted of activated carbon adsorption. Poor adsorptive capacities were observed for many of the organic compounds present in the wastewater due to competitive adsorption rather than poor bed design or operational problems. Any treatment technology capable of reducing this competition could extend the adsorption service cycle.

Initial bench scale SBR studies showed reduction of about 90% of the TOC was achieved. Supplementation of a strain of bacteria isolated from the landfill site improved the treatment efficiency of the reactor. Subsequent SBR studies were then performed using 1, 12 and 500 l reactors. All reactors operated with a MLSS from 8000 to 13,000 mg/l (an SBR operated with an MLSS of 5000 mg/l failed early in

the study). Hydraulic retention times of 1.7 and 1.0 days were also evaluated. Good performance was observed during these higher hydraulic loadings.

The 500 l SBRs were then operated to simulate long-term, full-scale operation of the reactor. Good removal efficiencies were observed with reactors that had MLSSs of 5000 and 10000 mg/l. The SBR resulted in reduction of the activated carbon requirement by 90%. Results obtained in the 1 l SBRs was reproduced in 12 l and 500 l units. The experimental data served as the basis for the design of a full-scale SBR-adsorption system.

Cloudy effluents (SS greater than 250 mg/l), due to populations of dispersed and/or filamentous bacteria, were observed several times during this study. They were caused by excessive organic loading, short React period, low D.O., nutrient deficiency and accumulation of toxic compounds. Effluent SS was less than 100 mg/l except when the feed TOC was higher than 3000 mg/l. The SBR performance was nearly unchanged when the feeding was suspended on holidays and weekends.

The integrated wastewater treatment system (biological treatment in SBRs followed by carbon adsorption polishing) produced a better quality effluent at lower overall cost. Since the biological treatment reduced TOC by 90%, net

savings of $526,000/year over 10 years was estimated to be realized if biological pretreatment was implemented

A novel way to treat a complex landfill leachate has been reported (Smith and Wilderer, 1986). A landfill near Hamburg, West Germany had a leachate containing organic solvents, phenol, several chlorinated hydrocarbons and heavy metals. A two-stage SBR treatment strategy was tested. This strategy involved treatment of the more readily degraded compounds in a first stage SBR followed by treatment of less concentrated, but more refractory compounds in a second stage "fixed film SBR." A fixed film reactor was chosen for the second stage because, due to low concentrations of substrate, doubt existed as to whether biological sludge flocs would develop and settle.

A silicone-membrane oxygenation system was used to provide oxygen transfer to the reactors. This system was employed to prevent the formation of gas bubbles and thereby reduce the amount of volatile organics released by stripping, so that more of the volatile organics would be available to the microorganisms as substrate.

The first stage SBR was a conventional 15 l glass biological reactor. The second stage reactor was constructed the same as the first, except there was no

mixer and it was filled with expanded-clay aggregate.

A synthetic leachate feed was fed to the reactors which had a soluble COD concentration of 1170 mg/l and the phenol content was 15 mg/l. The sludge used to seed the reactors was obtained from a local wastewater treatment plant and was augmented with water that had been filtered through soil obtained from the landfill. The suspended solids of the reactor was 3000 mg/l.

During the initial stage of operation, the reactor performance deteriorated appreciably over the 5 weeks of operation. The fraction of flocculant organisms in the first stage reactor consistently decreased and the effluent COD and suspended solids increased. These effluent suspended solids then became trapped in the second stage reactor. By the end of the initial seven weeks of operation, effluent suspended solids were appearing from the second stage reactor.

To correct these problems, a different strategy was employed in the next phase of operation. After a React period was completed, the normal amount of reactor volume was decanted from the second stage reactor. The remaining volume in the second stage reactor was placed in the first stage reactor. The contents of the first stage reactor, again after the React period, were then placed in the

second stage reactor. This resulted in a decreased hydraulic retention time for the stage one reactor to selectively favor flocculant organisms.

This operating strategy performed well over the 70 days of operation. Effluent quality, evaluated by measuring soluble COD and suspended solids, steadily improved over time. However, three weeks into this phase of the experiment the MLVSS of the first stage reactor was noted to have decreased to virtually zero, despite the fact that the reactor was performing consistently well. This was explained by the fact that the organisms in the reactor had become trapped between the reactor wall and the silicone tubing structure. So the first stage reactor was, in essence, also operating as a fixed film reactor.

Bench scale studies were then performed by taking the laboratory apparatus to the landfill site. Effluent concentrations of COD and TSS in all reactors steadily increased over time and were much higher than in the initial studies. From these results, it was apparent that none of the operating strategies investigated resulted in stable performance of the suspended growth SBR process, indicating that the suspended growth activated sludge process is not a suitable method of biological treatment of the leachate in question.

Studies Done On Nitrosophenol

Very little literature is available on nitrosophenol or treatment of wastewaters containing nitrosophenol. One article of particular interest to this research study described a method of analyzing phenols in water samples by first converting the phenols to nitrosophenol (Hassan, et al., 1987). This method was purported to have several advantages over the commonly used 4-aminoantipyrine method. These advantages include a lower detection limit for phenols (4 ug/l as opposed to 10 ug/l) and the capability of detecting para-substituted phenols.

The method involves converting all phenols and substituted phenols in a water sample to their respective nitrosophenol derivatives by the nitrosation reaction. These reaction products are then coupled with resorcinol to produce a chromophore whose optical absorbance can be measured at 480 nm. The color development obeys Beer's Law in the concentration range from 4 ug/l to 40 ug/l.

In another reference to nitrosophenol wastewaters, a patent has been issued (U.S. Patent # 4,391,715) concerning an improvement on the treatment of the raw waste resulting from production of nitrosophenol using sodium sulfite

(Coates, 1983).

During the peroxide oxidation of the mother liquor, large amounts of dark-colored foam are created which, at treatment facilities in the U.K., have hampered the oxidation of the wastewater. Coates (1983) has found that this foaming is due to the presence of a stable diazonium salt in the nitrosophenol raw wastewater. This salt is believed to cause the foaming by forming a co-polymer with other monomer units in the liquor, such as the phenolic compounds, and at the same time release nitrogen which causes the polymer to float up to the foam.

The foaming can be prevented by reacting the salt with sodium sulfite prior to chemical treatment of the raw waste. Treatment of the raw waste with sulfite under preferred conditions has been found to substantially decrease the toxicity of the liquor by breaking down the phenolic compounds.

Sims (1981) has reported the successful treatment of a nitrosophenol wastewater using chemical oxidation. In this process a pharmaceutical wastewater containing 6,000 mg/l of nitrosophenol was oxidized using hydrogen peroxide and iron. The resulting effluent was found to consistently meet a discharge limit of 50 mg/l nitrosophenol.

Studies Done on Phenol Degradation

Problems created in receiving waters by the presence of phenols in effluents include toxicity to aquatic life, increased BOD, and taste and odor problems in water subsequently used for potable purposes (Sims, 1981).

Methods of treating phenolic effluents include biological oxidation, chemical treatment, incineration, and physical treatment, such as carbon adsorption. Biological oxidation is the method commonly applied to large volumes of biodegradable phenolic effluents.

Chemical oxidants which are effective for the oxidation of phenols are hydrogen peroxide, chlorine dioxide, ozone and potassium permanganate. Of these chemical methods, hydrogen peroxide is the most cost effective method of treating effluents containing phenols.

When phenol or phenolic compounds are treated by biological processes, an important consideration that must be accounted for is substrate inhibition. Substrate inhibition occurs as a result of the substrate binding with the enzyme-substrate complex as well as the free enzyme (Grady and Lim, 1980). When this occurs, an enzyme-

substrate-substrate complex is formed which cannot undergo further reaction to yield the product.

With a nontoxic substrate, a higher substrate concentration results in a higher specific growth rate. With a toxic substrate, an increase in substrate concentration results in increased growth rate over a much more limited range. Beyond a critical substrate concentration, the toxicity of the substrate causes a decrease in growth rate, so that the peak specific growth rate is below the theoretical maximum growth rate for the system.

Some debate exists as to whether inhibition exists when a culture has been acclimated to phenol. Rozich and Gaudy (1984) have concluded that in the great majority of cases, with thoroughly acclimated populations, definite evidence was found that an inhibitory function more accurately depicted the behavior of a system treating phenol.

The kinetic relationship for biological treatment of non-inhibitory substrates is described by the Monod equation:

u = (umax * S)/(Ks + S)

where u = specific growth rate, 1/time,

umax = maximum specific growth rate, 1/time,

S = soluble substrate concentration, mg/l,

Ks = saturation constant, mg/l.

For inhibitory substrates, the Haldane relationship has been found to most accurately describe the kinetics of biodegradation,

$$u = (umax * S)/(Ks + S + (S^2/Ki))$$

where Ki = inhibition constant, mg/l.

Rozich and Gaudy (1985) have reported the values of these kinetic constants which were determined with over 100 batch growth curves. These values are: umax = 0.194/hr, Ks = 48 mg phenol/l, and Ki = 62 mg phenol/l. In addition, the biological decay constant, b, was determined to be 0.0195/hr.

Loading rates successfully achieved when treating phenol have been reported by Khararjian and Smith (1979). Using aerated lagoons and activated sludge to treat coke oven wastes, loading rates up to 0.86 g phenol/g MLSS-d were achieved. At this high loading rate, excessive foaming and sludge bulking were encountered occasionally, but at loading rates below 0.7 g phenol/g MLSS-d, the system operated smoothly. In another study using single

and multi-stage activated sludge processes for treatment of high strength phenolic wastes (phenol concentration averaged 3270 mg/l), bench scale studies showed that effluent concentrations of less than 0.1 mg/l could be achieved 40% of the time at loading rates of 0.1 to 0.3 g phenol/g MLSS-d.

Rozich and Gaudy (1985) have studied the effect of shock loading on a phenol-acclimated activated sludge culture. In this study a bench scale activated sludge system was operated at an influent concentration of 500 mg/l. When the influent concentration was instantaneously increased to 1000 mg/l, the system adjusted very well. The system was operated for 11 days at 1000 mg/l and then the influent concentration was instantaneously increased to 2000 mg/l. Six days after the shock was administered, the system had not achieved steady state. An increase in dispersed organisms was evident soon after the increase to 2000 mg/l. By the eighth day, washout of the activated sludge had begun to occur and the experiment was stopped. This experiment was then repeated and after 3 days of operation at 2000 mg/l, washout had occurred.

In a recent article, the variation of pH during phenol degradation was reported (Lallai and Mura, 1989). In this study it was found that the pH first decreased and then increased during the biodegradation. The initial

concentration of phenol determines the extent of the pH drop during the degradation. The minimum pH measured was found to coincide with the point at which the phenol had been exhausted, which is due to the production of organic acids. After exhaustion of the phenol, the pH was noted to rise again, but never back to its original pH before being fed phenol.

Uncoupling

A phenomenon that may or may not be applicable to the degradation of nitrosophenol production wastewater is uncoupling (Okey and Stensel, 1989). The uncoupling of oxidative phosphorylation causes substantial oxygen use without substrate assimilation. The term also refers to the uncoupling of the energy-yielding electron transport sequence from the energy-requiring formation of adenosine triphosphate (ATP).

The production of ATP regulates cell respiration rate through the cytochrome system. When uncoupled, regulation is lost and the cell respiration rate continues to increase until intracellular reserves are exhausted. Symptoms of uncoupling are increased rate of respiration, limited or no synthesis, and reduction in cell mass.

Any refractory alcohol with roughly the same dimensions as phenol appears to be capable of uncoupling. 4-Nitrophenol has been found to be a strong uncoupler (Clowes and Krahl, 1936) and nitrosophenol has the classic characteristics of an uncoupler. Uncouplers are generally alcohols roughly the size of the benzene ring in overall dimension, and are substituted with materials that normally impede metabolism or which incidentally increase the acid strength of the molecule.

Mitchell recognized that certain lipid soluble weak acids can cross a membrane in either the ionized form or the intact form (Mitchell, 1963). When crossing in the intact (non-ionized) form, they transport a proton which is then promptly released in the alkaline environment to react with a hydroxyl group. In the presence of proton-conducting molecules (uncouplers), the biosystem is uncoupled. More substrate is utilized to augment the now limited ATP production and the cell literally runs down.

Unexpected findings in biodegradation research involving chlorinated and nitrated phenols may have been due to uncoupling. These findings include low cell yield and inhibition at high concentrations which may or may not be related to uncoupling. Clearly, the halogenated and nitrated phenols have been shown to be biodegraded by acclimated cultures, but are not degraded by unacclimated

activated sludge which apparently experiences only the uncoupling phenomenon even when acclimated to the carbon skeleton.

The response of activated sludge to the presence of uncouplers falls into one or more of the four categories depending on the relative concentration (concentration ratio) of uncouplers and sludge, the chemical nature of the uncoupler and the presence of usable substrates. These four categories are: increased rate of endogenous respiration, reduced synthesis when metabolizing an exogenous substrate, reduction in the rate of usable substrate uptake, and toxicity at high concentration ratios.

III. Experimental Methods

Several parameters were monitored during operation of the batch reactors. These included Chemical Oxygen Demand (COD), phenol concentration, Mixed Liquor Suspended Solids (MLSS), Mixed Liquor Volatile Suspended Solids (MLVSS), nitrate nitrogen (NO3-N), nitrite nitrogen (NO2-N), and phoshporus. High Performance Liquid Chromotography (HPLC) was also attempted to identify the extent of nitrosophenol degradation. In addition, the oxygen uptake rate was measured in a number of experiments to gauge the metabolism of the mixed liquor.

The COD, phenol, nitrate nitrogen, nitrite nitrogen, and phosphorus tests were all based on formation of colored species and were measured with a Bausch & Lomb Spectronic 70 spectrophotometer.

Chemical Oxygen Demand

The chemical oxygen demand of an industrial wastewater is often used as a measure of degradation of a mixture of organic compounds. The COD test is based on the chemical

oxidation of the organic compounds in a wastewater to carbon dioxide and water, and the results are expressed on a mass basis in terms of the amount of oxygen required if it were the terminal electron acceptor.

In this study COD was measured using the Hach COD Reactor (Model #45600) with high range COD vials, which measured COD in the range 0 - 1500 mg/l. In the Hach method, test reagents are pre-mixed in vials. Reagents in the vial include potassium dichromate, silver sulfate, concentrated sulfuric acid, and mercuric sulfate. Silver sulfate is added as a catalyst and mercuric sulfate is added to suppress interference from chloride ions. (Interference from chloride occurs at a chloride ion concentration of greater than 2000 mg/l. The samples analyzed in this study had only traces of chloride in them.) Potassium dichromate is the oxidizing agent and oxidizes the available carbon and hydrogen to carbon dioxide and water. The production of reduced chromium Cr(III) as a result of the oxidation is proportional to the COD of the sample. This method is approved by the EPA (Federal Register, 1984).

Two ml of a sample or an aliquot of the sample is pipetted into a vial, the cap is put on the vial and mixed well. The vial is then placed in the COD reactor, which is a heating block that maintains a temperature of 150 degrees

C for two hours. After the two hour digestion period and a one hour cool down, the absorbance of the solutions in the vials are measured.

A standard curve was prepared for each lot of vials received. Potassium hydrogen phthalate was used to prepare a 1500 mg/l COD solution. In this study, 4 lots (150 vials per lot) were received from Hach. A typical COD Standard Curve is shown in Figure 1. As can be seen from Table 1 on the same page, correlations of the standard curves was always good. Initially all COD measurements were done in duplicate and the standard deviations were always found to be less than 5% of the mean. As a result, single measurements were used subsequently for routine monitoring of COD.

Phenol Concentrations

Total Recoverable Phenolics were measured using EPA Method 420.1 (Federal Register, 1984). In this procedure, phenol reacts with 4-aminoantipyrine in the presence of potassium ferricyanide to form a stable reddish brown colored antipyrine dye. The amount of color produced is a function of the concentration of phenolic material. This method cannot measure para-substituted phenols, so the concentrations of nitrosophenol and 4-nitrophenol were not measureable with this test. An experiment with a
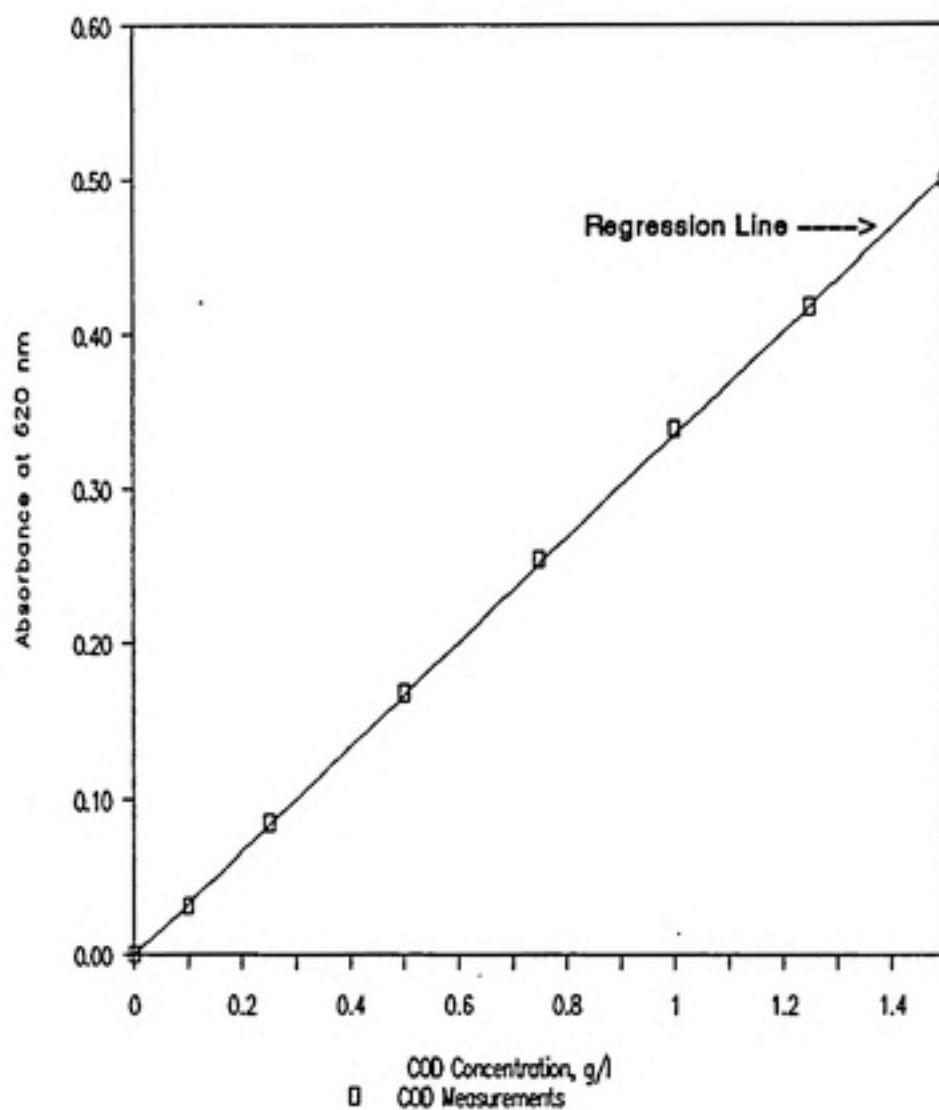
Figure 1: Typical COD Standard Curve. Measurements were taken with vials received 26 September 1989. r^2 = 0.9999

Date Vials Received	r^2
6 Feb	0.9997
28 Mar	0.9998
22 May	0.9999

Table 1: COD Standard Curve Correlations

nitrosophenol standard confirmed that nitrosophenol did not react with the aminoantipyrine.

A standard curve was prepared for each batch of 4-aminoantipyrine and potassium ferricyanide made. A 10 ug/l phenol solution was freshly prepared for each standard curve by dissolving 1 ml of liquid phenol in 1 liter of distilled water. This solution was then diluted 100:1 to give a 10 ug/l standard. Though the EPA method calls for making a standard curve in the range of 0 - 1 mg/l, the standard curves were found to be linear up to 0 - 10 mg/l. The standard curve was then broken up into a high and low range. A typical standard curve for the phenol test is shown in Figure 2.

The analytical method requires a distillation to remove interfering materials that may be present in a sample. Since the phenol test was used in this study as a daily measure of reactor performance, it was deemed infeasible to perform such a large number of distillations. The method of standard additions was performed on the reactor effluent to determine if interfering species were present to confound the data. The results of the standard additions test is also shown in Figure 2. The slope of the standard addition curve (0.151) is almost equal to the slope of the standard curve (0.148). In addition, the concentration measured in the standard addition sample is almost equal to

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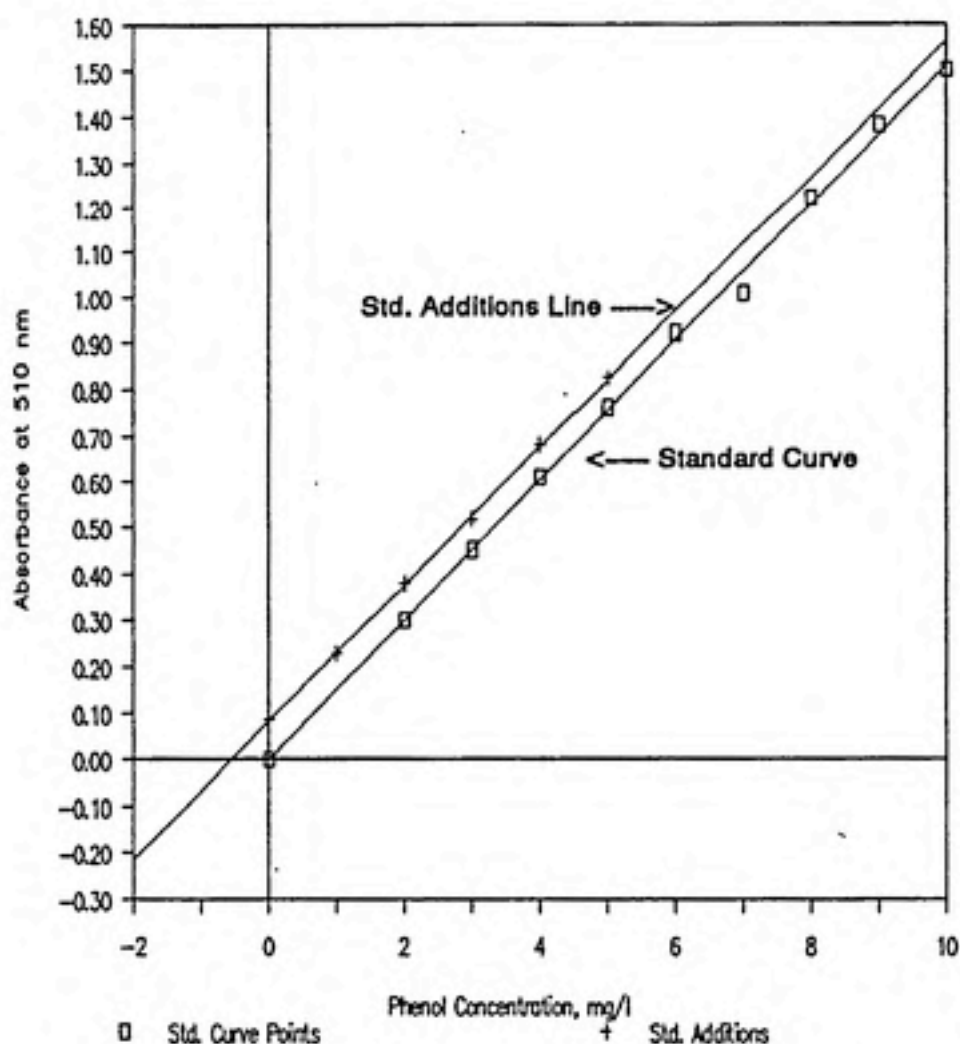
Figure 2: Typical Phenol Standard Curve Shown With Standard Additions Test. Standard curve measurements are for High Range values (1-10 mg/l) taken on 3 March 1989. Concentration measured in standard addition sample: 0.59 mg/l. X intercept: 0.60 mg/l.

Date	Low Range r^2	High Range r^2
29 Aug	0.9954	0.9962
1 Dec	0.9997	0.9969
3 Mar	0.9999	0.9987
26 Apr	0.9998	0.9998

Table 2: Phenol Standard Curve Correlations

the concentration read from the x-intercept of the standard addition curve. Consequently, there were very few, if any, interfering compounds in the reactor effluent.

All phenol concentrations measured on reactor effluents were performed in duplicate. Typical standard deviations were less than 1% of the mean.

Mixed Liquor Suspended Solids (MLSS)

Mixed liquor suspended solids were measured using EPA Method 160.2, Non-Filterable Residue (Federal Register, 1984). A known volume of mixed liquor was filtered through glass fiber filters that had been pre-rinsed with distilled water, placed in aluminum weighing pans, dried in a drying oven at 103 degrees C, and pre-weighed. After filtering the mixed liquor, the filters were again rinsed with distilled water to remove any filterable solids and the filters were again placed in the drying oven. All suspended solids filters were allowed to dry for at least one day before the first weight was taken. Each filter was weighed three times on consecutive days to determine the suspended solids. The difference in the filter's weight before and after filtering the mixed liquor was divided by the volume of mixed liquor filtered to determine the MLSS.

All suspended solids performed on the reactor mixed

liquors were done in triplicate. Standard deviations were found to be less than 5% of the mean.

Mixed Liquor Volatile Suspended Solids (MLVSS)

Volatile suspended solids were measured using EPA Method 160.4, Volatile Residue (Federal Register, 1984). After the MLSS was determined as described in the previous section, the filters were placed in a muffle furnace and heated to a temperature of 450 - 500 degrees C for at least two hours. These filters were then placed back into the drying oven at 103 degrees C and allowed to cool overnight. Three daily weights were also taken on the volatile suspended solids. The weights of the filters from the muffle furnace were subtracted from the MLSS weight to give the amount of volatile solids in the mixed liquor. Standard deviations for volatile suspended solids were also less than 5%. Typically, mixed liquor suspended solids were found to be greater than 85% volatile, ranging from 82% to 97%.

Nitrate Nitrogen (NO3-N)

The raw waste received from Sandoz was found to have high levels of nitrate (1150 mg/l NO3-N). This high nitrate concentration is due to the oxidation of excess sodium nitrite to sodium nitrate over time.

Initially, the concentration of nitrate nitrogen was measured with an ion specific electrode (Orion Research Model 930700). However, interfering species in the effluent matrix, such as sulfate, caused inaccurate readings when verified with the method of standard additions. Consequently, an alternative method of nitrate analysis was sought.

Approximate concentrations of nitrate nitrogen were measured using the Hach Cadmium Reduction Method. Pre-packaged NitraVer 5 nitrate reagent powder pillows were added to 25 ml dilutions of samples. The samples were shaken for one minute, allowed to react for 5 - 15 minutes, and absorbance was measured.

This method of analysis is a modification of the cadmium reduction method using gentisic acid in place of 1-naphthylamine. Cadmium metal in the pillows reduces nitrates to nitrites. The nitrites then react in an acidic medium with sulfanilic acid to form an intermediate diazonium salt, which when coupled with gentisic acid, forms an amber colored compound. Color intensity of the compound is in direct proportion to the nitrate and nitrite concentrations of the water sample.

The NitraVer 5 powder pillows can be used to measure nitrate nitrogen in a "high" range (0 - 30 mg/l NO3-N) and "medium" range (0 - 4.5 mg/l NO3-N) by measuring the

absorbance of the samples at 500 and 400 nm respectively. Interferences can be caused by the presence of strong oxidizing and reducing agents. Ferric ions cause false positive results. Chloride concentrations above 100 mg/l as Cl- will cause false negative results. None of these interfering species were believed to be present in concentrations high enough to affect the results.

All nitrate nitrogen tests were performed using the same lot of powder pillows. The standard curve for the high range method is shown in Figure 3. The standard curve for the medium range method is shown in Figure 4. All nitrate nitrogen tests were performed in duplicates and the standard deviations were found to be less than 5% of the mean. Checks of the veracity of the nitrate nitrogen tests were performed using the method of standard additions. The results of these tests are included in the calibration curve figures. As can be seen from Figure 3, some interferences were present in the mixed liquor matrix, which caused the slopes and actual concentrations measured in the standard additions curve at high range to differ from those in the standard curve. As shown in Figure 4, interferences were considerably less of a problem at higher sample dilution (lower nitrate concentration).

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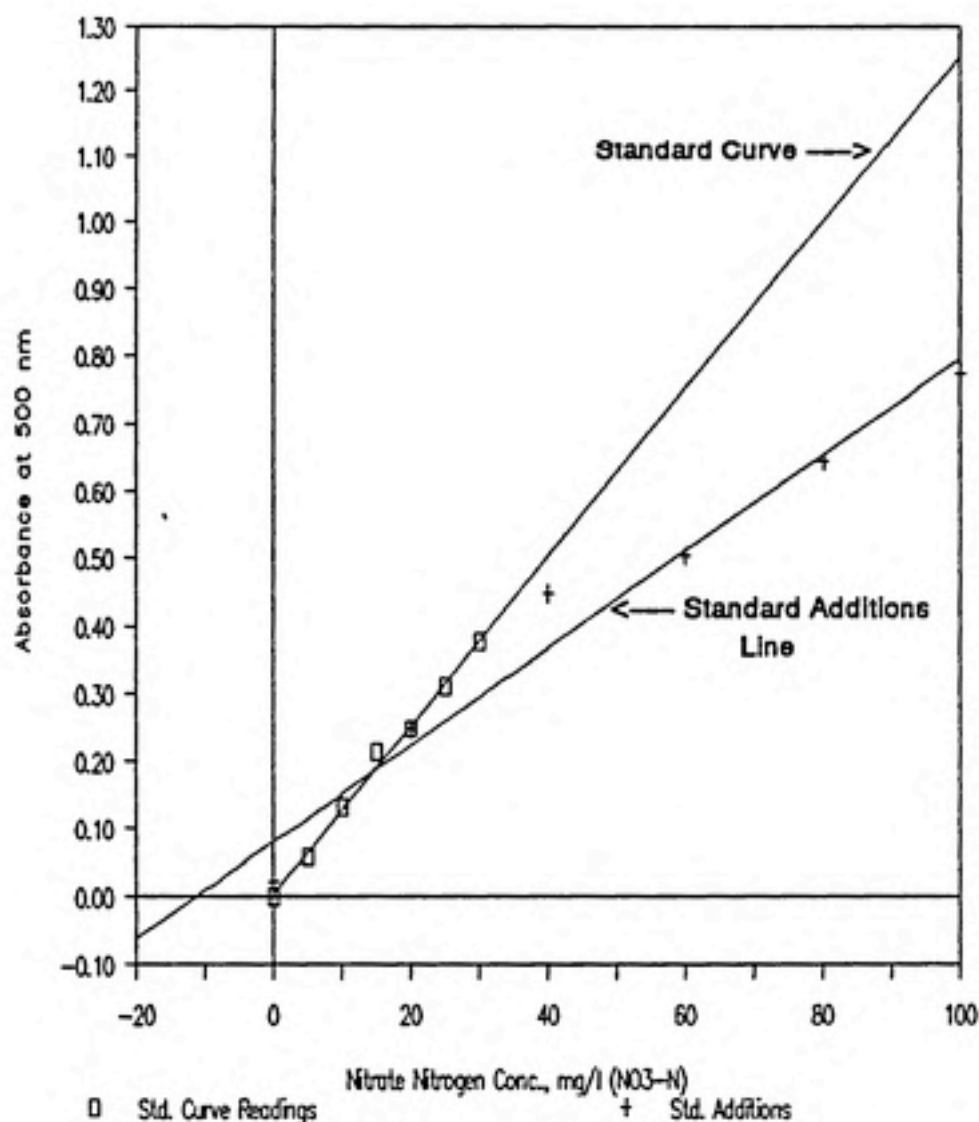
Figure 3: Nitrate Nitrogen Standard Curve (High Range) Shown With Standard Additions Test. Concentration measured in sample with no nitrate standard added: 9.0 mg/l. Actual concentration: 11.4 mg/l. Correlation coefficient of Standard Curve: 0.9940. Correlation coefficient of Standard Additions Line: 0.9700.
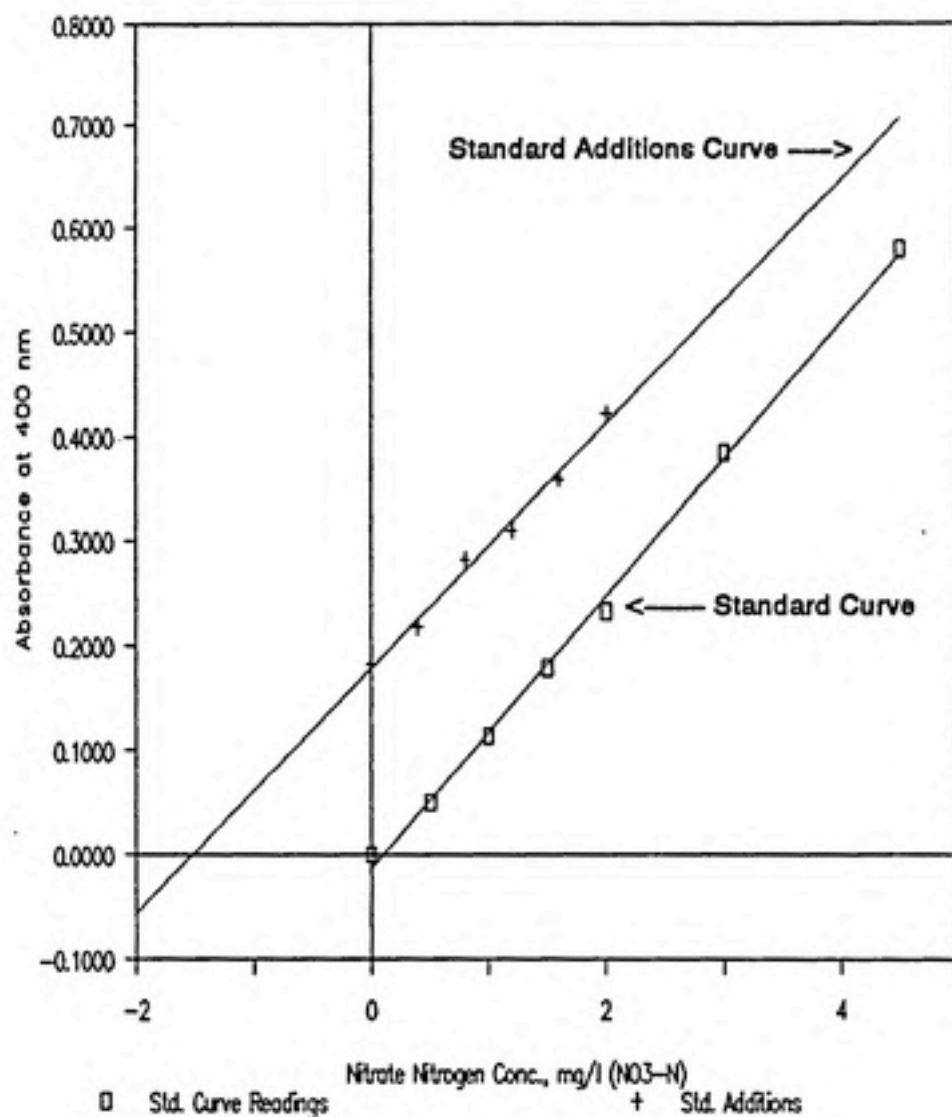
Figure 4: Nitrate Nitrogen Standard Curve (Medium Range) Shown With Standard Additions Test. Concentration measured in standard addition sample: 1.52 mg/l. Actual concentration: 1.50 mg/l. Correlation coefficient of Standard Curve: 0.9980. Correlation coefficient of Standard Additions Line: 0.9896.

Nitrite Nitrogen (NO2-N)

Nitrites were present in the raw waste due to unoxidized excess sodium nitrite and possibly as a result of degradation of nitrosophenol. Nitrites were measured by the Hach Diazotization Method. NitriVer 3 nitrite reagent powder pillows were added to 25 ml dilutions of samples. Samples were then shaken for one minute, allowed to react for 10 - 15 minutes and the absorbance was measured at 500 nm. The detection level of this test is 0 - 0.2 mg/l NO2-N. In this test, nitrite ions react with sulfanilic acid to form an intermediate diazonium salt. This salt reacts with chromotropic acid to produce a red-orange complex directly proportional to the amount of nitrite nitrogen present.

All nitrite nitrogen measurements taken during this study were from one lot of Hach Nitriver 3 reagent pillows. A standard curve was prepared using a 0.2 mg/l nitrite nitrogen standard solution. This standard curve is shown in Figure 5 along with a test for interferences by the method of standard additions. As can be seen, there was slight, if any, interference caused by the effluent matrix.

Phosphate

Phosphorus was added to the raw waste and synthetic feed as a nutrient for biological growth. The phosphate
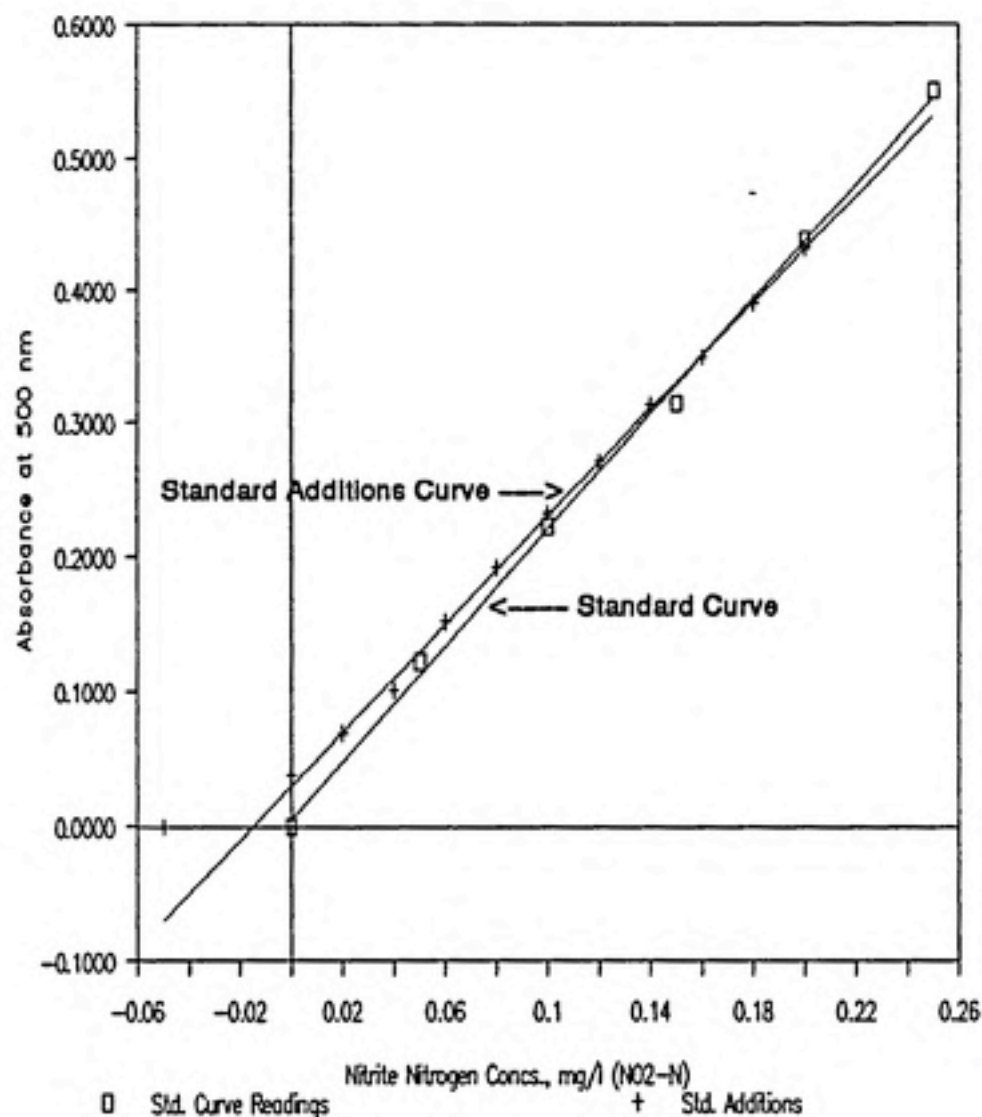
Figure 5: Nitrite Nitrogen Standard Curve Shown With Standard Additions Test. Concentration measured in standard addition sample: 0.015 mg/l. Actual concentration: 0.016 mg/l. Correlation coefficient of Standard Curve: 0.9982. Correlation coefficient of Standard Additions Line: 0.9993.

was added as a phosphate monobasic and dibasic buffer (0.1M KH2PO4/K2HPO4). The concentration of phosphate in the effluent was monitored to determine the amount of phosphate required to achieve biodegradation.

Phosphate was measured by the Hach Ascorbic Acid Method. The first step of this analytical procedure involves reaction of orthophosphate with molybdate in acid solution to form a yellow-colored phosphomolybdate complex. The phosphomolybdate complex is then reduced by ascorbic acid, causing a characteristic molybdenum blue species.

All phosphate measurements were performed using one lot of PhosVer 3 powder pillows. A standard curve for this lot of reagent pillows is shown in Figure 6. Measurements of reactor phosphate concentrations were all done in duplicates. Standard deviations were found to be less than 5% of the mean. A test for interferences was done by the method of standard additions. This test is also shown in Figure 6. Again, some interfering species were present in the effluent matrix. However, if standard curve values above 1.5 mg/l P are omitted, the slopes of the standard curve and standard additions curve are nearly parallel. Of 84 phosphate measurements taken during this study, only 2 samples had phosphate concentrations greater than 1.5 mg/l P.
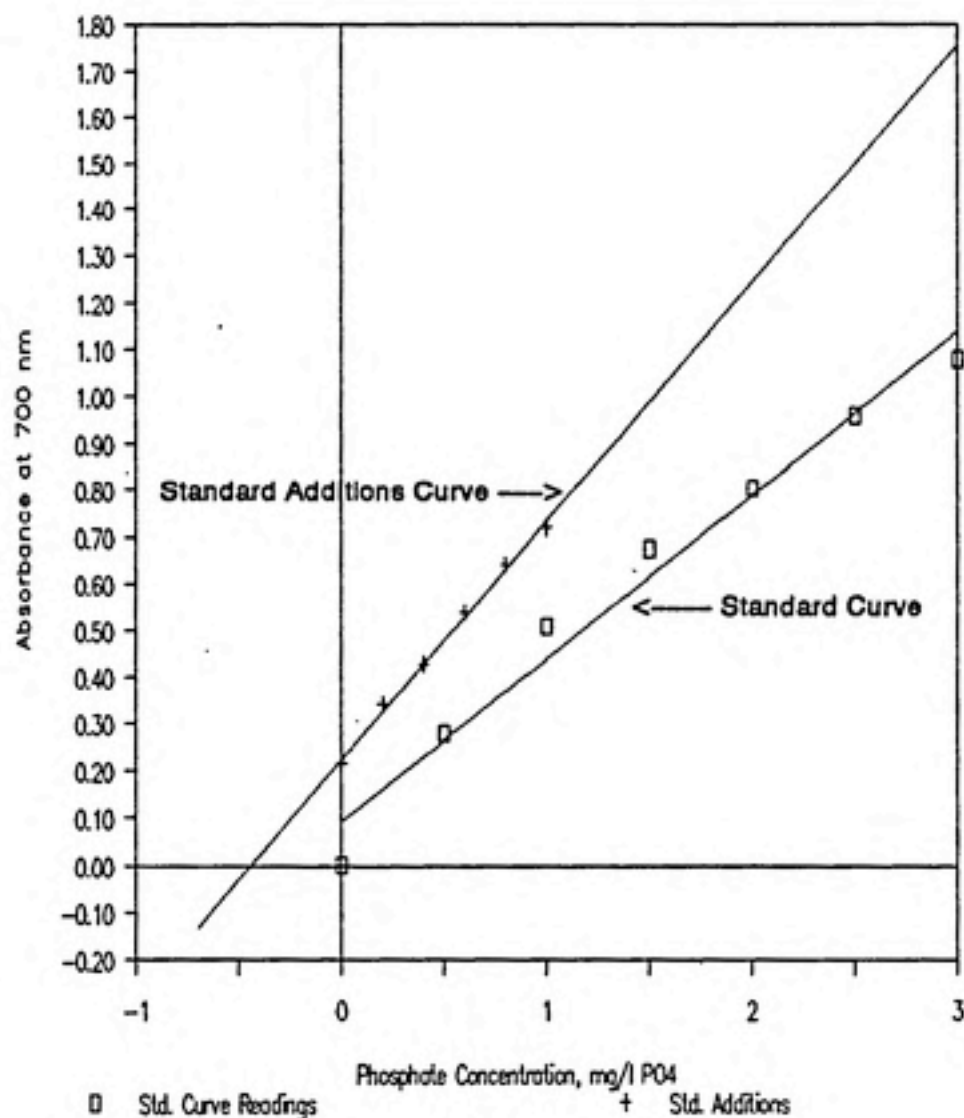
Figure 6: Phosphate Standard Curve Shown With Standard Additions Test. Concentration measured in standard addition sample: 0.388 mg/l. Actual concentration: 0.438 mg/l. Correlation coefficient of Standard Curve: 0.9764. Correlation coefficient of Standard Additions Line: 0.9977.

High Performance Liquid Chromotography (HPLC)

Limited HPLC data was collected during this study due to many equipment problems and the limited amount of time that a post-doctoral student was available to work with the HPLC unit. HPLC was performed on an ISCO HPLC (Model 2350 pump and 2360 gradient programmer, with UV detection at 254 nm) using a C_8 analytical reversed phase column (Supelcosil LC-8, 5 um packing, 15 cm X 0.46 cm). Gradient elution consisted of methanol:H2O at 35:65 (initial) to 100:0 over 20 minutes, then returned to 35:65 over 5 min., at a flow rate of 1.5 ml/min. Calibration curves were prepared for phenol, nitrosophenol, and 4-nitrophenol. Retention times were 1.0 to 1.5 min. for nitrosophenol, 1.9 to 2.2 min. for 4-nitrophenol and 2.7 to 3.3 min. for phenol.

Nitrosophenol standards gave a second peak at about 2.2 min. Based on the known retention time of 4-nitrophenol and the known presence of 4-nitrophenol as a by-product of nitrosophenol synthesis, this second peak was assumed to represent 4-nitrophenol. From the standard curve for 4-nitrophenol and the known addition of nitrosophenol, 4-nitrophenol was determined to be approximately 12% by weight of the nitrosophenol reagent.

Biological Oxygen Uptake Monitoring

Biological oxygen uptake was monitored using a YSI Model 5300 Biological Oxygen Monitor with a YSI Model 5331 Oxygen Probe. The Monitor is essentially a dissolved oxygen meter that is capable of measuring real time depletion of dissolved oxygen in a sample of mixed liquor. The probe was placed in a water-jacketed chamber (Gilson Medical Electronics, Middleton, WI) fitted with a ground glass stopper that contained a capillary bore hole for injection of reagents by syringe. The chamber was kept at a constant temperature with a constant temperature circulator. A schematic of the oxygen uptake system is shown in Figure 7.

Oxygen Uptake was measured as follows: Approximately 1.6 ml of mixed liquor was placed in the chamber. The stopper was placed in the top of the chamber to exclude air from the mixed liquor sample. The probe and sample were allowed to come to thermal equilibrium and the baseline oxygen uptake rate (representing either endogenous uptake or in-situ uptake, depending on the status of the mixed liquor sample) was recorded on a strip chart recorder. A known volume of a known concentration of substrate was then injected into the chamber with a microliter syringe.

The initial increase or decrease in the oxygen uptake rate after injection of substrate compared to the
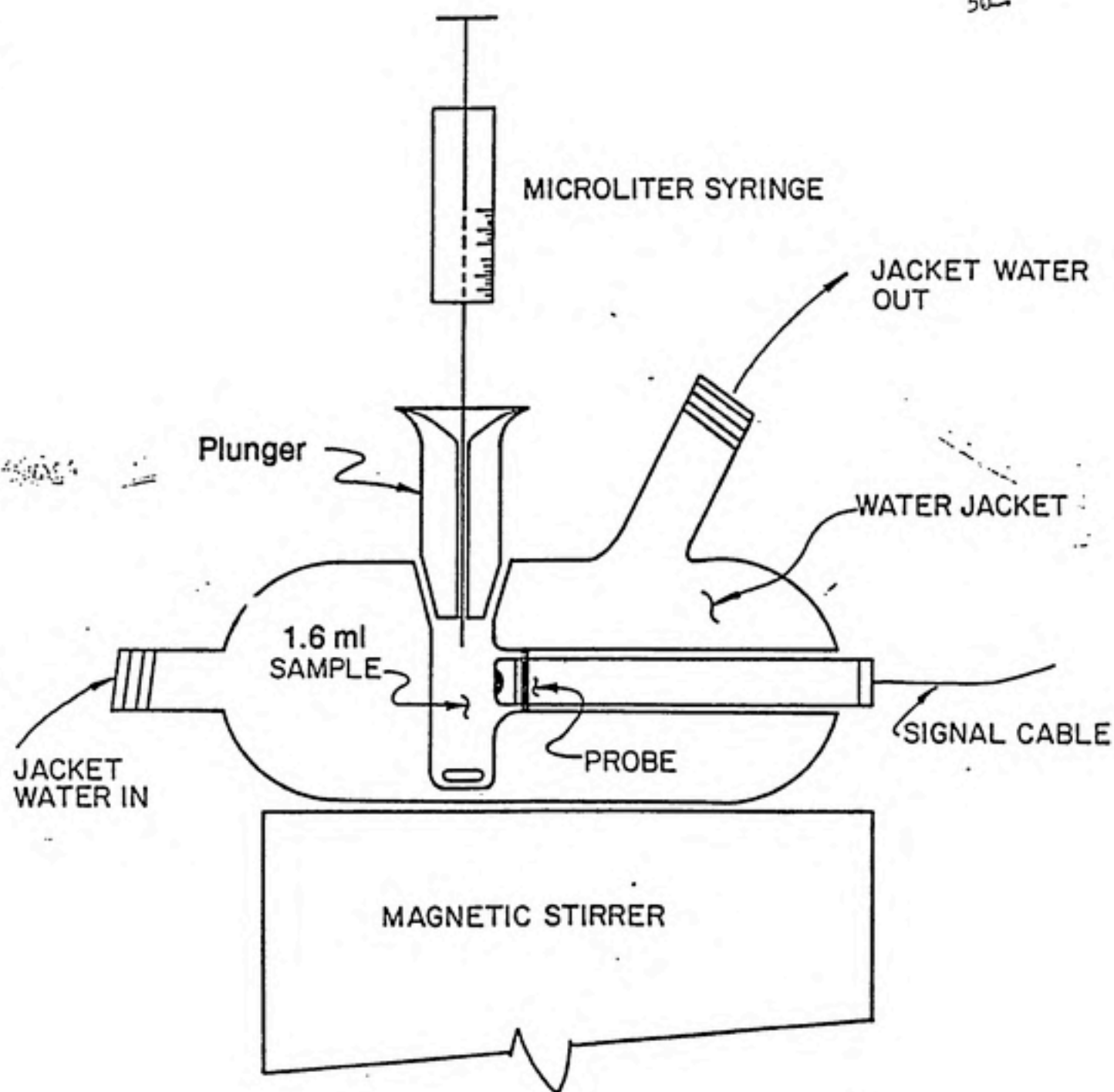
Figure 7: Schematic Drawing of Oxygen Uptake System

endogenous rate is a measure of the metabolic activity of the mixed liquor at that substrate concentration. Thus the biological oxygen uptake rates measured at various concentrations can be used to estimate various kinetic parameters such as umax (maximum specific growth rate), Ks (half-saturation constant), and Ki (inhibition constant).

Reactor Description And Operation

Two independent batch reactors were operated during this study, designated as Reactor I and Reactor II. The reactors were operated in Fill, React, Settle and Draw modes to simulate operation of an SBR.

1. Reactor I: Reactor I consisted of a 4 l Pyrex reaction kettle which received a feed solution by means of a peristaltic pump (Masterflex Model #N-07520). Feeding periods were controlled by an electronic timer (Chrontrol Model CD). Originally, a fritted disk was placed in the bottom of the reactor and used as the aeration device. Laboratory compressed air passed through a flow meter and was then humidified by passing it through a gas washing bottle prior to entering the reactor. After about four weeks of operation this system was found to be inadequate for providing enough air to the reactor for proper mixing and suspension of the mixed liquor. A maximum of 800 mls per minute of air could be delivered to the reactor with

this system. The fritted disk was replaced with a standard aquarium aeration stone, and the gas washing bottle was replaced with a stoppered flask configured to allow air to bubble through it. This configuration allowed air flow rates to the reactor of 1.5 to 2 liters per minute, which was found to be adequate for proper mixing during the react period.

The mixed liquor used for the reactor came from the Sandoz activated sludge basin. Two liters of mixed liquor were taken from the plant on 17 March 1989. One liter of the mixed liquor was aerated from 17 March until 3 September 1989. The mixed liquor was fed approximately 10 ml of raw waste every two to three days during this period. The other liter of mixed liquor was frozen. On 5 September the mixed liquor that had been aerated and the thawed mixed liquor that had been frozen were placed in the reactor and daily operation began.

The MLSS concentration in Reactor I varied greatly during this study. The concentration ranged from a low of 161 mg/l when mixing was accomplished by aeration at a low rate to 8519 mg/l when the contents of Reactor II was added to Reactor I near the end of the study. The average MLSS concentration found in 102 measurements was 1870 mg/l with a standard deviation of 1690 mg/l.

Originally the React period was controlled by opening and closing the air line manually. After 4 months of operation, a solenoid valve was placed on the air line following the humidifying flask. The solenoid valve was controlled by the timer.

Mixing of the mixed liquor was performed with a laboratory stirrer (Cole Parmer Stirpak Stirrer, Model 4554-00) and a high efficiency paddle. After only a few months of operation the stirrer became unreliable at mixing at a constant speed. The stirrer was taken out of the reactor and a magnetic stirrer with a large stir bar was used instead. The magnetic stirrer was operated only during the feed period by being plugged in to the same timer circuit as the feed pump.

The reactor vessel was normally operated at a liquid volume of 2.5 l. Graduations were placed on the side of the reactor at 0.1 l increments to aid in the withdrawal of the proper amount of mixed liquor or settled effluent each day. Withdrawal of reactor liquid (either mixed liquor or settled supernatant) was performed by opening a clamp on Tygon tubing that was attached to a hose barb at the 2.0 l mark in the side of the reactor.

Poor settling of the mixed liquor was observed from the onset of reactor operation. During most of the operating

period, the effluent samples from the reactor were centrifuged and the solids returned to the reactor. Centrifuging was accomplished by placing the reactor effluent into 50 ml plastic tubes and centrifuging at 2000 rpm for 20 minutes (centrifuge used was an International Equipment Company Model UV).

The reactor was initially operated using one cycle per day. The feed period consisted of a four hour Aerated Fill, followed by a 19 hour React period and a 1 hour Settle period. Draw only lasted for a few minutes and consisted of slowly draining the reactor from the 2.0 l mark by opening the clamp on the hose barb. On 26 September, the Aerated Fill period was increased to eight hours due to poor effluent quality. This mode continued virtually unchanged until February 7, when we began feeding a synthetic feed. The Fill period was changed to an eight hour period of mixing with no aeration. On 17 February, the Settle period was increased to two hours in order to decrease the effluent suspended solids. This mode of eight hour Fill, 14 hour React, two hour Settle lasted until 27 March with only minor changes in cycle times for short periods.

From 27 March until 1 May, the reactor was operated using two cycles per day. Each cycle consisted of a four hour Fill with mixing, no air, six hour React, and a two

hour Settle.

On 2 May, the number of cycles was increased to 3 per day. In addition, the solids from Reactor II were centrifuged and placed in Reactor I. The mode of cycle operation was a one hour Fill with mixing, one hour Fill with aerating, five and one-half hours React and a one and one-half hour Settle. This mode continued until 23 May, when the React period was increased to six hours and the settle period was decreased to one hour.

2. Reactor II: Reactor II consisted of a 4 l Erlenmeyer Flask which was also fed by using a peristaltic pump. Air was piped directly to an aeration stone at the bottom of the flask. Distilled water was added at the end of the react period to account for water lost due to aeration. The reactor was mixed during the feed period with a magnetic stirrer. The magnetic stirrer was plugged into the same timer circuit as the feed pump. Effluent was withdrawn by means of a second peristaltic pump (Masterflex Model N-07553). Care was taken to draw from the top of the mixed liquor.

The mixed liquor used for Reactor II was also obtained from the Sandoz activated sludge basin. Three liters of mixed liquor was collected on 10 November 1989 and taken to

the lab. It was aerated for 7 days and fed 10 mg of phenol each day. Normal feeding of the reactor started on 17 November. Again, due to poor settling of the mixed liquor, effluent samples were centrifuged and the solids returned to the reactor. The MLSS in Reactor II varied from 1498 to 6536 mg/l. The average of 29 MLSS measurements was 4110 mg/l with a standard deviation of 1450 mg/l.

Preparation Of Reactor Feeds

At the beginning of this study the reactors were fed raw nitrosophenol filtrate waste provided by Sandoz. In February, 1990 we ceased using this raw waste because of inconsistent reactor performance (effluent quality) and switched to a synthetic waste prepared in the lab. The rationale for using synthetic feed was that individual components could be varied independently to study their effects on reactor performance. These two feedstreams are described below:

1. Raw Waste: Two separate batches were received from Sandoz and were found to have quite different compositions. The characteristics of interest are tabulated in Table 3. The raw waste was kept refrigerated to inhibit natural degradation of the waste, but as can be seen from the table, the phenol and COD of the waste nevertheless decreased over time.

Table 3:   Characteristics of Raw Waste Received from Sandoz

1.   Raw Waste Received 31 August 1989

Date	Soluble COD (mg/l)	Phenol (mg/l)	Total Diss. Solids (mg/l)	Suspended Solids (mg/l)	pH
1 Sep	6842	1021	49000	800	3
12 Sep	6031	1010			
18 Sep	6476	1019			
26 Sep	5645	986			
3 Oct	5331	967			
8 Oct	5727	979			
16 Oct	5339	973			
22 Oct	5070	937			
8 Nov	----	965			
16 Nov	----	992			
24 Nov	----	984			
2 Dec	----	921			

2. Raw Waste Received 5 December 1989

Date	Soluble COD (mg/l)	Phenol (mg/l)	Total Diss. Solids (mg/l)	Suspended Solids (mg/l)	pH	Nitrate Nitrogen (mg/l NO3-N)
10 Dec	8490	245	63200		3.5	
11 Jan						
16 Jan	7505	143				
23 Jan				50		
30 Jan	----	195				
7 Mar						1160
8 Mar						1100
28 Mar						1150

Before feeding the raw waste to the reactors, it was neutralized to a pH of 6.5 using a 0.2N magnesium hydroxide slurry. Magnesium hydroxide was used as the neutralizing agent because the magnesium could be used by the microorganisms as a nutrient and because magnesium hydroxide is currently being used by Sandoz. Neutralized waste was filtered with qualitative filter paper (Whatman #1) to remove a black grainy insoluble residue that formed during the neutralization.

Phosphorus, ammonia, and trace elements were then added to the waste before feeding to the reactor. The amount of nutrients added is shown in Table 4.

2. Synthetic Feed: On February 8, 1990, the feed was changed to a synthetic mixture prepared in the lab. The concentrations of phenol, nitrosophenol, and 4-nitrophenol used were based on the average concentrations of these constituents found in 60 batch runs of nitrosophenol filtrate waste. The analyses were performed by Sandoz using HPLC. This data is contained in Appendix A.

Frequency distributions were performed on the data and are shown in Tables 5, 6, and 7. The frequency distribution of phenol appeared to follow a log normal distribution as shown in Figure 8. The nitrosophenol

Table 4: Nutrient Concentrations of the Feed

Element	Source	Reagent Conc. In Feed (mg/l)
Fe	FeSO4*7H2O	1.4
Zn	ZnSO4*7H20	0.8
Co	CoCl2*6H2O	0.12
Cu	CuSO4*5H2O	0.008
Mo	(NH4)6Mo7O24*4H2O	0.12
Ca	CaCl2	10
EDTA	Na2EDTA*2H2O	7.4
P	KH2PO4/K2HPO4	90
K	KH2PO4/K2HPO4	85.5
N	NH4Cl	200

Note: EDTA was added as a chelating agent to insure
the metals were dissolved.

Table 5: Data Distribution For Phenol

Conc. (mg/l)	# of Observs.	% of Observs. < Conc.
400	1	1.6
500	1	3.3
600	3	8.3
700	5	16.7
800	6	26.7
900	4	33.3
1000	7	61.7
1100	3	50.0
1200	6	60.0
1300	3	65.0
1400	3	70.0
1500	4	76.7
1600	5	85.0
1700	5	93.3
1800	3	98.3
1900	1	100.0

Table 6: Data Distribution For Nitrosophenol

Conc. (mg/l)	# of Observs.	% of Observs. < Conc.
700	4	6.7
800	0	6.7
900	1	8.3
1000	4	15.0
1100	5	23.3
1200	6	33.3
1300	8	46.7
1400	6	56.7
1500	3	61.7
1600	9	76.7
1700	5	85.0
1800	5	93.3
1900	1	95.0
2000	3	100.0

Table 7: Data Distribution For 4-Nitrophenol

Conc. (mg/l)	# of Observs.	% of Observs. < Conc.
100	4	6.7
120	9	21.7
130	8	35.0
140	9	50.0
160	8	63.3
180	9	78.3
200	5	86.7
300	3	91.7
500	1	93.3
900	4	100.00

Table 8: Data Distribution For Nitrosophenol:Phenol Ratio

Nitroso-phenol: Phenol Ratio	Number of Values < Ratio	Percent of Values < Ratio
0.50	0.00	0.00
0.75	3.00	5.00
1.00	10.00	21.70
1.25	21.00	56.70
1.50	11.00	75.00
2.00	11.00	93.30
3.00	2.00	96.70
4.00	1.00	98.30
5.00	1.00	100.00
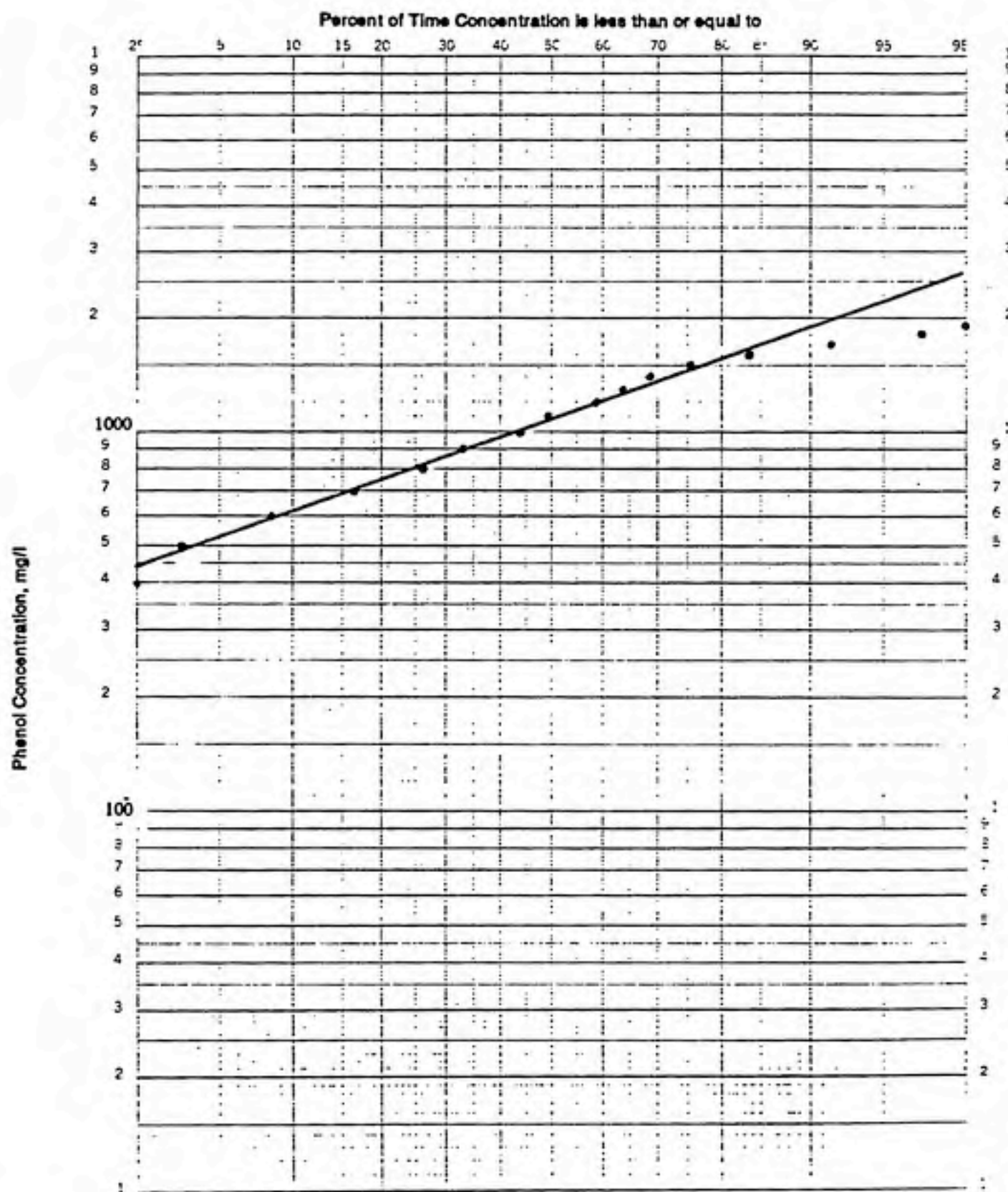
Figure 8: Frequency Distribution Plot of Phenol Data Supplied by Sandoz

distribution fit a normal distribution plot best, as seen in Figure 9. The 4-nitrophenol data did not seem to fit any frequency distribution since most of the concentrations measured centered near 200 mg/l.

Comparing the phenol concentration in the second batch of raw waste for this study (Table 3) to the distribution curve, this batch of waste was highly unrepresentative of typical waste production.

Table 8 shows the data distribution for the nitrosophenol:phenol ratio found in the data. The average ratio was 1.3 (std. dev. = 0.6) and varied from 0.66 to 4.1.

The average concentrations of the raw waste are 1340 mg/l nitrosophenol (std. dev. = 330 mg/l), 1110 mg/l phenol (std. dev. = 390 mg/l), and 190 mg/l 4-nitrophenol (std. dev. = 160 mg/l). The theoretical average COD of the raw waste based on the constituent concentrations of phenolic compounds was 5660 mg/l (std. dev. = 1380 mg/l).

Synthetic feed was prepared by first dissolving nitrosophenol (Aldrich Chemical Co.) in 0.1 N NaOH. The phenol was then added from a 50 g/l phenol stock solution. This stock solution was prepared by dissolving 50 ml melted
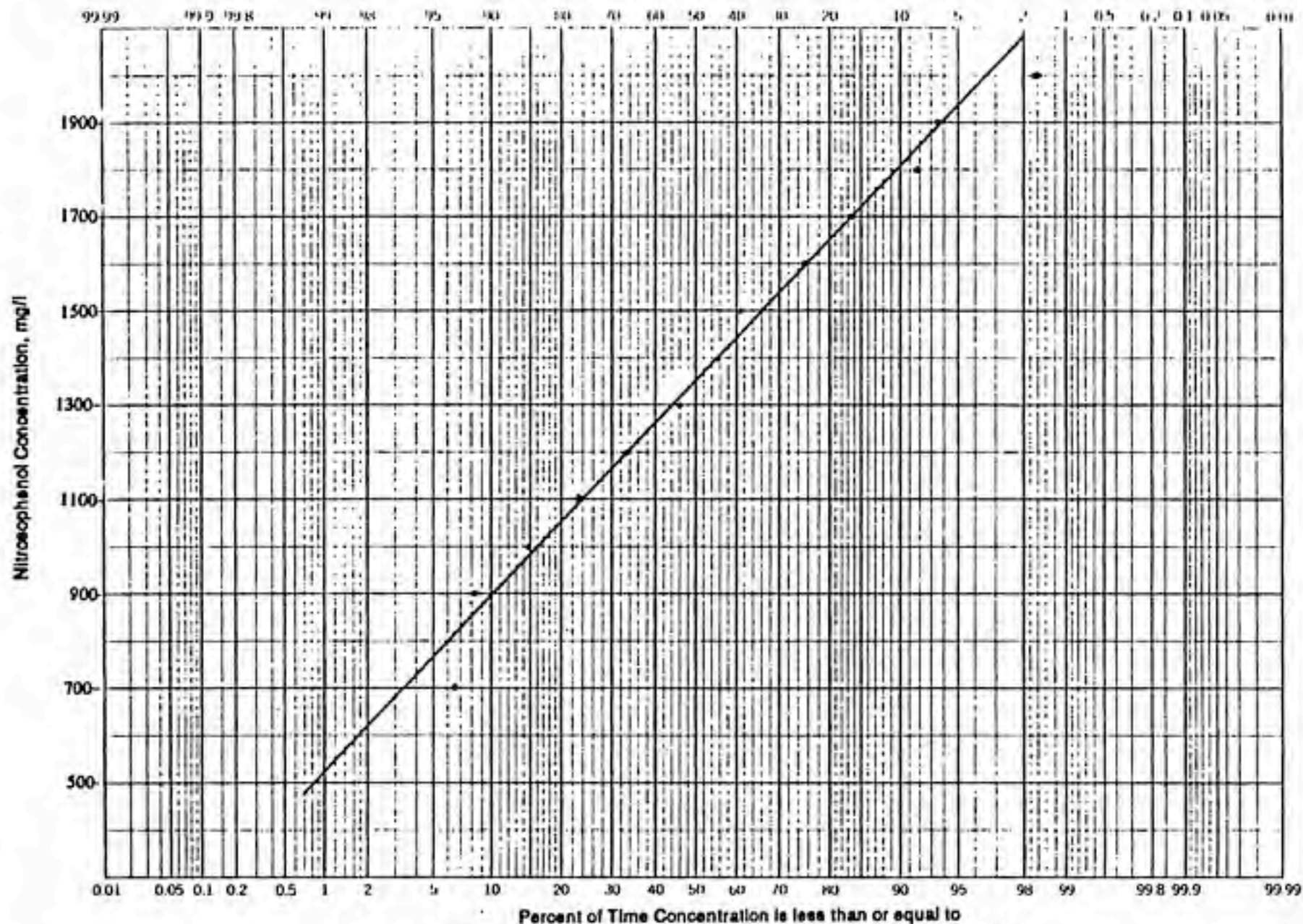
Figure 9: Frequency Distribution Plot, Phenol Data Supplied by Sandoz

phenol (Aldrich Chemical Co., density of reagent = 1.071 g/ml) in a 1 l volumetric flask. The 4-nitrophenol was added from a 10 g/l stock solution prepared by dissolving 1 g 4-nitrophenol reagent (Aldrich Chemical Co.) in a 100 ml volumetric flask. The synthetic feed was then neutralized to a pH of 6.8 with 1.2N HCl.

Since $Mg(OH)_2$ was no longer used as a neutralizing agent, $MgSO_4$ was added to the feed solution to a final concentration of 150 mg/l, which is the approximate concentration used in the preparation of the raw waste feed. Nitrate was also added in the form of sodium nitrate. The measured levels of COD, phenol, and nitrate-nitrogen are shown in Table 9. The nitrate level was incrementally increased with each batch of synthetic feed made to bring the concentration up to that of the raw waste. Nutrients were added to the synthetic feed prior to feeding in the same amounts as was added to the raw waste feed.

The major difference between synthetic feed and raw waste was in the sulfate concentration. Sulfate was intentionally kept to a low concentration because independent experiments (described in Chapter V) indicated that sodium sulfate was inhibitory at concentrations as low as 1%. Therefore, the synthetic feed had a substantially lower TDS concentration than the raw waste, with the difference primarily accounted for by sulfate salts.

Table 9: Measured and Theoretical Soluble COD, Phenol, and Nitrate

Date	Measured Soluble COD Conc. (mg/l)	Theor. COD* Conc. (mg/l)	Measured Phenol Conc. (mg/l)	Added Phenol Conc. (mg/l)	Measured Nitrate Conc. (mg/l NO3-N)	Added Nitrate Conc. (mg/l NO3-N)
6 Feb	4600	4730	1053	1200	----	0
14 Feb	----	4730	1257	1200	----	0
21 Feb	3480	4730	1155	1200	----	0
27 Feb	----	4730	1090	1200	----	0
2 Mar	4600	4730	----	1200	----	83
8 Mar	5639	5760	1044	1200	78	166
14 Mar	5401	5760	1027	1200	----	166
28 Mar	----	5760	1208	1200	288	330
7 Apr	6315	5760	1156	1200	----	580
5 May	----	5760	1244	1200	----	829
10 May	----	5760	1268	1200	911	829
23 May	----	5760	----	1200	----	912
30 May	----	5760	----.	1200	----	995

* Theoretical COD as calculated by summing theoretical COD of each organic constituent at its added concentration.

From 6 February to 7 March, the nitrosophenol content of the synthetic feed was not as high as desired due to measurement error. In addition, as discussed above, HPLC analysis indicated approximately 12% of the nitrosophenol reagent as purchased from Aldrich Chemical Co. is actually 4-nitrophenol. This was not accounted for in the preparation of the synthetic feed. Consequently, the nitrosophenol content was slightly lower and the 4-nitrophenol content was slightly higher than the average concentrations found in the raw waste.

The theoretical CODs of the three components of the feed are shown below:

Phenol: $C_6H_6O + 7O_2 \longrightarrow 6\ CO_2 + 3\ H_2O$

   (224 g O_2/94 g phenol) = 2.383 g COD/g

Nitrosophenol: $2\ C_6H_5O_2N + 15.5\ O_2 \longrightarrow$

          $12\ CO_2 + 2\ NO_3^- + 5\ H_2O$

   (496 g O_2/246 g nitrosophenol) = 2.016 g COD/g

4-Nitrophenol: $2\ C_6H_5O_3N + 14.5\ O_2 \longrightarrow$

              $12\ CO_2 + 2\ NO_3^- + 5\ H_2O$

   (464 g O_2/278 g 4-nitrophenol) = 1.67 g COD/g

The COD was measured on each of these components

individually to determine if the COD test was an accurate method of quantifying the total organic constituents in the feed. A 433 mg/l solution of the nitrosophenol salt, which has a theoretical COD of 513 mg/l had a measured COD of 507 mg/l (1% error). A 500 mg/l solution of 4-nitrophenol has a theoretical COD of 835 mg/l. The actual measured COD of this solution was 894 mg/l (7% error). A 500 mg/l phenol solution, with a theoretical COD of 1192 mg/l, had an actual measured value of 1285 mg/l (8% error).

IV. REACTOR PERFORMANCE

Overall Performance of the Reactors

Appendices B and C to this report contain daily and cumulative data collected on Reactors I and II, respectively. Included in the appendices are the volumes of feed, loading rates, reactor MLSS, influent and effluent concentrations of phenol and soluble COD, and the cycle times. Loading rates (F:M ratios) were calculated based on total React time (e.g., when feeding two cycles per day with a six hour React period, the time that appears in the denominator of the loading factor quotient is 12 hours or 0.5 days.). Also, since soluble COD was not measured every day, cumulative values of COD were computed using the prior effluent COD concentration measured. This method was also used for computations involving reactor MLSS and cumulative effluent phenol values, though effluent phenol was measured almost every day during the operation of the reactors.

Overall Performance of Reactor I

Reactor I was operated from 5 September 1989 to 31 May

1990 for a total of 268 days. The cumulative amounts of influent and effluent soluble COD and phenol are depicted in Figs. 10 and 11. Over the entire operating period, Reactor 1 was fed 12.315 l of raw waste and 24.518 l of synthetic feed. This volume of feed translates into an average daily feed volume of 138 ml. Over the entire operating period, the reactor removed 79.6% of the influent soluble COD and 95.9% of the added phenol. The average daily removal rate of soluble COD was 645 mg/d, and that for phenol was 141 mg/d.

Also included on Fig. 10 is the cumulative non-phenol COD fed to the reactor (i.e., the COD attributed to nitrosophenol and 4-nitrophenol). The difference between the non-phenol influent COD and the effluent COD indicates that a large fraction of the nitrosophenol was biodegraded.

To illustrate that most of the COD was biodegraded and not wasted or accumulated as suspended solids, it is necessary to determine what the effluent COD would have to be with no biodegradation of non-phenol COD. The total influent COD fed to the reactor less the effluent COD wasted from the reactor was 172.9 g. If this quantity had been wasted during this period in the effluent, then the effluent COD would have averaged 645 mg COD/d. For an average volume treated of 138 ml/d, the average COD
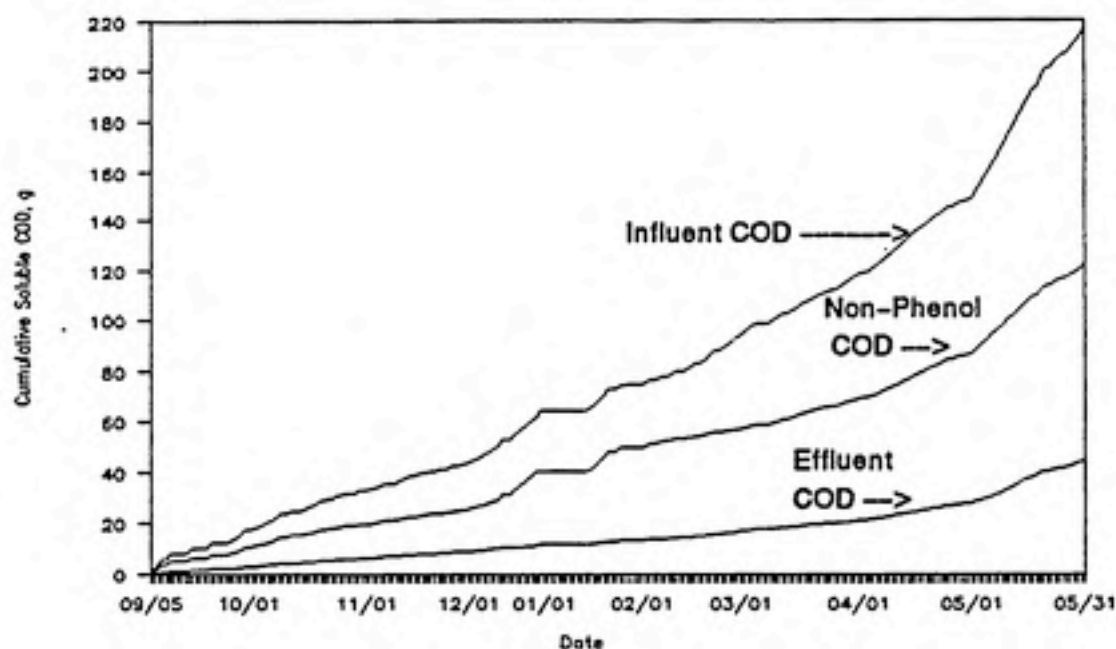
Figure 10: Cumulative Influent and Effluent Soluble COD, Reactor I. Raw waste was fed from 9/5/89 through 2/6/90. Synthetic feed was fed for the remainder of the project.
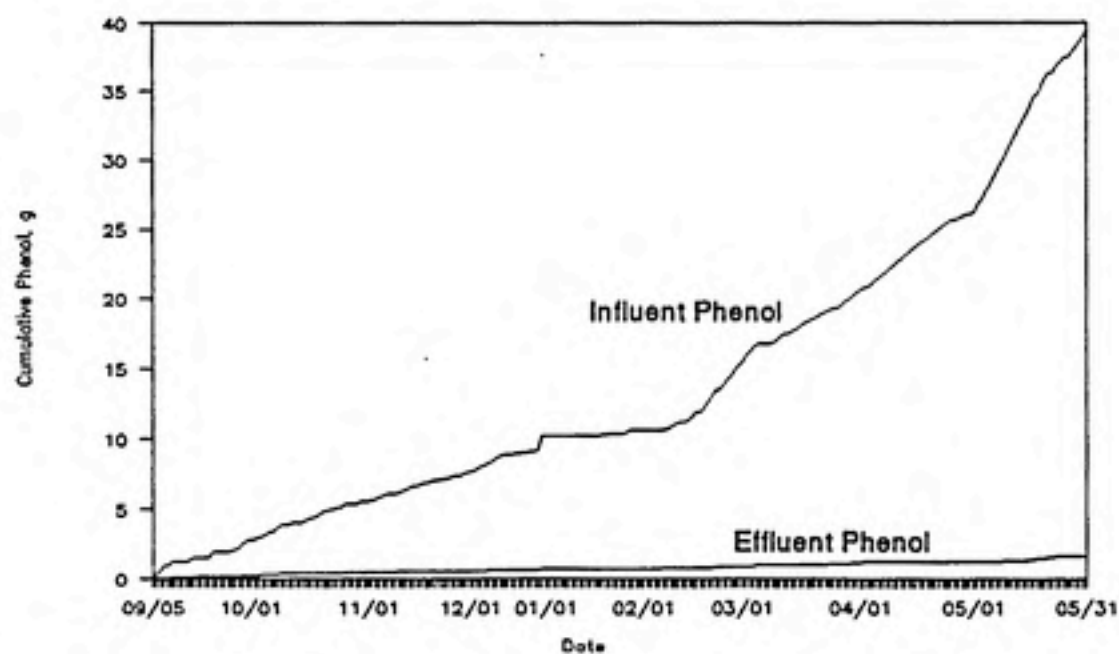
· Figure 11: Cumulative Influent and Effluent Phenol, Reactor I. Raw waste was fed from 9/5/89 through 2/6/90. Synthetic feed was fed for the remainder of the project.

associated with this wasting rate would have been 4,675 mg/l. If the COD of solids (either cell mass or precipitated nitrosophenol) is assumed to be 2.0 g COD/g solid, the effluent total suspended solids or accumulated MLSS in the reactor would have been 2,337 mg/l of feed treated. Since effluent solids were centrifuged and recycled to the reactor most of the time (176 days out of 268), and no increase of MLSS of this magnitude was noted in the reactor, a large part of the soluble non-phenol COD was mineralized during reactor operation.

Performance of Reactor I During Different Stages of Operation

Table 10 shows the percent phenol removed and average volumetric phenol removal rate for the reactor during the four distinct periods of operation that were described in the Experimental Methods section. Table 11 shows the percent soluble COD removed and average volumetric soluble COD removal rate for these periods.

As can be seen from the tables, overall removal of phenol was excellent, ranging from 93 to 97.5% removal. Reactor I had the lowest average volumetric phenol removal rate and percent phenol removed when feeding raw waste over one cycle per day. It also had the lowest average volumetric soluble COD removal rate, but had the best

Table 10: Percent Phenol Removed and Average Phenol Removal
Rate, Reactor I. (Average reactor volume = 2.5 l.)

Feed	Cycles Per Day	# of Days	Volume Fed (l)	Phenol Fed (g)	Phenol Removed (g)	Average Volumetric Phenol Removal Rate (g/d*m^3)	Percent Phenol Removed	Average Loading Rate (g COD/ g SS*d)
Raw Waste	1	154	12.31	10.63	9.90	25.6	93.1	0.286
Synthetic	1	48	7.75	8.65	8.31	69.2	96.1	0.197
Synthetic	2	36	6.33	6.92	6.75	75.2	97.5	0.417
Synthetic	3	30	10.44	13.32	12.92	172.4	97.0	0.195

Table 11: Percent Soluble COD Removed and Average Soluble COD Removal
Rate, Reactor I. (Average reactor volume = 2.5 l.)

Feed	Cycles Per Day	Number of Days	Volume Fed (l)	Soluble COD Fed (g)	Soluble COD Removed (g)	Average Volumetric Soluble COD Removal Rate (g/d*m^3)	Percent COD Removed	Average Loading Rate (g COD/ g SS*d)
Raw Waste	1	154	12.31	76.74	63.04	163.6	82.1	0.286
Synthetic	1	48	7.75	35.40	28.89	240.8	81.6	0.197
Synthetic	2	36	6.33	37.13	29.30	325.6	78.9	0.417
Synthetic	3	30	10.44	67.98	51.71	689.6	76.1	0.195

percent COD removed during this regimen. The best
percentage of phenol removed occurred when feeding
synthetic waste over 2 cycles per day. The best average
volumetric phenol and soluble COD removal rates occurred
when feeding synthetic feed over three cycles per day.
However, the solids from Reactor II were placed in Reactor
I at the beginning of the 3 cycle per day period,
increasing the MLSS from 2400 mg/l to 8500 mg/l. The
enhanced performance during this period is due to a higher
reactor MLSS (as can be seen by comparing the average
loading rates in Tables 10 and 11 for 2 and 3 cycles per
day).

Performance of the reactor was also analyzed using
cumulative phenol and COD removal while feeding synthetic
feed over 1, 2, and 3 cycles per day. These cumulative
values are shown in Figure 12 for phenol and Figure 13 for
COD. It is clear from these figures that substantially
more waste could be treated at 3 cycles per day than at 1
or 2 cycles per day. Again, however, this increase in
removal is largely due to the higher mixed liquor solids
concentrations employed while operating at 3 cycles per
day. Good correlations from linear regressions of the
cumulative removal data (as shown in Tables 12 and 13)
indicate relatively consistent performance of the reactor
(in terms of removal), even though effluent concentrations
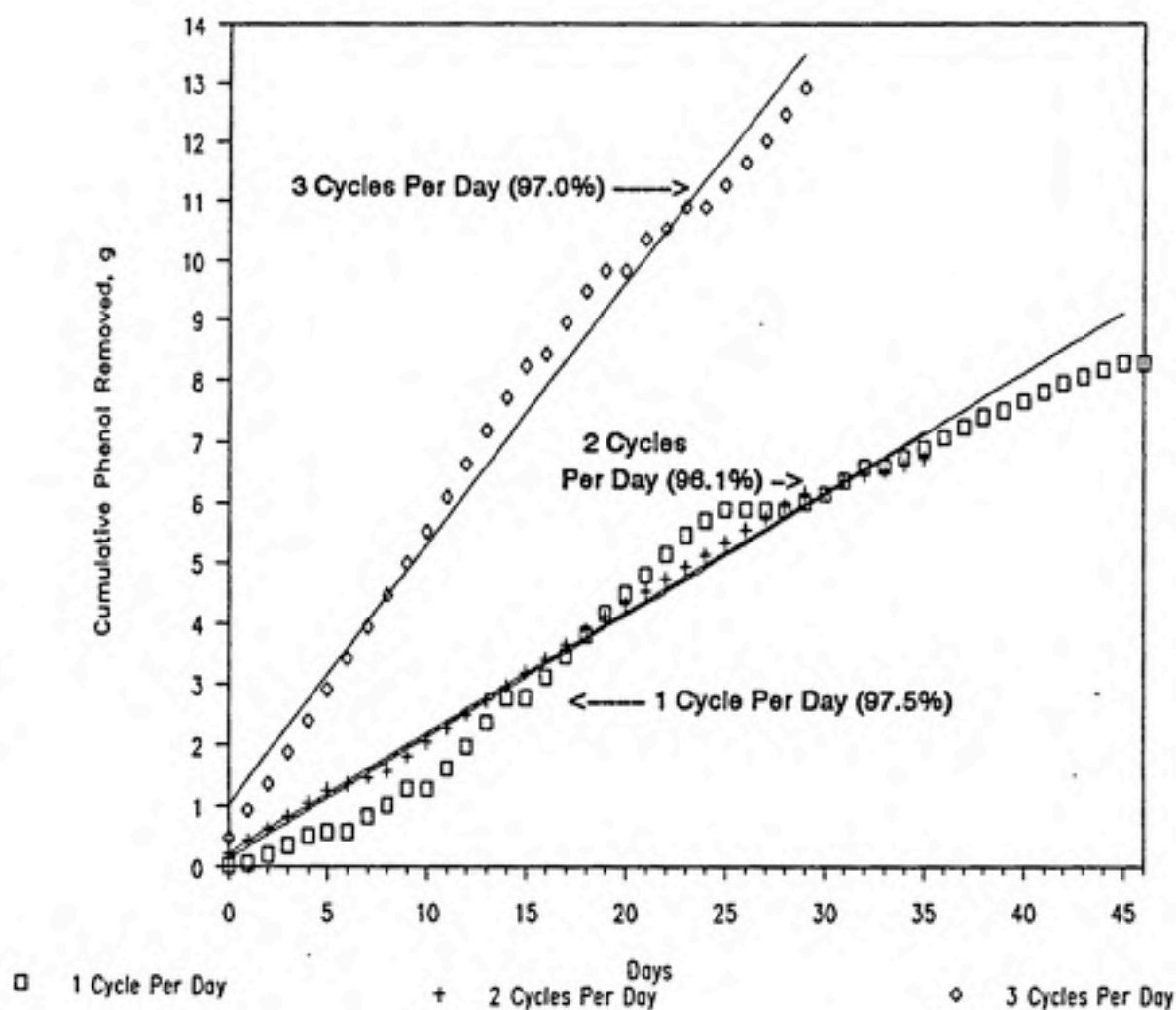
Figure 12: Cumulative Phenol Removed Feeding Reactor I Synthetic
Feed. Average removal efficiency for each cycle shown in parentheses.

Table 13: Results of Linear Regressions of Cumulative Soluble COD
Removed for Reactor I, Feeding Synthetic Feed.

Cycles Per Day	Slope (mg/d)	r^2
1	201	0.9726
2	199	0.9948
3	431	0.9845
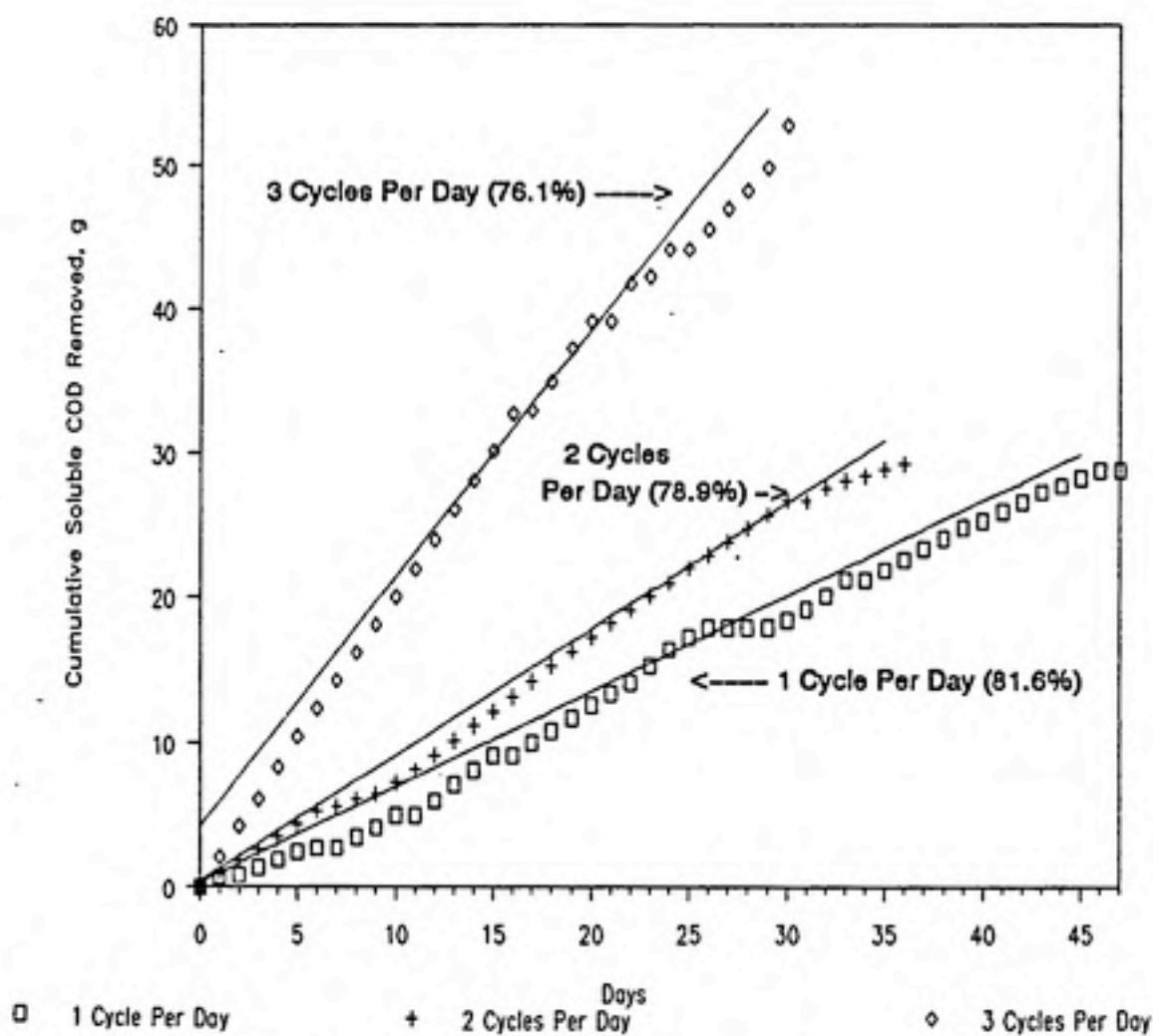
Figure 13: Cumulative Soluble COD Removed Feeding Reactor I Synthetic Feed. Average removal efficiency for each cycle shown in parentheses.

Table 13: Results of Linear Regressions of Cumulative Soluble COD Removed for Reactor I, Feeding Synthetic Feed.

Cycles Per Day	Slope (mg/d)	r^2
1	659	0.9940
2	872	0.9946
3	1718	0.9902

varied considerably from day to day.

Effluent Quality of Reactor I

One observation made during reactor operation was that effluent quality generally deteriorated whenever an attempt was made to increase loading rates. As a result, several methods of analyzing effluent data as a function of loading rate and reactor operating conditions were evaluated.

1. Feeding Raw Waste:

a. Effluent Phenol Concentrations: Figure 14 shows the average effluent phenol concentration plotted as a function of loading rate percentile ranges. The actual range of loading rates for each percentile range is provided in Table 14. Figure 14 clearly indicates that effluent quality generally decreased at increasing loading rates.

b. Effluent Soluble COD Concentrations: Table 15 and Figure 15 summarize the data for effluent soluble COD concentrations in a similar fashion. There was very little difference (350 mg/l or approximately 25%) in effluent COD quality over the entire loading rate range.

c. Data Distribution of Effluent Phenol

Table 14: Effluent Phenol versus Loading Rate, Reactor I, Raw Waste. Data for 74 days arranged by five percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.06–0.14	27.0
21 – 40	0.15–0.21	38.0
41 – 60	0.21–0.27	54.0
61 – 80	0.28–0.95	69.0
81 – 100	0.95–4.28	83.1

Fig. 14: Effluent Phenol Versus
Loading Rate, Reactor I, Raw Waste
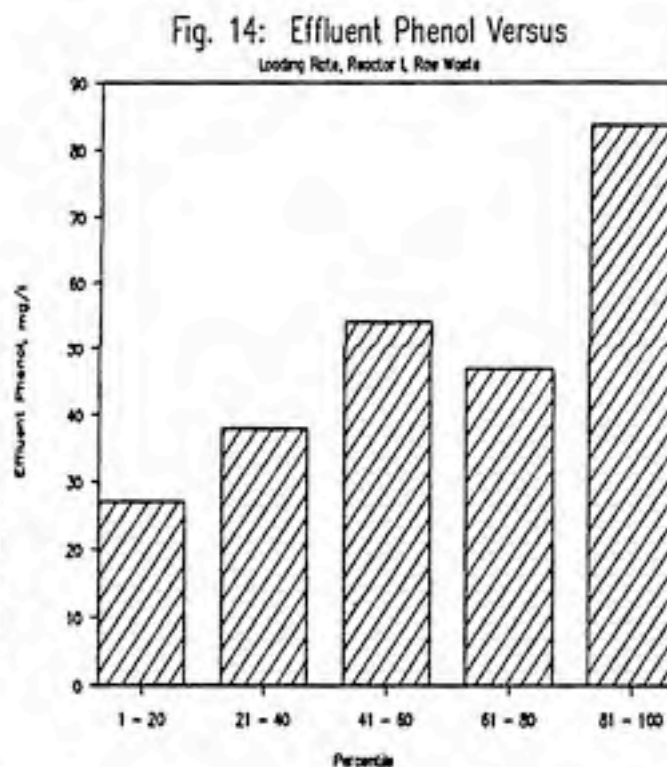
Table 15: Effluent Soluble COD versus Loading Rate, Reactor I, Raw Waste. Data for 25 days arranged by five percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent COD (mg/l)
1 – 20	0.10–0.17	1045
21 – 40	0.20–0.28	1102
41 – 60	0.29–0.51	1297
61 – 80	0.92–1.50	1397
81 – 100	1.53–2.19	1248

Fig. 15: Effluent COD Versus
Loading Rate, Reactor I, Raw Waste

Loading Rate, g COD/g SS*d
One Cycle Per Day
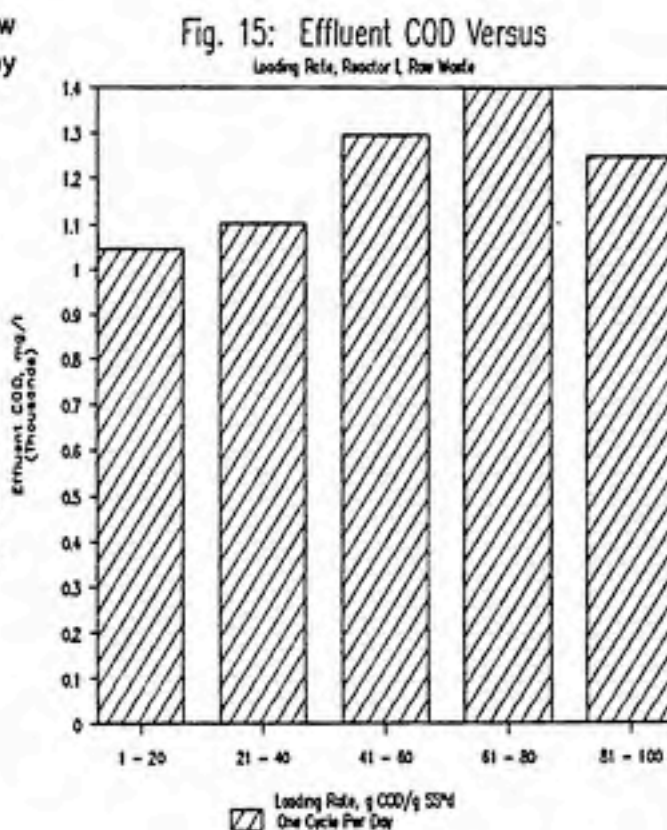
Concentrations: In Table 16, the data distribution for effluent phenol is shown for various concentration intervals. When raw waste was fed, the effluent phenol was never 10 mg/l or less (the target effluent concentration specified by Sandoz). However, the concentration was less than 50 mg/l almost 70% of the time.

2. Feeding Synthetic Feed:

a. Effluent Phenol Concentration: Figures 16, 17, and 18 show the average effluent phenol concentration as a function of loading rate percentile range for reactor operation at 1, 2, and 3 cycles per day respectively. Tables 17, 18, 19 show the loading rate range values. Except for the lowest loading rate range, the effluent phenol concentration tended to increase at increasing loading rates for two and three cycle per day operation. Results for the lowest loading rate range are anomalous because loading usually was decreased to low levels whenever effluent phenol concentrations began to increase. High effluent phenol concentrations typically remained, even at reduced loadings, for one or two days before returning to low levels. From Table 18 it is apparent that effluent quality for 2 cycle/day operation was consistently better at loading rates below 0.4 g COD/g SS-d.

Table 16: Data Distribution of
Effluent Phenol Concentrations,
Reactor I, Raw Waste.

Effluent Phenol Conc. (mg/l)	Number of Days When Less Than	Percent of Days When Less Than
10	0	0
20	14	18.9
30	14	37.8
40	10	51.3
50	13	68.9
75	3	73
100	12	89.2
>100	8	100

Table 17: Effluent Phenol versus Loading Rate, Reactor I, Synthetic Waste One Cycle Per Day. Data for 39 days arranged by five percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.04–0.18	72.0
21 – 40	0.18–0.21	27.0
41 – 60	0.21–0.24	35.0
61 – 80	0.26–0.32	41.0
81 – 100	0.33–0.40	32.0

Fig. 16: Effluent Phenol Versus
Loading Rate, Reactor I, Synth. Feed

Table 18: Effluent Phenol versus Loading Rate, Reactor I, Synthetic Feed, Two Cycles Per Day. Data for 34 days arranged by five percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.14–0.39	19
21 – 40	0.39–0.46	2
41 – 60	0.47	57
61 – 80	0.47–0.51	22
81 – 100	0.51–0.55	29

Fig. 17: Effluent Phenol Versus
Loading Rate, Reactor I, Synth. Feed

Table 19: Effluent Phenol
versus Loading Rate,
Reactor I, Synthetic Feed,
Three Cycles Per Day. Data
for 43 days arranged by five
percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.08–0.16	19
21 – 40	0.17–0.18	62
41 – 60	0.18–0.19	31
61 – 80	0.19–0.26	56
81 – 100	0.26–0.29	29

Fig. 18: Effluent Phenol Versus
Loading Rate, Reactor I, Synth. Feed
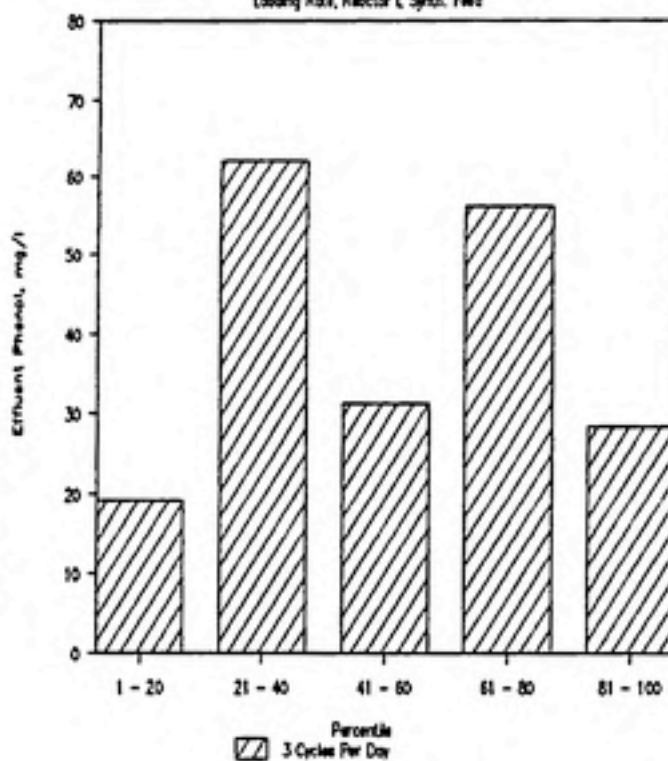
b.   Effluent Soluble COD Concentrations:
Figures 19 and 20 show average effluent COD concentrations
as a function of loading rate range for one and two cycles
per day.   Six COD measurements were collected during three
cycle per day operation and averaged 1620 mg/l (std. dev. =
240 mg/l).   There is no clear trend in effluent COD as a
function of loading rate for one cycle per day.   Effluent
COD appears to increase slightly as loading rate increases
for two cycles per day.

c.   Data Distribution of Effluent Phenol
Concentrations: Table 22 shows the results of a data
distribution performed on effluent phenol concentration.
Using the 10 mg/l effluent phenol goal, it can be seen that
when operating Reactor I at 2 cycles per day, the effluent
was less than 10 mg/l 68% of the time.   In addition,
concentrations of phenol were less than 50 mg/l 82% of the
time.

Removal of Phenol and Soluble COD

Removal of phenol and soluble COD were evaluated by
determining the specific removal rates and the percent
removals.   The specific removal rate was defined as the
mass of phenol or COD removed over a given 24 hour period
divided by the product of the mass of suspended solids in

Table 20: Effluent Soluble COD versus Loading Rate, Reactor I, Synthetic Feed, One Cycle Per Day. Data for 34 days arranged by five percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent COD (mg/l)
1 – 20	0.06–0.18	930
21 – 40	0.18–0.21	863
41 – 60	0.23–0.27	682
61 – 80	0.29–0.33	917
81 – 100	0.33–0.40	946

Fig. 19: Effluent COD Versus
Loading Rate, Reactor I, Synth. Feed

Table 21: Effluent Soluble COD versus Loading Rate, Reactor I, Synthetic Feed, Two Cycles Per Day. Data for 17 days arranged by five percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent COD (mg/l)
1 – 20	0.14–0.19	1246
21 – 40	0.21–0.45	1363
41 – 60	0.47	1401
61 – 80	0.47	1291
81 – 100	0.50–0.55	1707

Fig. 20: Effluent COD Versus
Loading Rate, Reactor I, Synth. Feed
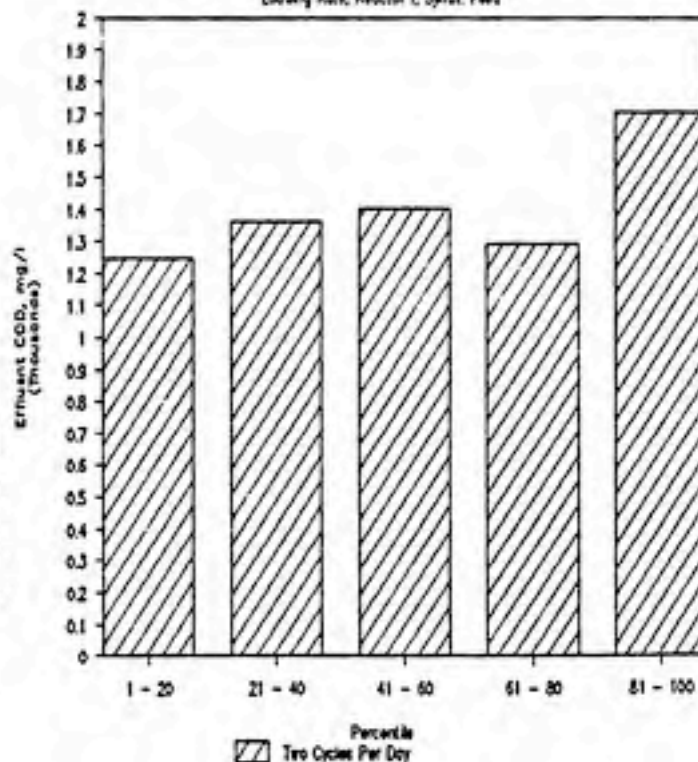
Table 22: Data Distribution of Effluent Phenol Concentrations, Reactor I, Synthetic Waste.

Effluent Phenol Conc. (mg/l)	1 Cycle Per Day		2 Cycles Per Day		3 Cycles Per Day	
	Number of Days When Less Than	Percent of Days When Less Than	Number of Days When Less Than	Percent of Days When Less Than	Number of Days When Less Than	Percent of Days When Less Than
10	15	38.5	23	67.6	12	28.6
20	8	59	3	76.5	8	47.6
30	0	59	0	76.5	3	54.8
40	2	64.1	1	79.4	5	66.7
50	3	71.8	1	82.4	0	66.7
75	3	79.5	0	82.4	5	78.6
100	2	84.6	2	88.2	2	83.3
>100	6	100	4	100	7	100

the reactor and the total React time over that 24 hour period (g phenol/g SS-d). The amount of phenol removed was defined as follows:

(mass of phenol fed + phenol in reactor at time of Fill)
  - (mass of phenol in reactor after React).

The amount of COD removed was determined analogously. Percent removal was defined as the amount of phenol or COD removed divided by the amount of phenol or COD fed. For a batch reactor, percent removal can exceed 100% if a substantial amount of residual substrate remained at the end of the previous cycle. For COD, only those days in which COD was measured are reported.

    1. Specific Removal Rate versus Loading Rate:

        a. Feeding Raw Waste: Figures 21 and 22 show the specific phenol and COD removal rates as functions of the loading rates. The 100% removal line is shown as the diagonal on these figures. The specific phenol removal rate tends to deviate substantially from the 100% removal line as the loading rate increases to above 0.10 g phenol/g SS-d. The small amount of data on specific removal of COD does not show any clear trends.

        b. Synthetic Feed: Figure 23 shows the

Figure 21: Specific Phenol Removal Rate versus Loading Rate, Reactor I, Feeding Raw Waste.

Figure 22: Specific Soluble COD Removal Rate versus Loading Rate, Reactor I Feeding Raw Waste

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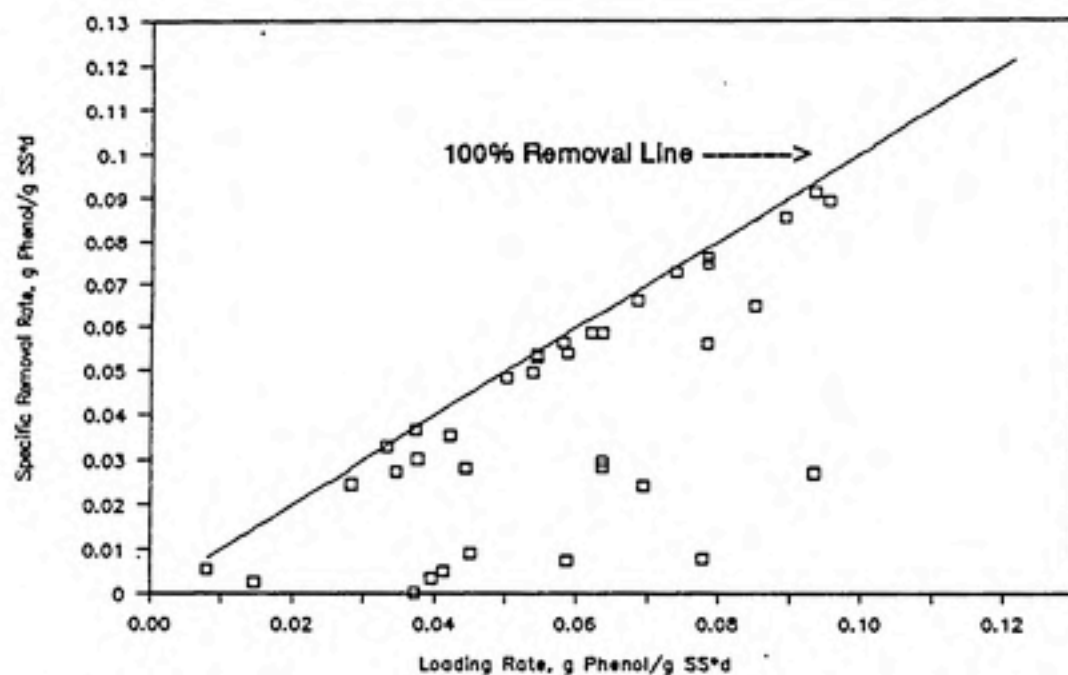
Figure 23: Specific Phenol Removal Rate versus Loading Rate, Reactor I, Synthetic Feed, One Cycle Per Day.
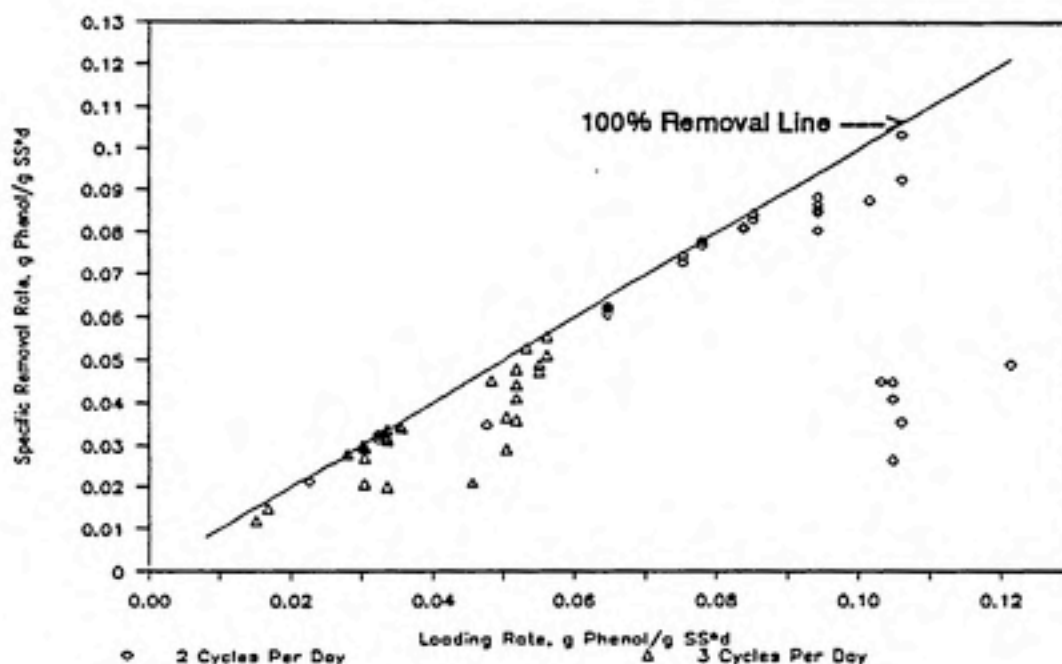
Figure 24: Specific Phenol Removal Rate versus Loading Rate, Reactor I, Synthetic Feed, Two and Three Cycles Per Day.

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specific phenol removal rates when operating 1 cycle per day.. Although good removal was observed at loading rates as high as 0.1 g phenol/g SS-d, there is clear inconsistency in removal at all loading rates. In Figure 24, the specific phenol removal line is shown for 2 and 3 cycles per day. The loading rates were higher for 2 cycles per day and good removal was achieved most of the time. Inconsistent removal occurred for 2 cycles per day at loading rates higher than 0.1 g/g-d. The loading rate for 3 cycles per day was much lower (again, due to higher MLSS) and there were also occasions during this operating period when poor phenol removal occurred. Overall, removal rates were more consistent, particularly at loading rates less than 0.1 g/g-d, for 2 and 3 cycle per day operation than at 1 cycle per day.

Figure 25 shows the specific soluble COD removal rates observed over 1, 2, and 3 cycles per day. Except for 1 cycle per day operation, the range of loading rates was too small to draw conclusions regarding the effects of loading rate on COD removal. Again, good COD removal was achieved for 1 cycle per day up to a loading rate of 0.4 g/g-d, but removal was inconsistent over the entire range.

2. Percent Phenol and Soluble COD Removed:

a: Raw Waste: Figures 26 and 27 show the
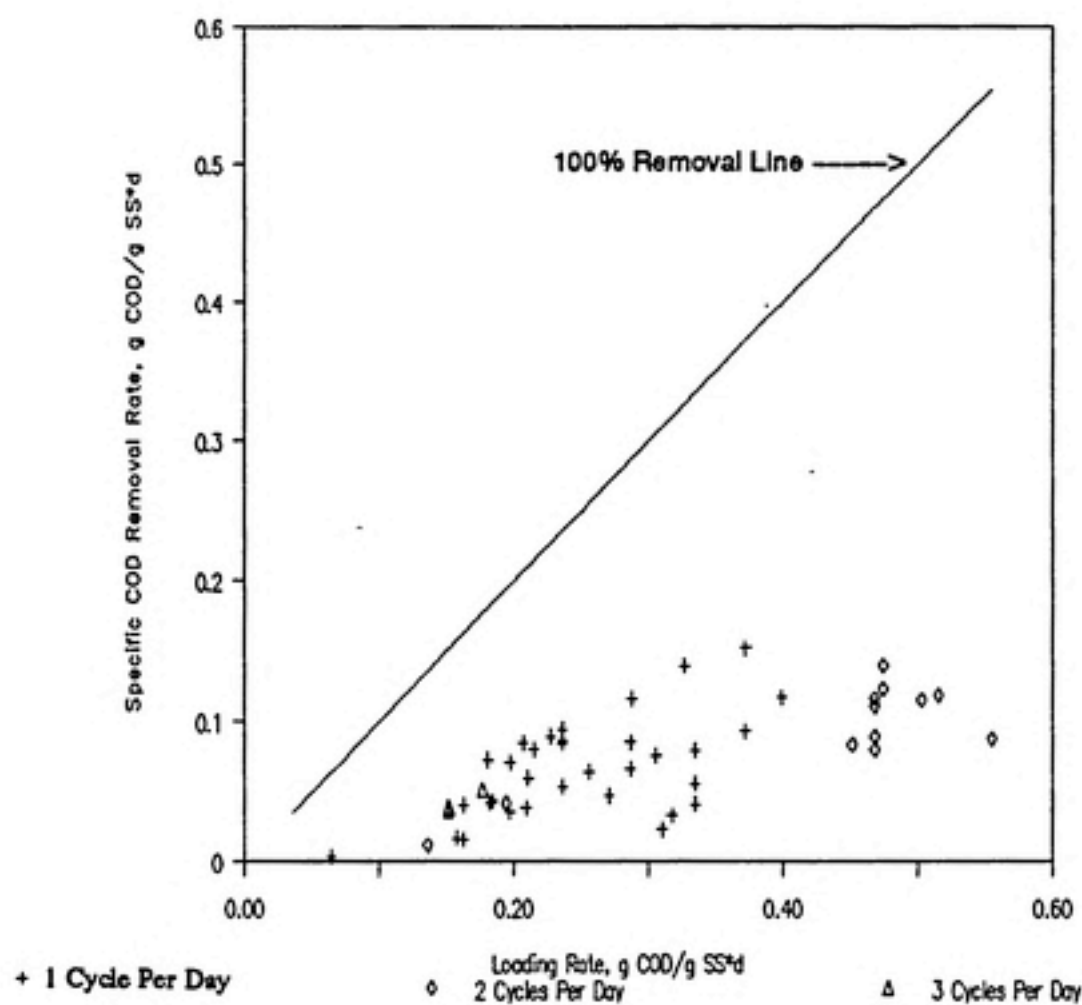
Figure 25: Specific Soluble COD Removal Rate versus Loading Rate, Reactor I
Synthetic Feed One, Two, and Three Cycles Per Day.
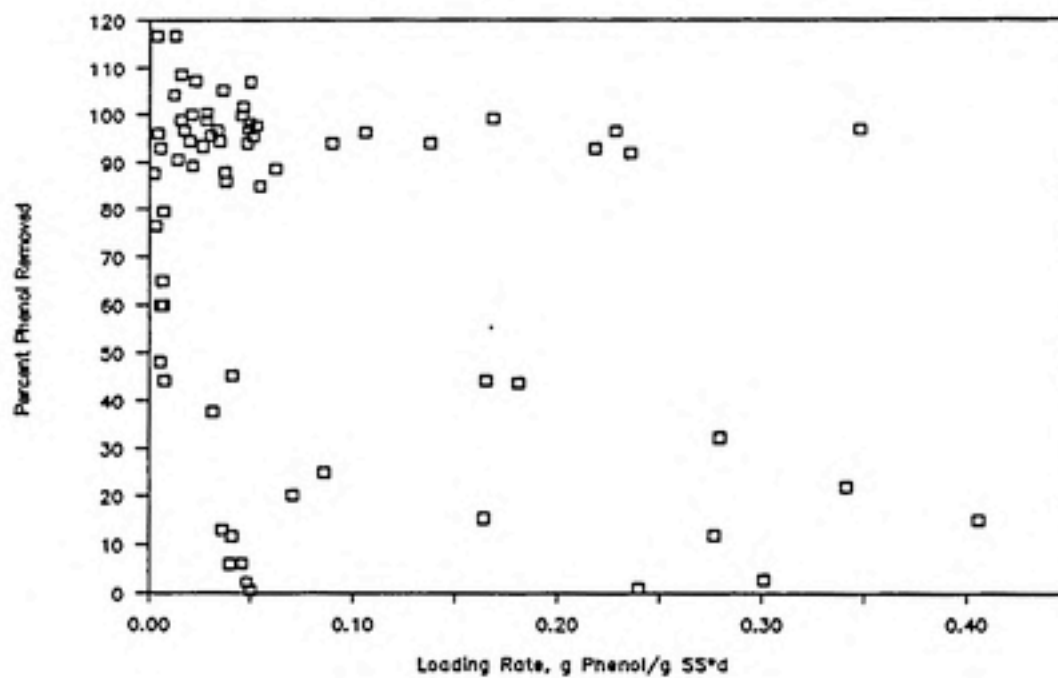
Figure 26: Percent Phenol Removed versus Loading Rate, Reactor I, Feeding Raw Waste.
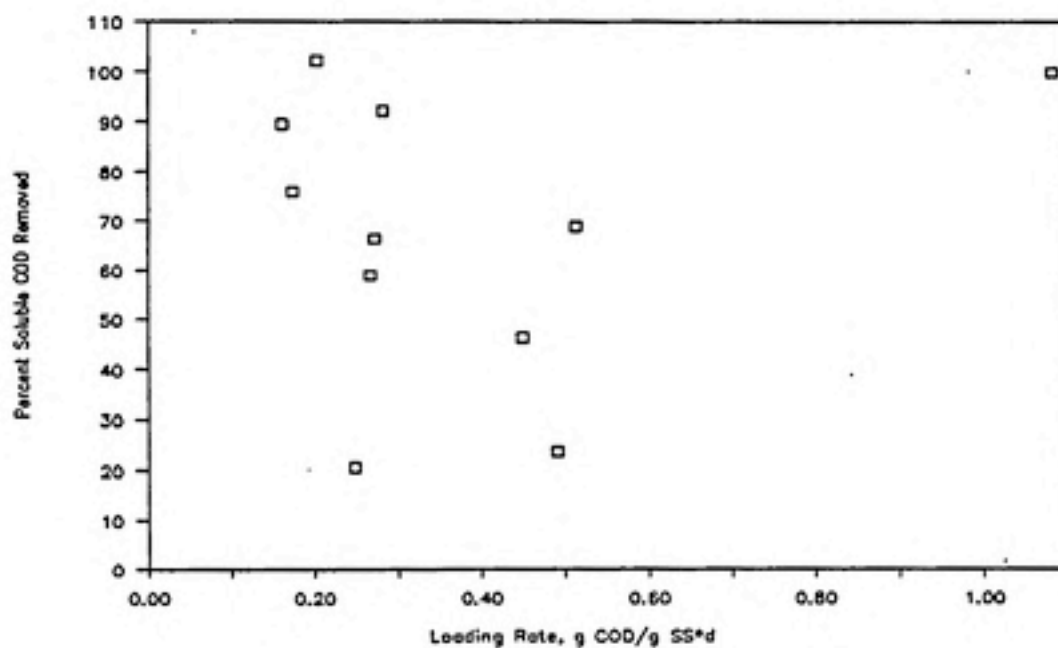
Figure 27: Percent Soluble COD Removed versus Loading Rate, Reactor I, Feeding Raw Waste.

percent phenol and COD removed when the reactor was fed raw waste. The removal of phenol is generally good at low loading rates, but above loading rates of 0.05 g/g-d, highly inconsistent performance was observed. The data contained in Figure 27 show no clear trends in percent soluble COD removed as a function of loading rate.

b. Synthetic Feed: Figure 28 shows the percent phenol removed for one cycle per day operation. Percentages removed of greater than 200% were achieved at loading rates less than 0.04 g phenol/g SS-d, when low loading rates were employed to bring the concentration down from uncacceptably high values. As can be seen from the figure, inconsistency is observed at 1 cycle per day. The percent of phenol removed for 2 and 3 cycles per day is plotted in Figure 29 as a function of loading rate. As stated above, performance generally was more consistent than for 1 cycle per day, but became inconsistent at phenol loading rates greater than 0.1 g/g-d. Figure 30 shows the percent soluble COD removed for all cycles. No clear trends can be gathered from this figure due to the scatter of the data and the lack of data for 2 and 3 cycles per day.
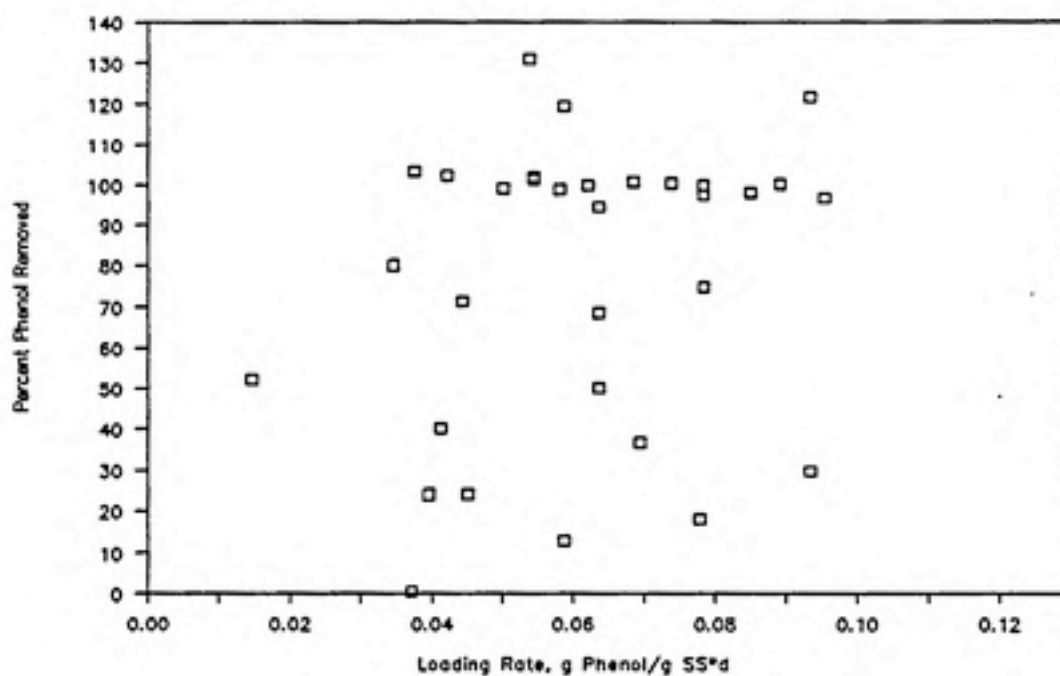
Figure 28: Percent Phenol Removed versus Loading Rate, Reactor I, Synthetic Feed, One Cycle Per Day.
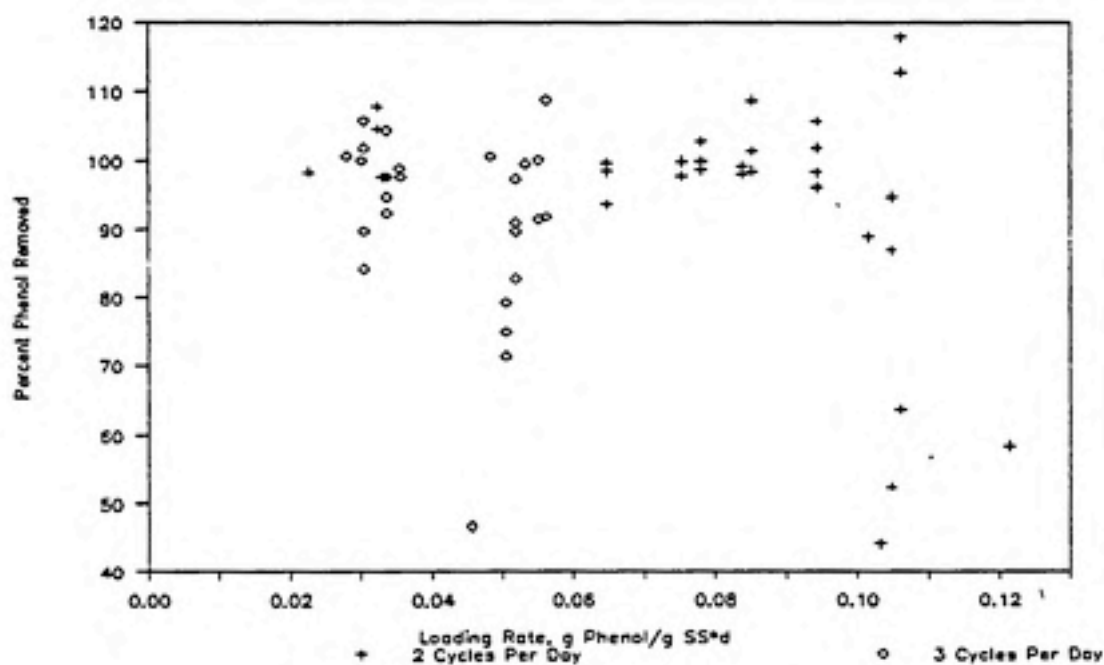
Figure 29: Percent Phenol Removal versus Loading Rate, Reactor I, Synthetic Feed, Two and Three Cycles Per Day.
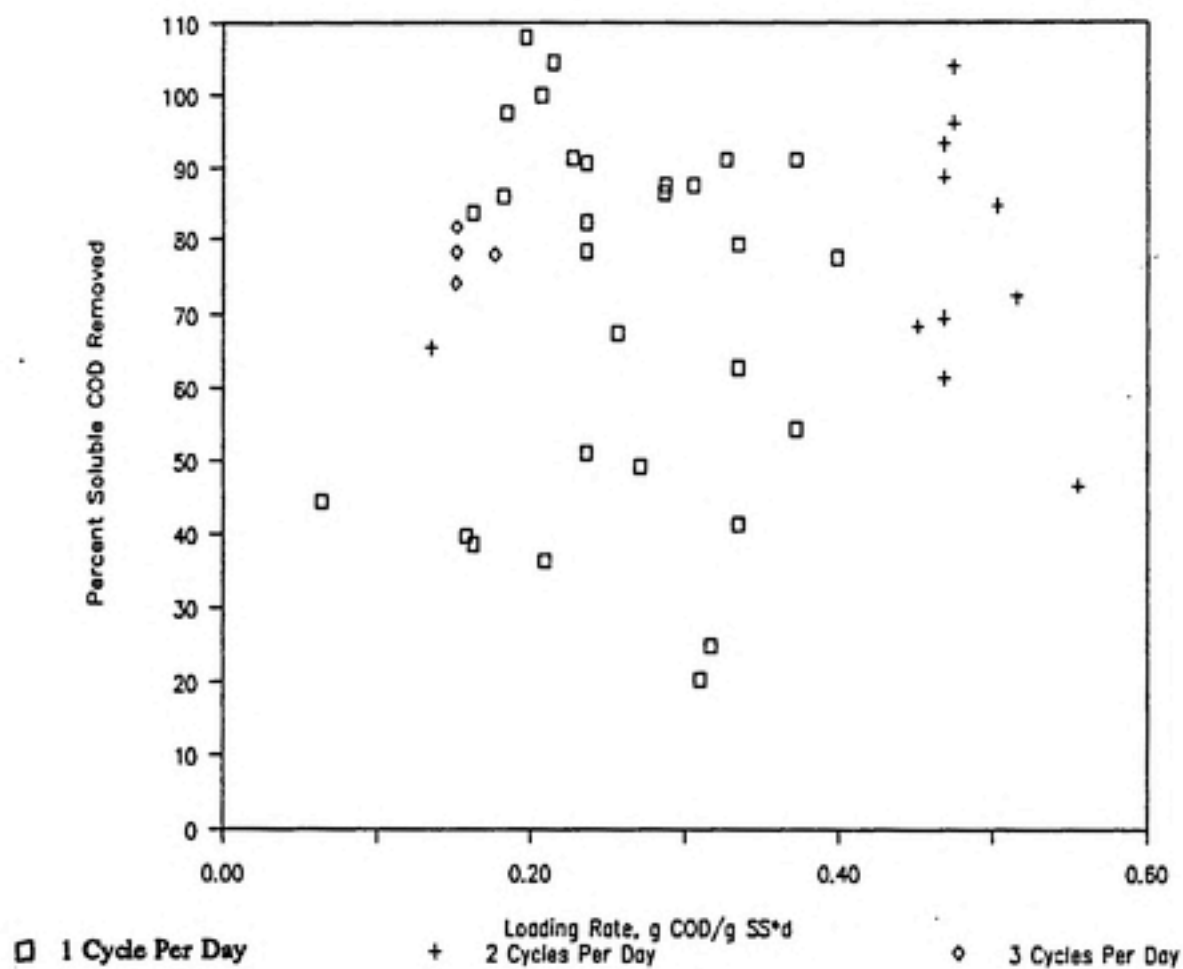
Figure 30: Percent Soluble COD Removed versus Loading Rate, Reactor I, Synthetic Feed, One, Two, and Three Cycles Per Day.

Overall Performance of Reactor II

Reactor II operated from 17 November 1989 to 1 May 1990. During this 165 day period, the reactor was fed 7.5 l of raw waste and 23.3 l of synthetic feed. This gives an average daily feeding volume of 190 ml. In addition, during the initial startup of the reactor, a total of 28.56 g of supplemental phenol was added to the reactor during the initial six weeks of reactor operation. This supplemental phenol was added because the raw waste fed during this time had a low concentration of phenol (245 mg/l). Additional supplemental phenol resulted in very high loading rates applied to the reactor and excellent performance. However, at the end of December the performance of the reactor deteriorated and phenol supplementation was stopped.

Figures 31 and 32 depict the cumulative influent and effluent phenol and soluble COD. The total soluble COD fed during this period was 247.5 g, and the total phenol fed was 58.7 g. The total soluble COD wasted was 39.5 g, which gives an overall removal of 84.1%. The daily average removal rate of soluble COD was 1,260 mg/d. The total phenol wasted was 1.25 g, or a removal of 97.9%. The average daily removal rate of phenol was 348 mg/d.

A calculation of the amount of solids that would need
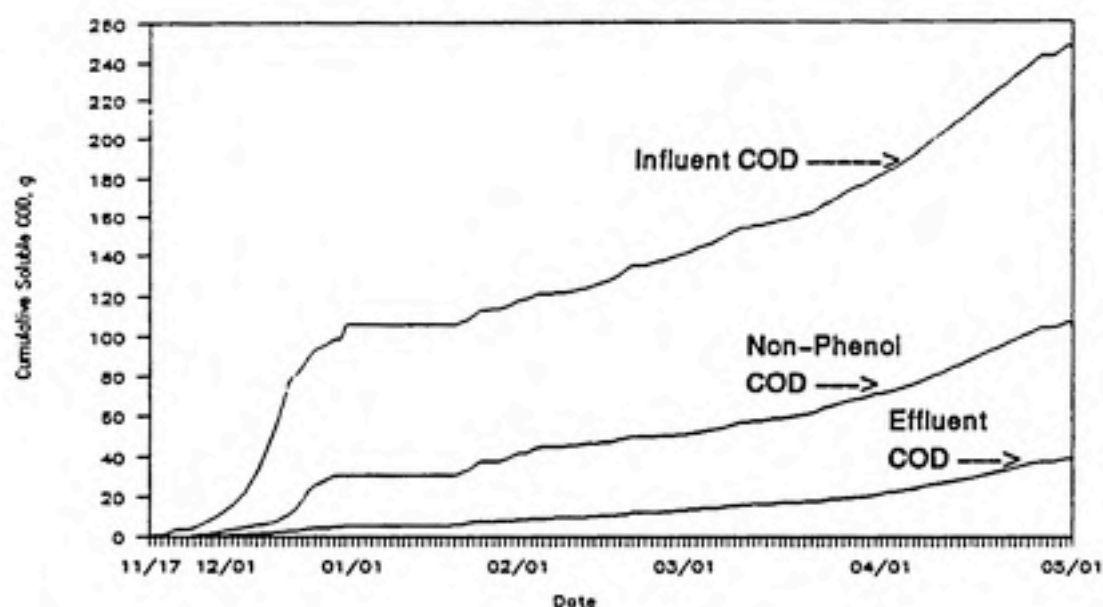
Figure 31: Cumulative Influent and Effluent Soluble COD, Reactor II. Raw Waste was fed from 11/17/89 through 2/9/90. Synthetic Feed was fed for the remainder of the project.
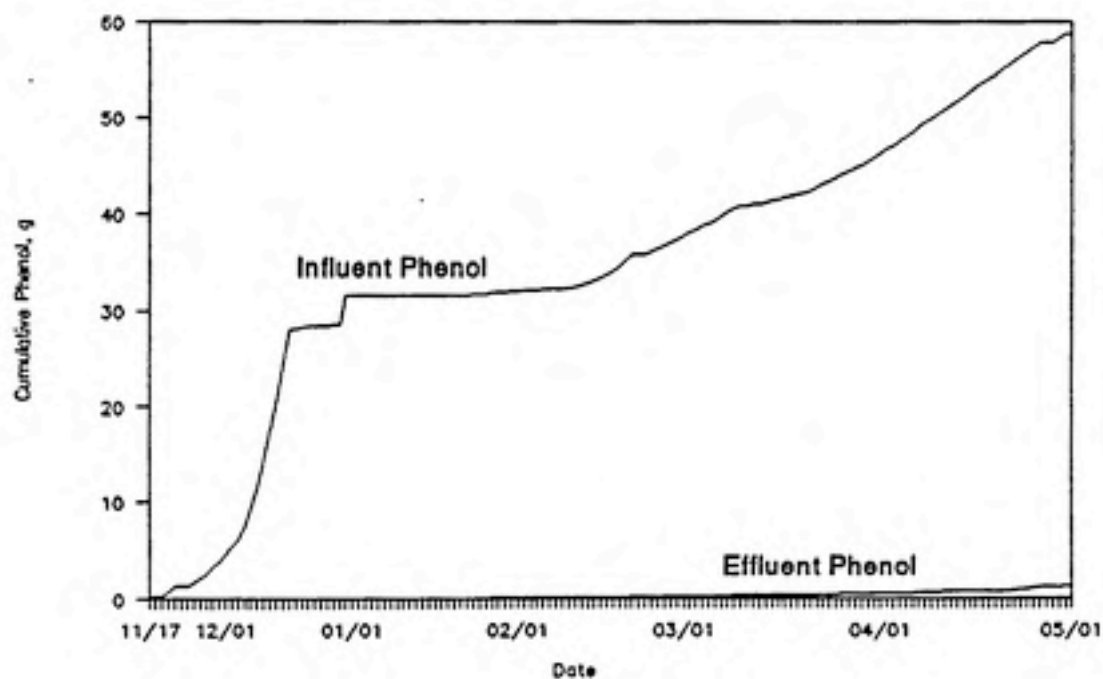
Figure 32: Cumulative Influent and Effluent Phenol, Reactor II. Raw waste was fed from 11/17/89 through 2/9/90. Synthetic feed was fed for the remainder of the project.

to be generated to account for the COD lost due to mechanisms such as precipitation or accumulation shows that for Reactor II, 6,635 mg of COD per liter of feed would be in the form of suspended solids. Assuming a biomass COD of 2.0 g COD/g solids, this would be over 3,300 mg of solids generated per liter of feed treated. These solids would have either accumulated in the reactor or been wasted as effluent solids if no biodegradation occurred. As was the case for Reactor I, effluent solids in Reactor II were returned to the reactor during most of the study (127 days out of 165) and no increase in MLSS of this magnitude was noted in Reactor II.

Performance of Reactor II During Different Stages of Operation

Table 23 shows the percent and average phenol removed from Reactor II over the three distinct periods of reactor operation. The best average volumetric phenol removal rate and percent phenol removed occurred feeding raw waste over one cycle per day. This is due to the fact that during the initial startup of Reactor II, a fresh culture from the Sandoz activated sludge system that was highly acclimated to phenol was used and was fed a substantial amount of phenol.

Table 23: Percent Phenol Removed and Average Phenol Removal
Rate, Reactor II. (Average reactor volume = 2.5 l)

Feed	Cycles Per Day	Number of Days	Volume Fed (l)	Phenol Fed (g)	Phenol Removed (g)	Average Volumetric Phenol Removal Rate (g/d*m^3)	Percent Phenol Removed	Average Loading Rate (g COD/ g SS*d)
Raw Waste	1	84	7.5	32.19	32.07	153.2	99.6	0.192
Synthetic	1	39	8.75	10.01	9.74	100	97.3	0.111
Synthetic	2	42	14.53	16.53	15.67	149.2	94.8	0.525

Table 24: Percent Soluble COD Removed and Average Soluble COD Removal
Rate, Reactor II. (Average reactor volume = 2.5 l.)

Feed	Cycles Per Day	Number of Days	Volume Fed (l)	Soluble COD Fed (g)	Soluble COD Removed (g)	Average Volumetric Soluble COD Removal Rate (g/d*m^3)	Percent COD Removed	Average Loading Rate (g COD/ g SS*d)
Raw Waste	1	84	7.50	122.11	112.49	535.6	92.1	0.192
Synthetic	1	39	8.75	39.92	31.90	327.2	79.9	0.111
Synthetic	2	42	14.53	85.45	63.64	606	74.5	0.525

Table 24 shows the percent soluble COD removed and average volumetric soluble COD removal rate for the three periods. The best percentage of COD removed occurred when the reactor was fed raw waste. The highest average volumetric soluble COD removal rate occurred when feeding synthetic feed twice a day.

Plots of cumulative phenol and soluble COD removed versus loading rate were also made for the period when synthetic feed was fed. These plots are shown in Figures 33 (phenol) and 34 (COD). Linear regressions of these lines were performed to assess the magnitude of the slopes, and results are shown in Tables 25 and 26. Again, good linear correlation indicates consistent performance of the reactor under these operating conditions. As Figure 33 shows, a better cumulative rate of phenol removal was achieved when the reactor was fed twice a day. As shown in Table 24, higher average loading rates were sustained during 2 cycle per day operation. The slope of the two cycles per day line is 50% greater than the slope for one cycle per day. The slope of the soluble COD removal line is almost twice as large for the two cycles per day line as for the one cycle per day. This, together with the fact that loading rates were substantially higher at two cycles per day, illustrates that reactor performance was improved by shifting operation from one to two cycles per day.
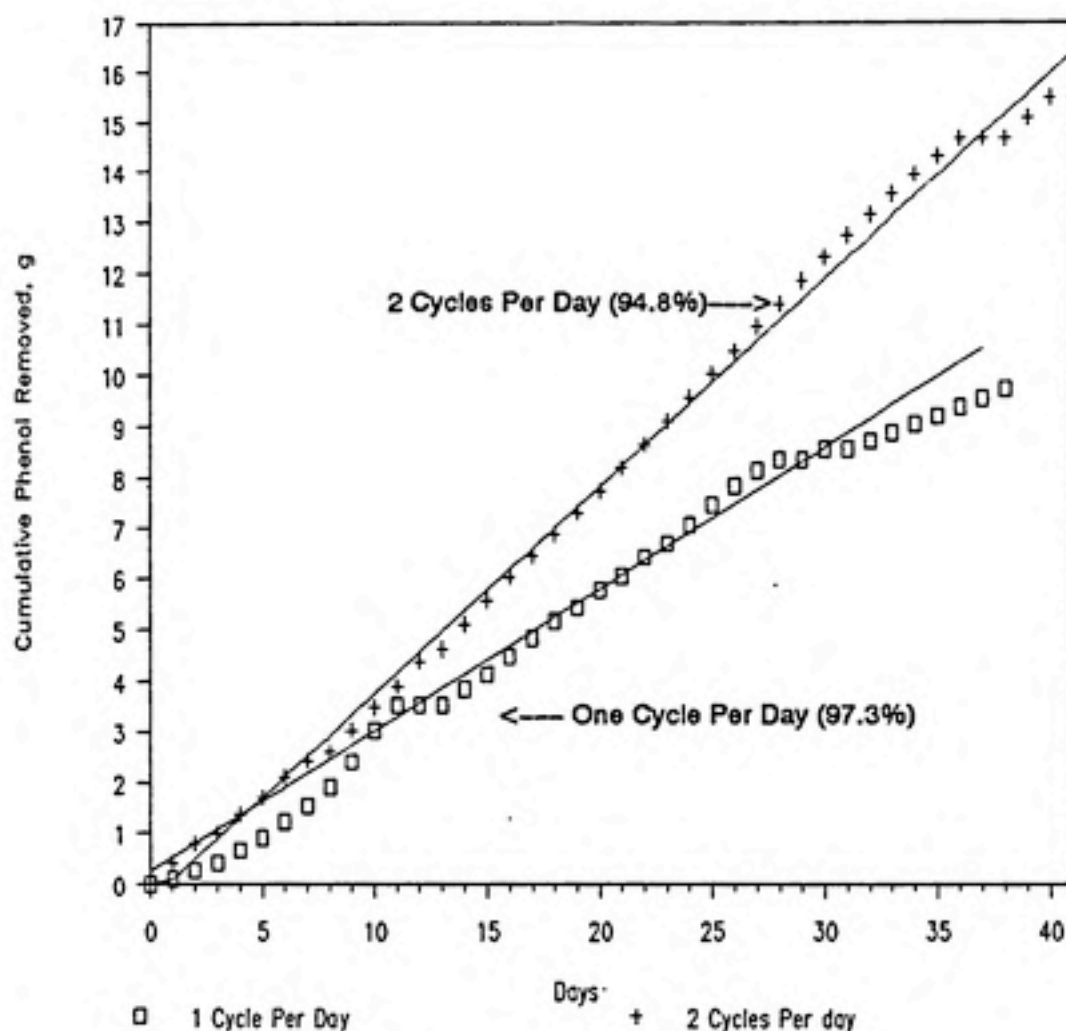
Figure 33: Cumulative Phenol Removed Feeding Reactor II Synthetic Feed.
Average removal efficiency for each cycle shown in parentheses.

Table 25: Results of Linear Regressions of Cumulative Phenol Removed
for Reactor II, Feeding Synthetic Feed.

Cycles Per Day	Slope (mg/d)	r^2
1	279	0.9853
2	407	0.9960
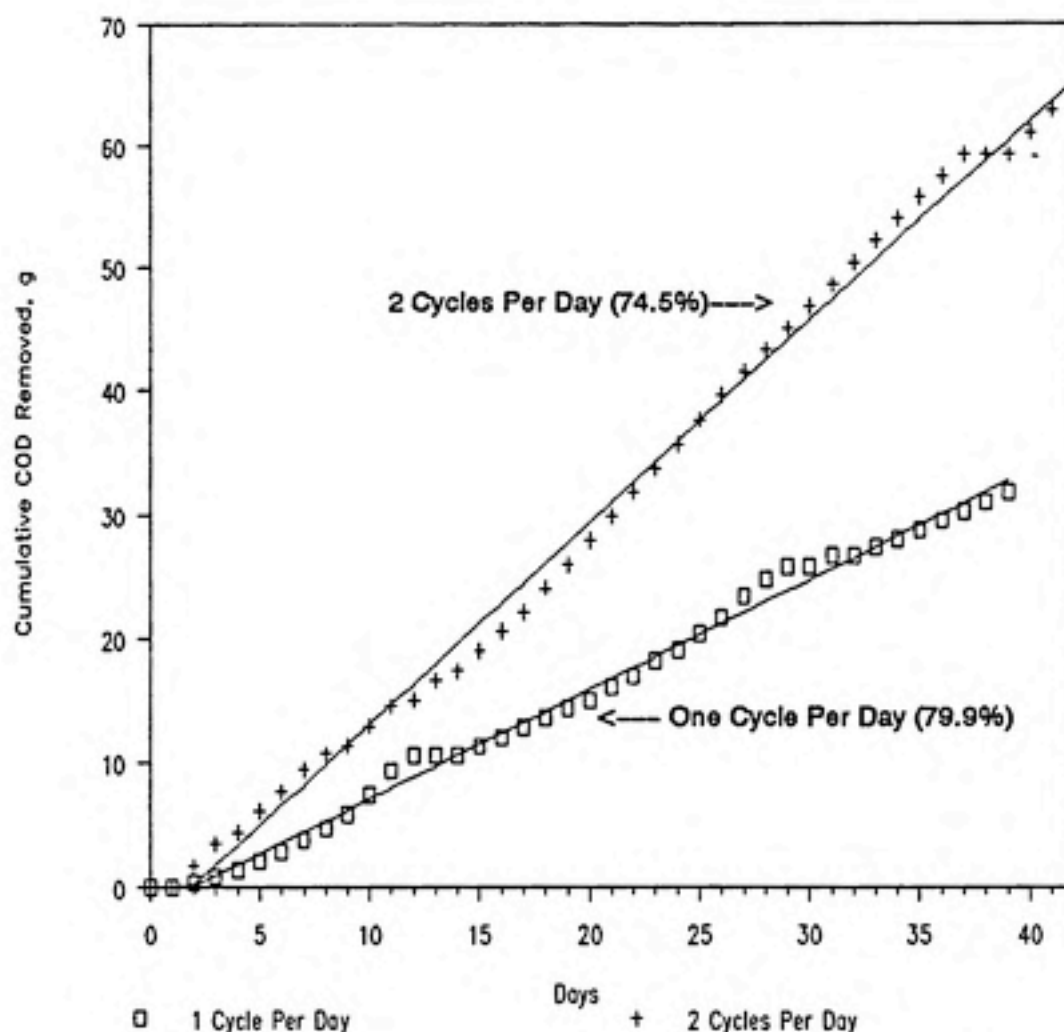
Figure 34: Cumulative Soluble COD Removed Feeding Reactor II Synthetic Feed.
Average removal efficiency for each cycle shown in parentheses.

Table 26: Results of Linear Regressions of Cumulative Soluble COD Removed
for Reactor II, Feeding Synthetic Feed.

Cycles Per Day	Slope (mg/d)	r^2
1	885	0.9935
2	1628	0.9950

Effluent Quality of Reactor II

1. Feeding Raw Waste:

a. Effluent Phenol Concentrations: Figure 35 shows the average effluent phenol concentrations as a function of five loading rate intervals. It is interesting to note that better effluent quality occured at higher loading rates, when supplemental phenol was fed to an acclimated culture.

b. Effluent Soluble COD Concentrations: Limited soluble COD measurements were collected during this period. The average soluble COD concentration measured in seven analyses was 1427 mg/l (std. dev. = 388 mg/l).

c. Data Distribution of Effluent Phenol Concentrations: Table 28 shows the data distribution of effluent phenol concentrations for Reactor II when feeding raw waste. The effluent phenol concentration was less than 10 mg/l 31.1% of the time during this period. Over two-thirds of the entire period, the effluent phenol was less than 50 mg/l.

2. Feeding Synthetic Feed:

a. Effluent Phenol Concentrations: Figures

Table 27: Effluent Phenol versus Loading Rate, Reactor II, Raw Waste. Data for 35 days arranged by five percentiles.

Percentile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.03–0.07	26.5
21 – 40	0.07–0.11	31.2
41 – 60	0.11–0.25	15.8
61 – 80	0.25–0.41	18.6
81 – 100	0.42–1.09	14.6

Fig. 35: Effluent Phenol Versus Loading Rate, Reactor II – Raw Waste
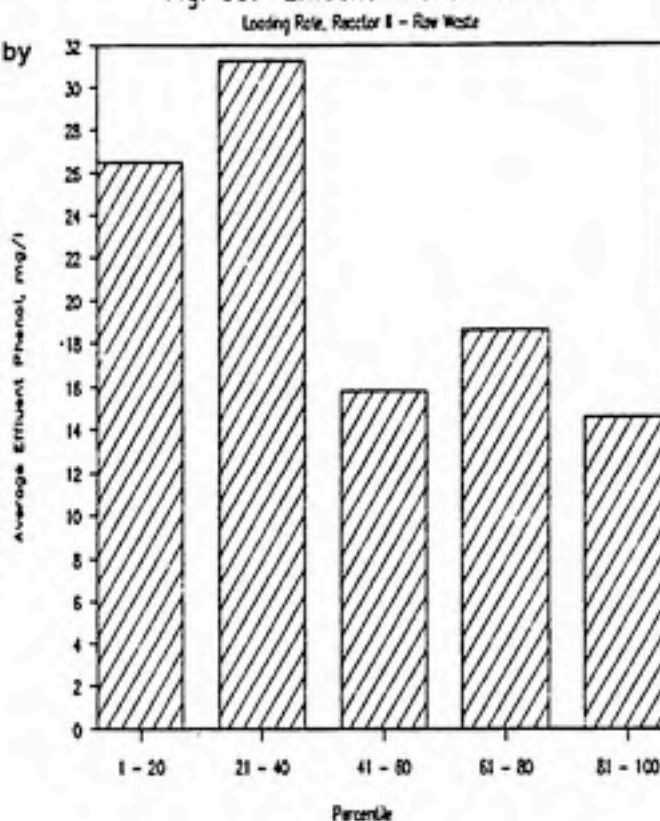
Table 28: Data Distribution of Effluent Phenol Concentrations, Reactor II, Feeding Raw Waste.

Effluent Phenol Conc. (mg/l)	Number of Days When Less Than	Percent of Days When Less Than
10	19	31.1
20	11	49.2
30	2	52.5
40	4	59
50	5	67.2
75	0	67.2
100	2	70.5
>100	18	100

36 and 37 show the effluent phenol concentrations as a function of loading rate interval when feeding synthetic feed one and two cycles per day, respectively. Good effluent quality was achieved up to a loading rate of 0.15 when feeding one cycle per day. At higher loading rates, achieved during two cycle per day operation, the effluent quality showed much more variability.

b. Effluent Soluble COD Concentrations: The COD concentrations measured during one cycle per day operation are shown in Figure 38. The average effluent COD concentrations were found to vary by approximately 30% over the entire range of loading rates, indicating effluent COD was not significantly affected by loading rate. The peak at the first loading rate range is due to feedings when reactor performance was poor during the previous 24 hour cycle. Otherwise, effluent COD generally increased as the loading rate incresed. Limited data is available on the effluent soluble COD concentration during two cycle per day operation. The eight analyses performed gave an average COD concentration of 1420 mg/l (std. dev. = 380 mg/l).

c. Data Distribution of Effluent Phenol Concentrations: A data distribution was performed on effluent phenol concentrations during the synthetic feed regimen, and is shown in Table 32. When operating at 1
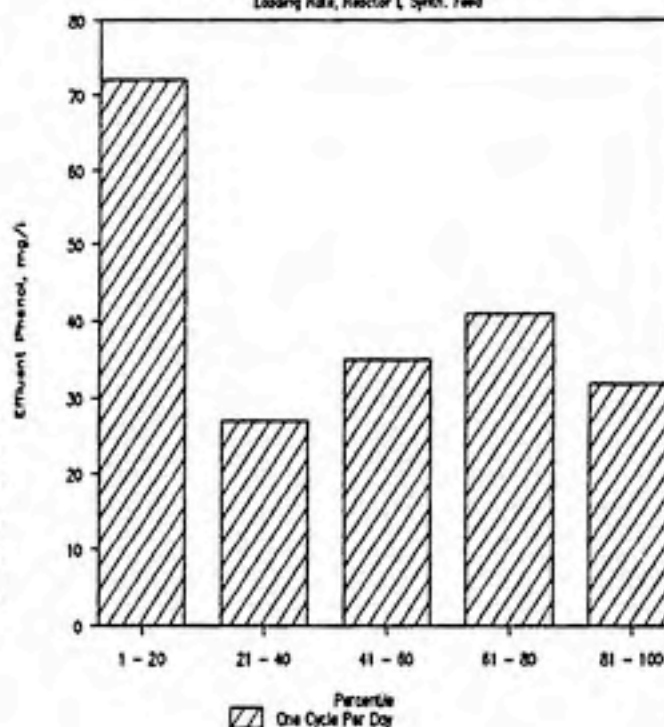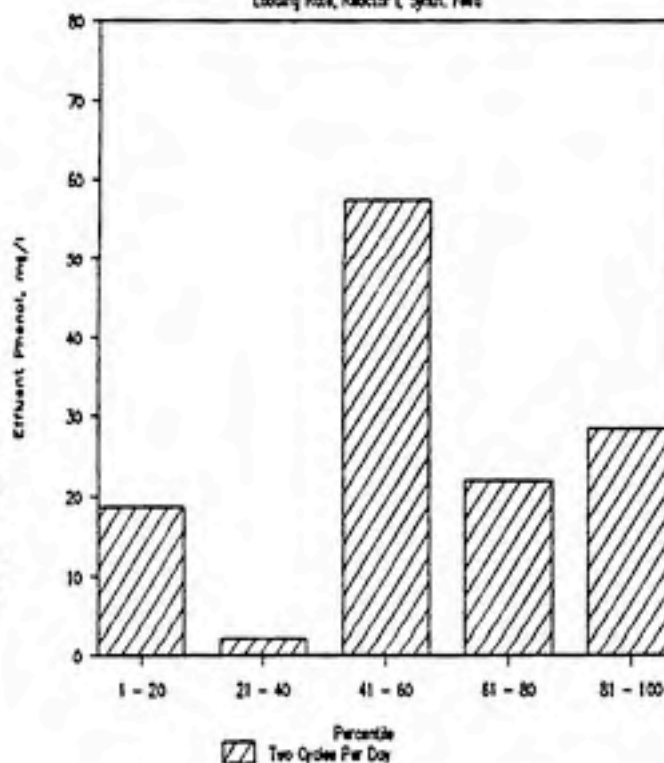
Table 29: Effluent Phenol versus Loading Rate, Reactor II, Synthetic Feed, One Cycle Per Day. Data for 32 days arranged by five percentiles.

Percent- ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.05–0.08	34.6
21 – 40	0.09–0.11	6.2
41 – 60	0.12–0.14	3.6
61 – 80	0.15–0.18	59.3
81 – 100	0.19–0.28	39.1

Fig. 36: Effluent Phenol Versus
Loading Rate, Reactor II – Synth. Feed

Percentile
One cycle per day
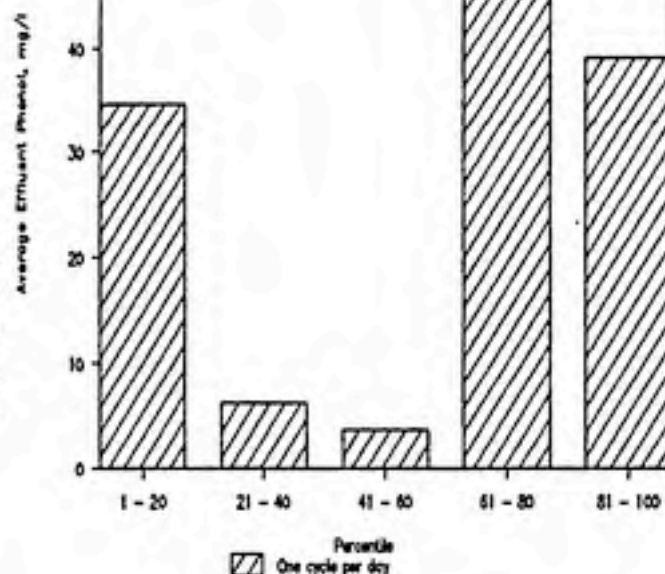
Table 30: Effluent Phenol versus Loading Rate, Reactor II, Synthetic Feed, Two Cycles Per Day. Data for 38 days arranged by five percentiles.

Percent- ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent Phenol (mg/l)
1 – 20	0.27–0.53	19.7
21 – 40	0.53–0.56	117.8
41 – 60	0.56–0.59	75.1
61 – 80	0.59–0.64	38.5
81 – 100	0.64–0.73	44.3

Fig. 37: Effluent Phenol Versus
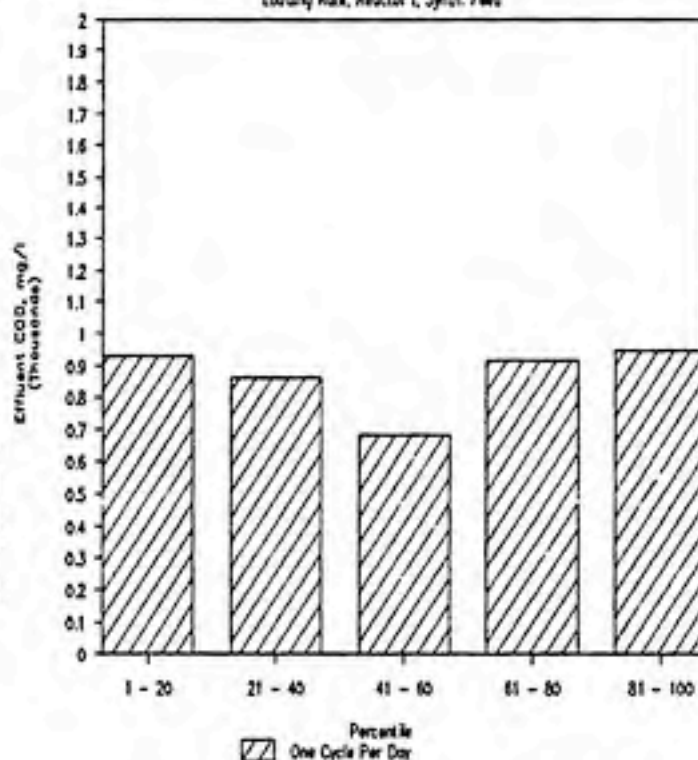Loading Rate, Reactor II – Synth. Feed

Percentile
Two cycles per day
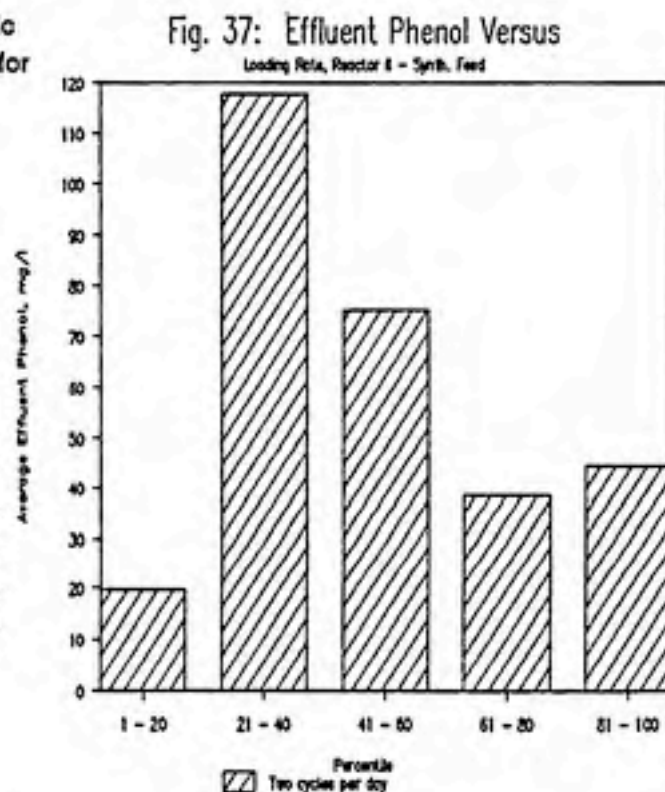
Table 31: Effluent Soluble COD versus Loading Rate, Reactor II, Synthetic Feed, One Cycle Per Day. Data for 35 days arranged by percentiles.

Percent-ile	Loading Rate Range (g COD/ g SS*d)	Average Effluent COD (mg/l)
1 – 20	0.05–0.08	1026
21 – 40	0.09–0.11	829
41 – 60	0.12–0.15	895
61 – 80	0.15–0.18	956
81 – 100	0.19–0.28	1048

Fig. 38: Effluent COD Versus Loading Rate, Reactor II, Synth. Feed
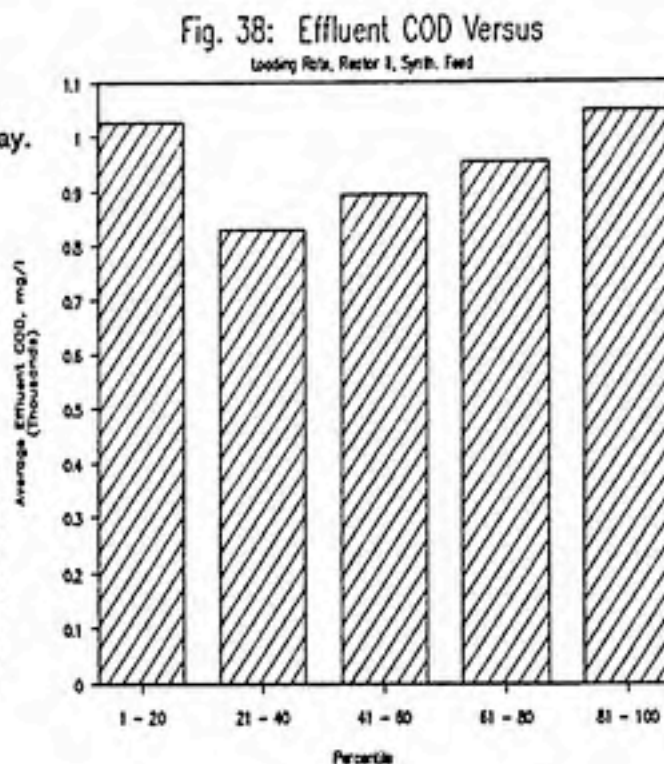
Table 32: Data Distribution of Effluent Phenol Concentrations, Reactor II, Feeding Synthetic Feed.

Effluent Phenol Conc. (mg/l)	1 Cycle Per Day		2 Cycles Per Day	
	Number of Days When Less Than	Percent of Days When Less Than	Number of Days When Less Than	Percent of Days When Less Than
10	20	52.6	14	34.1
20	8	73.7	3	41.5
30	3	81.6	1	43.9
40	0	81.6	4	53.7
50	0	81.6	0	53.7
75	1	84.2	6	68.3
100	2	89.5	3	75.6
>100	4	100	10	100

cycle per day, the effluent phenol concentration was less
than 10 mg/l 52.6% of the time and less than 50 mg/l 81.6%
of the time. During 2 cycle per day operation the effluent
phenol concentration was less than 10 mg/l 34.1% of the
time and less than 50 mg/l 53.7% of the time.

Removal of Phenol and Soluble COD

1. Specific Removal Rate versus Loading Rate:

a. Feeding Raw Waste: Figure 39 shows the
specific phenol removal rate versus the phenol loading rate
when raw waste was fed. Excellent removal was achieved at
virtually all loading rates used during this phase of
reactor operation, and indicates that higher loading rates
may have been sustainable during this period of operation.

b. Feeding Synthetic Feed: Figure 40 shows the
specific phenol removal rate as a function of phenol
loading rate for synthetic feed. As can be seen for both
cycle periods, there is marked inconsistency in reactor
performance. Figure 41 shows the specific soluble COD
removal rate as a function of COD loading rate. Again
inconsistent performance is evident, though increased
deviation from the 100% removal line does seem to appear at
loading rates of greater than 0.2 g/g-d.

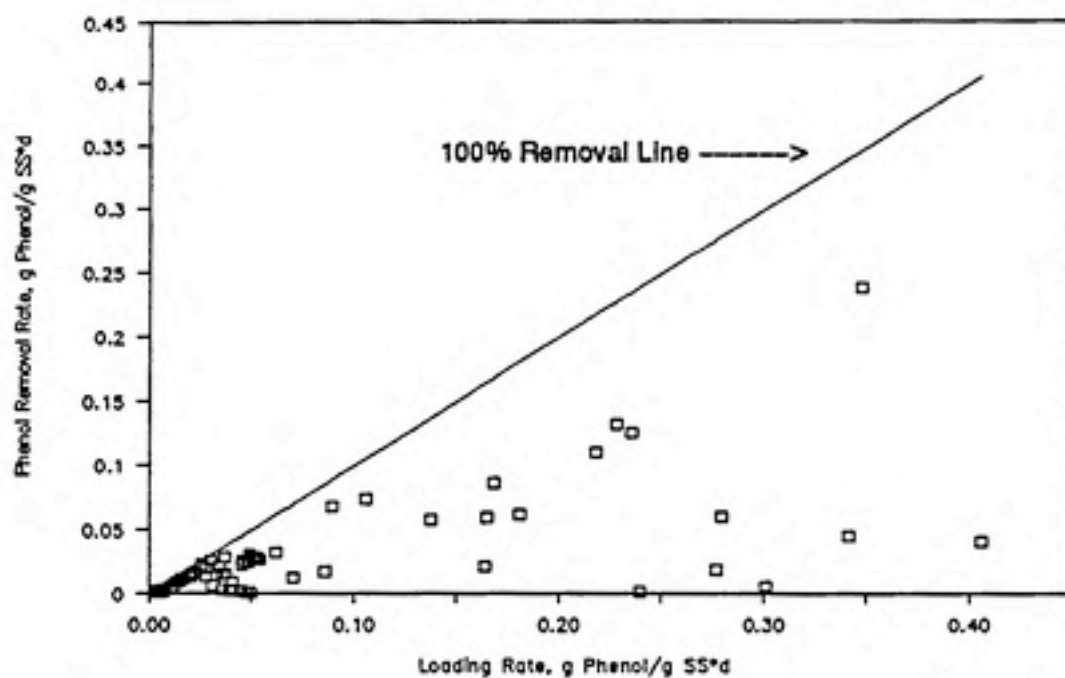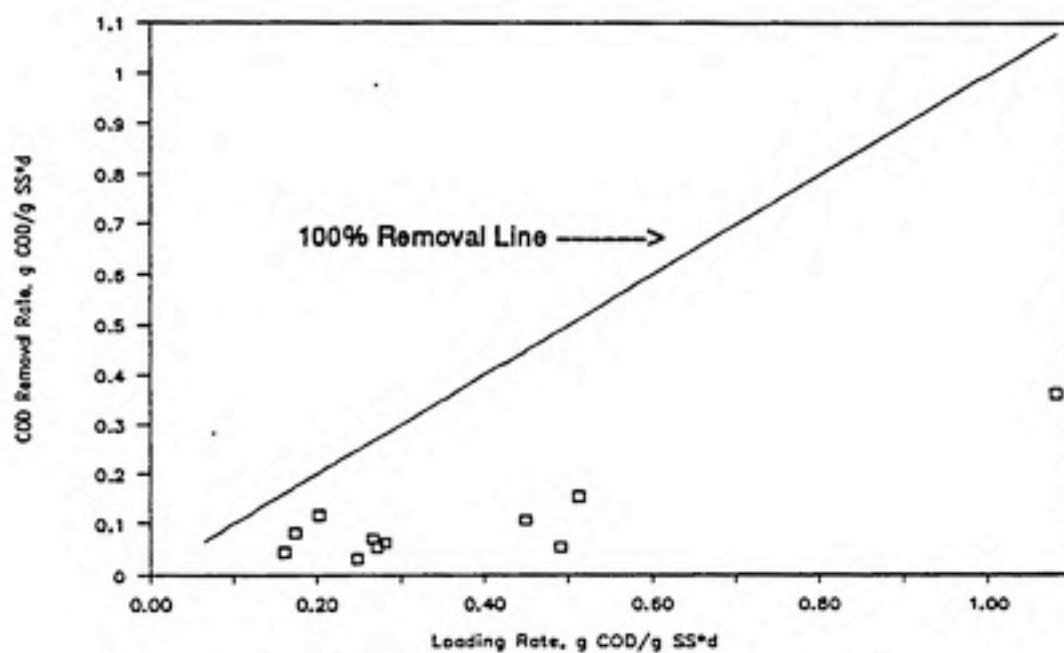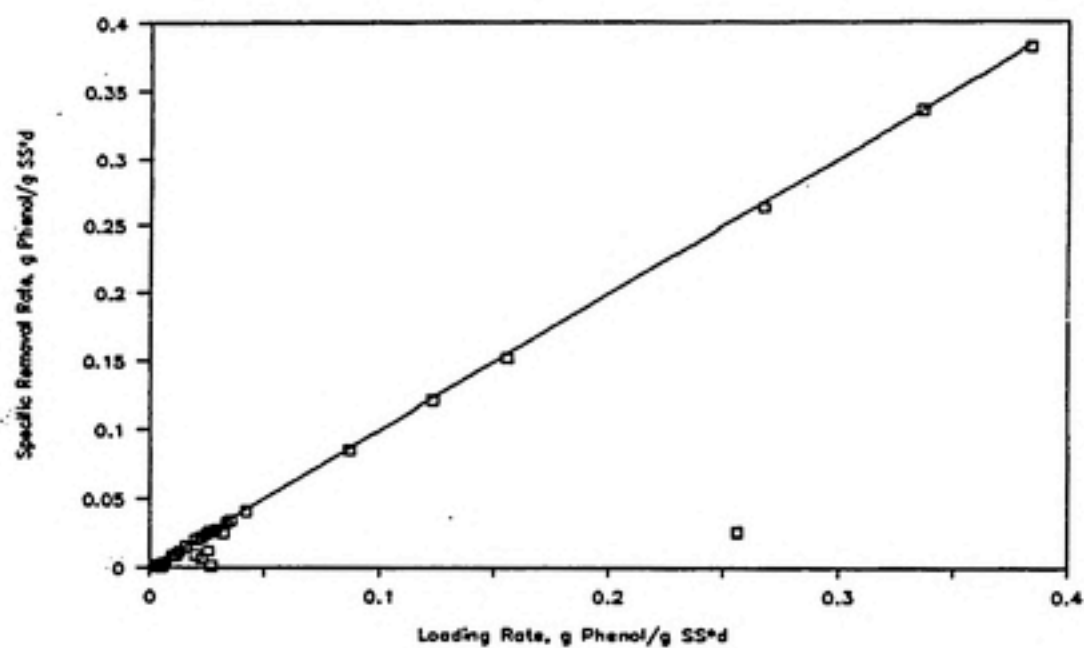Figure 39: Specific Phenol Removal Rate versus Loading Rate, Reactor II, Raw Waste.
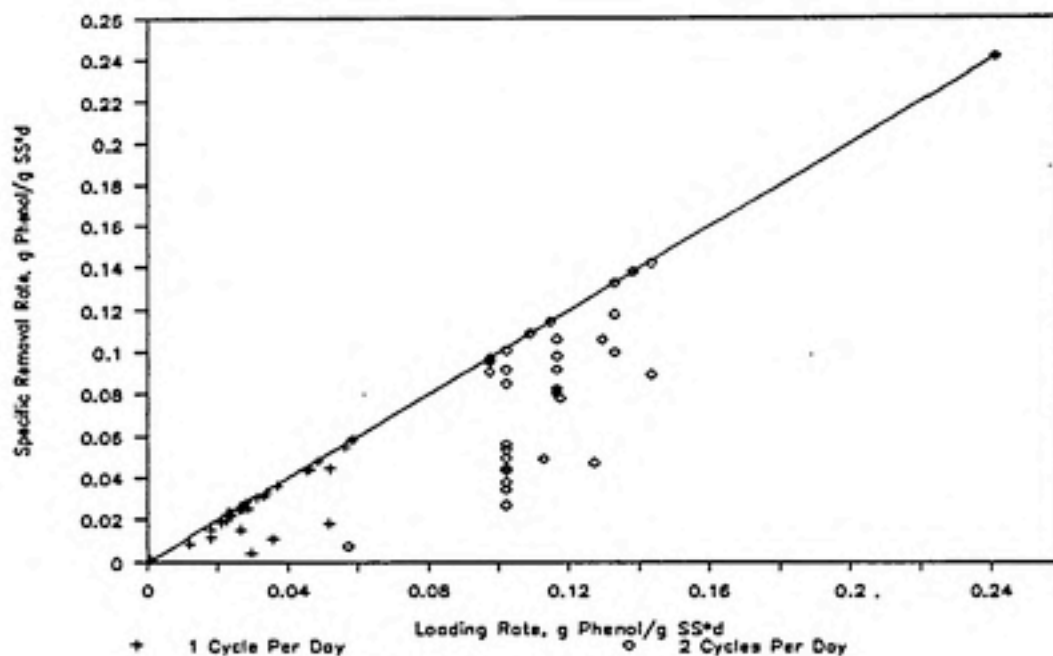
Figure 40: Specific Phenol Removal Rate versus Loading Rate, Reactor II, Synthetic Feed.
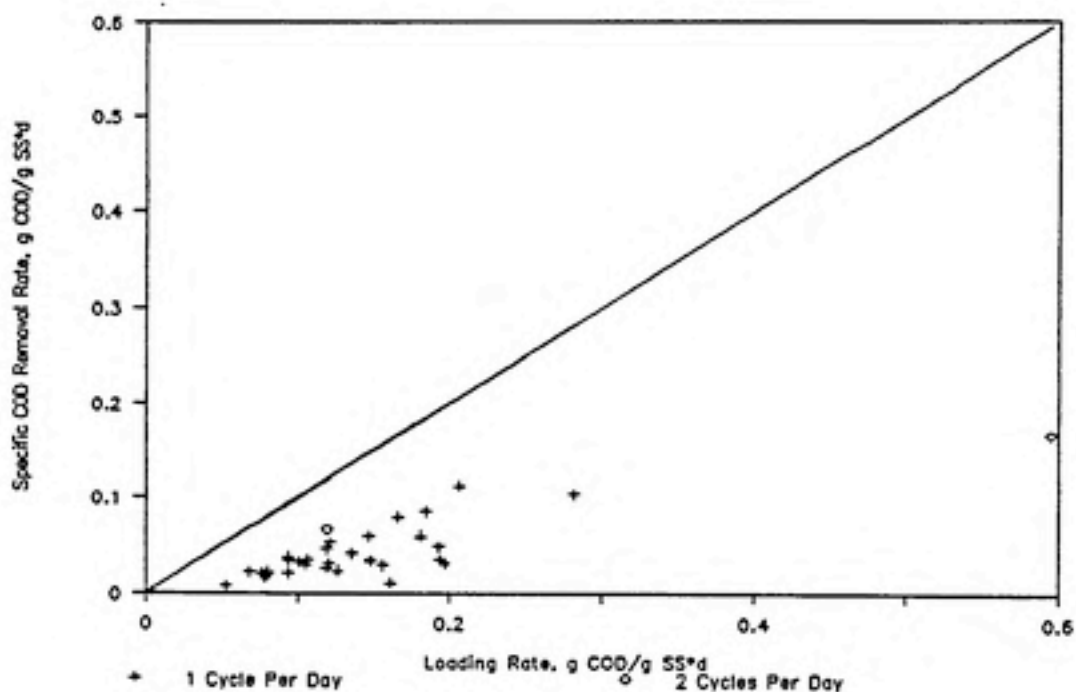
Figure 41: Specific Soluble COD Removal Rate versus Loading Rate, Reactor II, Feeding Synthetic Feed.

2. Percent Phenol and Soluble COD Removed:

a. Feeding Raw Waste: Figure 42 shows the percent phenol removed as a function of the phenol loading rate. The phenol removed during this period was generally very good. The poor performance at low loading rates is again due mostly to those days when low loading rates were applied to the reactor to bring down the reactor phenol concentration from previous days.

b. Feeding Synthetic Feed: Figure 43 shows the percent phenol removed for synthetic feed operation. There is much more inconsistency in this data than in the data for raw waste. Figure 44 shows the percent soluble COD removed as a function of loading rate for synthetic feed. Again, inconsistency in reactor performance is evident.

Effect of Wasting Rate on Reactor Performance

As has been mentioned previously, the mixed liquor in both reactors exhibited poor settling characteristics and during most of the project, effluent solids were centrifuged and returned to the reactor. However, in March 1990, intentional wasting of mixed liquor at the end of the React period was conducted to determine its effect on
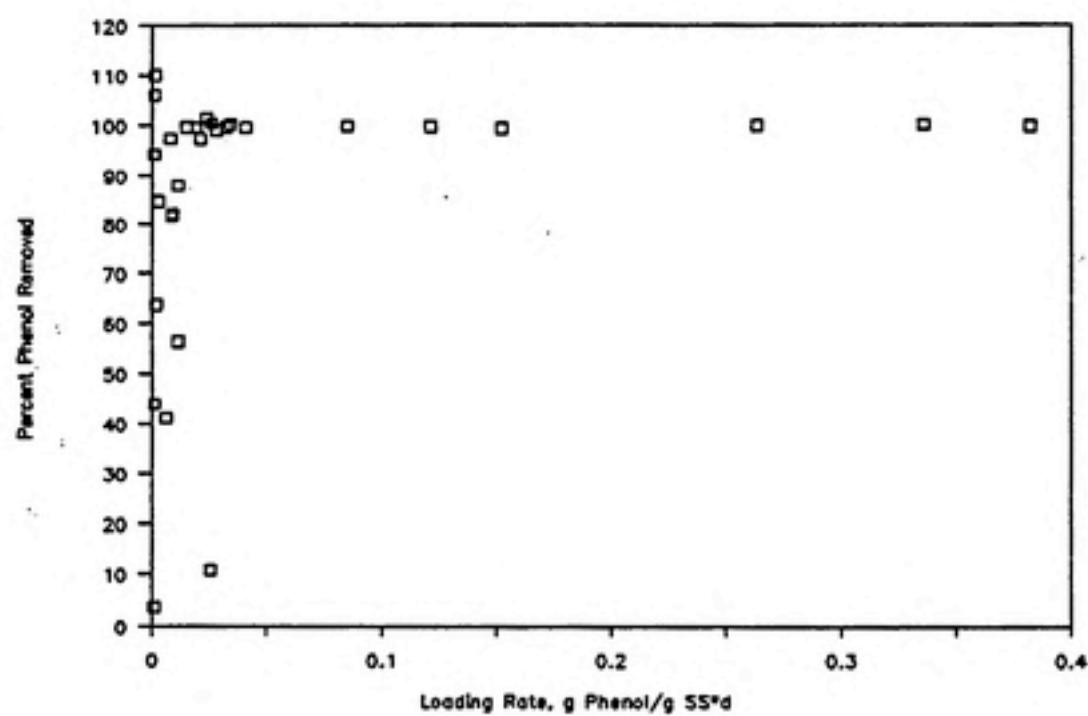
Figure 42: Percent Phenol Removed versus Loading Rate, Reactor II, Raw Waste.
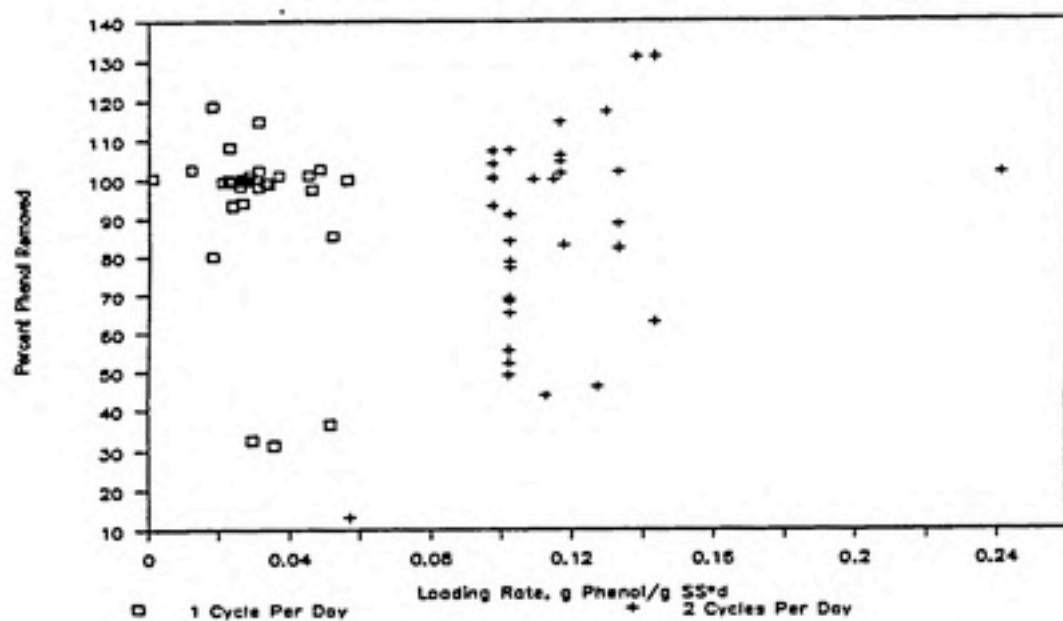
Figure 43: Percent Phenol Removed versus Phenol Loading Rate, Reactor II, Synthetic Feed.
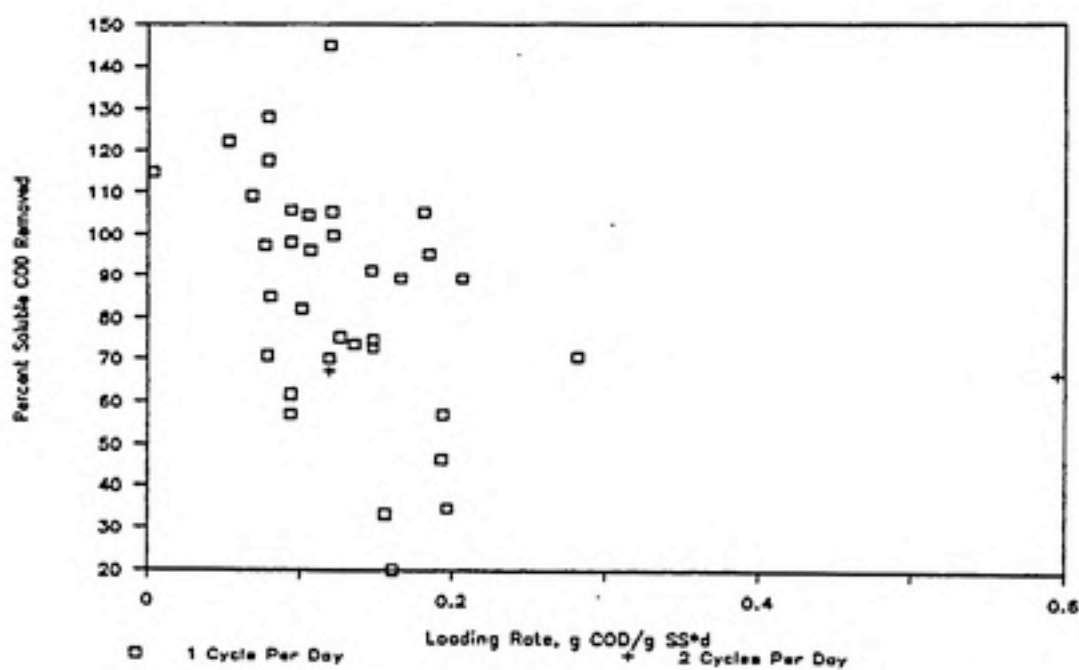
Figure 44: Percent Soluble COD Removed versus Loading Rate, Reactor II, Feeding Synthetic Feed.

performance. A 25 day mean cell residence time (MCRT) was used over a seven day period. Measurements of effluent phenol, COD, and MLSS were performed to monitor the performance of the Reactor.

1. Reactor I: Table 33 shows the results of the monitoring for Reactor I. Figure 45 shows these results graphically. As can be seen, the effluent concentrations of phenol and COD rose dramatically during the 7-day period, with an equally dramatic decrease in reactor MLSS.

2. Reactor II: Table 34 and Figure 46 show the results of the monitoring for Reactor II. Though no significant increase in effluent COD or phenol concentration was noticed during the monitoring period, the decrease in reactor MLSS by almost 50% portended a subsequent deterioration in reactor performance, and wasting was stopped.

Table 33: Effect of Wasting on Performance of Reactor I.
25 Day MCRT, 27 February – 5 March 1990.

Elapsed Time (days)	Effluent Phenol (mg/l)	Effluent Soluble COD (mg/l)	Reactor MLSS (mg/l)
1	7	605	3033
2	41.1	725	
3	39.1	777	2597
4	4.3	740	
5	103	915	
6	183.3	1154	
7	235.2	1260	2143
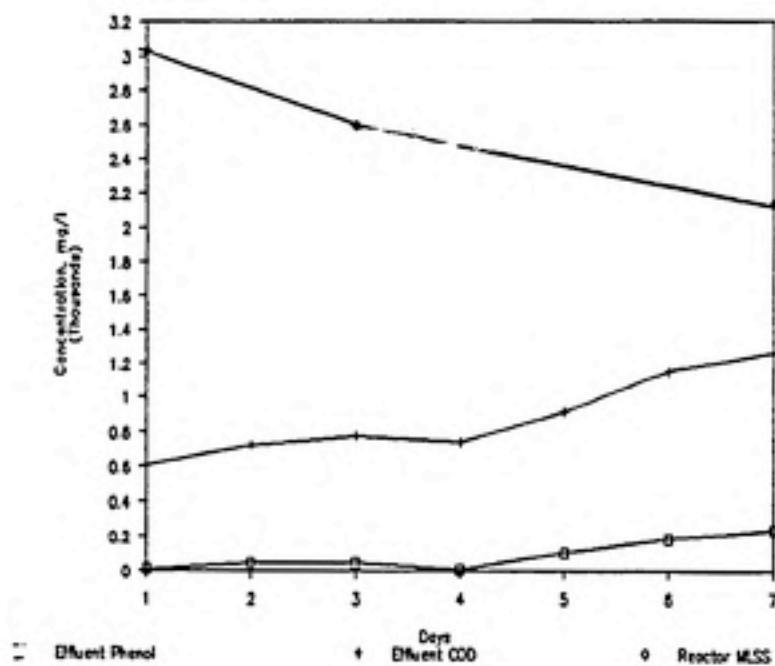
Figure 45: Effect of Wasting on Performance of Reactor I

Table 34: Effect of Wasting on Performance of Reactor II.
25 Day MCRT, 27 February – 5 March 1990.

Elapsed Time (days)	Effluent Phenol (mg/l)	Effluent Soluble COD (mg/l)	Reactor MLSS (mg/l)
1	1	848	5928
2	3.4	879	
3	4.3	868	5423
4	5.1	935	
5	4.3	840	
6	2.5	814	
7	2.8	712	4004

Effluent Phenol   + Effluent COD   ◊ Reactor MLSS
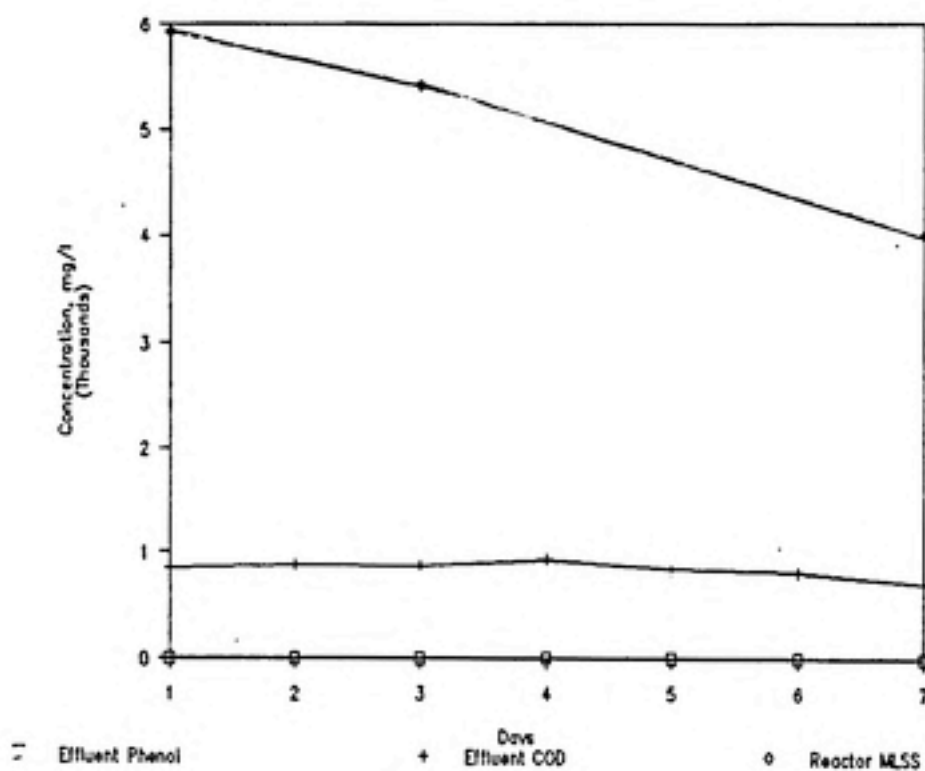
Figure 46: Effect of Wasting on Performance of Reactor II.

V. EXPERIMENTAL RESULTS

To quantify various phenomena that were observed or expected to occur, side experiments were performed throughout this project. These side experiments included: investigations into abiotic mechanisms of COD removal; shake flask and enrichment culture studies to determine various parameters which may affect cell growth; specific oxygen uptake rates to determine the effect of feed characteristics on cell respiration rates; measurement of feed constituents in the reactor during different cycle periods; specific studies on nitrosophenol alone to determine its chemical properties and effects on biological activity; and, a kinetic study to determine the microbial decay constant.

Abiotic Mechanisms of Removal

To ascertain that changes in COD and phenol concentrations were due to biological activitiy in the reactors, it was important to demonstrate that abiotic mechanisms were not significant. Several experiments were

carried out to accomplish this.

1. Loss of Phenol and COD by Stripping: 750 ml
of distilled water was placed in a 1000 ml flask and 100 ml
of raw waste were fed to the flask over 8 hours.
Phosphate, ammonia-nitrogen, and trace elements were mixed
in the feed. The concentrations of these nutrients are
shown in Table 4, Chapter III. Phenol, COD, and MLSS
concentrations were measured every day for one week. The
COD concentration remained at around 625 mg/l over the
entire period, and the phenol concentration decreased 2
mg/l per day from 106 mg/l to 92 mg/l. There was no
formation of suspended solids over the one week period.
Therefore, stripping of organic constituents was concluded
to be insignificant over periods typically employed between
sampling events used to monitor reactor performance
(typically 24 hours or less).

2. Precipitation under Reactor Conditions: The
effluent from Reactor I was used to determine if any of the
constituents in the matrix may cause precipitation of the
nitrosophenol. Effluent was filtered through Whatman 40
filters, then through a 0.45 micron membrane filter, and
finally through 0.2 micron membrane filters twice. The
synthetic feed used was prepared fresh and also filtered
through 0.2 micron membrane filters. Sixty-six ml of
effluent was available for the study. This volume was

split into two 33 ml aliquots. The amount of synthetic feed added to each 33 ml sample, 5.4 ml, was based on a volumetric loading rate to the reactor of 350 ml per 2.15 l mixed liquor. Each feed volume had the nutrient concentrations shown in Table 4, Chapter III. One effluent/feed mixture was aerated in an Erlenmeyer flask and the other (control) was placed on the bench and allowed to sit quiescently.

In a similar manner, synthetic feed at full strength was tested. A flask containing 50 ml of synthetic feed was aerated and a second flask (control) was allowed to sit on the bench unaerated. Suspended solids were measured after 5 days in all four flasks and the results are shown in Table 35. Although a significant quantity of solids (presumably precipitate) was generated in the effluent matrix samples, these solids were formed over a period of 5 days. Therefore, it does not appear that precipitation could account for losses of organic constituents observed over typical sampling intervals for the reactors.

3. Precipitation of Nitrosophenol as a Function of pH and Temperature: 1.2 liters of 1300 mg/l nitrosophenol was prepared with 150 mg/l MgSO4, 2000 mg/l NaNO3, and 2000 mg/l Na2SO4. The pH was adjusted to 8.0 and two 200 ml samples were taken and placed in BOD bottles

Table 35: Results of Precipitation Under Reactor Conditions Experiment

Sample	Suspended Solids After Five Days (mg/l)	Rate of Suspended Solids formation (mg/l–d)
Effluent Aerated	110	22
Effluent Control	171	34.2
Synthetic Aerated	18	3.6
Synthetic Control	0	0

which had been cleaned previously by detergent washing and
rinsing twice with distilled water. The pH was then
brought down to 7.0 and 6.0 and again two 200 ml aliquots
withdrawn at each pH and placed in BOD bottles. Baseline
suspended solids were taken in duplicate for each bottle.
One bottle from each pH set was placed in the refrigerator
(Temp = 4 degrees C) and the other was placed on the lab
bench. Suspended solids were measured over time using
Whatman GF/F glass fiber filters (0.7 micron particle
retention). Results are shown in Table 36. As shown,
precipitation was insignificant at pH 7 and 8.
Precipitation at pH 6, 16 mg/l per day, was more
significant, but these results also indicate precipitation
was not a major removal mechanism in the reactor.

4. Adsorption of Nitrosophenol onto Biomass: Two
50 ml aliquots of mixed liquor were removed from Reactor I
30 minutes after the end of a React period. To one
aliquot, 1000 mg/l NaN3 was added to inhibit biological
growth (confirmed by observing negligible oxygen uptake
when spiked with phenol). 10 mg of a stock solution of
nitrosophenol was then added to each aliquot, and soluble
COD measurements were performed over six hours. Shown in
Table 37 are the results of the experiment. These results
indicate adsorption of organic constituents was negligible.
The difference in soluble COD between the azide-treated and
-untreated samples is probably due to the contribution of

120

Table 36: Results of Precipitation Experiment.

pH	Temp (deg. C)	Day							Average Rate of Solids Formation (mg/l-d)	Std. Dev. (mg/l-d)
		0	3	6	10	13	17	23		
8	4	0	0	0	15	18	5	19	0.7	0.7
8	25	0	1	0	16	9	1	10	0.6	0.6
7	4	0	4	0	11	17	0		0.7	0.7
7	25	0	7	0	10	9	5	30	0.9	0.8
6	4	0	11	0	5	17	6	65	1.4	1.5
6	25	0	1	67	232	296	348	455	16	9

Table 37: Results of Adsorption Experiment.

Time After Pulse Feed (hrs)	Soluble COD	
	with NaN3	w/o NaN3
0.5	1864	1351
2	1891	1318
4	1924	1311
6	1924	1369

Note: The increase in COD expected by addition of nitrosophenol was 400 mg/l. Though soluble COD was not measured before addition of NaN3, the COD of Reactor I mixed liquor was 1207 mg/l the day before this experiment and was 1128 mg/l two days after the experiment.

azide to the COD measurement.

Shake Flask Experiments

The first studies done during this project were shake flask experiments to determine if the waste was biologically treatable, and to assess the need for nutrients and the effect of pH on growth. It was found that optical absorbance could not be used as a measure of growth in the shake flask cultures due to the highly colored nature of the feed mixture. Therefore, suspended solids were used as indicators of growth.

1. Need For Nutrients:

a. Initial Screening Test: One of the first shake flask experiments performed was to determine the need for ammonia-nitrogen, trace elements, and/or vitamins. A 20:1 dilution of raw waste was prepared for use as the source of organic carbon. Flasks were filled with 50 ml of the raw waste dilution and inoculated with 0.1 ml of mixed liquor from Reactor I. An additional sample (3a) was inoculated with 1.0 ml of mixed liquor. The concentrations of nutrients in the shake flasks are shown in Table 38. A key to the matrix used to perform the experiment is shown in Table 39. Shake flasks were run for 16 days and

Table 38: Nutrient Concentrations Used For the Shake Flask Experiments

Element	Nutrient Source	Reagent Conc. In Flask (mg/l)
Fe	FeSO4*7H2O	0.28
Zn	ZnSO4*7H2O	0.16
Co	CoCl2*6H2O	0.024
Cu	CuSO4*5H2O	0.002
Mo	(NH4)6Mo7O24*4H2O	0.024
Vitamins	Yeast Extract	1
P	KH2PO4/K2HPO4	90
K	KH2PO4/K2HPO4	85.5
N	NH4Cl	40

Table 39: Key to Sample Sets Used in Shake Flask Experiments

Sample Set	Nutrients		
	NH4Cl	Trace Elements	Yeast Extract
1	X		
2	X	X	
3	X	X	X
4	X		X
5		X	
6		X	X
7			X
8			

Note: "X" indicates Nutrient added.

suspended solids were measured. Results are shown in Figure 47. Since baseline MLSS measurements were not performed, the results are only qualitative. Sample set 2 did appear to show the largest amount of growth during the period, indicating ammonia-nitrogen and trace elements were required for optimum growth. It was concluded from this experiment that yeast extract would not be needed as a source of vitamins.

b. Study of Need for Nutrients Using Higher Concentration of Raw Waste: A subsequent shake flask experiment was performed using a 10:1 dilution of raw waste. The same nutrient matrix (Table 38) was used and the flasks were run for 13 days. Suspended solids were taken at the end of the experiment and the results are shown in Figure 48. All sample sets showed similar growth, and no trends are evident.

c. Need for Trace Elements: A 20:1 dilution of raw waste at pH 7.0 was prepared in November, 1989. A 2 ml inoculum of Reactor I mixed liquor was used. Three sample sets, representing trace elements at 3/5, 3 and 15 times the normal amount added to the feed, were prepared and baseline phenol and suspended solids concentrations were measured. Triplicate flasks were prepared in each set. Results are shown in Figure 49. There were significant differences in growth for each concentration of

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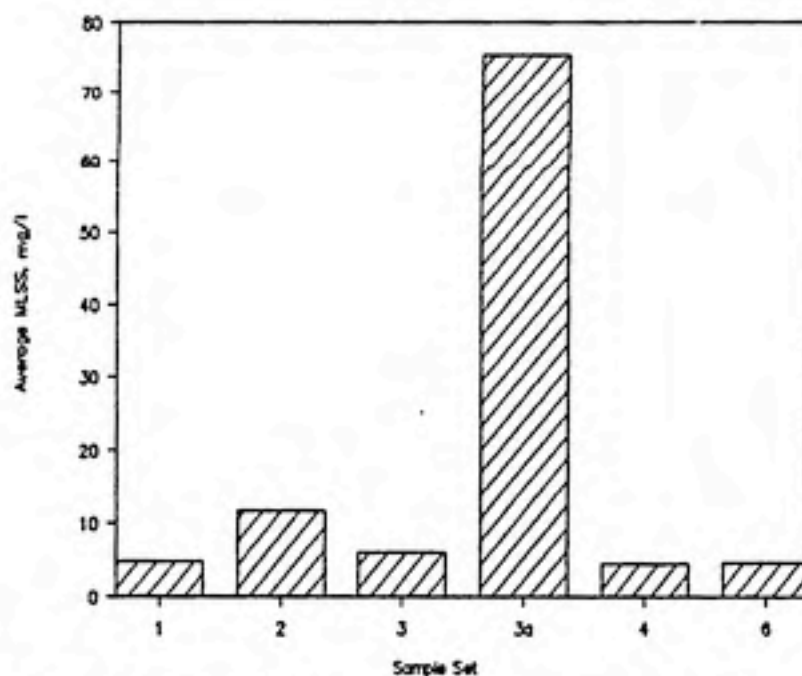
Figure 47: Initial Shake Flask Experiments to Determine Need for Nutrients. All samples inoculated with 0.1 ml Reactor I mixed liquor except Set 3a, which had 1.0 ml seed. Baseline MLSS concentrations were not performed.
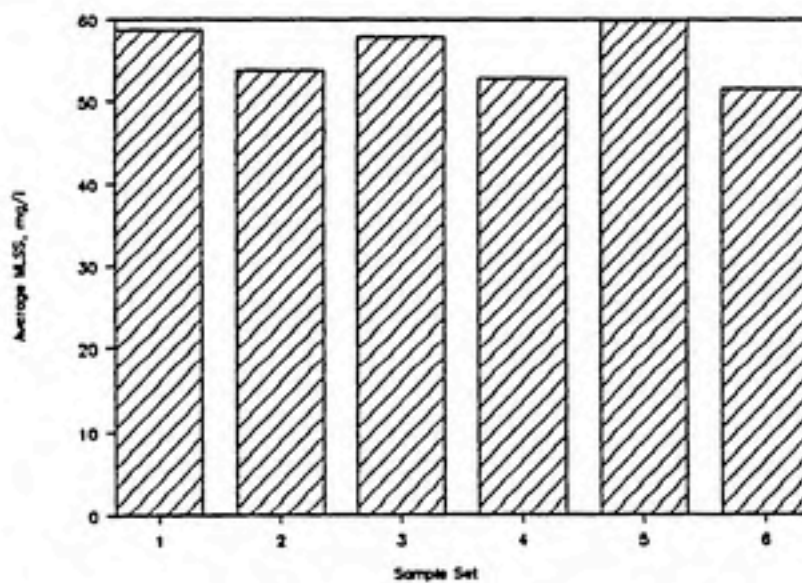
Figure 48: Subsequent Shake Flask Study of Need for Nutrients.
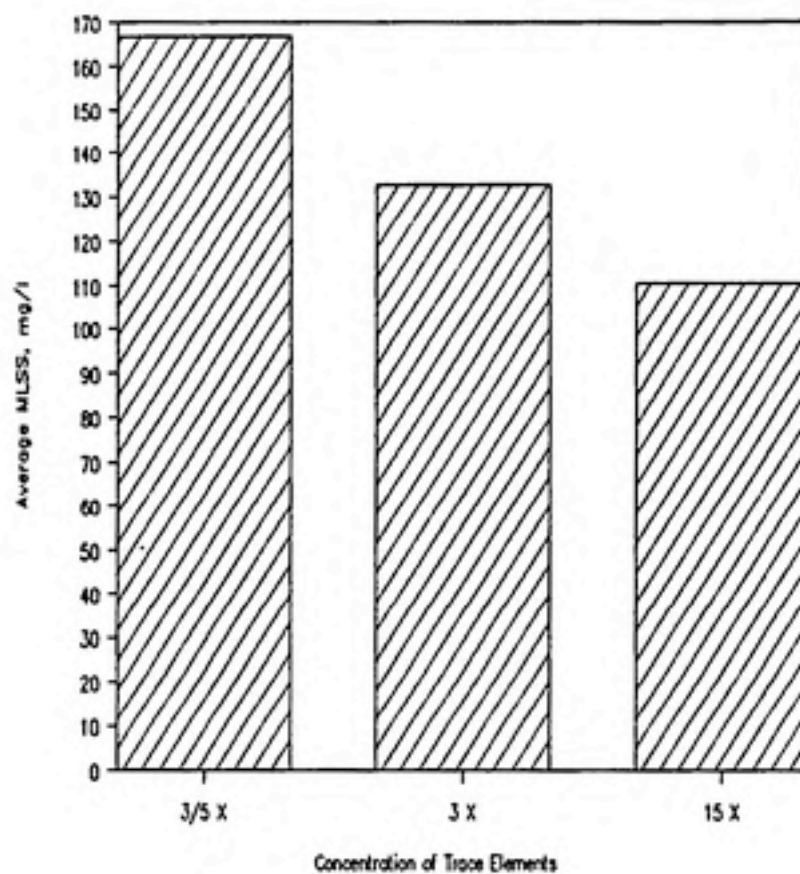
Figure 49: Effect of Trace Elements Concentration on Growth.

trace elements, with 3/5 times the normal trace element
concentration showing best growth. At 3 and 15 times the
normal trace element concentration, lower suspended solids
concentrations were observed, suggesting that the level
used was inhibitory to growth. Synthetic feed continued to
be prepared with the normal concentration of trace
elements.

d. Need for Ammonia-Nitrogen Using
Enrichment Cultures: In April, 1990, enrichment cultures,
which are described below, were used to determine the
amount of ammonia-nitrogen required for optimal growth of
the organisms. The results of this study are shown in
Tables 40 and 41. In Table 40, the need for ammonia-
nitrogen at all was evaluated. Two enrichment cultures
were run, one with NH4Cl, and one with no source of
ammonia-nitrogen. As can be seen from the table, average
phenol removal rates and yields based on phenol removal
were greater for the culture to which ammonia-nitrogen was
added. Once the need for ammonia was established,
additional enrichment cultures were run to see what
concentration of NH4Cl would give optimal growth. Table 41
shows the results of four separate culture runs. With each
increase in initial NH4Cl concentration, an increase in
average phenol removal rate and yield based on phenol is
seen up to a concentration of 667 mg/l. As a result of

Table 40: Determination of Need for Ammonia-Nitrogen Using Enrichment Cultures.

Elapsed Time (days)	NH4Cl Conc. (mg/l)	MLSS (mg/l)	Phenol Conc. (mg/l)	Average Phenol Removal Rate (mg/l-d)	Yield Based on Phenol Removed (g SS/g)
0	33.3		233.9		
3		8.5	187	15.6	0.18
7		37.6	3.5	45.9	0.16
0	0		230.3		
3		4.3	186.6	14.6	0.1
7		5.2	138	12.2	0.02
13		34.3	1.1	22.8	0.21

Table 41: Determination of Amount of Ammonia–Nitrogen Required for Biodegradation Using Enrichment Cultures.

Elapsed Time (days)	NH4Cl Conc. (mg/l)	MLSS (mg/l)	Phenol Conc. (mg/l)	Average Phenol Removal Rate (mg/l-d)	Yield Based on Phenol Removed (g SS/g)	Soluble COD Conc. (mg/l)	Average Soluble COD Removal Rate (mg/l-d)	Yield Based on COD Removed (g SS/g)
0	66.7		232.3			1274		
6		7.2	138.5	15.6	0.08	1006	44.7	0.03
9		14.5	34.2	22	0.07	722	61.3	0.03
12		78	0	19.4	0.34	576	58.2	0.11
0	333		225.6			1297		
6		8	132.4	11.7	0.09	1017	46.7	0.03
9		30	5.8	24.4	0.14	623	74.9	0.04
0	667		258.1					
6		5.5	137.2	20.2	0.05			
8		38.3	83.9	21.8	0.22			
11		62.4	38.4	20	0.28			
13		73.4	17.8	18.5	0.31			
0	2000		257.4					
6		<5	187.4	11.7				
8		8.3	158.3	14.6	0.08			
11		6.9	131.8	8.8	−0.05			
13		19.1	113.5	9.2	0.67			

this experiment, the amount of NH4Cl added to the feed was increased by a factor of 3.3.

    e. Need for Phosphorus: An estimate of the amount of phosphorus required for biodegradation was determined by tracking its depletion and the removal of soluble COD in the reactor. In February, 1990, the concentration of phosphorus in Reactor I was 35.7 mg/l. To bring down this concentration, no phosphorus was added to the feed for eight days. The results of the monitoring are shown in Table 42. Determination of the soluble COD removed was described in Chapter IV. The results indicate that 9.2 mg of phosphorus are required on average to remove 1 g of soluble COD. Table 43 shows the results for Reactor II. The phosphorus demand (12.3 mg P/g COD) is similar to that of Reactor I. Assuming the feed had an average of 6000 mg/l of COD, the original estimate of 90 mg P/liter of waste (15 mg P/g COD) was judicious.

    2. Effect of pH: 10:1 dilutions of raw waste were prepared at pH 4, 5, 6, and 7 and placed in shake flasks. These shake flasks were run for three weeks. pH measurements were taken every three days and showed the pH did not vary by more than 0.4 pH units over the entire 21 days. The results of the suspended solids analyses are shown in Figure 50. Optimal growth occurred at pH 5, with good growth at all other pHs. Since both reactors tended

Table 42: Determination of Need for Phosphorus in Reactor I. Average
Phosphorus Consumption is 9.2 mg P/g COD Removed (std. dev. = 5.2).

Date	P Conc. (mg P/l)	Std. Dev. (mg P/l)	COD Removed (mg)	P Added (mg P)	P Consumed (mg P)	P Consumed (mg P/g COD Removed)
Feb 23	35.7	0.3		0		
Feb 24	28.4	0.5	863	0	17	19.4
Feb 25	24	0.3	870	0	10	11.5
Feb 26	20.4	1.2	867	0	8	9.5
Feb 28	12.2	0.1	1689	0	19	11.2
Mar 2	10.9	0.5	1918	0	3	1.5
Mar 3				30		
Mar 4	12	0.2	1971	0	8	3.9
Mar 8	8.8	0.8	668	0	7	10.8
Mar 11				30		
Mar 12	4.8	0.1	3292	0	19	5.8

Note: Phosphorus consumed based on average reactor volume
before Fill of 2.3 l.

Table 43: Determination of Need for Phosphorus in Reactor II. Average
Phosphorus Consumption is 12.3 mg P/g COD Removed (std. dev. = 3.8).

Date	P Conc. (mg P/l)	Std. Dev. (mg P/l)	COD Removed (mg)	P Added (mg P)	P Consumed (mg P)	P Consumed (g P/g COD Removed)
Feb 23	33.1	0.8		0		
Feb 24	27.2	0.2	759	0	14	17.9
Feb 25	23.9	1.6	683	0	8	11.3
Feb 26	18.7	1	825	0	12	14.5
Feb 28	25.2	2.4	1570	0	———	
Mar 2	14.3	0.4	1702	0	25	14.7
Mar 3				30		
Mar 4	12.3	0.1	2115	0	15	7.0
Mar 8	17.3	0.1	5208	0	———	
Mar 11				30		
Mar 12	9.7	0.1	3313	0	27	8.2
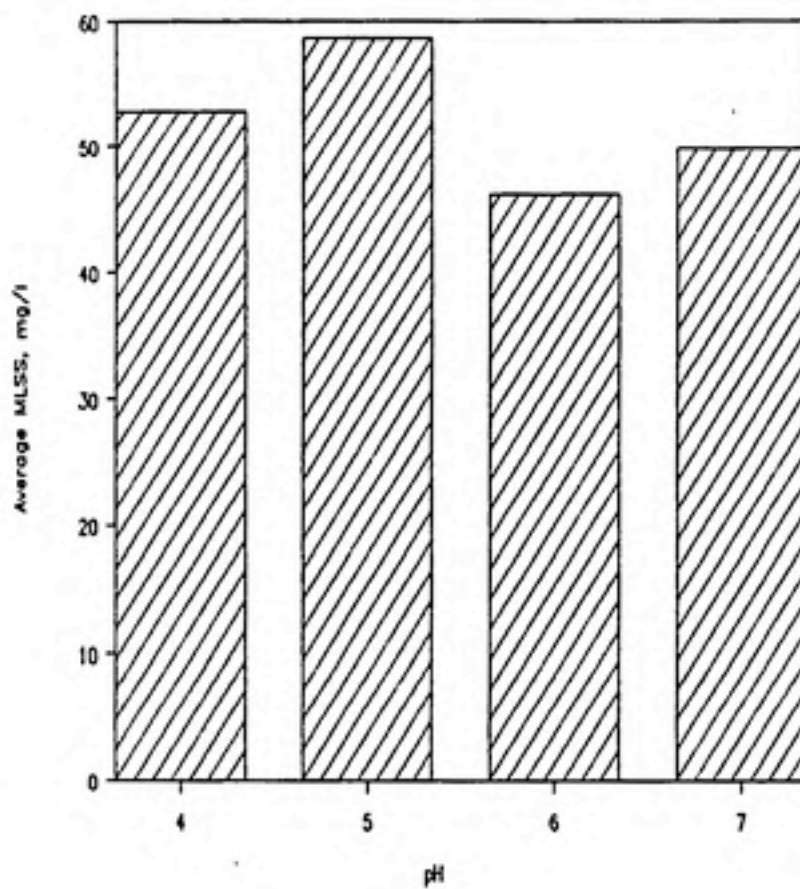
Figure 50: Effect of pH on Microbial Growth.

to stabilize at near neutral pH, this experiment indicated
pH adjustment of the feed would not be necessary for
optimum reactor operation.

Enrichment Cultures

On 5 February 1990, 250 ml of a 5:1 dilution of
synthetic feed was prepared in a 0.1M K2HPO4/KH2PO4 buffer.
Four ml of mixed liquor from Reactor II was added to the
dilution along with trace elements and ammonia-nitrogen
(NH4Cl). This culture was then aerated for five days.

Four ml of this culture and two ml of activated sludge
from the Farrington Road Wastewater Treatment Plant in
Durham, NC, was transferred to a new 5:1 dilution of
synthetic feed and was aerated for four days. The addition
of Farrington Road activated sludge probably had little,
if any, effect on the enrichment, as discussed below in the
Oxygen Uptake section. Four ml of this culture was again
transferred to a new 5:1 dilution and aerated for four
days. The entire 250 ml of enrichment culture was then
centrifuged and the solids were placed in a 5:1 dilution
which had a final volume of 500 ml. This culture was
aerated for four days and the solids from the entire 500 ml
was transferred to a new dilution that had a final volume
of 1000 ml.

This culture was aerated for 11 days. On the seventh
day, the MLSS was 108 mg/l. The culture was fed 100 mg
phenol on the eighth day, and 150 mg phenol on the ninth
day. The entire culture volume was centrifuged and half
the solids were transferred to a 500 ml volume of 5:1
dilution (referred to subsequently as "0% enrichment") and
the other half was transferred to a 5:1 dilution that had a
supplemented salt concentration of 2.0% (20,000 mg/l
Na2SO4, referred to below as "2% enrichment").

The 0% enrichment culture was maintained from 5 March
1990 to 11 May 1990. Frequent monitoring of phenol,
soluble COD, and MLSS concentrations was performed and
transfers to new 5:1 dilutions were performed whenever the
phenol concentration dropped to below 10 mg/l. Transfers
consisted of placing 12 ml of the liquid culture into a
liter of 5:1 dilution of synthetic feed.

Results of the monitoring are shown in Table 44. Also
included in the table are the average phenol and soluble
COD removal rates between sampling periods, and the net
yield based on soluble COD degradation. Where initial
phenol and COD concentrations were not measured, these
concentrations were estimated by dividing the measured
concentration in the synthetic feed by the dilution factor
(five). Suspended Solids concentrations at time zero were

Table 44: Phenol, Soluble COD, and MLSS Monitoring of 0% Salt Enrichment

Transfer Number	Elapsed Time (days)	Phenol Conc. (mg/l)	Soluble COD Conc. (mg/l)	MLSS (mg/l)	Phenol Removal Rate (mg/d)	Soluble COD Removal Rate (mg/d)	Yield (g SS/ g COD)
1	0						
	6			185			
2	0	227.6	1085				
	2	125.6	822	73	51.0	131.5	0.278
	4	1.5	425		62.1	198.5	
	5	1.1	397	153	0.4	28.0	0.188
3	0	224	1030				
	6	1	397	28	37.2	105.5	0.044
4	2	175.5		< 5			
	5	49.6		18	42.0		
	7	2	449	34	23.8		0.054
5	0	229	1057				
	6	1.5	441	18	37.9	102.7	0.029
6	0	205.8	912				
	5	2	218	37	40.8	138.8	0.053
7	0	233.9	1158				
	3	187		< 5	46.9		
	7	3.5		37	45.9		
8	0	232.3	1297				
	6	138.5	1006	8	15.6	48.5	0.027
	9	34.2	722	15	34.8	94.7	0.025
	12	0	576	80	11.4	48.7	0.445
9	0	258.1	1229				
	6	137.2		8	20.2		
	8	83.9		38.3	26.7		
	11	38.4		62	15.2		
	13	17.8		73	10.3		

estimated from the known final MLSS of the previous
enrichment.

The average phenol removal rate for the entire period
is 32.6 mg/l-d (std. dev. = 15.0 mg/l-d, 17 observations),
excluding the rate measured on Day 5 of Transfer 2. The
average soluble COD removal rate was 105.8 mg/l-d (std.
dev. = 46.8 mg/l-d, 9 observations), again excluding the
rate measured on Day 5 of Transfer 2. It should be noted
that the final concentrations of soluble COD in the
enrichment cultures were much lower than those observed in
the reactors.

Two observations from Table 44 are significant. First,
net yields over periods of days were quite variable, but
generally were low (less than 0.1 g SS/g COD removed) after
the first transfer. Also, removal rates per unit biomass
were substantially higher than was achieved in either
reactor. Such a result indicates that enrichment
techniques may be a useful method of biomass development
for reactor startup.

The 2% enrichment culture was maintained from 5 March
1990 to 30 May 1990. This culture was maintained
identically to the 0% culture and the results of the
monitoring are contained in Table 45. Negative yields in

Table 45: Phenol, Soluble COD, and MLSS Monitoring of 2% Salt Enrichment

Transfer Number	Elapsed Time (days)	Phenol Conc. (mg/l)	Soluble COD Conc. (mg/l)	MLSS (mg/l)	Phenol Removal Rate (mg/d)	Soluble COD Removal Rate (mg/d)	Yield (g SS/ g COD)
1	0						
	6			135			
2	0	218.7	1039				
	2	186.4	1039	115	16.1		
	4	150.5	868		18.0	85.5	
	6	117.1	757	177	16.7	55.5	0.220
	11	79.4			7.5		
	13	64.2		254	7.6		
	16	55.9		142	2.8		
	18	54.8		138	0.6		
	20	49.4	578	118	2.7	12.8	−0.330
3	0	235.6	1291				
	4	186.2	1151	117	12.4	35	0.836
	9	146.6		125	7.9		
	13	126.8		31	5.0		
	23	43.9	820	83	8.3	17.4	−0.103
	29	23.4	605	84	3.4	35.8	0.005
4	0	244.6	1297				
	5	181.3		70	12.7		
	20	18.9	509	180	10.8	39.4	0.228
5	0						
	10	42		182	24.4		
	11	26.8	582	225	15.2	61.9	0.330

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the early transfers are due to inhibition at high salt
concentration and simultaneous microbial decay. Inhibition
in the early transfers is also indicated by the slow rate
of phenol removal. By the final transfer, the phenol
removal rate approached that of the 0% enrichment.
Observed yields in the last two transfers appear to be
higher than those of the 0% enrichment. Inconsistent
trends in measured MLSS over time may indicate, however,
that there were sampling inconsistencies (non-homogeneous
dispersion of solids in the flask prior to sampling).

Biological Oxygen Uptake Monitoring

During the course of this study, the performance of the
reactors was also checked by performing biological oxygen
uptake rate measurements. These checks were performed
using both the raw waste and the synthetic feed. Overall,
it can be stated that oxygen uptake measurements were not
very reproducible. Consequently, conclusions drawn from
the tests are semi-quantitative only.

Lack of reproducibility probably was due to an
inability to obtain reproducible quantities of biomass for
individual measurements. Biomass tended to range in
character from grainy and rapid-settling to disperse and
non-settling. This heterogeneous nature of the biomass

made it difficult to take reproducible aliquots from an unstirred vessel (preliminary experiments indicated that long-term stirring affected the ability of the organisms to respire on phenol). Preliminary experiments also indicated that observed oxygen uptake rates depended on the point in the cycle that samples were withdrawn from the reactor.

In this report, the specific oxygen uptake rate measured on the sample resting in the chamber will be referred to as the endogenous SOUR. The oxygen uptake rate measured after injection of substrate into the chamber is referred to as the feeding SOUR. The difference between the feeding SOUR and the endogenous SOUR has been defined as the net SOUR. The concentration of substrate in the sample chamber after injection is referred to as the in-situ concentration. The mass ratio of COD or phenol to suspended solids after injection is referred to as the loading.

To compensate for the lack of reproducibility of the SOUR data, a SOUR ratio was defined. This SOUR ratio was determined by dividing the feeding SOUR by the endogenous SOUR. Use of this quotient normalizes the SOURs to account for the variable quantity of active biomass injected into the sample chamber during serial measurements. Since the feeding and endogenous SOURs are both proportional to the

biomass in the sample chamber, the SOUR ratio should be relatively constant at identical in-situ concentrations of substrate. SOUR ratios which are greater than 1 indicate stimulation of the oxygen uptake rate upon injection of substrate, whereas values less than 1 indicate a retardation of the uptake rate, which may be an indication of inhibition.

1. SOURs Measured using Raw Waste as the Substrate:

a. Reactor I: Feeding SOURs for Reactor I were typically in the range of 2 to 11 mg D.O./g SS-h when spiked with raw waste. Endogenous rates typically were on the order of 1 to 7 mg D.O./g SS-h, so that net uptake rates typically ranged between 1 to 4 mg D.O./g-h. The SOUR ratios are shown in Figure 51 as a function of specific loading. At a specific loading of 0.5 or higher, the uptake ratios drop below 1, indicating possible inhibition of the uptake rate.

b. Reactor II: Reactor II, during the initial stages of operation, had a net SOUR in the 10 - 20 mg D.O./g-h range. These high SOURs correspond to high rates of phenol and COD removal during the initial operating period of Reactor II (as discussed in Chapter
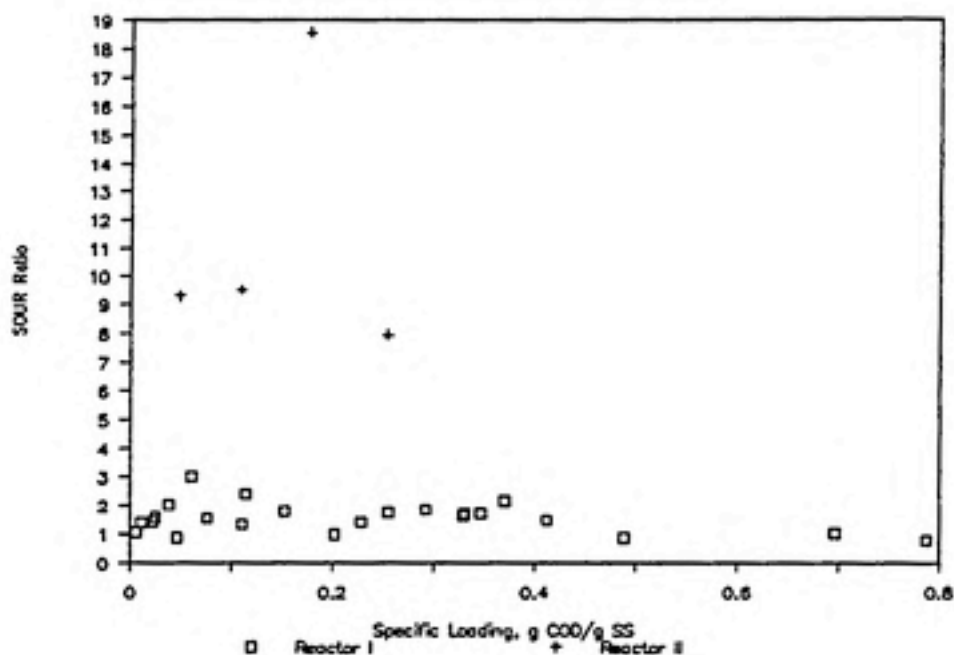
Figure 51: SOUR Ratios as a Function of Specific Loading, Reactors I and II, Using Raw Waste as Carbon Source. Reactor I measurements taken in October 1989 and February 1990. Reactor II measurements taken in November 1989.
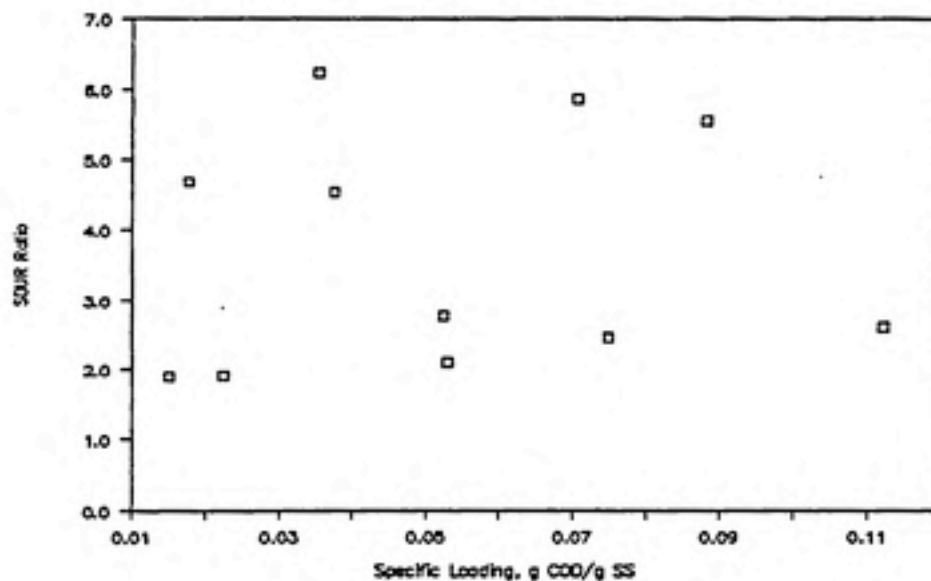
Figure 52: SOUR Ratios as a Function of Specific Loading, Reactor I, Using Synthetic Feed as Carbon Source. Measurements performed in February 1990, with reactor operating at one cycle per day.

IV). The SOUR ratios are shown in Figure 51. As can be seen, the ratios are three to six times higher than those measured in Reactor I. Also, the limited amount of data that was collected did not indicate any inhibition up to a specific loading of 0.25.

2. SOURs Measured Using Synthetic Feed as Substrate: Net oxygen uptake rates measured on Reactor I mixed liquor using synthetic feed as the substrate ranged from 2 to 5 mg D.O./g-h. The SOUR ratios are plotted in Figure 52 as a function of specific loading. This data is inconclusive due to the low loadings that were employed.

3. SOURs Measured Using Phenol as Substrate:

a. Reactor I: Net SOURs found when using phenol as the substrate ranged from less than 1 mg D.O./g SS-hr, to greater than 11. The SOUR ratios are shown in Figure 53 as a function of the in-situ phenol concentration. The ratios drop to below 1 at a concentration of 100 mg/l phenol or higher, indicating possible inhibition. It is clear from the trend in the data that phenol is inhibitory throughout much of the concentration range tested.

b. Reactor II: Net SOURs measured on Reactor II mixed liquor using phenol as substrate ranged
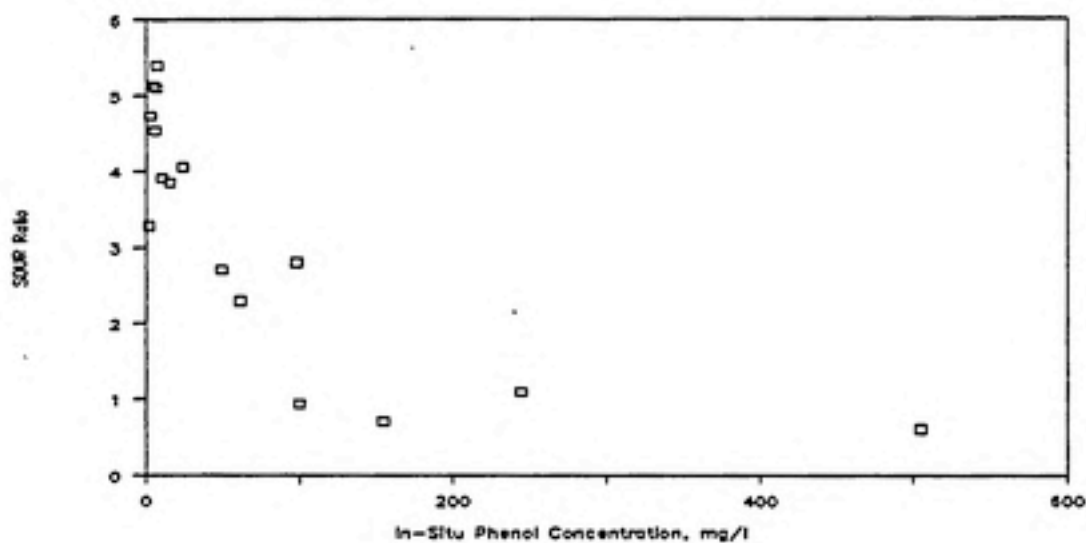
Figure 53: SOUR Ratios as a Function of Phenol Concentration, Reactor I. Measurements taken in February, 1990, when reactor was operating at two cycles per day.
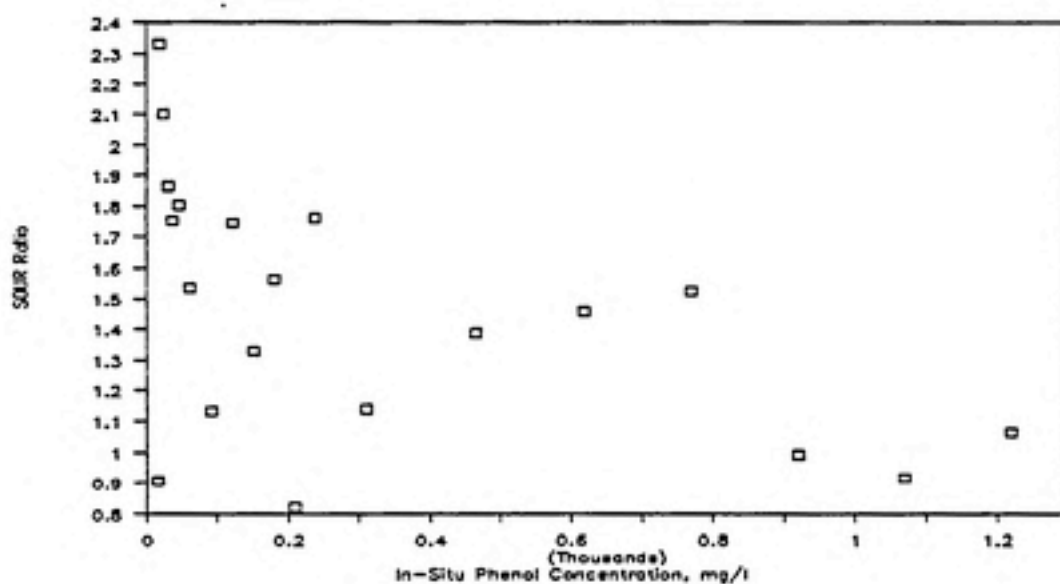
Figure 54: SOUR Ratios as a Function of Phenol Concentration, Reactor II. Measurements taken in April 1990, when reactor was operating at two cycles per day.

from 0.9 mg D.O./g SS-hr to 3. The SOUR ratios are plotted
in Figure 54 as a function of in-situ phenol concentration.
Inhibition appears to begin occurring at a concentration of
900 mg/l, indicating the mixed liquor was well acclimated
to high concentrations of phenol.

4. Inhibition by Feed Components: The inhibitory
effects of nitrosophenol, nitrite (NaNO2), 4-nitrophenol
and dissolved solids were studied using biological oxygen
uptake rate data. The effects of these compounds on the
SOUR was measured using the mixed liquor from Reactor I.
The in-situ phenol concentration was maintained at 10 mg/l
for each measurement. This concentration was found to give
a consistently measureable net SOUR. After each sample
stabilized at the phenol concentration, 4-nitrophenol,
nitrosophenol, and nitrite were injected to give in-situ
concentrations equal to that at the end of a Fill period.
As can be seen from Table 46, these compounds caused no
inhibition of the metabolic rate. In fact, addition of
nitrosophenol caused a marked increase in the oxygen uptake
rate.

5. SOURs Measured Using Activated Sludges from
Municipal Wastewater Treatment Plants: Oxygen uptake
experiments were performed with activated sludge samples
collected form the Orange Water and Sewer Authority (OWASA)

Table 46: Effect of Feed Species on Inhibition of the Specific
Oxygen Uptake Rate in Reactor I.

Compound Added	In–Situ Conc. of Comp'd (mg/l)	SOUR with phenol only (mg DO/ g SS–hr)	Feeding SOUR (mg DO/ g SS–hr)	Net SOUR (mg DO/ g SS–hr)	SOUR Ratio
4–nitrophenol	8	3.3	3.4	0.0	1.01
nitrosophenol	52	2.7	2.8	0.1	1.05
nitrosophenol	52	2.4	3.0	0.6	1.23
nitrite	1	1.8	2.1	0.3	1.15
nitrite	5	1.8	1.9	0.1	1.08

Note: Phenol concentration was 10 mg/l. Once mixed liquor sample
in oxygen uptake chamber became thermally stable, the phenol was
injected. Then after equilibrium was reached, the above compound
was added at the in–situ concentration shown.

Wastewater Treatment Plant, Chapel Hill, NC, and the
Farrington Road Wastewater Treatment Plant. These
experiments were performed to see if either of these mixed
liquors responded to phenol or raw waste. The OWASA mixed
liquor showed no response (no increase or decrease in net
SOUR) to raw waste and the Farrington Road mixed liquor
showed no response to phenol as a substrate. This
indicated that an acclimation period would have been
required, during which these organisms would possibly
develop enzymes to degrade phenolic compounds, and that the
best source of phenol-acclimated mixed liquor would be from
the Sandoz activated sludge basins.

Events During Different Cycle Periods

1. Phenol and soluble COD concentration profiles:

a. Reactor I, Feeding Synthetic Feed, One
Cycle Per Day: On 19 March 1990, the concentrations of
phenol and soluble COD were monitored during non-
consecutive Fill and React periods. Reactor I was
operating on a four hour Fill, 18 hour React, two hour
Settle cycle. The results of the monitoring are shown in
Table 47. It is interesting to note that a significant
portion of soluble COD and phenol are taken up during the

Table 47: Phenol and Soluble COD Concentration Profiles For Reactor
I During Non-Consecutive Fill and React Periods. Synthetic Feed Fed
Over One Cycle Per Day.

Period	Elapsed Time (hrs)	Measured Phenol Conc. (mg/l)	Theoretical Phenol Conc. (mg/l)	Measured COD Conc. (mg/l)	Theoretical COD Conc. (mg/l)
Fill	0	0		898	
	2	28.8	34	931	1051
	4	67.4	81.6	1095	1265
React	0	52.5	86.4	1046	1326
	2	41.2		1052	
	4	0		976	
	6			1117	

Table 48: Phenol and Soluble COD Concentration Profiles During
React For Reactor I. Synthetic Feed Fed Over Two Cycles Per Day.

Elapsed Time (hrs)	Measured Phenol Conc. (mg/l)	Phenol Removal Rate (mg/l-h)	Measured COD Conc. (mg/l)	COD Removal Rate (mg/l-h)
0.25	53.8		1801	
0.5	52.5	5.2	1703	392
1	50.5	5	1788	-170
1.5	48.9	3.2	1729	118
2	45.3	7.2	1743	-28
2.5	46.8	-3	1685	116
3	44.9	3.8	1707	-44
3.5	36.9	16	1694	26
4	33	7.8	1644	100
4.5	31.5	3	1707	-126
5	20.7	21.6	1618	178
5.5	17.2	7	1609	18
6	14.7	5	1602	14
8			1460	71

Note: Theoretical phenol concentration at beginning of
React: 52.5 mg/l. Theoretical COD at beginning of React:
1715 mg/l.

Fill period. Since all phenol was degraded by the fourth
hour of React, it is clear the reactor could have handled a
higher loading rate.

b. Reactor I, Feeding Synthetic Feed, Two
Cycles Per Day: A more detailed study of phenol and
soluble COD profiles was performed on 22 April 1990.
During this period, Reactor I was operated over two cycles
a day with a four hour Fill, six hour React, 2 hour Settle.
The results of this monitoring are shown in Table 48. On
this day of sampling, the reactor did not degrade the
phenol completely before the end of the React period. In
fact, the React period was extended an additional two hours
to see how much of the soluble COD would degrade if
aeration were extended. Approximately 10% of the reactor
COD was degraded in the additional two hours. The phenol
removal rate does appear to increase once the reactor
phenol concentration drops below 32 mg/l, suggesting that
inhibitory concentrations of phenol lie above 30 mg/l.

2. Measurement of Nitrate Nitrogen During Anoxic
Conditions (Denitrification): 200 ml of mixed liquor was
taken from Reactor I after a React period on 22 May 1990.
This aliquot was placed in an Erlenmeyer flask and stirred
moderately on a magnetic stirrer. Parafilm covered the
mouth of the Erlenmeyer to exclude air from the mixed
liquor, thus maintaining anoxic conditions. Nitrate,

phenol, and soluble COD measurements were taken before and after pulse feeding this mixed liquor 12 ml of synthetic feed. The nitrate concentration was measured approximately every 2 hours thereafter for a total of 8 hours. The results are shown in Table 49. Based on the theoretical concentrations of nitrate and phenol, approximately 25% of the available nitrate nitrogen was removed over the first 1.75 hours monitored. A decrease in the expected soluble COD concentration over this period, without a corresponding decrease in phenol concentration, may indicate that nitrosophenol is taken up as a result of nitrate respiration.

3. Biological Oxygen Uptake Measurements: Oxygen uptake rates were measured on the mixed liquor from Reactor I during a React period (reactor was operating at a loading rate of 0.25 g/g-d, 2 cycles per day). Oxygen uptake rates were determined every half hour during a 6 hour React period. Specific oxygen uptake rates are shown as functions of phenol and soluble COD concentrations in Figures 55 and 56, respectively. At the end of the React period, the phenol had not all been degraded.

The oxygen uptake rate was monitored for an additional two hours after React, and the uptake rate was noted to begin decreasing after 6.5 hours. Relatively low SOURs at

Table 49: Denitrification After a Pulse Feeding of Synthetic Feed.

Hours After Feed	Nitrate-N Conc. (mg/l)	Theor. Nitrate-N Conc. (mg/l)	Phenol Conc. (mg/l)	Theor. Phenol Conc. (mg/l)	Soluble COD (mg/l)	Theor. Soluble COD (mg/l)
-0.25	863		3		1444	
0		915		74.8		1791
0.25	824		70.8		1697	
1.75	715					
3	717					
5.25	703					
6.75	713		57.5		1936	

Note: Theoretical concentrations of nitrate-N, phenol, and soluble COD based on feeding 12 ml synthetic feed to 200 ml Reactor I mixed liquor.
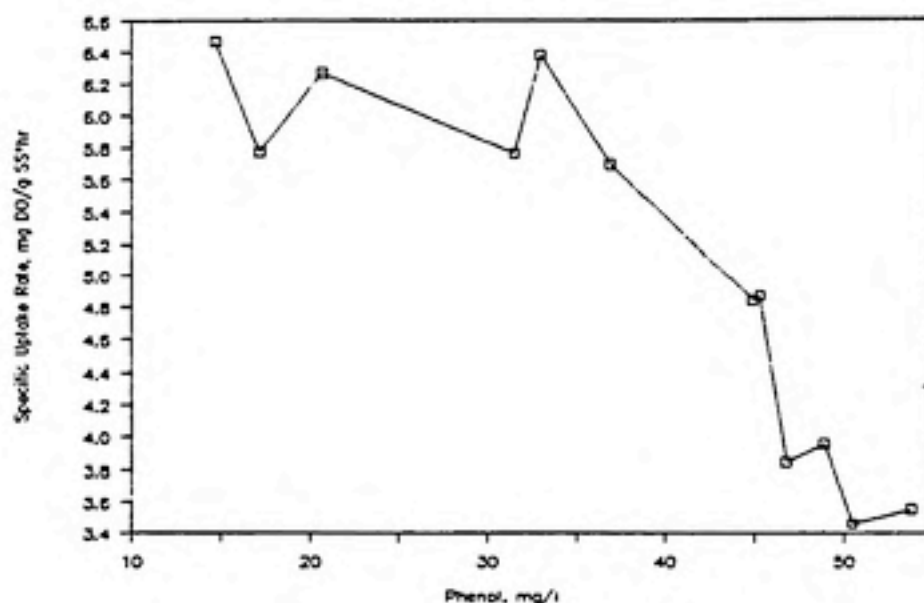
Figure 55: Specific Oxygen Uptake Rate as a Function of Phenol Concentration. Measurements taken during a React period, Reactor I, feeding synthetic feed one cycle per day.
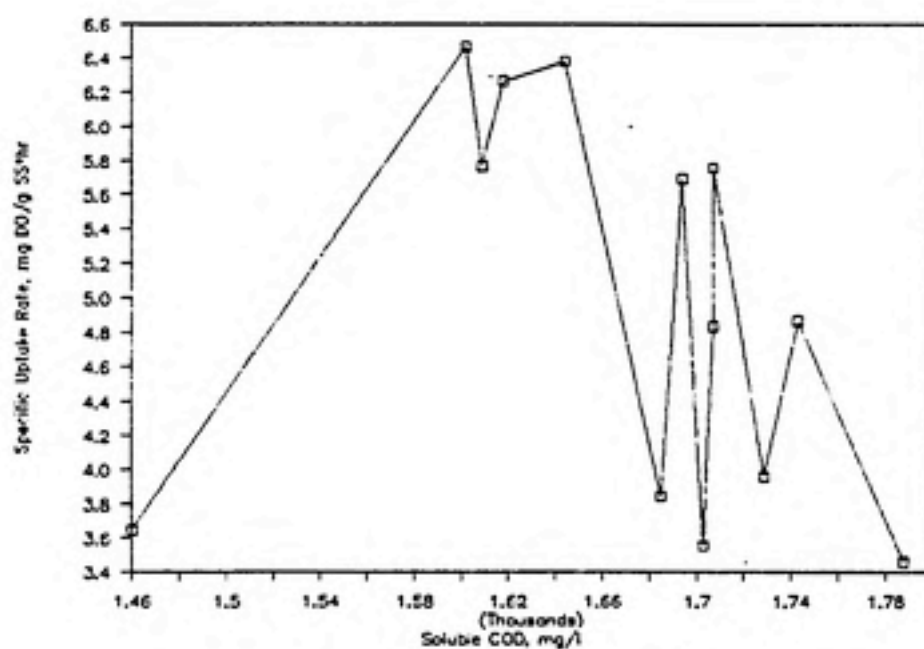
Figure 56: Specific Oxygen Uptake Rate as a Function of Soluble COD Concentration. Measurements taken during a React period, Reactor I, feeding synthetic feed one cycle per day.

the beginning of React seem to indicate inhibition of respiration at the inital concentrations of organic substrate. However, since React is characterized by a sudden shift from anaerobic to aerobic conditions, it is possible that low initial respiration rates represent a period of metabolic adjustment (new enzyme synthesis) to the shift in oxygen tension. There is no information in the SBR literature to support either explanation.

4. Determination of Yield During React Period: An attempt was made to estimate the yield of microorganisms resulting from the biodegradation of the synthetic feed. On 27 April 1990, total and soluble COD were measured as a function of time during a React period. The results are shown in Table 50. As can be seen from the table, no estimate of yield could be made from this data. It was anticipated that the total COD during the React period would increase as a result of biomass production on the synthetic feed added. However, the total COD actually decreased during the React period. In fact, the decrease in the total COD was greater than the decrease in soluble COD. This may be due to rapid accumulation of substrate by the biomass during the Fill period, with subsequent endogenous metabolism of the stored substrate during the React period.

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Table 50: Determination of Yield During React Period.

Period	Total COD (mg/l)	Standard Deviation (mg/l)		Soluble COD (mg/l)	Standard Deviation (mg/l)
Start of React	6270	480		1477	10
Middle of React	6050	67		1448	6
End of React	5860	8		1383	3
Overall Decrease in COD	410			94	

Note: Soluble COD of Reactor effluent measured two days before experiment was 1314 mg/l. Effluent soluble COD measured one day after experiment was 1274 mg/l. All samples were taken in duplicate.

Specific Studies On Nitrosophenol

      1. Titration of Nitrosophenol: 3.9 grams of nitrosophenol was dissolved in 300 ml of 0.1N NaOH. The pH probe was calibrated at pH 7.0 and pH 10.0. A 2.4N HCl solution was prepared by diluting 20 ml reagent grade concentrated HCl to 100 ml with distilled water. The results of the titration are shown in Figure 57 on the following page. A more defined titration was done between pH 11 and pH 8 as this is where the inflection point apparently occurs. This "blow up" of the inflection point is shown in Figure 58. The pKa appears to be approximately 9.5. This measured pKa differs markedly from a previously published value of 6.48 (Dean, 1985), though the presence of approximately 12% 4-nitrophenol in the nitrosophenol reagent may account for part of the difference.

      2. Fate of Nitrogen from Nitrosophenol Degradation: On 10 April 1990, 2 sets of triplicate flasks were prepared using 1.2 l of a 5:1 dilution of synthetic feed to which 150 mg/l MgSO4 and 2500 mg/l Na2SO4 had been added. Sodium nitrate was not added to the feed so that small changes in nitrate and nitrite concentrations could be measured more easily. Phosphate buffer and trace elements were added to the dilution. Each flask was filled with 400 ml of the dilution and 4 ml of enrichment culture. One set of flasks received 27.7 mg/l NH4Cl. MLSS, nitrate-
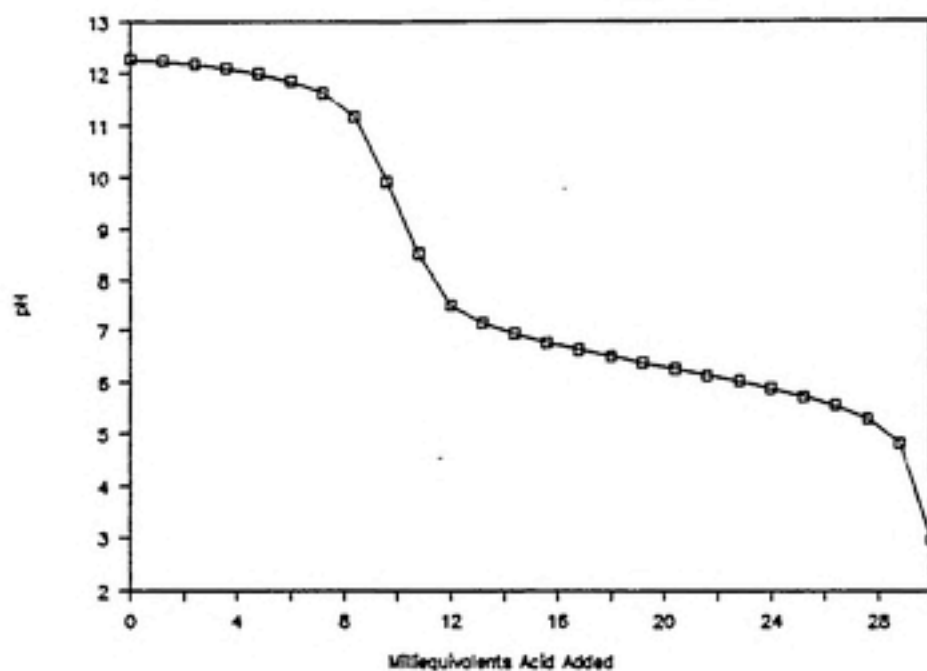
Figure 57: Titration Curve For Nitrosophenol.
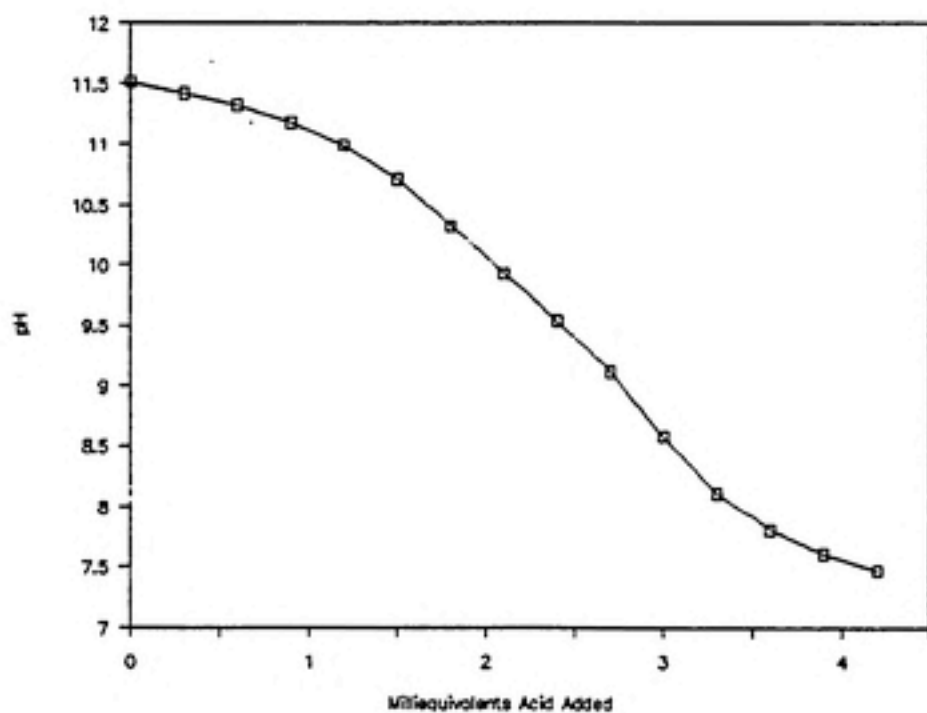
Figure 58: Blowup of Inflection Point for Nitrosophenol Titration.

nitrogen, nitrite-nitrogen, COD, and phenol concentrations were measured immediately after inoculation and after 9 days of growth. Results are shown in Table 51. It is clear from the table that there was relatively little change in non-phenol COD over the 9-day period, indicating little removal of nitrosophenol. There was a small but significant increase in nitrite concentration in both sets of flasks which would be consistent with mineralization of nitrosophenol.

3. Growth on Nitrosophenol Alone. In a preliminary experiment to evaluate growth on nitrosophenol as the sole carbon source, two flasks were filled with 500 ml each of 1300 mg/l nitrosophenol. To each flask, 10 ml of Reactor II mixed liquor was added. Baseline MLSS and soluble COD were measured in each flask. The flasks were aerated for four days. On the fourth day, the COD had dropped 5% (25 mg/l) and the suspended solids decreased by over 50%. This indicated that a substantially larger inoculum might be required to develop enrichment cultures able to use nitrosophenol as a sole carbon source.

4. Nitrosophenol Degradation in Reactor I: 140 ml of synthetic feed was prepared with phenol and nitrosophenol (no 4-nitrophenol added). Eight hours after feeding, the effluent phenol concentration was 16 mg/l. A synthetic feed was then prepared using only 1300 mg/l

Table 51: Fate of Nitrogen During Nitrosophenol Degradation.

Parameter	with NH4-N	Std. Dev.	without NH4-N	Std. Dev.
MLSS: day 0	0		1.1	1.1
day 9	10.2	3.5	12.9	3.6
NO3-N: day 0	25.3	1.1	23.9	1.1
day 9	22.7	1.7	24.2	2
NO2-N: day 0	0.131	0.082	0.131	0.049
day 9	0.629	0.091	0.866	0.053
Soluble COD: day 0	1144		1093	
day 9	537	34	655	123
Phenol: day 0	233.6	1.4	225	1.4
day 9	0		34.3	13

Note: Measurements with standard deviations shown were taken in triplicate.

nitrosophenol and inorganic salts (no phenol or 4-nitrophenol). 140 ml of this solution was fed over each of two 4-hour mixed Feed periods. Soluble COD was measured at the end of the React cycle and Fill cycles as shown in Table 52. The small change in soluble COD over the Fill period for nitrosophenol alone was less than the theoretical increase expected with each feeding and suggests that nitrosophenol was taken up by the biomass over this period. As discussed above, this removal of nitrosophenol cannot be accounted for simply by physical adsorption.

5. Oxygen Uptake Rates Using Nitrosophenol as a Substrate: Limited data were collected on the effect of nitrosophenol on respiration. If nitrosophenol were a growth substrate, SOURs would tend to increase as concentration increased (below an inhibitory range). Actual responses varied from slight stimulation of respiration at 1 mg/l nitrosophenol to slight inhibition at 60 mg/l.

Measurement of b, Microbial Decay Constant

The microbial decay constant for the mixed liquor was calculated based on measured MLSS values taken over six

Table 52: Degradation of Nitrosophenol as Sole Carbon Source in Reactor Feed.

	Sample Period	Feed Components	Effluent Phenol Conc. (mg/l)	Effluent Soluble COD Conc. (mg/l)
First Cycle	End of React	Phenol/Nitrosophenol	15.9	1738
Second Cycle	End of React	Nitrosophenol Alone	0	1750
Third Cycle	End of Fill	Nitrosophenol Alone		1723
	End of React	Nitrosophenol Alone		1736

Note: 155 mg/l soluble COD added to the reactor with each feeding of nitrosophenol alone.

days. A 100 ml aliqout of Reactor I mixed liquor was removed from the reactor and aerated. The MLSS samples were taken each day in triplicate and the results are shown in Table 53. The value of b was determined by plotting the ln of X (MLSS on each day) divided by Xo (initial MLSS) over time. The results are shown in Figure 59. The decay constant was found to be 0.0089/d.
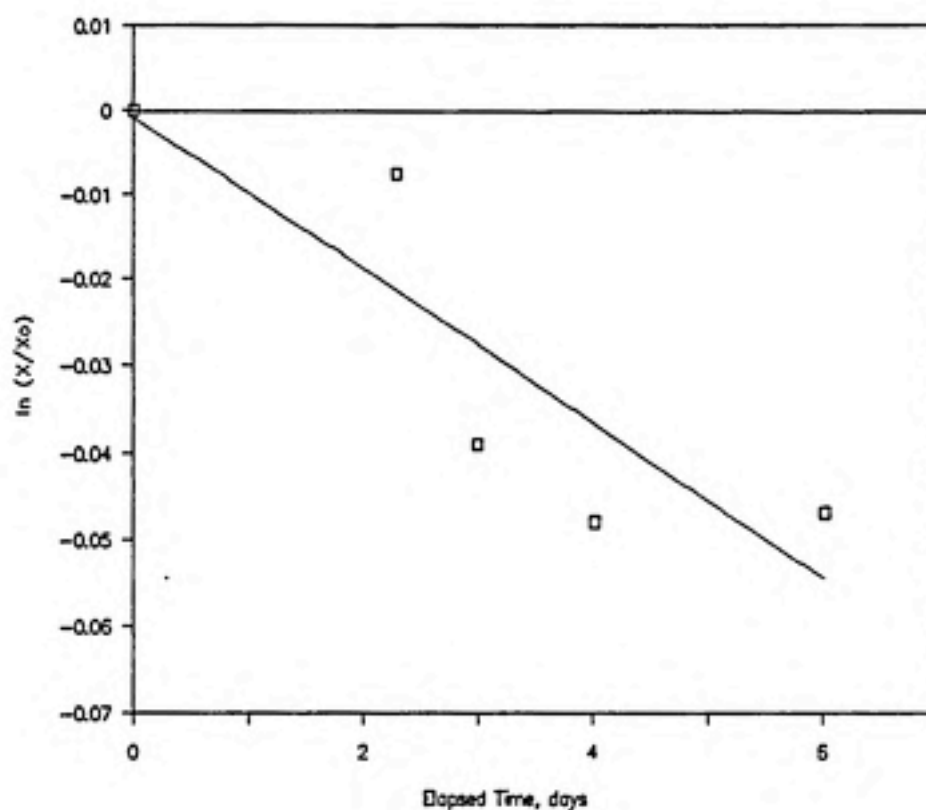
Figure 59: Determination of Decay Constant. Slope of curve is −0.0089/d. $r^2 = 0.7563$.

Table 53: Measurement of Mixed Liquor Decay over Time. Suspended solids values in boldface were used in calculation of b.

Date	Time	Elapsed Time (days)	MLSS (mg/l)	Std. Dev. (mg/l)
23 May	1100	0	6534	385
24 May	1015	0.96875	6683	303
25 May	1800	2.2917	6485	338
26 May	1100	3	6284	304
27 May	1130	4.0208	6228	176
28 May	1030	4.9792	6419	181
29 May	1130	6.0208	6235	180

VI. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The inhibitory effects of a phenolic feed fed to an SBR can be overcome by increasing the number of cycles per day. Consequently, substantially more waste can be treated as the number of cycles per day is increased. The best phenol and COD removal rates and the highest loading rates occurred when feeding synthetic waste over 2 cycles per day.

2. Effluent quality generally decreased as attempts were made to increase the loading rates.

3. Both reactors had high effluent suspended solids throughout the study period. The mixed liquor was noted to settle poorly. Wasting of reactor sludge and effluent suspended solids adversely affected the performance of the reactors.

4. Net sludge yields measured in enrichment cultures ranged from 0.029 to 0.836 g/g COD. However, net sludge

yields in the reactor appeared to be low, and were not sufficient to make up for losses of solids in the effluent. Consequently, artificial means of retaining biomass in the reactors had to be employed. In practice, techniques such as supplementation with an easily degradable substrate or use of polyelectrolytes to promote flocculation may be necessary. The value of b, the microbial decay constant, was determined at the end of this study to be 0.0089/d.

5. In Reactor II, better effluent quality was achieved when the raw waste, which had a relatively low phenol concentration (245 mg/l) was supplemented with additional phenol. Reactor II showed more inconsistency in performance when fed synthetic waste. The reason for this is uncertain, although substantial loss of biomass through feeding toxic amounts of phenol occurred before switching to synthetic feed.

6. Loss of phenol and soluble COD by air stripping was found to be insignificant. Precipitation of nitrosophenol under reactor conditions was found to be occurring, but at a much smaller rate than actual observed removal of soluble COD.

7. Addition of supplemental ammonia nitrogen was found to enhance the production of biomass and phenol

removal rates in enrichment cultures. The amount of phosphorus required in the feed to the reactors was found to be between 9 and 12 mg P/g COD. Trace elements were also necessary for optimum growth, but apparent toxicity was observed when metal concentrations were five times higher than normally fed.

8. Growth in shake flask experiments was essentially independent of pH. Also, pH stabilized near neutral in the reactors, so that pH adjustment would not be needed for optimum reactor performance.

9. Enrichment culture techniques may be a useful method of biomass development for reactor startup.

10. No inhibition of oxygen uptake rate was noted when nitrosophenol, nitrite, and 4-nitrophenol were added to a sample at the same concentration as in the reactor at the end of Fill. However, since nitrosophenol and 4-nitrophenol could act as uncouplers (Okey and Stensel, 1989), lack of respiration inhibition is not necessarily indicative that these compounds are not inhibitory to growth at typical in-reactor concentrations.

11. During the period when synthetic feed was being fed to Reactor I, it was determined a significant amount of phenol was taken up during the Fill period. Several

experiments also indicated that nitrosophenol may be accumulated intracellularly during Fill. This uptake may be related to nitrate consumption.

Recommendations

1. Use sequencing batch reactors to remove the bulk of the phenol and COD from the nitrosophenol production wastewater. Maintain the peroxide oxidation system as a possible polishing step for batches that may not meet effluent phenol standards.

2. Have Sandoz perform HPLC analysis of reactor effluent and the nitrosophenol filtrate treatment effluent (after peroxide oxidation) to compare the end products of the two treatment techniques.

3. Continue research to:

    a. Determine optimal number of cycles, maximum amount of feed that can be added per cycle, minimal feeding and react times, the effect of long periods of no feeding if the nitrosophenol production ceases for a period of time.

    b. Determine if neutralization of the raw waste

with lime (solubility of CaSO4 [gypsum] = 2.41 g/l), and
the concomitant reduction in dissolved solids enhances
biodegradation of the raw waste.

    c. Reevaluate the wet analytical method for the
analysis of nitrosophenol to determine concentrations of
influent and effluent nitrosophenol in the reactors and
estimate the degree of nitrosophenol degradation.

    d. Determine if an optimum phenol:nitrosophenol
ratio exists for the degradation of nitrosophenol.

    e. Institute a random feed concentration program
to the reactor, varying concentrations of phenol and
nitrosophenol to simulate the frequency distribution of the
60 HPLC runs done by Sandoz.

    f. Determine if enhanced settling of the effluent
can be achieved by adding an easily degradable carbon
source or polymer.

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VIII. APPENDICES

Appendix A: HPLC Data on Raw Waste Constituents Submitted by Sandoz.

Appendix B: Daily and Cumulative Data Collected on Reactor I. 5 September 1989 - 31 May 1990.

Appendix C: Daily and Cumulative Data Collected on Reactor II. 17 November 1989 - 1 May 1990.

Appendix A

Table A1: Results of 60 HPLC Measurements on Nitrosophenol Influent And Effluent. Data provided by Sandoz Chemicals

	Influent			Effluent		
Batch	4-Nitro-phenol Conc. (mg/l)	Nitroso-phenol Conc. (mg/l)	Phenol Conc. (mg/l)	4-Nitro-phenol Conc. (mg/l)	Nitroso-phenol Conc. (mg/l)	Phenol Conc. (mg/l)
76	127.3	645.8	833.9	0.0	0.0	0.0
77	168.2	941.8	916.2	0.0	0.0	0.0
78	113	668.1	781	0.0	0.0	0.0
79	144.5	1016.1	759.5	0.0	0.0	0.0
80	139.9	1171.2	699.2	0.0	0.0	0.0
81	150.6	1461.3	598.1	0.0	0.0	0.0
82	143.2	1029.4	732.4	0.0	0.0	0.0
83	162.7	1596.1	844.5	0.0	0.0	0.0
84	134.9	938.6	549.8	0.0	0.0	0.0
85	145.6	1028.6	554.4	0.0	0.0	0.0
86	164.2	1293	670.3	0.0	0.0	0.0
87	162.4	1672.5	408.4	0.0	0.0	0.0
88	27.4	1217.7	810	0.0	1.0	0.0
89	200	1218.3	675	0.0	0.0	0.0
90	13.8	1434	363	0.0	0.0	0.0
91	167.5	1264	741.3	0.0	0.0	0.0
92	162	1568	1110	0.0	0.0	0.0
93	842.4	1248.4	945	0.0	0.0	0.0
94	710.7	1529.7	732	0.0	0.0	0.0
95	683.3	1699.5	930.4	0.0	0.0	0.0
96	710	1012.5	603.7	0.0	0.0	0.0
97	427.7	1247.4	1010.8	0.0	0.0	0.0
98	179.2	1216.1	916	0.0	0.0	0.0
99	114.4	1091.6	731.8	0.0	0.0	0.0
100	153	1583.2	823.9	0.0	0.0	0.0
101	185.2	1640.1	1508.2	0.0	0.0	0.0
102	161.9	1178.1	908.4	0.0	-0.0	0.0
103	181.7	1357.2	1118.6	0.0	0.0	0.0
104	154.7	1573.7	1249.3	0.0	0.0	0.0
105	196.2	1602.3	1462.6	0.0	0.0	0.0
106	135	1326	1586	0.0	0.0	0.0
107	136	1177.5	1774	0.0	0.0	0.0
108	273.2	1265.4	1801	0.0	0.0	0.0
109	125.8	1606.7	1629.6	0.0	0.0	0.0
110	113.1	1375.2	1429.4	0.0	0.0	0.0

Appendix A

Table A1: Results of 60 HPLC Measurements on Nitrosophenol Influent And Effluent. Data provided by Sandoz Chemicals

	Influent			Effluent		
Batch	4-Nitro-phenol Conc. (mg/l)	Nitroso-phenol Conc. (mg/l)	Phenol Conc. (mg/l)	4-Nitro-phenol Conc. (mg/l)	Nitroso-phenol Conc. (mg/l)	Phenol Conc. (mg/l)
111	113.3	1740.1	1552	0.0	0.0	0.0
112	112.4	1922.8	1620	0.0	0.0	0.0
113	115.1	1949.8	1523.4	0.0	0.0	0.0
114	127.4	1801.2	1729.5	0.0	0.0	0.0
115	138.5	1774.2	1761	0.0	0.0	0.0
116	126.3	1708.3	1667.1	0.0	0.0	0.0
117	136.4	1779.4	1671	<5.0	<5.0	<5.0
118	133	1700.6	1617.8	<5.0	<5.0	<5.0
119	135.3	1906	1587.7	<5.0	<5.0	<5.0
120	117.9	1310	1359	0.0	0.0	0.0
121	116.9	1164.5	1441.2	0.0	0.0	0.0
122	97.6	1178	1134.6	0.0	0.0	0.0
123	97.7	1584	1113	0.0	0.0	0.0
124	126.7	926.1	1172	0.0	0.0	0.0
125	124.5	1558.4	1453	0.0	0.0	0.0
126	205.4	664.7	953.4	0.0	0.0	0.0
127	269	672.6	645.6	0.0	0.0	0.0
128	182.4	831.9	977.7	0.0	0.0	0.0
129	165.2	1171.1	1097.8	0.0	0.0	0.0
130	135.2	981.2	1017.6	0.0	0.0	0.0
131	156.8	1327	1207.5	0.0	0.0	0.0
132	160	1319.3	1217.9	0.0	0.0	0.0
133	122	1493	1321.4	0.0	0.0	0.0
134	119.5	1508	1198.4	0.0	0.0	0.0
135	123.9	1587.2	1352.6	0.0	0.0	0.0
Average:	187.8	1340.9	1110.1	0.0	0.0	0.0
Std Dev:	15.9	33.1	36.9	0.0	0.0	0.0

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Table B1: Biodegradation in Reactor I, Sep 1989

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Inf. COD (mg)	Cum. Inf. NonPhenol COD (mg)	Feed Phenol (mg/l)	Cum. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)
09/05	0		0	0		0	4875	259	5.3	2.5	0.00
09/06	294	6842	2012	1296	1021	300	4305	261	6.1	2.7	0.17
09/07	294	6842	4023	2592	1021	600	4000	249	6.2	2.6	0.20
09/08	294	6842	6035	3889	1021	901	3530	81	2.3	2.4	0.25
09/09	0	6842	6035	3889	1021	901	4168	106	2.5	2.2	0.00
09/10	300	6842	8087	5211	1021	1207	3308	88	2.7	2.4	0.27
09/11	0	6842	8087	5211	1021	1207	2884	36	1.2	2.1	0.00
09/12	0	6031	8087	5211	1010	1207	2277	45	2.0	2.0	0.00
09/13	0	6031	8087	5211	1010	1207	2698	49	1.8	1.8	0.00
09/14	0	6031	8087	5211	1010	1207	1175	14	1.2	1.8	0.00
09/15	180	6031	9173	5864	1010	1389	582	44	7.6	1.8	1.08
09/16	190	6031	10319	6552	1010	1581	505	52	10.3	2.5	0.95
09/17	0	6031	10319	6552	1010	1581	592	191	32.3	2.5	0.00
09/18	0	6476	10319	6552	1019	1581	698	298	42.7	2.5	0.00
09/19	0	6476	10319	6552	1019	1581	5060	174	3.4	2.3	0.00
09/20	0	6476	10319	6552	1019	1581	1658	35	2.1	2.5	0.00
09/21	320	6476	12391	7848	1019	1907	1926	92	4.8	2.5	0.45
09/22	0	6476	12391	7848	1019	1907	1539	83	5.4	2.5	0.00
09/23	0	6476	12391	7848	1019	1907	1857	51	2.7	2.5	0.00
09/24	0	6476	12391	7848	1019	1907	1049	186	17.7	2.5	0.00
09/25	0	6476	12391	7848	1019	1907	1459	83	5.7	2.4	0.00
09/26	110	5645	13012	8210	986	2015	1757	61	3.5	2.3	0.16
09/27	80	5645	13464	8474	986	2094	698	268	38.4	2.4	0.28
09/28	195	5645	14564	9116	986	2286	934	123	13.2	2.4	0.51
09/29	250	5645	15976	9940	986	2533	1252	104	8.3	2.4	0.49
09/30	300	5645	17669	10929	986	2829	1988	95	4.8	2.5	0.36

Table BI: Biodegradation in Reactor I, Sep 1989

Date	Effluent COD (mg/l)	COD Std. Dev. (mg/l)	COD % Error	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day
09/05	503	221	44.0	1258	0	8.0	0.5	6.2	19.9	0	--
09/06	646	40	6.2	1553	190	14.7	0.8	5.6	35.2	4	1
09/07	580	49	8.4	1339	360	18.8	0.2	1.2	43.3	10	1
09/08	1224	2	0.2	2578	720	33.2	0.7	2.2	69.8	20	1
09/09	1147	15	1.3	2524	720	26.7	0.1	0.4	58.8	20	1
09/10	1389	26	1.9	2951	1137	142.9	3.1	2.2	303.7	62	1
09/11	1624	4	0.3	3411	1137	136.8	12.8	9.3	287.2	62	1
09/12	1162	17	1.5	2324	1137	100.0	3.9	3.9	200.0	62	1
09/13	1677	0	0.0	3019	1137	116.4	0.3	0.2	209.5	62	1
09/14	1198	7	0.5	2156	1137	27.3	0.4	1.5	49.1	62	1
09/15	1200	10	0.8	1943	1353	84.3	3.8	4.5	136.5	78	1
09/16	1458	0	0.0	3367	1630	133.0	0.0	0.0	307.3	103	1
09/17	1277	2	0.2	3127	1630	56.0	0.0	0.0	137.2	103	1
09/18	1155	--	ERR	2830	1630	32.4	0.0	0.0	79.4	103	1
09/19	985	2	0.2	2264	1630	27.1	0.0	0.0	62.3	103	1
09/20	783	6	0.8	1956	1630	21.8	0.2	1.0	54.4	103	1
09/21	1228	0	0.0	2676	2023	125.9	0.8	0.7	274.5	143	1
09/22	1131	35	3.1	2826	2023	115.6	0.0	0.0	289.0	143	1
09/23	937	4	0.5	2343	2023	81.2	0.4	0.5	203.1	143	1
09/24	714	9	1.2	1784	2023	18.6	0.1	0.5	46.5	143	1
09/25	606	8	1.3	1453	2023	18.9	0.4	2.1	45.4	143	1
09/26	660	2	0.3	1445	2095	20.2	0.1	0.5	44.2	145	1
09/27	617	17	2.8	1431	2145	19.0	0.1	0.5	44.1	147	1
09/28	739	0	0.0	1629	2289	23.2	0.1	0.4	51.2	151	1
09/29	1123	2	0.2	2427	2571	98.5	0.0	0.0	211.8	176	1
09/30	--	--	ERR	ERR	2910	77.1	0.0	0.0	169.6	252	1

Table B1: Biodegradation in Reactor I, Sep 1989

Date	React Period (hrs)	Feed Period (hrs)	Settle Period (hrs)	Effluent Volume (ml)
09/05	--	--	--	0
09/06	24	4	0	400
09/07	23	4	1	300
09/08	23	4	1	125
09/09	23	0	1	10
09/10	23	4	1	125
09/11	23	0	1	125
09/12	23	0	1	10
09/13	23	0	1	10
09/14	23	0	1	75
09/15	23	4	1	75
09/16	23	4	1	50
09/17	23	0	1	100
09/18	23	0	1	50
09/19	23	0	1	50
09/20	23	0	1	250
09/21	23	0	1	250
09/22	23	0	1	250
09/23	23	0	1	250
09/24	23	0	1	250
09/25	23	0	1	240
09/26	23	8	1	230
09/27	23	8	1	240
09/28	23	8	1	240
09/29	23	8	1	240
09/30	23	0	1	100

Table B2: Biodegradation in Reactor I, Oct 1989

Date	Feed COD (mg/l)	Con. Inf. COD (mg)	Feed Phenol (mg/l)	Con. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS·d)	Effluent COD (mg/l)	COD Std. Dev. (mg/l)
10/01	5645	17669	986	2829	1093	25	2.3	2.4	0.00	--	--
10/02	5645	17867	986	2864	1248	214	17.1	2.4	0.07	--	--
10/03	5645	18431	986	2962	----	---	ERR	2.4	0.20	--	--
10/04	5645	19334	986	3120	677	91	13.4	2.3	0.61	--	--
10/05	5645	19758	986	3194	----	---	ERR	2.3	0.28	--	--
10/06	5645	21169	986	3440	----	---	ERR	2.5	0.95	--	--
10/07	5645	21169	986	3440	257	55	21.4	2.4	0.00	--	--
10/08	5727	22314	979	3636	245	41	16.7	2.4	2.03	1102	17
10/09	5727	24032	979	3930	161	60	37.3	2.6	4.28	--	--
10/10	5727	24032	979	3930	200	11	5.5	2.5	0.00	1206	21
10/11	5727	24032	979	3930	217	50	23.0	2.4	0.00	--	--
10/12	5727	24891	979	4077	187	70	37.4	2.4	2.00	1412	9
10/13	5727	24891	979	4077	204	58	28.4	2.4	0.00	--	--
10/14	5727	24891	979	4077	163	19	11.7	2.4	0.00	1181	4
10/15	5727	25321	979	4150	223	17	7.6	2.5	0.80	--	--
10/16	5339	25855	973	4247	246	48	19.5	2.5	0.92	1108	0
10/17	5339	26522	973	4369	220	33	15.0	2.5	1.29	--	--
10/18	5339	27136	973	4481	214	41	19.2	2.5	1.20	1260	13
10/19	5339	27937	973	4627	262	9	3.4	2.6	1.25	--	--
10/20	5339	29005	973	4821	269	6	2.2	2.7	1.53	1382	51
10/21	5339	29005	973	4821	215	31	14.4	2.6	0.00	--	--
10/22	5070	29765	937	4962	204	26	12.7	2.6	1.50	1430	17
10/23	5070	29765	937	4962	217	44	20.3	2.6	0.00	--	--
10/24	5070	30830	937	5159	191	20	10.5	2.7	2.19	1394	9
10/25	5070	30830	937	5159	286	14	4.9	2.5	0.00	--	--
10/26	5070	31844	937	5346	308	34	11.0	2.7	1.30	--	--
10/27	5070	31844	937	5346	293	73	24.9	2.6	0.00	--	--
10/28	5070	31844	937	5346	229	44	19.2	2.6	0.00	--	--
10/29	5070	31844	937	5346	276	26	9.4	2.5	0.00	1241	4
10/30	5070	32858	937	5534	245	12	4.9	2.7	1.63	--	--
10/31	5070	32858	937	5534	907	36	4.0	2.7	0.00	--	--

Table B2: Biodegradation in Reactor I, Oct 1989

Date	COD % Error	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)	Feed Period (hrs)
10/01	ERR	ERR	2910	23.7	0.1	0.4	56.9	251	1	23	0
10/02	ERR	ERR	2950	23.5	0.1	0.4	55.6	252	1	23	8
10/03	ERR	ERR	3062	25.4	0.1	0.4	58.4	254	1	23	8
10/04	ERR	ERR	3243	26	0.1	0.4	59.9	259	1	23	8
10/05	ERR	ERR	3328	23.8	0	0.0	53.0	261	1	23	8
10/06	ERR	ERR	3610	76.3	0	0.0	171.7	280	1	23	0
10/07	ERR	ERR	3610	33.1	0.3	0.9	79.4	280	1	23	8
10/08	1.5	2424	3830	35.7	0.1	0.3	78.5	287	1	23	8
10/09	ERR	ERR	4161	142.9	0.6	0.4	328.7	330	1	23	0
10/10	1.8	3015	4161	41.3	0.6	1.5	103.3	330	1	23	0
10/11	ERR	ERR	4161	38.5	0	0.0	92.4	330	1	23	8
10/12	0.6	3177	4373	86.3	0	0.0	194.2	343	1	23	0
10/13	ERR	ERR	4373	41.3	0.1	0.2	99.1	343	1	23	0
10/14	0.4	2834	4373	37.1	0	0.0	89.0	343	1	23	8
10/15	ERR	ERR	4461	37.4	0.2	0.5	90.7	345	1	23	8
10/16	0.0	2604	4572	37.4	0.1	0.3	87.9	349	1	23	8
10/17	ERR	ERR	4711	39.9	0.1	0.3	92.8	354	1	23	8
10/18	1.0	3005	4855	40.3	0	0.0	96.1	359	1	23	8
10/19	ERR	ERR	5044	39.7	0	0.0	95.3	365	1	23	8
10/20	3.7	3455	5321	84.2	0.9	1.1	210.5	382	1	23	0
10/21	ERR	ERR	5321	41.9	0.1	0.2	106.8	382	1	23	8
10/22	1.2	3504	5535	88.7	0.5	0.6	217.3	395	1	23	0
10/23	ERR	ERR	5535	36.5	0.3	0.8	93.1	395	1	23	0
10/24	0.6	3401	5828	98.1	0.3	0.3	239.4	416	1	23	0
10/25	ERR	ERR	5828	38.7	0	0.0	96.8	416	1	23	8
10/26	ERR	ERR	6107	105.4	0	0.0	260.7	437	1	23	0
10/27	ERR	ERR	6107	104.8	0	0.0	272.5	437	1	23	0
10/28	ERR	ERR	6107	98.1	0.3	0.3	250.2	437	1	23	0
10/29	0.3	3103	6107	42	0.3	0.7	105.0	437	1	23	8
10/30	ERR	ERR	6355	108.3	0.6	0.6	265.3	458	1	23	0
10/31	ERR	ERR	6355	92.9	0.1	0.1	250.8	458	1	23	0

Table B2: Biodegradation in Reactor I, Oct 1989

Date	Settle Period (hrs)	Effluent Volume (ml)	MCRT (days)
10/01	1	500	
10/02	1	100	
10/03	1	200	
10/04	1	230	
10/05	1	100	
10/06	1	100	50
10/07	1	100	
10/08	1	150	33
10/09	1	100	
10/10	1	50	
10/11	1	50	
10/12	1	100	
10/13	1	50	
10/14	1	65	
10/15	1	75	
10/16	1	65	
10/17	1	55	
10/18	1	65	
10/19	1	60	
10/20	1	100	
10/21	1	60	
10/22	1	100	
10/23	1	100	
10/24	1	150	
10/25	1	50	
10/26	1	80	
10/27	1	70	
10/28	1	75	
10/29	1	50	
10/30	1	50	
10/31	1	50	

Table B3: Biodegradation in Reactor I, Nov 1989

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Inf. COD (mg)	Feed Phenol (mg/l)	Cum. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
11/01	0	5070	32858	937	5534	997	77	7.7	2.6	0.00	1226
11/02	100	5070	33365	937	5628	---	--	ERR	2.7	0.20	----
11/03	87	5070	33805	937	5709	891	60	6.7	2.7	0.19	----
11/04	110	5070	34364	937	5812	---	--	ERR	2.6	0.25	----
11/06	120	5070	34972	937	5925	924	82	8.9	2.7	0.26	----
11/07	125	5070	35606	937	6042	---	--	ERR	2.7	0.27	----
11/08	0	5070	35606	965	6042	862	28	3.2	2.7	0.00	----
11/09	0	5070	35606	965	6042	---	--	ERR	2.6	0.00	1287
11/10	120	5070	36214	965	6158	956	48	5.0	2.6	0.26	----
11/11	125	5070	36848	965	6278	---	--	ERR	2.6	0.27	----
11/12	130	5070	37507	965	6404	980	36	3.7	2.6	0.28	----
11/13	135	5070	38192	965	6534	---	--	ERR	2.6	0.29	1298
11/14	106	5070	38729	965	6636	879	43	4.9	2.7	0.24	----
11/15	0	5070	38729	965	6636	---	--	ERR	2.6	0.00	----
11/16	125	5070	39363	992	6760	1081	66	6.1	2.6	0.24	----
11/17	130	5070	40022	992	6889	---	--	ERR	2.6	0.24	----
11/19	0	5070	40022	992	6889	---	--	ERR	2.6	0.00	----
11/20	100	5070	40529	992	6988	971	53	5.5	2.6	0.21	----
11/21	0	5070	40529	992	6988	---	--	ERR	2.6	0.00	----
11/22	100	5070	41036	992	7088	---	--	ERR	2.6	0.21	----
11/24	0	5070	41036	984	7088	944	63	6.7	2.6	0.00	1259
11/25	80	5070	41442	984	7166	---	--	ERR	2.6	0.17	----
11/26	90	5070	41898	984	7255	1307	206	15.8	2.5	0.15	----
11/27	100	5070	42405	984	7353	---	--	ERR	2.5	0.16	----
11/28	0	5070	42405	984	7353	2839	24	0.8	2.6	0.00	972
11/29	90	5070	42861	984	7442	---	--	ERR	2.7	0.06	----
11/30	100	5070	43368	984	7540	---	--	ERR	2.7	0.07	----

Table B3: Biodegradation in Reactor I, Nov 1989

Date	COD Std. Dev. (mg/l)	COD % Error	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Phenol Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)
11/01	0	0.0	3188	6355	40.4	0.2	0.5	105.0	452	1	23
11/02	--	ERR	ERR	6478	44.6	0.2	0.4	113.7	456	1	23
11/03	--	ERR	ERR	6584	41.3	0.0	0.0	105.9	460	1	23
11/04	--	ERR	ERR	6719	40.8	0.1	0.2	101.6	465	1	23
11/06	--	ERR	ERR	6865	40.9	0.5	1.2	103.5	469	1	23
11/07	--	ERR	ERR	7019	83	0.1	0.1	209.6	480	1	23
11/08	--	ERR	ERR	7019	58.2	0.1	0.2	154.2	480	1	23
11/09	17	1.3	3346	7019	39.2	0	0.0	101.9	480	1	23
11/10	--	ERR	ERR	7174	40.6	0.4	1.0	100.7	485	1	23
11/11	--	ERR	ERR	7335	40.9	0.5	1.2	101.2	490	1	23
11/12	--	ERR	ERR	7502	40.9	0.5	1.2	99.0	495	1	23
11/13	13	1.0	3135	7677	46.4	0	0.0	112.1	501	1	23
11/14	--	ERR	ERR	7815	78.5	0.1	0.1	199.7	510	1	23
11/15	--	ERR	ERR	7815	40.5	0.1	0.2	103.3	510	1	23
11/16	--	ERR	ERR	7977	39	0.1	0.3	96.5	515	1	23
11/17	--	ERR	ERR	8146	85.7	0.3	0.4	211.7	526	1	23
11/19	--	ERR	ERR	8146	40.7	0.1	0.2	105.8	526	1	23
11/20	--	ERR	ERR	8276	61.6	0.1	0.2	154.0	532	1	23
11/21	--	ERR	ERR	8276	38.5	0.1	0.3	100.1	532	1	23
11/22	--	ERR	ERR	8406	72.2	0	0.0	180.5	539	1	23
11/24	4.2	0.3	3273	8406	38.9	0	0.0	101.1	539	1	23
11/25	--	ERR	ERR	8506	40.7	0.2	0.5	100.5	542	1	23
11/26	--	ERR	ERR	8620	40.1	0	0.0	96.6	546	1	23
11/27	--	ERR	ERR	8745	64.5	0.3	0.5	151.6	552	1	23
11/28	13	1.3	2527	8745	27.1	0.3	1.1	70.5	552	1	23
11/29	--	ERR	ERR	8833	21	0.1	0.5	53.8	554	1	23
11/30	--	ERR	ERR	8930	23.3	1.1	4.7	60.6	557	1	23

Table 83: Biodegradation in Reactor I, Nov 1989

Date	Feed Period (hrs)	Settle Period (hrs)	Effluent Volume (ml)
11/01	8	1	50
11/02	8	1	100
11/03	8	1	100
11/04	8	1	100
11/06	8	1	100
11/07	0	1	50
11/08	0	1	50
11/09	8	1	100
11/10	8	1	100
11/11	8	1	120
11/12	8	1	100
11/13	8	1	50
11/14	0	1	50
11/15	8	1	100
11/16	8	1	100
11/17	0	1	50
11/19	8	1	100
11/20	0	1	50
11/21	8	1	100
11/22	0	1	50
11/24	8	1	100
11/25	8	1	100
11/26	8	1	150
11/27	0	1	600
11/28	8	1	100
11/29	8	1	100
11/30	8	1	200

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Table B4: Biodegradation in Reactor I, Dec 1989

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Inf. COD (mg)	Feed Phenol (mg/l)	Cum. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS·d)	Effluent COD (mg/l)
12/01	110	5070	43926	984	7648	----	---	ERR	2.8	0.08	----
12/02	120	5070	44534	921	7759	----	---	ERR	2.6	0.09	----
12/03	130	5070	45193	921	7878	----	---	ERR	2.7	0.09	----
12/04	140	5070	45903	921	8007	2654	133	5.0	2.6	0.11	971
12/05	150	5070	46664	921	8146	----	---	ERR	2.7	0.12	----
12/06	160	5070	47475	921	8293	----	---	ERR	2.7	0.12	----
12/07	180	5070	48387	921	8459	3103	1539	49.6	2.7	0.11	----
12/08	210	5070	49452	921	8652	----	---	ERR	2.7	0.13	----
12/10	230	5070	50618	921	8864	----	---	ERR	2.8	0.15	----
12/12	250	8490	52741	245	8925	----	---	ERR	2.8	0.26	----
12/13	0	8490	52741	245	8925	----	---	ERR	2.8	0.00	----
12/14	0	8490	52741	245	8925	----	---	ERR	2.8	0.00	----
12/15	200	8490	54439	245	8974	2664	121	4.5	2.7	0.25	----
12/17	150	8490	55712	245	9011	----	---	ERR	2.5	0.18	----
12/19	150	8490	56986	245	9048	----	---	ERR	2.5	0.18	----
12/21	150	8490	58259	245	9084	----	---	ERR	2.7	0.18	----
12/23	150	8490	59533	245	9121	----	---	ERR	2.7	0.18	----
12/25	150	8490	60806	245	9158	----	---	ERR	2.5	0.18	----
12/29	150	8490	62080	245	9195	----	---	ERR	2.8	0.18	----
12/30	150	16000	64480	6667	10195	2491	88	3.5	2.6	0.39	2829

Table B4: Biodegradation in Reactor I, Dec 1989

Date	COD Std. Dev. (mg/l)	COD % Error	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)
12/01	---	ERR	ERR	9037	22.3	0.1	0.4	58.9	559	1	23
12/02	---	ERR	ERR	9154	19	0.0	0.0	47.1	562	1	23
12/03	---	ERR	ERR	9280	19.3	0.4	2.1	48.6	564	1	23
12/04	16	1.6	2389	9416	21.5	0.8	3.7	52.9	567	1	23
12/05	---	ERR	ERR	9562	25.5	0.3	1.2	63.8	571	1	23
12/06	---	ERR	ERR	9717	20.1	0.5	2.5	50.0	574	1	23
12/07	---	ERR	ERR	9892	18.5	0.1	0.5	46.6	578	1	23
12/08	---	ERR	ERR	10096	----	---	ERR	ERR	578	1	23
12/10	---	ERR	ERR	10319	15.4	0.1	0.6	38.8	582	1	23
12/12	---	ERR	ERR	10562	26.1	0	0.0	65.6	588	1	23
12/13	---	ERR	ERR	10562	27.8	0.2	0.7	77.8	588	1	23
12/14	---	ERR	ERR	10562	27.9	0.1	0.4	78.1	588	1	23
12/15	---	ERR	ERR	10564	36.2	0.3	0.8	90.5	595	1	23
12/17	---	ERR	ERR	10710	37.2	0.2	0.5	87.4	601	1	23
12/19	---	ERR	ERR	10855	42.6	0.2	0.5	100.1	607	1	23
12/21	---	ERR	ERR	11001	----	---	ERR	ERR	607	1	23
12/23	---	ERR	ERR	11147	----	---	ERR	ERR	607	1	23
12/25	---	ERR	ERR	11292	----	---	ERR	ERR	607	1	23
12/29	---	ERR	ERR	11438	75.8	0	0.0	197.1	618	1	23
12/30	42	1.5	6790	11862	409	0	0.0	981.6	680	1	23

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Table B4: Biodegradation in Reactor I, Dec 1989

Date	Feed Period (hrs)	Settle Period (hrs)	Effluent Volume (ml)	MCRT (days)
12/01	8	1	150	
12/02	8	1	150	
12/03	8	1	250	50
12/04	8	1	175	100
12/05	8	1	150	
12/06	8	1	230	
12/07	8	1	200	
12/08	8	1	200	
12/10	8	1	250	
12/12	8	1	300	
12/13	0	1	300	
12/14	0	1	300	
12/15	8	1	400	
12/17	8	1	150	
12/19	8	1	200	
12/21	8	1	0	
12/23	8	1	300	
12/25	8	1	0	
12/29	8	1	350	
12/30	0	1	150	

Table B5: Biodegradation in Reactor I, Jan 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Inf. COD (mg)	Feed Phenol (mg/l)	Cum. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/g SS*d)	Effluent COD (mg/l)
01/01	0	16000	64480	6667	10195	----	---	ERR	2.55	0.00	----
01/03	0	16000	64480	6667	10195	----	---	ERR	2.55	0.00	----
01/04	0	16000	64480	6667	10195	----	---	ERR	2.5	0.00	----
01/05	0	16000	64480	6667	10195	----	---	ERR	2.3	0.00	----
01/07	0	16000	64480	6667	10195	----	---	ERR	2.28	0.00	----
01/08	0	16000	64480	6667	10195	----	---	ERR	2.2	0.00	----
01/10	0	16000	64480	6667	10195	----	---	ERR	2.2	0.00	1917
01/11	0	16000	64480	6667	10195	2748	133	4.8	2.3	0.00	----
01/12	0	16000	64480	6667	10195	----	---	ERR	2.3	0.00	----
01/14	0	16000	64480	6667	10195	----	---	ERR	2.3	0.00	----
01/15	0	16000	64480	6667	10195	----	---	ERR	2.25	0.00	----
01/16	0	16000	64480	6667	10195	----	---	ERR	2.2	0.00	941
01/17	100	7505	65231	143	10209	----	---	ERR	2.2	0.12	----
01/18	150	7505	66356	143	10231	----	---	ERR	2.2	0.19	----
01/19	180	7505	67707	143	10256	----	---	ERR	2.3	0.22	----
01/20	210	7505	69283	143	10287	2026	107	5.3	2.45	0.33	----
01/21	230	7505	71009	143	10319	----	---	ERR	2.65	0.36	----
01/22	250	7505	72886	143	10355	----	---	ERR	2.5	0.39	----
01/23	0	7505	72886	143	10355	2308	31	1.3	2.5	0.00	----
01/24	0	7505	72886	143	10355	----	---	ERR	2.5	0.00	1355
01/25	200	7505	74387	143	10384	----	---	ERR	2.5	0.27	1558
01/26	0	7505	74387	143	10384	----	---	ERR	2.5	0.00	----
01/27	100	4800	74867	2000	10584	----	---	ERR	2.45	0.09	----
01/29	0	4800	74867	2000	10584	----	---	ERR	2.4	0.00	----
01/30	0	4800	74867	2000	10584	----	---	ERR	2.45	0.00	----
01/31	0	4800	74867	2000	10584	2305	103	4.5	2.45	0.00	----

Table B5: Biodegradation in Reactor I, Jan 1990

Date	COD Std. Dev. (mg/l)	COD % Error	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Effluent MLSS (mg/l)	Cycles per day
01/01	---	ERR	ERR	11862	426	3.2	0.8	1086.3	680		1
01/03	---	ERR	ERR	11862	417	2.2	0.5	1063.4	680		1
01/04	---	ERR	ERR	11862	394	0.0	0.0	985.0	680		1
01/05	---	ERR	ERR	11862	330.4	0.5	0.2	759.9	680		1
01/07	---	ERR	ERR	11862	304.4	0.9	0.3	694.0	680		1
01/08	---	ERR	ERR	11862	294.5	1.4	0.5	647.9	680		1
01/10	4	0.2	4218	11862	281.3	3.6	1.3	618.9	680		1
01/11	---	ERR	ERR	11862	268.8	2.3	0.9	618.2	680		1
01/12	---	ERR	ERR	11862	264	1.8	0.7	607.2	680		1
01/14	---	ERR	ERR	11862	171.3	3.2	1.9	394.0	680		1
01/15	---	ERR	ERR	11862	16.1	0.4	2.5	36.2	680		1
01/16	32	3.4	2070	11862	14.5	2.3	15.9	31.9	680		1
01/17	---	ERR	ERR	11956	15.3	0.7	4.6	32.1	682		1
01/18	---	ERR	ERR	12097	16.9	0.2	1.2	34.6	684		1
01/19	---	ERR	ERR	12267	15.5	1.3	8.4	32.9	687		1
01/20	---	ERR	ERR	12464	17.7	0.5	2.8	39.6	691		1
01/21	---	ERR	ERR	12680	17.5	0.4	2.3	42.4	695		1
01/22	---	ERR	ERR	12916	33.6	0.2	0.6	75.6	703		1
01/23	---	ERR	ERR	12916	36	0.6	1.7	90.0	703		1
01/24	4	0.3	3390	12916	40.5	0	0.0	101.3	703		1
01/25	0	0.0	3583	13227	45.1	0.1	0.2	103.7	712	593	1
01/26	---	ERR	ERR	13227	44.2	1.1	2.5	110.5	712		1
01/27	---	ERR	ERR	13383	116.1	0.2	0.2	272.8	724		1
01/29	---	ERR	ERR	13383	111.9	1.1	1.0	268.6	724		1
01/30	---	ERR	ERR	13383	110.1	1.8	1.6	269.7	724		1
01/31	---	ERR	ERR	13383	113.4	0.5	0.4	277.8	724		1

Table B5: Biodegradation in Reactor I, Jan 1990

Date	React Period (hrs)	Feed Period (hrs)	Settle Period (hrs)	Effluent Volume (ml)
01/01	23	0	1	25
01/03	23	0	1	150
01/04	23	0	1	500
01/05	23	0	1	250
01/07	23	0	1	100
01/08	23	0	1	25
01/10	23	0	1	100
01/11	23	0	1	25
01/12	23	0	1	25
01/14	23	0	1	50
01/15	22.5	0	1.5	25
01/16	22.5	8	1.5	100
01/17	23	8	1	100
01/18	23	8	1	100
01/19	23	8	1	100
01/20	23	8	1	100
01/21	23	8	1	400
01/22	23	0	1	25
01/23	23	0	1	25
01/24	23	8	1	100
01/25	23	0	1	25
01/26	23	8	1	100
01/27	23	0	1	25
01/29	23	0	1	25
01/30	23	0	1	25
01/31	23	0	1	25

Table B6: Biodegradation in Reactor I, Feb 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Inf. COD (mg)	Feed Phenol (mg/l)	Cum. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
02/01	0	7505	74867	195.0	10584	2305	103	4.5	2.45	0.00	----
02/03	140	7505	75618	195	10604	----	---	ERR	2.4	0.14	1087
02/04	100	7505	76368	195	10623	----	---	ERR	2.4	0.14	----
02/05	0	7505	76368	195	10623	2615	120	4.6	2.4	0.00	----
02/06	50	7505	76743	195	10633	----	---	ERR	2.35	0.10	1203
02/07	110	7505	77569	195	10654	----	---	ERR	2.3	0.21	1119
02/08	30	4600	77707	1053	10686	----	---	ERR	2.4	0.04	----
02/10	140	4600	78351	1053	10833	----	---	ERR	2.5	0.16	931
02/11	150	4600	79041	1053	10991	2347	81	3.5	2.55	0.18	868
02/12	150	4600	79731	1053	11149	----	---	ERR	2.5	0.16	964
02/13	80	4600	80099	1053	11233	----	---	ERR	2.55	0.06	1007
02/14	0	4600	80099	1257	11233	----	---	ERR	2.4	0.00	889
02/15-	200	4600	81019	1257	11485	3052	53	1.7	2.45	0.20	798
02/16	165	4600	81778	1257	11692	----	---	ERR	2.5	0.16	768
02/17	215	4600	82767	1257	11962	3224	46	1.4	2.45	0.21	714
02/18	0	4600	82767	1257	11962	----	---	ERR	2.2	0.00	722
02/19	260	4600	83963	1257	12289	----	---	ERR	2.4	0.23	705
02/20	290	4600	85297	1257	12654	2906	22	0.8	2.5	0.33	651
02/21	350	3480	86515	1155	13058	----	---	ERR	2.5	0.29	636
02/22	400	3480	87907	1155	13520	----	---	ERR	2.55	0.21	883
02/23	0	3480	87907	1155	13520	----	---	ERR	2.5	0.00	603
02/24	300	3480	88951	1155	13867	3033	70	2.3	2.5	0.21	603
02/25	300	3480	89995	1155	14213	----	---	ERR	2.45	0.24	582
02/26	300	3480	91039	1155	14560	----	---	ERR	2.5	0.24	590
02/27	300	3480	92083	1155	14906	----	---	ERR	2.45	0.24	605
02/28	300	3480	93127	1155	15253	----	---	ERR	2.5	0.24	725

Table B6: Biodegradation in Reactor I, Feb 1990

Date	COD Std. Dev. (mg/l)	COD % Error	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Phenol Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)
02/01	---	ERR	ERR	13383	17.7	0.0	0.0	43.4	724	1	23
02/03	15	1.4	2457	13535	17	0.5	2.9	38.4	726	1	23
02/04	---	ERR	ERR	13644	24.2	0.2	1.0	55.7	728	1	23
02/05	---	ERR	ERR	13644	26.6	0.9	3.4	63.8	728	1	23
02/06	51	4.2	2767	13704	18.9	0	0.0	43.5	729	1	15
02/07	5	0.4	2451	13827	47.6	0	0.0	104.2	734	1	15
02/08	---	ERR	ERR	13861	17.7	0.9	5.1	41.9	735	1	15
02/10	9	1.0	2197	13991	14.8	0.5	3.4	34.9	737	1	15
02/11	6	0.7	2084	14121	12.2	0.5	4.1	29.3	739	1	15
02/12	8	0.8	2352	14266	71.7	0	0.0	175.7	749	1	17
02/13	0	0.0	2486	14346	84.7	0.2	0.2	209.2	756	1	23
02/14	N/A	N/A	2135	14346	44.1	0	0.0	105.8	756	1	15
02/15	N/A	N/A	1796	14506	11.4	0.7	6.1	25.7	759	1	15
02/16	N/A	N/A	1793	14633	34	0.2	0.6	79.4	764	1	15
02/17	N/A	N/A	1595	14786	11	0	0.0	24.6	767	1	14
02/18	N/A	N/A	1589	14786	9	0	0.0	19.8	767	1	14
02/19	N/A	N/A	1509	14970	8.2	0.4	4.9	17.5	769	1	16
02/20	N/A	N/A	1438	15158	6.7	0.3	4.5	14.8	771	1	13.5
02/21	N/A	N/A	1367	15381	11	0	0.0	23.7	774	1	14
02/22	N/A	N/A	1898	15734	123.8	0	0.0	266.2	824	1	22
02/23	N/A	N/A	1508	15734	6.5	0	0.0	16.3	824	1	14
02/24	N/A	N/A	1327	15915	5.3	0.1	1.9	11.7	826	1	16
02/25	N/A	N/A	1250	16089	4.8	0	0.0	10.3	827	1	14
02/26	N/A	N/A	1298	16267	4.1	0.1	2.4	9.0	828	1	14
02/27	N/A	N/A	1302	16448	7	0.1	1.4	15.1	830	1	14
02/28	N/A	N/A	1594	16666	41.1	0.1	0.2	90.4	843	1	14

Table B6: Biodegradation in Reactor I, Feb 1990

Date	Feed Period (hrs)	Settle Period (hrs)	Effluent Volume (ml)	MCRT (days)
02/01	8	1	100	
02/03	8	1	100	
02/04	0	1	100	
02/05	4	1	100	
02/06	8	1	100	
02/07	8	1	250	
02/08	8	1	65	
02/10	8	1	100	
02/11	8	1	150	
02/12	6	1	180	
02/13	0	1	200	
02/14	8	1	100	
02/15	8	1	150	
02/16	8	1	250	
02/17	8	2	250	
02/18	0	2	50	
02/19	6	2	250	
02/20	8	2.5	350	
02/21	8	2	400	
02/22	0	2·	400	
02/23	8	2	300	
02/24	6	2	300	
02/25	8	2	250	
02/26	8	2	300	
02/27	8	2	250	25
02/28	8	2	250	25

Table B7: Biodegradation in Reactor I, Mar 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Inf. COD (mg)	Feed Phenol (mg/l)	Cum. Inf. Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
03/01	273	3480	94077	1155	15568	2597	109	4.2	2.45	0.26	777
03/02	270	4600	95457	1155	15915	----	---	ERR	2.45	0.37	740
03/03	300	4600	96837	1155	16261	----	---	ERR	2.45	0.37	915
03/04	250	4600	97987	1155	16550	----	---	ERR	2.5	0.31	1154
03/05	200	4600	98907	1155	16781	----	---	ERR	2.5	0.16	1260
03/06	0	4600	98907	1155	16781	2143	49	2.3	2.5	0.00	1087
03/07	0	4600	98907	1155	16781	----	---	ERR	2.4	0.00	1002
03/08	0	5639	98907	1044	16781	----	---	ERR	2.38	0.00	892
03/09	100	5639	99471	1044	16885	----	---	ERR	2.45	0.18	655
03/10	150	5639	100317	1044	17042	----	---	ERR	2.5	0.27	788
03/11	200	5639	101445	1044	17251	1979	11	0.6	2.45	0.40	859
03/12	250	5639	102854	1044	17512	----	---	ERR	2.5	0.32	1197
03/13	0	5639	102854	1044	17512	----	---	ERR	2.45	0.00	902
03/14	150	5401	103664	1027	17666	----	---	ERR	2.5	0.29	928
03/15	160	5401	104529	1027	17830	----	---	ERR	2.5	0.31	915
03/16	170	5401	105447	1027	18005	1883	123	6.5	2.5	0.33	933
03/17	170	5401	106365	1027	18179	----	---	ERR	2.5	0.33	1085
03/18	170	5401	107283	1027	18354	----	---	ERR	2.5	0.33	1147
03/19	100	5401	107823	1027	18457	----	---	ERR	2.5	0.20	1052
03/20	150	5401	108633	1027	18611	1940	176	9.1	2.5	0.29	937
03/21	150	5401	109444	1027	18765	----	---	ERR	2.5	0.18	926
03/22	160	5401	110308	1027	18929	----	---	ERR	2.5	0.24	---
03/23	100	5401	110848	1027	19032	----	---	ERR	2.6	0.15	---
03/24	120	5401	111496	1027	19155	----	---	ERR	2.7	0.18	---
03/25	120	5401	112144	1027	19278	1593	50	3.1	2.5	0.22	---
03/26	0	5401	112144	1027	19278	----	---	ERR	2.45	0.00	931
03/27	200	5401	113224	1027	19484	----	---	ERR	2.5	0.54	---
03/28	200	5401	114304	1208	19725	----	---	ERR	2.5	0.54	---
03/29	175	5401	115250	1208	19937	----	---	ERR	2.5	0.47	---
03/30	200	5401	116330	1208	20178	1844	156	8.5	2.5	0.47	---
03/31	200	5401	117410	1208	20420	----	---	ERR	2.55	0.47	---

Table B7: Biodegradation in Reactor I, Mar 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)	Feed Period (hrs)	Settle Period (hrs)
03/01	1691	16878	39.1	0.1	0.3	85.1	854	1	14	8	2
03/02	1613	17078	4.3	0.0	0.0	9.4	855	1	14	8	2
03/03	1968	17352	103.1	0.0	0.0	221.7	886	1	14	8	2
03/04	2596	17641	183.3	0.2	0.1	412.4	932	1	14	8	2
03/05	2898	17893	235.2	1.2	0.5	541.0	979	1	22	0	2
03/06	2717	17893	191	1.4	0.7	477.5	979	1	22	0	2
03/07	2405	17893	169.2	0	0.0	406.1	979	1	22	0	2
03/08	2122	17893	111.8	0.7	0.6	266.1	979	1	14	8	2
03/09	1540	17958	1.6	0.2	12.5	3.8	979	1	14	8	2
03/10	1851	18077	2	0.2	10.0	4.7	979	1	14	8	2
03/11	1933	18248	1.5	0	0.0	3.4	980	1	14	8	2
03/12	2694	18548	92.2	0.5	0.5	207.5	1003	1	22	0	2
03/13	2211	18548	2.3	0.2	8.7	5.6	1003	1	14	8	2
03/14	2182	18687	1.5	0	0.0	3.5	1003	1	14	8	2
03/15	2142	18833	2	0.2	10.0	4.7	1003	1	14	8	2
03/16	2173	18992	5.7	0.2	3.5	13.3	1004	1	14	8	2
03/17	2527	19176	40.2	0.2	0.5	93.7	1011	1	14	8	2
03/18	2573	19371	59.4	0.5	0.8	138.4	1021	1	14	8	2
03/19	2525	19477	2.1	0	0.0	5.0	1021	1	14	8	2
03/20	2202	19617	0.8	0	0.0	1.9	1021	1	14	8	2
03/21	2177	19756	13.0	0.2	1.5	30.6	1023	1	22	0	2
03/22	ERR	19904	62.1	0.5	0.8	145.3	1033	1	18	4	2
03/23	ERR	19997	12.0	0.2	1.7	30.0	1034	1	18	4	2
03/24	ERR	20108	107.9	0.2	0.2	278.4	1047	1	18	4	2
03/25	ERR	20219	140.8	0.5	0.4	335.1	1064	1	18	4	2
03/26	2280	20219	0.9	1.3	144.4	2.2	1064	1	22	0	2
03/27	ERR	20405	46.9	0.2	0.4	107.9	1074	2	6	4	2
03/28	ERR	20591	83.4	0.2	0.2	191.8	1090	2	6	4	2
03/29	ERR	20754	107.5	0.7	0.7	249.9	1109	2	6	4	2
03/30	ERR	20940	112.7	1.9	1.7	259.2	1132	2	6	4	2
03/31	ERR	21126	146.9	0.2	0.1	345.2	1161	2	6	4	2

Table B7: Biodegradation in Reactor I, Mar 1990

Date	Effluent Volume (ml)	MCRT (days)
03/01	236	25
03/02	236	25
03/03	250	25
03/04	200	25
03/05	100	25
03/06	75	25
03/07	100	
03/08	100	
03/09	100	
03/10	200	
03/11	200	
03/12	250	
03/13	100	
03/14	160	
03/15	200	
03/16	200	
03/17	170	
03/18	100	
03/19	150	
03/20	200	
03/21	25	
03/22	150	
03/23	150	
03/24	300	
03/25	540	
03/26	25	
03/27	150	
03/28	200	
03/29	150	
03/30	200	
03/31	200	

Table B8: Biodegradation in Reactor I, Apr 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS·d)	Effluent COD (mg/l)
04/01	200	5401	118450	1208	20662	1844	156	8.5	2.55	0.47	----
04/02	200	5401	119030	1208	20782	----	---	ERR	2.50	0.47	----
04/03	100	5401	119570	1208	20903	----	---	ERR	2.60	0.23	----
04/04	90	5401	120056	1208	21012	1859	98	5.3	2.45	0.21	1237
04/05	200	5401	121137	1208	21254	----	---	ERR	2.50	0.47	1185
04/06	200	5401	122217	1208	21495	----	---	ERR	2.50	0.47	1073
04/07	200	6315	123480	1156	21726	----	---	ERR	2.50	0.55	1256
04/08	200	6315	124743	1156	21958	1962	38	1.9	2.50	0.51	----
04/09	200	6315	126006	1156	22189	----	---	ERR	2.50	0.51	1180
04/10	200	6315	127269	1156	22420	----	---	ERR	2.50	0.51	1225
04/11	200	6315	128532	1156	22651	----	---	ERR	2.50	0.51	----
04/12	200	6315	129795	1156	22882	----	---	ERR	2.50	0.51	----
04/13	200	6315	131058	1156	23114	2173	110	5.1	2.50	0.46	----
04/14	200	6315	132321	1156	23345	----	---	ERR	2.50	0.46	----
04/15	200	6315	133584	1156	23576	----	---	ERR	2.50	0.46	----
04/16	200	6124	134809	1021	23780	----	---	ERR	2.50	0.45	1431
04/17	200	6124	136033	1021	23984	----	---	ERR	2.50	0.45	1471
04/18	200	6124	137258	1021	24189	2094	28	1.3	2.50	0.47	1386
04/19	200	6124	138483	1021	24393	----	---	ERR	2.50	0.47	1464
04/20	200	6124	139708	1021	24597	----	---	ERR	2.55	0.47	1375
04/21	200	6124	140933	1021	24801	----	---	ERR	2.50	0.47	1442
04/22	200	6124	142157	1021	25005	2031	32	1.6	2.40	0.50	1460
04/23	200	6124	143382	1021	25210	----	---	ERR	2.55	0.50	----
04/24	200	6124	144607	1021	25414	2477	85	3.4	2.55	0.39	----
04/25	200	6124	145832	1021	25618	----	---	ERR	2.50	0.39	1314
04/26	0	6124	145832	1021	25618	----	---	ERR	2.30	0.00	----
04/27	200	6124	147057	1021	25822	----	---	ERR	2.50	0.39	----
04/28	100	6124	147669	1021	25924	----	---	ERR	2.35	0.19	1274
04/29	70	6124	148098	1021	25996	----	---	ERR	2.40	0.14	1256
04/30	100	6124	148710	1021	26098	----	---	ERR	2.30	0.19	1207

Table B8: Biodegradation in Reactor I, Apr 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Effluent MLSS (mg/l)	Cycles per day	React Period (hrs)	Feed Period (hrs)
04/01	ERR	21312	140.4	0.5	0.4	329.9	1189	740	2	6	4
04/02	ERR	21498	-----	---	ERR	ERR	1203		2	6	4
04/03	ERR	21592	87.0	0.2	0.2	217.5	1212		2	6	4
04/04	2920	21703	36.0	0.0	0.0	85.0	1215		2	6	4
04/05	2725	21940	16.6	0.9	5.4	38.2	1218		2	6	4
04/06	2467	22154	2.8	0.5	17.9	6.4	1219		2	6	4
04/07	2889	22405	12.9	0.0	0.0	29.7	1222	875	2	6	4
04/08	ERR	22657	15.3	0.4	2.6	35.2	1225		2	6	4
04/09	2714	22893	8.7	0.2	2.3	20.0	1226		2	6	4
04/10	2817	23138	6.2	0.0	0.0	14.3	1228		2	6	4
04/11	ERR	23383	9.3	0.2	2.2	21.4	1229		2	6	4
04/12	ERR	23628	10.0	0.2	2.0	23.0	1231		2	6	4
04/13	ERR	23873	1.0	0.2	20.0	2.3	1232		2	6	4
04/14	ERR	24118	2.3	0.2	8.7	5.3	1232		2	6	4
04/15	ERR	24363	0.8	0.0	0.0	1.8	1232		2	6	4
04/16	3291	24649	0.8	0.0	0.0	1.8	1232		2	6	4
04/17	3383	24943	2.5	0.9	36.0	5.8	1233		2	6	4
04/18	3188	25220	0.0	0.0	ERR	0.0	1233		2	6	4
04/19	3368	25513	0.0	0.0	ERR	0.0	1233		2	6	4
04/20	3231	25788	1.0	0.2	20.0	2.4	1233		2	6	4
04/21	3316	26076	1.0	0.2	20.0	2.3	1233		2	6	4
04/22	3212	26368	2.5	0.5	20.0	5.5	1234		2	6	4
04/23	ERR	26660	2.8	0.0	0.0	6.6	1234		2	6	4
04/24	ERR	26952	2.8	0.0	0.0	6.6	1235		2	6	4
04/25	3023	27215	3.8	0.0	0.0	8.7	1236		2	6	0
04/26	ERR	27215	0.0	0.0	ERR	0.0	1236		2	6	4
04/27	ERR	27478	5.1	0.2	3.9	11.7	1237		2	6	4
04/28	2867	27605	1.6	0.7	43.7	3.6	1237		2	6	4
04/29	2927	27693	2.0	0.2	10.0	4.7	1237		2	6	4
04/30	2655	27814	0.0	0.0	ERR	0.0	1237		2	6	4

Table B8: Biodegradation in Reactor I, Apr 1990

Date	Settle Period (hrs)	Effluent Volume (ml)
04/01	2	250
04/02	2	0
04/03	2	350
04/04	2	150
04/05	2	200
04/06	2	200
04/07	2	200
04/08	2	200
04/09	2	200
04/10	2	200
04/11	2	200
04/12	2	200
04/13	2	200
04/14	2	220
04/15	2	200
04/16	2	200
04/17	2	200
04/18	2	200
04/19	2	200
04/20	2	250
04/21	2	200
04/22	2	200
04/23	2	250
04/24	2	250
04/25	2	250
04/26	2	200
04/27	2	200
04/28	2	50
04/29	2	100
04/30	2	230

Table B9: Biodegradation in Reactor I, May 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
05/01	90	6315	149278	1156	26202	2477	85	3.4	2.20	0.18	----
05/02	200	6315	151836	1156	26670	----	---	ERR	3.10	0.29	----
05/03	405	6315	154394	1156	27138	8519	217	2.5	2.65	0.16	1129
05/04	375	6315	156762	1156	27572	----	---	ERR	2.45	0.15	----
05/05	420	6315	159414	1244	28094	----	---	ERR	2.50	0.17	----
05/06	420	6315	162066	1244	28617	----	---	ERR	2.50	0.17	----
05/07	420	6315	164719	1244	29139	----	---	ERR	2.50	0.17	1738
05/08	420	6315	167371	1244	29662	5528	191	3.5	2.50	0.28	----
05/09	420	6315	170023	1244	30184	----	---	ERR	2.60	0.28	----
05/10	420	6315	172675	1268	30717	----	---	ERR	2.60	0.28	----
05/11	420	6315	175328	1268	31249	----	---	ERR	2.55	0.28	----
05/12	420	6315	177980	1268	31782	6410	390	6.1	2.50	0.24	----
05/13	450	6315	180822	1268	32353	----	---	ERR	2.60	0.26	----
05/14	450	6315	183664	1268	32923	----	---	ERR	2.55	0.26	----
05/15	450	6315	186505	1268	33494	----	---	ERR	2.60	0.26	----
05/16	450	6315	189347	1268	34064	----	---	ERR	2.55	0.26	----
05/17	450	6315	192189	1268	34635	6452	615	9.5	2.55	0.25	----
05/18	150	6315	193136	1268	34825	----	---	ERR	2.20	0.08	----
05/19	450	6315	195978	1268	35396	----	---	ERR	2.50	0.25	----
05/20	450	6315	198820	1268	35966	----	---	ERR	2.50	0.25	----
05/21	300	6315	200714	1268	36347	----	---	ERR	2.55	0.17	----
05/22	0	6315	200714	1268	36347	6663	229	3.4	2.50	0.00	1444
05/23	450	6315	203556	1268	36917	----	---	ERR	2.70	0.23	----
05/24	150	6315	204503	1268	37108	----	---	ERR	2.50	0.08	----
05/25	300	6315	206398	1268	37488	----	---	ERR	2.50	0.15	----
05/26	0	6315	206398	1268	37488	----	---	ERR	2.50	0.00	1652
05/27	300	6315	208292	1268	37868	----	---	ERR	2.55	0.15	1756
05/28	300	6315	210187	1268	38249	----	---	ERR	2.55	0.15	1711
05/29	300	6315	212081	1268	38629	6674	282	4.2	2.50	0.15	1702
05/30	350	6315	214291	1268	39073	----	---	ERR	2.50	0.18	1693
05/31	350	8465	217254	1273	39519	----	---	ERR	2.50	0.24	----

Table B9: Biodegradation in Reactor I, May 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Effluent MLSS (mg/l)	Cycles per day	React Period (hrs)	Feed Period (hrs)
05/01	ERR	28055	1.1	0.0	0.0	2.3	1237		2	6	0
05/02	ERR	28544	1.3	0.2	15.4	3.8	1238		3	5.5	2
05/03	2534	28967	1.4	0.0	0.0	3.1	1238		3	5.5	2
05/04	ERR	29442	0.0	0.0	ERR	0.0	1238		3	5.5	2
05/05	ERR	29916	11.0	0.1	0.9	22.9	1243		3	5.5	2
05/06	ERR	30390	0.0	0.0	ERR	0.0	1243		3	5.5	2
05/07	3615	31120	15.9	0.1	0.6	33.1	1249	2211	3	5.5	2
05/08	ERR	31850	31.0	0.1	0.3	64.5	1252		3	5.5	2
05/09	ERR	32580	24.5	0.2	0.8	53.4	1273		3	5.5	2
05/10	ERR	33309	2.3	0.1	4.3	5.0	1274		3	5.5	2
05/11	ERR	34039	18.9	0.1	0.5	40.3	1282	1092	3	5.5	2
05/12	ERR	34822	14.8	0.1	0.7	30.8	1288		3	5.5	2
05/13	ERR	35604	17.5	0.0	0.0	37.6	1296		3	5.5	2
05/14	ERR	36386	34.9	0.2	0.6	73.3	1311	1201	3	5.5	2
05/15	ERR	37168	50.9	0.0	0.0	109.4	1334		3	5.5	2
05/16	ERR	37950	81.6	0.2	0.2	171.4	1371		3	5.5	2
05/17	ERR	38211	123.5	0.7	0.6	259.4	1427		3	5.5	2
05/18	ERR	38993	24.7	0.0	0.0	50.6	1430		3	5.5	2
05/19	ERR	39775	67.6	0.5	0.7	138.6	1461	550	3	5.5	2
05/20	ERR	40296	120.9	0.0	0.0	247.8	1515		3	5.5	2
05/21	ERR	40296	100.7	0.2	0.2	226.6	1545	576	3	5.5	0
05/22	3611	40946	3.0	0.2	6.7	7.5	1545		3	5.5	2
05/23	ERR	41163	115.5	0.2	0.2	259.9	1597		3	6	2
05/24	ERR	41596	38.9	0.3	0.8	91.4	1603		3	6	2
05/25	ERR	41596	60.7	0.2	0.3	133.5	1621		3	6	2
05/26	4130	42092	2.1	0.0	0.0	5.3	1621		3	6	2
05/27	3950	42618	17.4	0.0	0.0	39.1	1627		3	6	2
05/28	3849	43132	6.8	0.2	2.9	15.3	1629	604	3	6	2
05/29	3743	43727	3.4	0.1	2.9	7.5	1630		3	6	2
05/30	3639	44320	4.9	0.4	8.2	10.5	1631		3	6	2
05/31	ERR	44320	8.4	0.1	1.2	18.1	1634		3	6	2

Table 89: Biodegradation in Reactor I, May 1990

Date	Settle Period (hrs)	Effluent Volume (ml)	
05/01	2	25	Added Bench Solids
05/02	1.5	1000	
05/03	1.5	550	Waste Eff. Solids
05/04	1.5	350	Waste Eff. Solids
05/05	1.5	400	Waste Eff. Solids
05/06	1.5	400	Waste Eff. Solids
05/07	1.5	400	Waste Eff. Solids
05/08	1.5	400	Waste Eff. Solids
05/09	1.5	500	Return Eff. Solids
05/10	1.5	500	
05/11	1.5	450	
05/12	1.5	400	
05/13	1.5	500	
05/14	1.5	450	
05/15	1.5	550	
05/16	1.5	500	
05/17	1.5	500	
05/18	1.5	175	
05/19	1.5	450	
05/20	1.5	300	
05/21	1.5	50	
05/22	1.5	450	
05/23	1	650	
05/24	1	300	
05/25	1	250	
05/26	1	300	
05/27	1	350	
05/28	1	350	
05/29	1	350	
05/30	1	350	
05/31	1	350	

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Table C1: Biodegradation in Reactor II, Nov - Dec 1989

Date	Phenol Added (mg)	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)
11/17	0	0	5070	0	992	0	6500	---	ERR	3	0.00
11/19	250	0	5070	610	992	250	----	---	ERR	3	0.03
11/20	0	0	5070	610	992	250	----	---	ERR	3	0.00
11/21	500	0	5070	1830	992	750	----	---	ERR	3	0.06
11/22	410	100	5070	3337	992	1259	----	---	ERR	3	0.08
11/24	0	0	5070	3337	984	1259	----	---	ERR	3	0.00
11/25	0	0	5070	3337	984	1259	----	---	ERR	3.5	0.00
11/26	200	100	5070	4332	984	1558	----	---	ERR	3.5	0.05
11/27	300	150	5070	5825	984	2005	6535	435	6.7	3.5	0.07
11/28	350	150	5070	7439	984	2503	----	---	ERR	3.5	0.07
11/29	400	150	5070	9176	984	3050	----	---	ERR	3.5	0.08
11/30	500	150	5070	11156	984	3598	----	---	ERR	3.5	0.09
12/01	600	150	5070	13381	984	4446	----	---	ERR	3.5	0.10
12/02	600	200	5070	15859	921	5230	----	---	ERR	3.5	0.11
12/03	750	200	5070	18703	921	6164	----	---	ERR	3.5	0.13
12/04	1000	200	5070	22157	921	7348	4015	---	ERR	3.5	0.25
12/05	1500	200	5070	26831	921	9032	----	---	ERR	3.5	0.34
12/06	2000	135	5070	32395	921	11157	----	---	ERR	3.5	0.41
12/07	2700	135	5070	39668	921	13981	3103	1539	49.6	3.5	0.69
12/08	3000	200	5070	48002	921	17165	----	---	ERR	3.5	0.79
12/10	3000	200	5070	56336	921	20349	----	---	ERR	3.5	0.79
12/12	3500	200	8490	66574	245	23898	----	---	ERR	3.5	0.97
12/13	4000	200	8490	78032	245	27947	----	---	ERR	3.5	1.09
12/14	0	400	8490	81428	245	28045	----	---	ERR	3.5	0.33
12/15	0	500	8490	85673	245	~28168	----	---	ERR	3.5	0.42
12/17	0	500	8490	89918	245	28290	1498	78	5.2	3.4	0.89
12/19	0	400	8490	93314	245	28388	----	---	ERR	2.9	0.71
12/21	0	213	8490	95122	245	28441	----	---	ERR	2.6	0.38
12/23	0	213	8490	96931	245	28493	----	---	ERR	2.8	0.38
12/25	0	213	8490	98739	245	28545	----	---	ERR	3	0.38
12/29	0	0	8490	98739	245	28545	----	---	ERR	2.9	0.00
12/30	3000	0	8490	106059	245	31545	4468	77	1.7	2.75	0.63

Table C1: Biodegradation in Reactor II, Nov - Dec 1989

Date	Effluent COD (mg/l)	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)	Feed Period (hrs)
11/17	----	ERR	0	1.2	0.0	0.0	3.6	0	1	23	0
11/19	----	ERR	1	11.3	0.5	4.4	33.9	0	1	23	0
11/20	----	ERR	1	2.00	0.0	0.0	6.0	0	1	23	0
11/21	----	ERR	2	1.3	0	0.0	3.9	0	1	23	0
11/22	----	ERR	99	164.9	0	0.0	478.2	16	1	23	0
11/24	----	ERR	115	130.2	1.1	0.8	390.6	16	1	23	0
11/25	----	ERR	118	3.6	0	0.0	12.6	16	1	23	4
11/26	----	ERR	209	3.9	0	0.0	13.3	17	1	23	4
11/27	----	ERR	342	4.3	1	23.3	14.4	18	1	23	4
11/28	----	ERR	474	7.9	0	0.0	26.5	19	1	23	4
11/29	----	ERR	609	5.30	0.2	3.8	17.8	20	1	23	4
11/30	----	ERR	744	6.7	0.1	1.5	22.4	21	1	23	4
12/01	----	ERR	879	6.9	0	0.0	23.1	22	1	23	4
12/02	----	ERR	1057	6.1	0	0.0	20.1	23	1	23	4
12/03	----	ERR	1236	6.9	0.1	1.4	22.8	25	1	23	4
12/04	878	2897.4	1412	7.4	0.1	1.4	24.4	26	1	23	4
12/05	----	ERR	1587	8.5	0.1	1.2	28.1	27	1	23	4
12/06	----	ERR	1706	12	0	0.0	40.4	29	1	23	4
12/07	----	ERR	1824	12.2	0.1	0.8	41.1	32	1	23	4
12/08	----	ERR	2000	----	---	ERR	ERR	32	1	23	4
12/10	948.2	3129.1	2190	1.10	0.1	9.1	3.6	32	1	23	4
12/12	----	ERR	2379	1.3	0.1	7.7	4.3	33	1	23	4
12/13	----	ERR	2569	4.6	0.4	8.7	15.2	35	1	23	4
12/14	----	ERR	2948	4.9	0	0.0	15.2	37	1	22.5	4
12/15	----	ERR	3422	11.1	0.7	6.3	33.3	42	1	22.5	4
12/17	----	ERR	3896	29.9	0.2	0.7	86.7	42	1	22.5	4
12/19	----	ERR	4276	41.7	0.2	0.5	104.3	42	1	22.5	4
12/21	----	ERR	4478	----	---	ERR	ERR	42	1	22.5	4
12/23	----	ERR	4679	----	---	ERR	ERR	42	1	22.5	4
12/25	----	ERR	4881	----	---	ERR	ERR	42	1	22.5	4
12/29	----	ERR	4881	83.1	1.1	1.3	241.0	60	1	22.5	4
12/30	5137	14126.8	5517	1060.09	9.1	0.9	2915.0	60	1	22.5	4

Table C1: Biodegradation in Reactor II, Nov - Dec 1989

Date	Settle Period (hrs)	Effluent Volume (ml)	Comments
11/17	1	25	
11/19	1	25	
11/20	1	250	10 d MCRT
11/21	1	300	8 d MCRT
11/22	1	25	Waste Eff. Solids
11/24	1	50	Waste Eff. Solids
11/25	1	350	Waste Eff. Solids
11/26	1	350	Waste Eff. Solids
11/27	1	100	Waste Eff. Solids
11/28	1	50	Waste Eff. Solids
11/29	1	200	Return Eff. Solids
11/30	1	200	
12/01	1	200	
12/02	1	200	
12/03	1	300	
12/04	1	300	
12/05	1	400	
12/06	1	400	
12/07	1	500	
12/08	1	600	
12/10	1	450	
12/12	1	400	
12/13	1	400	
12/14	1.5	400	
12/15	1.5	500	
12/17	1.5	750	
12/19	1.5	400	
12/21	1.5	0	
12/23	1.5	400	
12/25	1.5	0	
12/29	1.5	380	
12/30	1.5	250	

Table C2: Biodegradation in Reactor II, Jan 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
01/01	0	8490	106059	245	31545	4462	156	3.5	2.55	0.00	----
01/03	0	8490	106059	245	31545	----	---	ERR	2.4	0.00	----
01/04	0	8490	106059	245	31545	----	---	ERR	2.5	0.00	----
01/05	0	8490	106059	245	31545	----	---	ERR	2.5	0.00	----
01/07	0	8490	106059	245	31545	----	---	ERR	2.3	0.00	----
01/08	0	8490	106059	245	31545	----	---	ERR	2.3	0.00	----
01/10	0	8490	106059	245	31545	----	---	ERR	2.5	0.00	2455
01/11	0	8490	106059	245	31545	6248	67	1.1	2.4	0.00	----
01/12	0	8490	106059	245	31545	----	---	ERR	2.5	0.00	----
01/14	0	8490	106059	245	31545	----	---	ERR	2.5	0.00	----
01/15	0	8490	106059	245	31545	----	---	ERR	2.5	0.00	----
01/16	0	7505	106059	143	31545	----	---	ERR	2.5	0.00	----
01/17	0	7505	106059	143	31545	----	---	ERR	2.5	0.00	----
01/18	0	7505	106059	143	31545	----	---	ERR	2.5	0.00	----
01/19	0	7505	106059	143	31545	----	---	ERR	2.5	0.00	----
01/20	0	7505	106059	143	31545	----	---	ERR	2.5	0.00	----
01/21	0	7505	106059	143	31545	----	---	ERR	2.5	0.00	----
01/22	200	7505	107560	143	31574	----	---	ERR	2.6	0.13	----
01/23	130	7505	108536	143	31592	4896	51	1.0	2.3	0.11	----
01/24	300	7505	110787	143	31635	----	---	ERR	2.5	0.25	1502
01/25	350	7505	113414	143	31685	----	---	ERR	2.5	0.29	1817
01/26	0	7505	113414	143	31685	----	---	ERR	2.5	0.00	----
01/27	100	4800	113894	2000	31885	----	---	ERR	2.5	0.05	----
01/29	0	7505	113894	143	31885	----	---	ERR	2.5	0.00	----
01/30	140	7505	114945	195	31912	----	---	ERR	2.5	0.12	----
01/31	200	7505	116446	195	31951	3005	166	5.5	2.5	0.25	----

Table C2: Biodegradation in Reactor II, Jan 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Cycles per day	React Period (hrs)	Feed Period (hrs)	Settle Period (hrs)
01/01	ERR	5517	960	6.8	0.7	2448.0	60	1	22.5	0	1.5
01/03	ERR	5517	908	1.0	0.1	2179.2	60	1	22.5	0	1.5
01/04	ERR	5517	739	14.0	1.9	1847.5	60	1	22.5	0	1.5
01/05	ERR	5517	549	2.7	0.5	1372.5	60	1	22	0	2
01/07	ERR	5517	474	7.0	1.5	1090.2	60	1	22	0	2
01/08	ERR	5517	440	2.7	0.6	1012.0	60	1	22.5	0	1.5
01/10	6137.5	5517	396.4	2.7	0.7	991.0	60	1	22	0	2
01/11	ERR	5517	355.4	2.8	0.8	853.0	60	1	22.5	0	1.5
01/12	ERR	5517	347.6	6.4	1.8	869.0	60	1	22.5	0	1.5
01/14	ERR	5517	325.2	3.6	1.1	813.0	60	1	22.5	0	1.5
01/15	ERR	5517	313	2.7	0.9	782.5	60	1	22.5	0	1.5
01/16	ERR	5517	322	3.6	1.1	805.0	60	1	22.5	0	1.5
01/17	ERR	5517	304	1.0	0.3	760.0	60	1	23	0	1
01/18	ERR	5517	309.8	1.8	0.6	774.5	60	1	23	0	1
01/19	ERR	5517	272	0.9	0.3	680.0	60	1	23	0	1
01/20	ERR	5517	40.6	0.0	0.0	101.5	60	1	23	0	1
01/21	ERR	6008	11.1	0.2	1.8	27.8	60	1	19	4	1
01/22	ERR	6327	10	0.1	1.0	24.0	62	1	19	4	1
01/23	ERR	7054	10.9	0.2	1.8	23.7	63	1	19	4	1
01/24	3304.4	7589	15.7	0.0	0.0	34.5	68	1	19	4	1
01/25	3906.5	7589	45.6	0.0	0.0	98.0	84	1	19	4	1
01/26	ERR	7771	41.2	0.9	2.2	103.0	84	1	19	0	1
01/27	ERR	7771	88.2	0.7	0.8	211.7	93	1	19	4	1
01/29	ERR	8025	15.4	0.5	3.2	38.5	93	1	19	0	1
01/30	ERR	8389	14.3	0.2	1.4	33.7	95	1	19	4	1
01/31	ERR	8389	15.90	0.2	1.3	36.6	98	1	19	4	1

Table C2: Biodegradation in Reactor II, Jan 1990

Date	Effluent Volume (ml)	MCRT (days)
01/01	150	
01/03	300	
01/04	500	
01/05	150	
01/07	25	
01/08	25	
01/10	10	
01/11	10	
01/12	100	25
01/14	100	25
01/15	10	25
01/16	10	25
01/17	10	25
01/18	10	25
01/19	10	
01/20	10	
01/21	100	
01/22	400	
01/23	100	
01/24	400	
01/25	100	
01/26	100	
01/27	100	
01/29	200	
01/30	200	
01/31	250	

Table C3: Biodegradation In Reactor II, Feb 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
02/01	250	7505	118322	195	32000	3005	166	5.5	2.5	0.32	1666
02/03	100	2400	118562	1000	32100	----	---	ERR	2.5	0.08	1359
02/04	200	7505	120063	195	32139	----	---	ERR	2.5	0.23	----
02/05	180	7505	121414	195	32174	3307	331	10.0	2.5	0.21	----
02/06	43	7505	121737	195	32182	----	---	ERR	2.5	0.05	1819
02/07	0	7505	121737	195	32182	----	---	ERR	2.5	0.00	----
02/08	50	7505	122112	195	32192	----	---	ERR	2.5	0.06	----
02/10	0	7505	122112	195	32192	----	---	ERR	2.5	0.00	1378
02/11	100	4600	122572	1053	32297	4648	59	1.3	2.5	0.05	1337
02/12	150	4600	123262	1053	32455	----	---	ERR	2.5	0.08	1206
02/13	150	4600	123952	1053	32613	----	---	ERR	2.5	0.08	1085
02/14	200	4600	124872	1257	32865	----	---	ERR	2.5	0.11	1003
02/15	200	4600	125792	1257	33116	6207	198	3.2	2.5	0.08	933
02/16	250	4600	126942	1257	33430	----	---	ERR	2.5	0.00	790
02/17	250	4600	128092	1257	33744	6080	222	3.7	2.5	0.10	794
02/18	300	4600	129472	1257	34122	----	---	ERR	2.5	0.12	716
02/19	400	4600	131312	1257	34624	----	---	ERR	2.5	0.17	709
02/20	500	4600	133612	1257	35253	5948	287	4.8	2.5	0.21	694
02/21	500	3480	135352	1155	35830	----	---	ERR	2.5	0.16	1020
02/22	0	3480	135352	1155	35830	----	---	ERR	2.5	0.00	954
02/23	0	3480	135352	1155	35830	----	---	ERR	2.5	0.00	887
02/24	300	3480	136396	1155	36177	5928	286	4.8	2.5	0.08	950
02/25	255	3480	137284	1155	36471	----	---	ERR	2.5	0.07	803
02/26	300	3480	138328	1155	36818	----	---	ERR	2.5	0.09	729
02/27	300	3480	139372	1155	37164	----	---	ERR	2.42	0.09	848
02/28	300	3480	140416	1155	37511	----	---	ERR	2.5	0.09	879

Table C3: Biodegradation In Reactor II, Feb 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Effluent MLSS (mg/l)	Cycles per day	React Period (hrs)	Feed Period (hrs)
02/01	3749	8806	36.4	0.0	0.0	81.9	107		1	19	4
02/03	3262	8941	16.1	0.9	5.6	38.6	109		1	20	3
02/04	ERR	9213	24.2	0.2	0.8	55.7	114		1	19	4
02/05	ERR	9458	33.3	0	0.0	77.3	120		1	19	4
02/06	4469	9536	35.2	0	0.0	86.5	121		1	19	0
02/07	ERR	9536	35.2	0	0.0	88.0	121		1	18	4
02/08	ERR	9627	41.2	1.4	3.4	100.9	123		1	18	0
02/10	3445	9627	19.1	1.1	5.8	47.8	123		1	19.5	2.5
02/11	3209	9761	18	0	0.0	43.2	125		1	18	4
02/12	2834	9942	29.8	0.5	1.7	70.0	129		1	18	4
02/13	2550	10104	16.2	0.2	1.2	38.1	132		1	18	4
02/14	2307	10305	14.2	0.5	3.5	32.7	135		1	18	4
02/15	2145	10491	13.5	0.5	3.7	31.1	137		1	18.5	3.5
02/16	1778	10689	11.8	0.2	1.7	26.6	140		1	18	4
02/17	1787	10887	11	0.4	3.6	24.8	143		1	18	4
02/18	1575	11102	11	0.5	4.5	24.2	146		1	18	4
02/19	1489	11386	7.6	0.2	2.6	16.0	149		1	17.5	4
02/20	1388	11733	6.6	0.1	1.5	13.2	153		1	18	4
02/21	2040	12243	152.5	0	0.0	305.0	229	697	1	18	0
02/22	2385	12243	136.8	0	0.0	342.0	229		1	22	0
02/23	2218	12243	89	0	0.0	222.5	229		1	21	4
02/24	2090	12528	97.3	0.9	0.9	214.1	258	478	1	21	4
02/25	1803	12733	28	0.2	0.7	62.9	265		1	21	4
02/26	1604	12951	4.6	0	0.0	10.1	267		1	18	4
02/27	1798	13206	1	0.3	30.0	2.1	267		1	18	4
02/28	1934	13469	3.4	0.1	2.9	7.5	268		1	18	4

Table C3: Biodegradation In Reactor II, Feb 1990

Date	Settle Period (hrs)	Effluent Volume (ml)	
02/01	1	100	
02/03	1	200	
02/04	1	180	
02/05	1	100	
02/06	1	10	
02/07	2	150	
02/08	2	10	
02/10	1	100	
02/11	2	150	
02/12	2	150	
02/13	2	200	
02/14	2	200	
02/15	2	250	
02/16	2	250	
02/17	2	300	
02/18	2	400	
02/19	2.5	500	Waste Eff. Solids
02/20	2	500	Waste Eff. Solids
02/21	2	10	Return Eff. Solids
02/22	2	10	Return Eff. Solids
02/23	2	300	Waste Eff. Solids
02/24	2	300	Waste Eff. Solids
02/25	2	300	Waste Eff. Solids
02/26	2	300	Waste Eff. Solids
02/27	2	220	25 day MCRT
02/28	2	300	25 day MCRT

Table C4: Biodegradation in Reactor II, Mar 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate (g COD/ g SS*d)	Effluent COD (mg/l)
03/01	230	3480	141216	1155	37777	5423	262	4.8	2.5	0.08	868
03/02	300	4600	142596	1155	38123	----	---	ERR	2.5	0.14	935
03/03	235	4600	143677	1155	38395	----	---	ERR	2.5	0.11	840
03/04	325	4600	145172	1155	38770	----	---	ERR	2.5	0.15	814
03/05	230	4600	146230	1155	39036	----	---	ERR	2.4	0.09	712
03/06	325	4600	147725	1155	39411	4004	84	2.1	2.5	0.18	647
03/07	350	4600	149335	1155	39815	----	---	ERR	2.5	0.19	907
03/08	375	5639	151450	1044	40207	----	---	ERR	2.55	0.28	1009
03/09	320	5639	153255	1044	40541	----	---	ERR	2.5	0.20	1349
03/10	250	5639	154664	1044	40802	----	---	ERR	2.5	0.16	1627
03/11	0	5639	154664	1044	40802	2932	228	7.8	2.5	0.00	1074
03/12	215	5639	155877	1044	41026	----	---	ERR	2.5	0.19	1282
03/13	0	5639	155877	1044	41026	----	---	ERR	2.5	0.00	1028
03/14	150	5401	155687	1027	41180	----	---	ERR	2.5	0.13	1103
03/15	150	5401	157497	1027	41334	----	---	ERR	2.5	0.12	1024
03/16	160	5401	158361	1027	41499	3310	174	5.3	2.5	0.12	807
03/17	160	5401	159225	1027	41663	----	---	ERR	2.5	0.12	859
03/18	170	5401	160143	1027	41838	----	---	ERR	2.5	0.15	898
03/19	170	5401	161062	1027	42012	----	---	ERR	2.5	0.15	937
03/20	180	5401	162034	1027	42197	2867	83	2.9	2.5	0.18	853
03/21	190	5401	163060	1027	42392	----	---	ERR	2.5	0.29	926
03/22	380	5401	165112	1027	42782	----	---	ERR	2.5	0.57	---
03/23	400	5401	167273	1027	43193	----	---	ERR	2.7	0.60	872
03/24	200	5401	168353	1027	43399	----	---	ERR	2.5	0.30	---
03/25	375	5401	170378	1027	43784	2379	95	4.0	2.5	0.68	---
03/26	340	5401	172215	1027	44133	----	---	ERR	2.4	0.62	---
03/27	400	5401	174375	1027	44544	----	---	ERR	2.3	0.73	---
03/28	290	5401	175941	1155	44879	----	---	ERR	2.4	0.53	---
03/29	150	5401	176752	1156	45052	----	---	ERR	2.4	0.27	1348
03/30	400	5401	178912	1155	45515	2579	50	1.9	2.5	0.67	---
03/31	400	5401	181072	1156	45977	----	---	ERR	2.6	0.67	1478

Table C4: Biodegradation in Reactor II, Mar 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Effluent MLSS (mg/l)	Cycles per day	React Period (hrs)	Feed Period (hrs)
03/01	1970	13669	4.3	1.4	32.6	10.7	269	2393	1	18	4
03/02	2057	13949	5.1	0.2	3.9	12.6	271		1	18	4
03/03	1901	14146	4.3	---	ERR	10.6	272		1	18	4
03/04	1769	14411	2.5	0	0.0	6.2	272		1	18	4
03/05	1544	14574	2.8	0	0.0	6.7	273		1	20	4
03/06	1406	14785	5.7	5.5	96.5	14.1	275	1642	1	19.5	4
03/07	1949	15102	1.0	0.2	20.0	2.5	275		1	20	4
03/08	2194	15480	20.4	0.2	1.0	51.3	283		1	18	4
03/09	2941	15912	142.2	0	0.0	350.9	328		1	22	4
03/10	3660	16318	193.3	0.5	0.3	478.4	377		1	21	0
03/11	2684	16318	1.8	0	0.0	4.5	377		1	18	4
03/12	2929	16594	58.9	0.7	1.2	146.0	389		1	20.5	0
03/13	2570	16594	1.3	0.2	15.4	3.3	389		1	18.5	4
03/14	2605	16760	5.1	0	0.0	12.7	390		1	21	4
03/15	2406	16914	0.0	0	ERR	0.0	390		1	22	4
03/16	1888	17043	0.0	0	ERR	0.0	390	1103	1	21	4
03/17	2010	17180	0.0	0	ERR	0.0	390		1	21	4
03/18	2092	17333	0.0	0	ERR	0.0	390		1	18	4
03/19	2183	17492	0.0	0	ERR	0.0	390		1	18	4
03/20	1978	17646	---	-	ERR	ERR	390	1924	1	18	4
03/21	2140	17822	0.0	0	ERR	0.0	390		2	6	4
03/22	ERR	18174	0.0	0	ERR	0.0	390		2	6	4
03/23	2006	18523	0.0	0	ERR	0.0	390		2	6	4
03/24	ERR	18697	66.5	0.2	0.3	164.9	403		2	6	4
03/25	ERR	19024	34.8	0.2	0.6	85.7	416		2	6	4
03/26	ERR	19320	53.5	0	0.0	126.6	435	562	2	6	4
03/27	ERR	19669	0.0	0	ERR	0.0	435		2	6	4
03/28	ERR	19922	71.0	0	0.0	168.3	455		2	6	4
03/29	3033	20124	0.0	0	ERR	0.0	455		2	6	4
03/30	ERR	20663	60.7	1.4	2.3	149.3	479		2	6	4
03/31	3251	21254	2.1	1.9	90.5	5.4	480		2	6	4

Table C4: Biodegradation in Reactor II, Mar 1990

Date	Settle Period (hrs)	Comments
03/01	2	25 d MCRT
03/02	2	25 d MCRT
03/03	2	25 d MCRT
03/04	2	25 d MCRT
03/05	2	25 d MCRT
03/06	2	25 d MCRT
03/07	2	25 d MCRT
03/08	2	25 d MCRT
03/09	2	Waste Eff. Solids
03/10	2	Waste Eff. Solids
03/11	2	Waste Eff. Solids
03/12	2	Waste Eff. Solids
03/13	2	Waste Eff. Solids
03/14	2	Waste Eff. Solids
03/15	2	Waste Eff. Solids
03/16	2	Waste Eff. Solids
03/17	2	Waste Eff. Solids
03/18	2	Waste Eff. Solids
03/19	2	Waste Eff. Solids
03/20	2	Waste Eff. Solids
03/21	2	Waste Eff. Solids
03/22	2	Waste Eff. Solids
03/23	2	Return Eff. Solids
03/24	2	
03/25	2	
03/26	2	
03/27	2	
03/28	2	
03/29	2	
03/30	2	
03/31	2	

Table C5: Biodegradation in Reactor II, Apr 1990

Date	Feed Added (ml)	Feed COD (mg/l)	Cum. Influent COD (mg)	Feed Phenol (mg/l)	Cum. Influent Phenol (mg)	Reactor MLSS (mg/l)	MLSS Std. Dev. (mg/l)	MLSS % Error	Reactor Volume (l)	Loading Rate [g COD/ g SS*d]	Effluent COD (mg/l)
04/01	400	5401	182192	1208	46380	2579	50	1.9	2.6	0.67	----
04/02	400	5401	184353	1208	46863	----	---	ERR	2.5	0.67	----
04/03	200	5401	185433	1208	47105	----	---	ERR	2.7	0.34	----
04/04	400	5401	187593	1208	47588	2907	91	3.1	2.5	0.59	1426
04/05	400	5401	189754	1208	48071	----	---	ERR	2.5	0.59	1487
04/06	400	5401	191914	1208	48555	----	---	ERR	2.6	0.59	----
04/07	400	6315	194440	1156	49017	----	---	ERR	2.5	0.70	----
04/08	400	6315	196966	1156	49479	3172	157	4.9	2.5	0.64	----
04/09	400	6315	199492	1156	49942	----	---	ERR	2.5	0.64	----
04/10	400	6315	202018	1156	50404	----	---	ERR	2.5	0.64	----
04/11	400	6315	204544	1156	50867	----	---	ERR	2.5	0.64	----
04/12	400	6315	207070	1156	51329	----	---	ERR	2.55	0.64	----
04/13	400	6315	209596	1156	51791	3723	52	1.4	2.55	0.53	----
04/14	400	6315	212122	1156	52254	----	---	ERR	2.55	0.53	----
04/15	400	6315	214648	1156	52716	----	---	ERR	2.5	0.53	----
04/16	400	6315	217174	1156	53179	----	---	ERR	2.7	0.53	----
04/17	400	6315	219700	1156	53641	----	---	ERR	2.55	0.53	1935
04/18	400	6315	222226	1156	54103	3550	171	4.8	2.55	0.56	----
04/19	400	6315	224752	1156	54566	----	---	ERR	2.5	0.56	1868
04/20	400	6315	227278	1156	55028	----	---	ERR	2.5	0.56	----
04/21	400	6315	229804	1156	55491	----	---	ERR	2.6	0.56	----
04/22	400	6315	232330	1156	55953	----	---	ERR	2.5	0.56	----
04/23	400	6315	234856	1156	56415	----	---	ERR	2.5	0.56	----
04/24	400	6315	237382	1156	56878	----	---	ERR	2.5	0.56	----
04/25	400	6315	239908	1156	57340	----	---	ERR	2.5	0.56	----
04/26	400	6315	242434	1156	57803	----	---	ERR	2.5	0.56	----
04/27	0	6315	242434	1156	57803	----	---	ERR	2.5	0.00	----
04/28	0	6315	242434	1156	57803	----	---	ERR	2.5	0.00	----
04/29	400	6315	244960	1156	58265	----	---	ERR	2.5	0.56	----
04/30	400	6315	247486	1156	58727	----	---	ERR	2.5	0.56	----
05/01	0	6315	247486	1156	58727	----	---	ERR	2.5	0.00	----

Table C5: Biodegradation in Reactor II, Apr 1990

Date	Reactor COD (mg)	Cum. Eff. COD (mg)	Eff. Phenol (mg/l)	Std. Dev. (mg/l)	Phenol % Error	Reactor Phenol (mg)	Cum. Eff. Phenol (mg)	Effluent MLSS (mg/l)	Cycles per day	React Period (hrs)	Feed Period (hrs)
04/01	ERR	21845	0.0	0.0	ERR	0.0	480	768	2	6	4
04/02	ERR	22436	---	---	ERR	ERR	480		2	6	4
04/03	ERR	22732	3.5	---	ERR	8.8	481		2	6	4
04/04	2995	23302	0	0	ERR	0.0	481		2	6	4
04/05	3122	23897	21.8	0.2	0.9	45.8	489		2	6	4
04/06	ERR	24492	50.4	0.5	1.0	110.9	510		2	6	4
04/07	ERR	25086	143.9	1.5	1.1	302.2	567	1124	2	6	4
04/08	ERR	25681	94.2	0.9	1.0	197.8	605		2	6	4
04/09	ERR	26276	76.4	0.2	0.3	160.4	635		2	6	4
04/10	ERR	26870	53	1.2	2.3	111.3	657		2	6	4
04/11	ERR	27465	36.3	0.5	1.4	76.2	671		2	6	4
04/12	ERR	28060	18.7	0.2	1.1	40.2	679		2	6	4
04/13	ERR	28654	2.5	0.7	26.9	5.6	680		2	6	4
04/14	ERR	29249	1.8	0	0.0	3.9	680		2	6	4
04/15	ERR	29844	0.6	0.8	133.3	1.3	681		2	6	4
04/16	ERR	30438	11.9	0.5	4.2	27.4	685		2	6	4
04/17	4161	31212	3.5	0	0.0	7.5	687		2	6	4
04/18	ERR	31986	18.9	0	0.0	40.6	694		2	6	4
04/19	3923	32734	2.3	0.7	30.4	4.8	695		2	6	4
04/20	ERR	33481	31.1	0.2	0.6	65.3	708		2	6	4
04/21	ERR	34228	104.6	0.7	0.7	230.1	750		2	6	4
04/22	ERR	34975	131.5	1.9	1.4	276.2	802		2	6	4
04/23	ERR	35723	169.7	0.7	0.4	356.4	870		2	6	4
04/24	ERR	36470	184.7	0	0.0	387.9	944		2	6	4
04/25	ERR	37217	212.9	0	0.0	447.1	1029		2	6	0
04/26	ERR	37964	267.5	1	0.4	551.8	1136		2	6	4
04/27	ERR	37964	157.3	0	0.0	393.3	1136		2	6	4
04/28	ERR	37964	34.3	1	2.9	85.8	1136		2	6	4
04/29	ERR	38711	98.9	0.2	0.2	207.7	1176		2	6	4
04/30	ERR	39459	177.5	0.7	0.4	372.8	1247		2	6	4
05/01	ERR	39459	108.3	0.2	0.2	270.8	1247		2	6	4

Table C5: Biodegradation in Reactor II, Apr 1990

Date	Settle Period (hrs)	Effluent Volume (ml)
04/01	2	450
04/02	2	400
04/03	2	600
04/04	2	400
04/05	2	400
04/06	2	500
04/07	2	400
04/08	2	400
04/09	2	400
04/10	2	400
04/11	2	400
04/12	2	450
04/13	2	470
04/14	2	440
04/15	2	415
04/16	2	590
04/17	2	450
04/18	2	450
04/19	2	400
04/20	2	500
04/21	2	400
04/22	2	400
04/23	2	400
04/24	2	400
04/25	2	20
04/26	2	
04/27	2	
04/28	2	
04/29	2	
04/30	2	
05/01	2	