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BIO-OXIDATION OF THIOCYANATES TYPICAL OF
COAL CONVERSION EFFLUENTS

Final Report

By
Ronald D. Neufeld
L. Mattson
P. Lubon

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University of Pittsburgh
Pittsburgh, Pennsylvania

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FINAL REPORT

BIO-OXIDATION OF THIOCYANATES TYPICAL
OF
COAL CONVERSION EFFLUENTS

by

Ronald D. Neufeld, PI
Associate Professor of Civil Engineering

and

L. Mattson, P. Lubon
Graduate Students in Civil Engineering

UNIVERSITY OF PITTSBURGH

Pittsburgh, PA 15261

January 8, 1981

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ABSTRACT

Thiocyanates have been found in most coal conversion and coke plant effluents. The objectives of this study were to develop data for the biological degradation rate kinetics of thiocyanate removal, and to develop material balance information for the fate of sulfur and nitrogen resulting from such bio-decomposition of aqueous thiocyanates.

A literature review of thiocyanate bio-degradation indicates that while much biochemistry information is available, little information in the biological processing arena is known. Much of the available information in this latter category has been developed either by the U.S. Steel Industry or by Soviet Union scientists. A brief review of Russian literature is also provided.

Based on both batch and continuous culture experiments utilizing an "activated sludge" type of system with strictly thiocyanate degrading organisms, the specific utilization rate for SCN degradation was found to follow a substrate inhibition biokinetic relationship as:

$$d(\text{SCN})/dt-X = 2.24 / [1 + (5/\text{SCN}) + (\text{SCN}/1340)^6]$$

where; $d(\text{SCN})/dt-X$ = lb SCN used/lb biomass-day
SCN = mg/L SCN in effluent

The observed biomass sludge production rate was quantified as a function of sludge age in the bio-reactor.

The major metabolic by-products of SCN aerobic biodegradation are ammonia and sulfate, with such formation being stoichiometric with SCN. High levels of SCN in coal conversion and Stretford system effluents may lead to biological nitrification process requirements to be added to the wastetreatment scheme for compliance with BAT effluent ammonia discharge restrictions.

KEY WORDS:

Coal conversion	Wastewater Treatment
Thiocyanate	Ammonia
Environmental Control Technology	
Biological Processes	Activated Sludge
Water Pollution Control	

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Department of Civil Engineering
University of Pittsburgh
Pittsburgh, PA. 15261

Introduction:

Effluents from coking, coal gasification, and other coal carbonization processes often contain high levels of polynuclear aromatic hydrocarbons (PAH), phenolics, thiocyanates, free and fixed ammonia, cyanides, sulfides, sulfates, and alkalinity. Chemical analysis of such effluents varies from process to process due to differing conditions of coal carbonization, gas scrubbing temperatures, and type of coal feedstock used.

In a coal gasification facility, ground coal, which may be pretreated to destroy its agglomerating properties, is fed

to a gasifier where it reacts with steam and oxygen. Bed temperatures and product gas composition may be varied within limits by the steam-to-coal and oxygen-to-coal ratios employed. In fixed bed and some fluidized bed gasifiers, much of the coal carbon is converted to CO, CO₂, and CH₄, however, a small fraction amounting to 4% to 6% of the feed carbon, appears as liquid effluent tars and potential water pollutants from the scrubbed product gas (1).

Little is known of the formation of thiocyanate (SCN) during gasification. Luthy (2) indicates that one possible gas phase mechanism for the formation of aqueous thiocyanate is the reaction of carbon disulfide and ammonia. In the coking industry, the formation of thiocyanate can be explained on the basis of oxidation of coke oven gas constituents through various complex reactions in the aqueous phase to form thiocyanate and thiocyanate complexes. As indicated by Luthy, such reactions may involve the complexation of aqueous polysulfides and thiosulfates with cyanide. Similar aqueous phase reactions are thought to also exist with coal conversion liquid effluents.

Pollutant production data for four different coal gasification processes is given in Table I as a function of coal

feed type on a pound produced per pound coal gasified-moisture and ash free (MAF) basis. This table indicates the quantity of thiocyanate produced per ton of coal gasified can vary from about 0.07 to 2.5 lb. SCN/ton coal MAF. The quantity of wastewater production is directly related to the degree of steam decomposition in the gasifier and moisture content of the coal. By using the data in Table I and assuming that approximately one pound of wastewater is produced per pound of coal (MAF) gasified, then the expected effluent thiocyanate concentration will range between 35 to 1250 mg/L (1).

Research has been underway at the University of Pittsburgh to investigate certain key aspects of control technology development associated with coal conversion facilities. The purpose of this paper is to report on some research efforts involving the biodegradation of thiocyanate (SCN) as found in some coal conversion and coke plant wastewaters.

Klein et. al. (3) have indicated that the most probable technologies for coal conversion aqueous waste treatment include ozonation, adsorption, biological degradation, solvent extraction, membrane processes, and coagulation-flocculation. In the specific area of thiocyanate/cyanide removal, investigated processes include ozonation, adsorption, biological

Table 1. - Normalized Production of Gasifier Wastewater Pollutants (lb/ton of coal (MAF) + coefficient of variation, if available) After ref #1

Parameter	SYNTHANE			LURGI	GFETC		HYGAS
	Montana Rosebud	Illinois #6	N.Dakota Lignite	Montana Rosebud	200 psi	Lignite 400 psi	Lignite Run #37
BOD	27.1 ± 34%			66.5	7		
TOC	22.1 ± 69%	21.1 ± 23%	40.7 ± 24%		13.9	8.3	39.1
COD	55.5 ± 64%	64.2 ± 12%	70.6 ± 33%	103			
PHENOL	8.72 ± 79%	9.12 ± 22%	10.8 ± 36%	21.8		6.8	11.4
OIL & TAR	1.77 ± 44%	1.96 ± 34%		3.2	2.8	0.78	
ACETONE SOL. ^{a/}	1.98 ± 62%	2.26 ± 36%					
THIOCYANATE	0.067 ± 105%	0.67 ± 40%	0.053 ± 71%	0.08			2.5
CYANIDE ($\times 10^{-4}$)	2 ± 225%	7.8 ± 89%	2.1 ± 110%	200			0.287
H ₂ S	0.033 ± 95%			0.57			
TOTAL SULFUR	0.449 ± 22%			1.31			0.2
FREE + FIXED NH ₃	14.0 ± 29%			72.1	6.6	6.6	13.1
ALKALINITY	3.95 ± 33%			219	13.3	12.1	
TOTAL TAR + OIL PRODUCTION ^{b/}	30.4 ± 83%	77.6 ± 50%		210	70.1	55.5	
WASTEWATER PRODUCTION	2740 ± 46%	3920 ± 19%	3300 ± 42%	2976	916	736	

^{a/} Acetone Soluble Tars: A measure of high molecular weight organics precipitated from pretreated gasifier water by pH depression, an analytical technique developed at PETC.

^{b/} Measured prior to settling and hence is not part of the wastewater.

degradation, and chlorination.

Chlorination has been the traditional approach to thiocyanate and cyanide removal in the metal plating industry where the end products are first cyanate and then carbon dioxide and nitrogen gas. This approach however is not applicable to coal conversion processes due to the phenolic nature of the gasifier effluents and the tendency of the formation of toxic compounds such as cyanates, chlorinated phenols and hydrocarbons, chloroamines, and cyanogen chloride.

Kostenbader and Flecksteiner (4) investigated the biological oxidation of coke plant "weak ammonia liquor". The maximum thiocyanate loading oxidized in their activated sludge units was 4.8 lb/day-100 cu ft aeration volume, with oxidation efficiencies ranging from less than 10% to greater than 99%. No explainable reason could be construed for such variations.

Cousins and Mindler (5) demonstrated that cyanide and thiocyanate oxidation was operationally inconsistent with ammonia concentrations of 1250 mg/L. With levels of ammonia of 100 mg/L or less, thiocyanate destruction was complete with concurrent reduction in cyanide level.

Barker and Thompson (6) report that thiocyanate is only partially removed at low organic loadings of waste from a gas cleaning and by-product recovery system. Residual thiocyanate in the effluent from the carbonaceous reactor was a major contributor to COD in the plant effluent.

In a report by the British Coke Research Association (7), it was observed that thiocyanate concentrations above 2200 mg/L could not be treated at a detention time of 30 hours. Up to about 600 mg/L there is a straight forward relationship between influent thiocyanate concentration and retention time for a removal to a residual of 2 mg/L. No kinetics however were quantified for thiocyanate removal in this research effort.

Neufeld and Valiknac (8) developed mixed cultures taken from a coke plant biological waste treatment facility capable of degrading thiocyanate from levels of 2000 mg/L to 1 mg/L in a nine hour aeration period. Maximum biodegradation rates were observed in the pH range between 6.7 to 7.2 with inhibition appearing at pH levels of 7.6 and higher. Substrate inhibition was noted to occur at thiocyanate concentrations above 500 mg/L.

Keto et. al. (9) conducted studies with coke oven gas desulfurization waste solutions containing 2520 ppm of thio-

cyanate. The waste solution was treated with an activated sludge acclimated to thiocyanate-containing waste solutions. After a retention time of 12 days, the waste solution was void of thiocyanate.

McLee (10) investigated the treatment of wastewaters from coke plants containing phenols and 800 ppm thiocyanate by a two stage activated sludge system with 8 hour residence time. The thiocyanate level decreased in the first stage to 200 ppm and was almost completely eliminated in the second step.

Cooper and Catchpole (11) report on the efficiency of treatment of coke-oven liquors containing phenols, thiocyanate, $S_2O_3^{2-}$, CN^- , and NH_4^+ by the activated sludge process. Efficiency is said to be dependent on liquor composition, e.g. low concentration of phenols, and on the geometry of the aeration tank. For efficient biological treatment, a two stage process is recommended.

Catchpole and Cooper (11) suggested the addition of glucose to full-scale treatment processes as a growth factor. They claimed of improvements in the oxidation of thiocyanate solutions and of some coke-oven liquors, both in regards to reduction in the minimum retention time at which the processes would successfully operate, and in the

clarity of the treated effluent.

Scott (12) describes a single stage fluidized bed bioreactor used for treating the aqueous waste produced by a coal hydrocarbonization bench scale facility. Preliminary results indicated a single contacting stage can reduce thiocyanate levels in the aqueous waste to one to five mg/L from an average initial concentration of 380 mg/L.

Ludberg and Nicks described the design of a full-scale activated sludge dephenolization plant (13) designed for both phenol and thiocyanate removal, with pretreatment consisting of ammonia stripping. While an average of 99.3% of influent phenol was removed, thiocyanate removal efficiency was erratic, with an average of only 58.8% of the influent thiocyanate being removed. In addition, ammonia concentrations were found to increase due to the decomposition of thiocyanate.

Ganczarczyk (14) studied this design and performed laboratory and pilot-scale experiments on the effluents from the above-mentioned plant in order to attain ammonia removal, and to reduce the amount of other residual pollutants. The utilization of a second stage in the treatment of these coke-plant effluents was deemed necessary in order

to meet BATEA effluent standards by 1983. Results were excellent, with an average of 90% ammonia removal, despite temporary shock loadings and temperature problems. Thiocyanate was reduced to less than 1.0 mg/L, and total cyanides to about 3.5 mg/L. Though not fully dealt with in the paper, nitrite formation was considerable, and to a lesser extent, nitrate formation. Denitrification would be the next problem to consider in this treatment process.

Shista et al. (15) used activated carbon for the removal of thiocyanate from wastewater. A wastewater containing 116 ppm of thiocyanate was treated with $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ and hydrochloric acid at pH=1. After coming in contact with 4000 ppm activated carbon for one hour, the supernatant wastewater contained 2.6 ppm thiocyanate. No studies were done to give an indication of possible removal capabilities at higher thiocyanate levels.

Juntgen and Klein (16) investigated the merits of using activated carbon for the treatment of wastes from coking and coal gasification plants. It was discovered that levels of total organic carbon in the range of 800 to 1900 mg/L were reduced to concentrations between 80 to 250 mg/L after contact with activated carbon. The TOC remaining after treatment was

found to be composed of cyanides and thiocyanates. Therefore, despite the large removal efficiencies for the organic pollutants by the activated carbon, much of the initial cyanogen content remained after treatment.

Neufeld and Spinola (17) investigated the effectiveness of ozonation on wastewater from an experimental coal gasification plant. Except for the low boiling compounds, all organics analyzed were substantially oxidized to lower concentration levels under severe ozonation, that is, under higher ozone to waste application rates. In addition, the thiocyanate concentration was reduced from 445 to 240 mg/L while the cyanide concentration increased from 1.3 to 10.2 mg/L. This indicates a reduction of total soluble cyanogens.

Juntgen and Klein (16) have presented limiting values of some substances to the three main decomposing compounds of coke-plant effluents. They concluded that for efficient phenol degradation, ammonium concentration should not exceed 1700 mg/L, thiocyanate concentration should not exceed 250 mg/L, sulfide concentration should not exceed 25 mg/L, and metal ions concentration should not exceed 5 mg/L. The maximum phenol concentration considered for biological treatment should not exceed 500 mg/L.

For efficient thiocyanate removal, the ammonium chloride concentration should not exceed 1000 mg/L, thiosulfate concentration should not exceed 100 mg/L, phenols concentration should not exceed 25 mg/L, and the metal ions concentration should not exceed 5 mg/L.

For efficient ammonia degradation, phenols concentration should not exceed 50 mg/L, thiocyanate concentration should not exceed 10 mg/L, and cyanide concentration should not exceed 10 mg/L (16).

Ashmore et al. (17) used the occurrence of low concentrations of thiocyanate (zero to a few mg/L) in biologically treated effluents as the criterion of effective treatment. They indicated that removal of thiocyanate was not successful until most of the phenols had been oxidized, and that the optimum pH range was 6.7-7.3.

Retention time was given a fundamental significance in the above-mentioned study, and it was found that given a period of 20 hours, 2000 mg/L of thiocyanate could be degraded to between 0 and 1 mg/L. But when the retention time was reduced to 15 hours, the influent thiocyanate concentration had to be reduced to 500 mg/L. This corresponds closely with the value of 470 mg/L given by Neufeld et. al. (8) as the concentration for the maximum thiocyanate removal rate. Above this concentration, thiocyanate substrate inhibition was exhibited.

THIOCYANATE MICROBIOLOGY

Thiocyanate is considered to be an inorganic compound in some literature, and is referred to as an organic compound elsewhere. In addition, both autotrophic and heterotrophic bacteria have been isolated which are able to utilize thiocyanate.

Happold et. al. (18) isolated an organism which could oxidize thiocyanate on a media consisting of phosphate, trace metals, and thiocyanate, and incubated aerobically at 30°C. The pH of the medium was 7.0-7.2. Young cultures were found to oxidize thiocyanate quantitatively to sulfate and ammonia. In an 8-day experiment with an initial feed of 240 mg/L of potassium thiocyanate, 96% of the nitrogen and 98% of the sulfur was recovered in the forms of ammonia and sulfate, respectively. After the disappearance of thiocyanate, the organisms were observed to clump. In older unfed cultures, elemental sulfur was found to be contained within these clumps. Upon the resumption of the feeding of thiocyanate, free sulfur would often separate from the clumps. Through this study, an unusual example of an organism able to use one simple inorganic compound as its source of energy (sulfur), nitrogen, and carbon was given. The name given this organism was Thiobacillus thiocyanoxidans.

The initial step of thiocyanate metabolism is the hydrolysis of thiocyanate to sulfide, ammonia, and carbon dioxide (18). It appears that the organism can obtain its carbon requirements by hydrolysis of thiocyanate and subsequent absorption of carbon dioxide, since theoretical amounts of carbon dioxide are not produced.

Youatt (19) observed that cultures of Thiobacillus thio-
cyanoxidans oxidized potassium thiocyanate according to a molar ratio of three oxygen to two thiocyanate. The products of oxidation were found to be K_2SO_4 , $(NH_4)_2SO_4$, CO_2 , and cell protoplasm.

Happold, Johnstone, Rogers, and Youatt (20) isolated the bacterium Thiobacillus thio-
cyanoxidans on a media containing phosphate, trace metals, and thiocyanate. The cultures were found to oxidize thiocyanate to ammonia and sulfate with material balance closures of approximately 90-95 percent.

Katayama and Kuraishi (21) isolated a bacterium identified as Thiobacillus thio-
parus from activated sludge used for the treatment of thiocyanate contained in cokeoven liquor. Potassium thiocyanate in concentrations of 500 mg/L was completely assimilated in 60 hours. Thiosulfate was found to inhibit the assimilation of thiocyanate but elemental sulfur did not.

Stafford and Callely isolated a heterotrophic bacterium which used thiocyanate as its sole source of cellular nitrogen and sulfur (22). It was a pseudomonad, most similarly resembling Pseudomonas stutzeri.

When thiocyanate and ammonium ions were present together in the growth medium, thiocyanate degradation did not occur until the ammonium ions were nearly used up. The addition of ammonium ions to a culture growing with thiocyanate inhibited the further utilization of this compound, though the effect was not instantaneous. During thiocyanate utilization, no intra- or extra-cellular sulfur was produced, nor was sulfide detected. However, the sulfate concentration of the medium increased during the growth of the culture, with thiocyanate acting as the sole source of added sulfur (22).

The organism was able to metabolize phenol and thiocyanate simultaneously, which classify it as heterotrophic and make it potentially useful in the biological treatment of coal conversion effluents.

REVIEW OF RUSSIAN LITERATURE

A significant number of references made to Russian literature was encountered in conducting a literature search dealing with thiocyanate removal technology and coal conversion effluents. Although English translations of the entire articles are scarce, some were found to be abstracted in detail in various issues of Chemical Abstracts. Due to the predominance of Russian literature on this subject area, a brief summary of key articles with titles follows.

Thiocyanate Oxidizing Organisms

In a paper entitled "Isolation and Study of Several Representatives of Unicellular Green Algae Resistant to Cyanides" (23) the authors reported two species, Scenedesmus obigus and S. acuminatus, that were capable of decomposing and assimilating cyanide and thiocyanate ions in increasing amounts. The algae had initially been isolated and repeatedly grown on media containing up to 25 mg/L of potassium cyanide.

Papkov et al. presented an article entitled "Selection of Thermophilic Cultures for Purification of Waste Water of By-Product Coke Plants" (24). The wastewater

stream of a coke plant typically has a temperature of approximately 60°C. In order to biologically purify these wastewaters, it is necessary to cool the streams down to the optimal temperature of 30-34°C. Five strains of thermophilic microorganisms which are capable of oxidizing phenols and thiocyanates were identified, which operate in the optimal temperature range of 55-70°C, thus making it unnecessary to cool down the waste streams. The organisms are: Bacterium filiforme, Bacillus cylindricus, Bacillus subdenticulatus, Bacillus thermophenolicus, and Bacillus calidus.

The oxidation efficiencies of phenols and thiocyanates in aeration tanks were increased by a factor of 2 to 2.5 after filling the tanks with specially grown micro-organisms. In a paper entitled "Improvement in the Biochemical Purification of Phenol-Containing Waste Waters in Aeration Tanks", (35) the authors explained that suitable organisms grown on an inert porous material could be more effective as a purifying biomass. The porosity of the material was of primary importance, whereas its nature did not have an effect on the oxidation process.

Activated Sludge Processes

In the article "Effect of Some Contaminants in Waste Waters from the Coal Tar Industry on Biochemical Oxidation of Thiocyanates", (26) it was reported that the presence of hydroquinone affects thiocyanate oxidation. Concentrations of 1, 5, and 10 mg/L of hydroquinone increased the time required for effective biochemical oxidation of thiocyanate by 17, 31, and 48 percent, respectively. In addition, pyrocatechol and resorcinol decreased oxidation only at concentrations greater than 20 and 10 mg/L, respectively. It was also found that 0.1 mg/L nickel, 0.1 mg/L copper, 1.0 mg/L lead, and 1.0 mg/L zinc interrupted thiocyanate oxidation.

The 20-day Biochemical Oxygen Demand (BOD) index was reported to inadequately reflect the wastewater characteristics of by-product coke manufacture (27) in an article entitled "Acceptability of the BOD Index for Characteristics of Waste Waters from By-Product Coke Manufacture". In addition, it was reported that in simultaneous treatment of phenol and thiocyanate, the phenol destruction increased two to three times by increasing the temperature from 20°C to 32°C. Thiocyanate concentration was considered to be the determining factor in the

biochemical treatment process due to its "resisting" nature.

Laboratory investigations were conducted on dephenolized wastewater, as described in a paper entitled "Biochemical Purification of Waste Waters Containing Thiocyanates" (28). It was found that the oxidation of thiocyanates was affected by the presence of residual phenols, and 15 mg/L of phenol was considered to be the limiting concentration. For efficient biochemical oxidation of wastewaters in this study, it was suggested that the aeration period not be less than 17 hours, and the temperature not be less than 19-22°C.

A paper entitled "Hygienic Evaluation of the Effectiveness of a Pre-Purification of Waste Waters from the Coal-Tar Chemical Industry in Biological Reservoirs", (29) indicates that a treatment plant for a coal-tar works consisted of a cascade of 3 ponds of identical size. Wastewater components were phenols (5 mg/L to 100 mg/L), thiocyanates (200 mg/L), and ammonia (300-500 mg/L). The results as described in the article indicated a great improvement in organoleptic, general sanitary, and basic water quality indices during treatment. Color, odor, and transparency improved; suspended matter, BOD, and oxidizability decreased; and the concentrations of ammonia-nitrogen, phenols, and thiocyanates decreased by 60, 96.5, and 94%, respectively, after 15 days.

Alternate Technologies - Russian

In a paper entitled "Use of Ozone for Additional Purification of Waste Waters from By-Product Coke Plants", (30) treatment efficiencies for the disinfection of previously biochemically treated coke-plant effluents were reported to be 99.9%. Concentrations of ozone used were 100-160 mg/L, with the ozone requirements being based upon the content of phenols and thiocyanates within the effluents to be treated.

The use of the EDE-10-P anion exchanger was investigated for collecting thiocyanate and thiosulfate ions from waste-waters of a coke-plant (31). Experiments were first conducted on prepared water solutions, and then on actual coke-plant waste-waters. The adsorption process was carried out in columns at air temperature, and resulted in the removal of 99.6% of the thiocyanate ions, and 99% of the thiosulfate ions. Complete regeneration of the exchanger was achieved through the use of a 5% solution of sodium hydroxide.

In an article by Zamelin entitled "Removal of Thiocyanates from Waste Waters", (32) a Russian literature review is presented containing 32 references on biological and chemical methods, including chlorine, ozone, and ion-exchange processes.

Biological processes may be designed for the sequential removal of both phenol and thiocyanate. In order for this to be effective, the design of the system should be based on the biokinetics of thiocyanate, since steel industry practice indicates that thiocyanate degradation occurs after phenol degradation. In lieu of a one stage system that is often the industry standard, it may be more practical from a kinetic viewpoint to design a series of linked bio-reactors, the first for phenolics, the second for thiocyanates, and perhaps a third for ammonia reduction. In this manner, each subsystem may be operated at pH's and sludge ages consistent with the needs of the specific biological population utilized. Prior to implementing this approach however, a site specific economic systems analysis must be done and compared with judgement as to the better one-sludge designs to cope with historic operational instability data for existing one stage systems.

Based on research outlined above, it appears that the questions of phenolic removal, thiocyanate removal, and ammonia removal are parts of one overall interlocked biochemical system.

Thiocyanate levels inhibit phenol degradation biokinetics (33) phenol inhibits ammonia removal (nitrification) bio-kinetics (34), thiocyanate biodegradation yields ammonia as an end product, and high levels of un-ionized ammonia (a function of total ammonia

and pH) tend to inhibit nitrification biokinetics (34). Despite the relatively complicated biochemistry, well designed-biological processes are the most pragmatic approach to the treatment of coal conversion and steel industry wastewaters. Accordingly, the overall goal of our research program is to better understand and quantify the fundamental kinetic relationships relative to the environmental chemical and process considerations that are necessary for the proper flow sheet design and operation of industrial wastewater treatment facilities.

At the present time, several states including Pennsylvania have strict restrictions concerning the discharge of cyanogens and cyanides. Thiocyanates are considered by Pennsylvania as a cyanogen and thiocyanates are considered a "BAT" pollutant for the coke industry (35). Thus, a regulatory incentive exists for the removal of cyanogens for the environmentally acceptable operation of coal gasification processes.

RESEARCH GOALS AND OBJECTIVES

The objective of this research is to develop a kinetic expression and material balance for nitrogen and sulfur for the biological degradation of aqueous thiocyanates as found in coal conversion process wastewaters.

In order to achieve this objective, the following experimental goals were set:

- (1) Develop batch and continuous cultures of thiocyanate-degrading organisms.
- (2) Determine appropriate biological kinetic parameters describing specific rates of thiocyanate utilization by such organisms.
- (3) Develop design parameters for the successful operation of an activated-sludge system for thiocyanate-degrading organisms.
- (4) Monitor nitrogen and sulfur species around the reactor as functions of operating conditions.

BIOKINETIC CONSIDERATIONS

One key to utilizing any biological process for industrial purposes is understanding the applicable biokinetics. Many substances act as nutrients at low concentration levels, and serve as toxic inhibitors at higher levels. Based on this research, thiocyanate is one such substance.

Mathematically, a relationship for substrate inhibition may be written as:

$$v = \frac{V_{\max}}{1 + \frac{K_m}{S} + \left(\frac{S}{K_i}\right)^n} \quad (1)$$

where K_i = inhibition constant

n = order of inhibition

$V_{\max}, K_m$ = constants

As K_i approaches infinity, equation 1 approaches the classical Michaelis-Menten kinetics. Figure 1 is a conceptual plot which classical Michaelis-Menten kinetics with the substrate inhibition model of equation 1. Figure 2 illustrates the inverse of equation 1 as:

$$\frac{1}{v} = \frac{1}{V_{\max}} + \left(\frac{K_m}{V_{\max}}\right) \left(\frac{1}{S}\right) + \left\{\frac{S^n}{K_i^n}\right\} \left(\frac{1}{V_{\max}}\right) \quad (2)$$

The curvature of Figure 2 at low S^{-1} values (high substrate levels) is due to the inhibition term of equation (1)

The values of K_m and $V_{\max}$ can usually be determined in accord with the Lineweaver-Burke plot by considering low sub-

SUBSTRATE INHIBITION FUNCTION

Figure 1.

INVERSE RELATIONSHIP OF SUBSTRATE INHIBITION

Figure 2

strate levels only. Values of K_i and n are best fit by a numerical and graphical procedure as shown by Neufeld et. al. (36).

THIOCYANATE BIOCHEMISTRY

Based on laboratory observations coupled with data presented in the literature, the following equations best represent the biochemical degradation of aqueous thiocyanates (SCN).

Equation 3 indicates sulfate as an end product of thiocyanate degradation, a result which as shown below agrees with the literature, and is also observed in our biological reactors. In accord with this equation, a coal conversion waste stream of about 200 mg/L SCN would contain an additional 331 mg/L additional sulfate and an additional 59 mg/L ammonia after aerobic thiocyanate biodegradation.

Equation 4 shows sulfide as a byproduct of thiocyanate anaerobic degradation. It has been observed during the course of this research that if SCN laden sludge is settled for a few minutes with no air sparging through the system,

upon resumption of aeration, unpleasant hydrogen sulfide odors rapidly permeate the laboratory until air stripping totally removes the biologically formed H_2S from solution.

Equation 5 indicates the formation of free sulfur with concurrent rise in pH. Free sulfur has not been visually noted in our reactors, nor has the tendency for rise in pH during the course of aeration. Thus, equation 5 does not appear to occur to any great extent in the experimental system. It is possible however, that equation 5 may be kinetically favored over equation 3 in systems where the level of dissolved oxygen is limited.

EXPERIMENTAL PROCEDURES

During the course of this study, 5 semi-continuous batch reactors followed by 14 continuous completely mixed reactors were evaluated. Two of the continuous reactors failed, leaving 12 continuous systems for the study.

DEVELOPMENT OF BIO-SLUDGE

Prior to the start of this study, about 20 liters of activated sludge were obtained from the Clairton, PA coke plant of the United States Steel Corporation. The sludge, as brought to the Environmental Engineering Laboratories of the University of Pittsburgh, was amber in color, had significant floating oils, and exhibited strong phenol and cresol odors (8). It was aerated for two days to allow for stripping and removal of soluble volatile organic materials, and for the skimming of oily materials from the surface.

A daily diet of 100 mg/L of thiocyanate and 100 mg/L of dextrose was fed to the culture to enable thiocyanate acclimation. Organisms that were capable of growing on the media remained in the reactor, and those that weren't capable were washed out of the system. After about six months, the culture

was considered acclimated sufficiently enough to begin batch experimentation. Approximately one year of study was performed on this active culture prior to gathering the data described in this report.

PHASE I - BATCH OPERATION

Four fill-and-draw semi-continuous reactors were maintained during the course of this half of the study. Two Pyrex glass reactors each had a volume of 4 liters with a working volume of 3.5 liters. Two other Plexiglas reactors each had a volume of 15 liters with a working volume of 8 liters.

Sludge ages were varied throughout experimentation over a range of 5 to 15 days. A specific volume of mixed liquor suspended solids was removed from each reactor daily, and this volume was determined by multiplying the reciprocal of the desired sludge age by the working reactor volume.

All batch reactors were operated at a hydraulic detention time of 2 days, which was maintained by drawing off half of the liquid volume upon daily settling out of the solids, and replacing this volume with feed solution and tap water. The pH was adjusted to 7.0 upon completion of daily feeding and reaeration of the reactors.

A complete mix and ample aeration was attained in each reactor through the use of electrically-powered mixing paddles and air stones. The smaller reactors required only the use of air stones, while the larger reactors utilized both the paddles and the air stones to eliminate "dead spaces" where air stones alone could not reach. A regulator was used to insure uniform air flow.

All mixed liquor that was wasted from the active cultures from maintenance of sludge age was deposited into a "bug bank", a separate 20 liter, aerated Pyrex bottle. The purpose of this reservoir was to hold surplus acclimated microorganisms in case of a reactor failure (i.e., washout, accidental death, etc.), or for use in the start-up of other experiments. This population was periodically fed thiocyanate feed solution, as described in the following section. When the reservoirs became filled to capacity, no more than half of the volume was discarded.

Figure 3 is a drawing of the laboratory set-up for the batch reactor study mentioned above.

The thiocyanate used in this study was the sole source of carbon for the culture. It was fed in concentrations of 1500 and 2000 mg/L as the influent to the batch reactors, using potassium thiocyanate as the stock reagent.

FIGURE 3

Laboratory Apparatus Set-Up for Batch Reactor Study

Trace metals and phosphorus were added to the feed solution to insure proper growing conditions for the microorganisms. These nutrients were the same as those required for the dilution water of the Biochemical Oxygen Demand (BOD) analysis, as found in Standard Methods for the Examination of Water and Wastewater (37). The phosphate buffer, supplying the phosphorus, maintained the pH of the feed solution at 7.1 ± 0.2 .

The COD/N/P ratios in the reactors which were fed 1500 and 2000 mg/L of thiocyanate per day were

28.5/6.24/1 and 23.4/5.12/1, respectively. This indicates that phosphorus was not limited in the biological systems. In addition, the presence of excess phosphate in the effluent was periodically tested using Hach PhosVer III Phosphate Reagent Pillows (38). Results of this qualitative test were always positive.

Tap water was used to dilute the concentrated feed components somewhat before adding them to the cultures. Table 2 lists the nutrients and their stock concentrations. Table 3 summarizes the operating parameters of the batch reactors.

TABLE 2

Stock Nutrients Used for Proper Culture Growth

Constituent	Concentration (g/L)
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	22.5
CaCl_2	27.5
$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	0.25
K_2HPO_4	43.5
KH_2PO_4	17.0

TABLE 3

Operating Parameters of Batch Reactors - 2 day hydraulic detention time
- Temp. = $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$

Reactor no.	Sludge Age (days)	SCN feed (mg/L-day)	FeCl_3 (mg/L)	MgSO_4 (mg/L)	CaCl_2 (mg/L)	Phos. Buffer (mg/L)	Reactor Vol.(L)
R1	15	1500	.14	12.8	15.7	711.8	3.5
R2A	10	1500	.14	12.8	15.7	711.8	3.5
R2B	5	1500	.14	12.8	15.7	711.8	3.5
R3	15	2000	.09	16.9	20.6	578.3	8.0
R4	10	2000	.09	16.9	20.6	578.3	8.0

PHASE II - CONTINUOUS REACTOR STUDIES

Continuous-feed reactor experiments took place during the second half of this study. Two reactors were in use at all times, each in various stages of experimentation. The microorganisms used in this study were obtained from either the batch reactors, and/or from the waste storage bottle.

DESCRIPTION OF APPARATUS

The aeration compartment had a volume of 20 liters with a working Volume of 15 liters. Five air stones supplied the air for each compartment. Air flow was maintained at a uniform rate via a pressure regulator.

The thiocyanate feed solution for each reactor was placed in a 48 liter Pyrex bottle, and was continuously stirred using a magnetic spin-bar and a Fisher Vuemix magnetic stirrer. Feed was pumped from the feed bottle into the reactor, using a Research Appliance Company bellows pump (Model 4500).

Effluent flowed from an opening placed at the surface of the liquid level, the opening being encased by a clarification

apparatus. The clarifier consisted of a rectangular box, measuring approximately 9" X 3" X 2" (9 inches being the vertical length), with two opposing baffles placed 45° to the vertical. The upper baffle was attached one inch below the effluent opening, and the lower baffle was attached $2\frac{1}{2}$ inches below the upper baffle. The purpose of this clarification apparatus was to keep the mixed liquor from escaping over the weir and to provide an undisturbed area for settling.

Effluent was collected in a 20 liter bottle equipped with a slight vacuum suction. The purpose of the suction was to insure against the possibility of clogging by an accidental build-up of sludge either around the effluent opening or in the effluent tubing. Bottles (both feed and collection), pumps, and all tubing were cleaned periodically to prevent this type of build-up.

The pH was continuously controlled in each reactor, as described in a later section. This set-up for each reactor included a Horizon pH Controller (Model 5997-20) equipped with one pump each for acid solution and base solution. The pumps used were a Cole-Parmer Masterflex peristaltic pump for the acid, and a Research Appliance (Model 4500) for the base. Concentrations of the acid and base solutions were determined according to the needs of each system, so as not to upset the hydraulic detention time.

The entire aeration tank, including the clarification apparatus, was made from Plexiglas. A hinged lid was also used to minimize the effects of evaporation.

Figure 4 depicts the apparatus set-up used in the continuous study.

VERIFICATION OF ASSUMPTION OF COMPLETE MIX IN REACTORS-TRACER STUDIES

Prior to the actual start-up of continuous culture study, a complete mix test was performed upon the reactor.

In the case of a continuous-flow stirred-tank reactor, if a continuous flow of a nonreactive tracer were injected into the inlet of the reactor, the appearance of the tracer at the outlet would occur as a function of time (39). In the test performed on our reactors, methyl blue dye was placed in the reactor, and tap water was pumped through. The disappearance of the dye should then follow the equation defining a washout curve:

$$L/L_0 = e^{-t/t_d} \quad (6)$$

where L = concentration of dye at time t ,

L_0 = concentration of dye at $t = 0$,

t = time (minutes), and

t_d = detention time

FIGURE 4

Laboratory Apparatus Set-Up for Continuous Reactor Study

In this experiment an initial concentration of 100 mg/L of methyl blue was placed in the reactor. A detention time of 20 minutes was selected and a flow rate of the influent tap water was determined by dividing the reactor volume by the detention time. Samples were taken from the reactor every two minutes for the first twenty minutes, and every 5 minutes thereafter until the test was completed. The concentration of the dye was determined by comparing absorbance readings from a Bausch and Lomb Spectronic 20 spectrophotometer with a calibration curve prepared from methyl blue concentrations ranging from 0 to 100 mg/L. Results were then compared with theoretical values as calculated from equation 6, and shown in Figure 5. From this it can be concluded that a complete mix does occur in the reactor, with only a slight deviation from the theoretical existing.

DESCRIPTION OF CONTINUOUS CULTURE OPERATION

Sludge ages were varied between 8.2 and 216.6 days throughout experimentation. As in the batch studies, the daily volume of mixed liquor suspended solids to be removed was determined by multiplying the reciprocal of the desired sludge age by the working reactor volume. Sludge ages were

Figure 5

then recalculated using data measured of the volatile suspended solids content of the effluent. Tap water was used to replace the volumes removed, which in turn were placed in the storage containers.

A hydraulic detention time of one day was used throughout the continuous phase of study, and this was maintained by adjusting the flow rate of the feed solution into the reactor. A 15 liter per day rate was used. The pumps were checked daily and the flow rates were adjusted when necessary.

The pH was controlled continuously by using solutions of hydrochloric acid and sodium hydroxide. These were chosen so as not to interfere with the nitrogen and sulfur balances of the system. The range of pH values used in this study was 5.0-8.0. Table 4 lists the conditions of each reactor, its corresponding sludge age, and the pH under which it was operated. As in the batch reactor studies, thiocyanate was the sole source of carbon to the culture systems.

The COD/N/P ratio for all continuous reactors was calculated to be 9.5/2.1/1, indicating that phosphorus was not limited in the biological system. In addition, the presence of excess phosphate in the effluent was periodically tested

TABLE 4

Operating Parameters of Continuous Feed Reactors

Influent Feed = 1000 mg/L SCN

Temp. = $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$

Hydraulic Detention Time = 1 day

Reactor #	Sludge Age (days)	pH
1	8.2	7
3	15.0	7
4	6.7	7
5	10.3	7
6	15.1	7
7	17.1	7
8	152.0	7
9	216.6	7
10	16.2	6
11	16.3	8
12	17.1	5

qualitatively using the method described above.

ANALYTICAL METHODS

Analytical methods were common to both the batch reactor study and the continuous reactor study.

Thiocyanate determinations were made daily upon each reactor in accordance with the colorimetric method outlined in Standard Methods for the Examination of Water and Wastewater (37). The calibration curve exhibited excellent stability over time. This method proved accurate for the purposes of this study, however, "relatively clean" water was used and thiocyanate was the only contaminant present.

Alkalinity, mixed liquor suspended solids, Sludge Volume Index (SVI), Zone Settling Rate and mixed liquor volatile suspended solids determinations were made two to three times each week, according to the procedures outlined in Standard Methods (37).

SULFUR SPECIES

In order to close the material balance for sulfur,

many possibilities had to be examined by way of determining sulfur species in the reactor effluents.

An attempt was made to determine if the presence of gypsum precipitate (CaSO_4) existed. One liter of mixed liquor suspended solids was collected and settled out. After draining off the supernate, the sludge material was filtered and fired in a porcelain dish at 550°C . The ash was dissolved in acid and a sulfate determination (described later) was made, revealing no presence of sulfate.

According to solubility product calculations, the presence of calcium sulfate precipitation was unlikely in the continuous culture systems. It was, however, possible in both batch systems due to the higher concentrations of sulfate normally present in the reactors. The possibility of calcium phosphate precipitation existed in all culture systems due to the high phosphate levels present. The extent of either of these reactions, however, is unknown.

The threshold odor concentration of hydrogen sulfide is between 0.01 and 0.1 ug/L in clean water (37). At no time was this odor detected in an aerated reactor. However, when sludge was allowed to settle, unaerated, strong H_2S odors were prevalent upon reaeration. In addition, lead acetate test papers were periodically placed in the clarifier area for the detection of dissolved sulfides. Tests always resulted in a negative reaction.

The presence of sulfite ions (SO_3^-) was tested periodically using Quantofix test papers, which can detect the ions in the parts per million range. Tests for this substance resulted in negative reactions.

Sulfate determinations were made according to Standard Methods, (37) using the turbidimetric procedure. Standard solutions were frequently tested and the calibration curve often updated due to the tendency of this curve to shift with time.

NITROGEN SPECIES

In order to close the material balance for nitrogen, several nitrogen species were examined for their presence in the effluent.

Nitrites and nitrates were determined according to the Hach Method (38). The low level procedures were used since high levels were not expected. Figures 6 and 7 show the standard curves developed for nitrite-nitrogen and nitrate-nitrogen determinations, respectively using stock solutions of sodium nitrite and potassium nitrate, for the determination of $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$.

Ammonia determinations were made using an Orion Research Ammonia Electrode (Model 95-10) with Corning Digital Analyzer (Model 125). The probe was calibrated prior to each analysis, and showed good stability. Figure 8 shows the standard calibration curve for ammonia.

According to the theoretical considerations for the ammonia probe, a 10-fold change in ammonia concentration would result in approximately a 58 millivolt slope (37). The slope that appears in the ammonia calibration curve shows a slope of 57.5 millivolts per 10-fold concentration change. Tests for ammonia were performed 2-3 times per week.

A series of experiments were made to determine the nitrogen content of the biological cells contained in the reactors. Using COD apparatus, a sample of mixed liquor suspended solids was digested in sulfuric acid and potassium dichromate. After cooling, the pH of each sample was raised to about 3-4 with sodium hydroxide, and set aside to re-cool. Later, an ammonia analysis was made on the sample, and from this value was subtracted the ammonia content of the sample prior to digestion. Cell nitrogen content was evaluated after several trial runs, using sludge from different reactors under different conditions.

Tests for total cyanides and cyanides amenable to chlorination were performed on effluent samples in order to check the possibility of this conversion of thiocyanate. The method followed was that outlined by Standard Methods, (37) using a Wheaton Cyanide Distillation Kit.

ENGINEERING PARAMETER EVALUATION

Oxygen Requirements

Respirometric evaluations were periodically done in order to determine oxygen requirements for the culture systems. Oxygen utilization was measured after a system had reached steady state which occurred when thiocyanate utilization remained constant and the biomass growth rate became constant. When these conditions existed, oxygen utilization was determined by withdrawing a sample of at least 250 milliliters of mixed liquor and allowing it to aerate for about one minute to insure saturation with oxygen. Immediately prior to testing, volatile suspended solids, thiocyanate, and temperature were measured. A sample of mixed liquor is poured into a 250 milliliter Erlenmeyer flask containing a magnetic stirring bar, completely filling the flask. A dissolved oxygen probe, mounted in a rubber stopper, is carefully inserted in the flask to form a complete seal with no air bubbles or pockets. The contents of the flask are stirred continuously using a Fisher Vuemix stirrer. A Yellow Springs Instrument Company mode 51A dissolved oxygen meter was used to establish dissolved oxygen uptake as a function of time. Readings were taken until oxygen levels

in the flask fell below 2 mg/L. All respirometric tests were conducted at a temperature of $22^{\circ}\text{C.} \pm 2^{\circ}\text{C.}$

In order to determine endogenous respiration rates, a sample of mixed liquor from a system at steady state was allowed to aerate for at least 5 days in order to assure that the level of thiocyanate present is zero. When this condition is met, dissolved oxygen utilization was determined as before. The decay constant, b , can then be determined by allowing the mixed liquor to aerate for an extended period of time and measuring the decrease in volatile suspended solids as a function of time.

KINETIC STUDIES

Phase I - Batch

A kinetic study was done using one 8 liter batch reactor with a sludge age of ten days. The temperature of the biomass throughout the experiment remained constant at $25^{\circ}\text{C.} \pm 2^{\circ}\text{C.}$ The initial alkalinity was measured to be 287 mg/L as CaCO_3 . The pH ranged from eight at the onset of the experiment to 7.5 when the study was terminated. The experiment was conducted for a total of 16 hours which time levels of

thiocyanate, ammonia, sulfate, suspended solids, and pH were measured every 15 minutes during the first hour of the study and thereafter every half hour for the remainder of the experiment. All raw data for this phase as collected is given in table 5.

Phase II - Continuous Culture Kinetic Data

As outlined above, 12 continuous culture systems were studied with sludge ages ranging from 8.3 to 227.4 days. Each reactor was maintained and tested in the manner previously described until steady state was achieved. Steady state was evaluated only after a minimum operation period of 2 or 3 sludge ages.

Table 5

Raw Data-Typical Batch Kinetic Study

Time (hours)	pH	MLSS (mg/L)	NH ₃ (mg/L)	SO ₄ ²⁻ (mg/L)	SCN (mg/L)
0.0	8.0	1540	520	2300	1375
0.25	8.0	1500	520	2300	1425
0.5	8.0	1550	520	2350	1375
0.75	7.95	1470	540	2350	1375
1.0	7.9	1460	540	2400	1400
1.5	7.8	1400	540	2520	1337.5
2.0	7.65	1540	540	2570	1337.5
2.5	7.55	1540	540	2510	1375
3.0	7.5	1470	560	2600	1250
3.5	7.45	1470	560	2650	1250
4.0	7.4	1540	590	2900	1275
4.5	7.35	1490	640	2950	1200
5.0	7.35	1540	640	3000	1125
5.5	7.35	1440	660	3100	1075
6.0	7.35	1470	660	3350	1037.5
6.5	7.35	1540	700	3400	968.75
7.0	7.4	1560	720	3400	937.5
7.5	7.4	1540	760	3600	862.5
8.0	7.4	1580	780	3750	825
8.5	7.45	1610	780	3900	788.5
9.0	7.45	1540	820	3950	725
9.5	7.45	1650	880	4000	650
10.0	7.45	1710	880	4100	612.5
10.5	7.5	1780	920	4450	550
11.0	7.5	1850	920	4550	458.3
11.5	7.5	1790	1000	4650	416.67
12.0	7.55	1830	1000	4800	366.67
12.5	7.55	1850	1040	4850	300
13.0	7.55	1920	1260	6000	240
13.5	7.55	1810	1260	6050	190
14.0	7.55	1780	1320	6100	144
14.5	7.55	1830	1320	5800	106
15.0	7.55	1960	1320	6300	54
15.5	7.55	1810	1320	6350	5
16.0	7.55	1830	1320	6450	0

RESULTS AND CONCLUSIONS

Figures 9 and 10 present typical results for SCN from continuous culture reactors operating at steady state. The figures illustrate means and standard deviation values for parameters utilized in developing biokinetic relationships. Data for other reactors is given in Appendix A and B.

Figure 4 is an overall kinetic plot of specific SCN utilization rate, "v" (lb SCN/lb VSS-day) as a function of SCN in solution. In accord with the theory of substrate inhibition, the specific utilization rate rises with increasing SCN level to a maxima and decreases with a further increase in SCN level.

Using numerical and standard graphical techniques, the equation of fit describing SCN biokinetics is:

$$v = 2.24 / \{ 1 + (5/\text{SCN}) + (\text{SCN}/1340)^6 \} \quad (7)$$

Setting $dv/d(\text{SCN}) = 0$ indicates a maxima in SCN specific utilization occurs at 467 mg SCN/L. This finding agrees with the earlier work of Neufeld and Valiknac (8) who observed qualitative substrate inhibition at SCN levels of about 500 mg/L.

BIOMASS PRODUCTION

The relationship:

$$\Delta X = (a)_{ob} \Delta \text{SCN} \quad (9)$$

FIGURE 11

SCN UTILIZATION RATE vs. SCN CONCENTRATION

may be used to equate overall biomass production with thiocyanate degradation where

ΔX = weight of VSS grown

ΔSCN = weight of SCN oxidized

a_{ob} = observed overall yield coefficient

This equation may be modified for application to continuous culture system by noting:

$$\Delta X / (X \Delta t) = (a)_{ob} \{ \Delta \text{SCN} / (X \Delta t) \} \quad (10)$$

and:

$$1/\theta = (a)_{ob} \{ \Delta \text{SCN} / X \Delta t \} \quad (11)$$

where: θ = operational sludge age (day^{-1})

$\Delta \text{SCN} / \{ X \Delta t \}$ = steady state value of specific thiocyanate removal rate as obtained from continuous culture experiments (lb SCN removed/lb VSS-day)

Figure 12 is a plot of measured yield coefficients for each continuous culture reactor as a function of sludge age. Yield coefficients appear to follow a relationship of the form:

$$(a)_{ob} = 0.117 \text{ lb VSS grown/lb SCN removed} \quad (12)$$

for sludge ages (θ) less than 28 days

and

$$(a)_{ob} = 4.6 \theta^{-1.1} \quad \text{for sludge ages greater} \quad (13)$$

than 28 days.

FIGURE 12

Observed Cell Yield vs. Sludge Age

These values may be used with the biokinetic relationship of equation 1 to develop a design and operating diagram as shown on figure 13.

The equation of figure 13 is:

$$1/\theta = (a)_{ob} (2.24) / \{ 1 + (5/S) + (S/1340)^6 \} \quad (14)$$

This figure is significant in that it serves to explain some of the observed instabilities in industrial wastetreatment for SCN degradation. The relative flatness of this figure at SCN sludge ages in excess of about 6½ days implies process stability when operating in this range. Such process stability can be observed in well operated coke plant biological waste treatment facilities.

While the critical sludge age appears to be 4.14 days, sludge ages of six days or less would appear to exhibit process instabilities. The positive slope at higher SCN levels reflects the influence of the substrate inhibition term as shown on equation 14.

Figure 14 is an expansion of figure 13 at lower effluent SCN values. Superimposed on this calculated curve are 5 steady-state data point for continuous culture reactors maintained at pH values of 5, 6, and 7 at a sludge age of about 16 days. Little difference can be seen between these reactors, and for all practical purposes, they demonstrate similar operating characteristics.

FIGURE 13

THIOCYANATE CONCENTRATE vs SLUDGE AGE

FIGURE 14

THIOCYANATE CONCENTRATION vs. SLUDGE AGE (SCN levels below 50mg/L)

PROPERTIES OF SCN-DEGRADING SLUDGE

One key to the understanding of any biological system is an evaluation of sludge physical properties of settling. Figure 15 presents data of SCN sludge settling velocity as a function of suspended solids concentration, and figure 16 presents data of sludge volume index as a function of sludge age. From the ranges of values observed in our experiment, both figures indicate no settling difficulties should be expected in the design and operation of clarifiers for SCN degrading sludge. It should be cautioned however, that figures 15 and 16 were developed for an essentially pure thiocyanate degrading biological sludge. Pure sludges are not expected to exist in field systems. The organisms responsible for thiocyanate degradation would in fact be mixed with other heterotrophic organisms that are also responsible for phenolic and other organic degradation. Thus the data presented for sludge settling indicates that the thiocyanate organisms, if alone in solution, should pose no difficulties in operation. Such data should not be extrapolated for field use.

OXYGEN UTILIZATION

Metcalf and Eddy (39) present the following equation for the computation of the theoretical oxygen requirements for the removal of oxygen demanding organic matter in wastewater for biological system.

FIGURE 15

SLUDGE VOLUME INDEX vs. SLUDGE AGE

FIGURE 15

SETTLING VELOCITY vs. SUSPENDED SOLIDS

$$\begin{aligned} \text{O}_2(\text{lb/day}) &= (\text{O}_2 \text{ equivalent of substrate used/day}) \\ &- K (\text{mass of organisms wasted/day}) \end{aligned} \quad (15)$$

where:

$$K = \text{O}_2 \text{ equivalent of biomass (lb O}_2 \text{ used/lb biomass)}$$

In order to apply the above equation to this study, COD tests were conducted on the thiocyanate degrading organisms in accordance with Standard Methods for the Examination of Water and Wastewater (37). An average value for the COD of thiocyanate degrading organisms in our study was found to be 1.76 (gCOD/gVSS). Thus the above equation may be rewritten as

$$\begin{aligned} \text{O}_2(\text{g/day}) &= (\text{total mass of SCN utilized, g/day}) \\ &- 1.76 (\text{mass of organisms wasted, g/day}) \end{aligned} \quad (16)$$

The conceptual equation given above may be rewritten more concisely as follows:

$$\text{gO}_2 \text{ used/day} = 1.1 Q(\text{C}_0 - \text{C}) - 1.76 \{x(V/\theta)\} \quad (17)$$

where:

- Q = flow rate liters per day
- C₀ = influent SCN concentration
- C = effluent SCN concentration
- X = mixed liquor volatile suspended solids (g/L)
- V = reactor volume
- θ = sludge age days
- 1.1 = O₂ equivalent of SCN
- 1.76 = O₂ equivalent of SCN volatile suspended solid

Figure 17 shows a relationship between oxygen requirements as computed from the above equation as a function of operational sludge age. In order to utilize the above equation, a relationship between equilibrium biomass level sludge age and thio-cyanate used must be developed. Such an equation may be presented as follows:

$$X = a \frac{(C_i - C)}{(1 + b\theta)} \frac{\theta}{\theta_h} \quad (18)$$

where X equals volatile suspended solids (mg/L), C_i equals influent substrate (1000 mg/L SCN), C equals effluent SCN, θ_h equals hydraulic detention time (days), θ equals sludge age (days). The biokinetic relationship as shown in equation (14) can be used to provide us with a relationship of θ and C . The effluent information, as a function of sludge age, is presented on figure 17. As a result, evaluations of equilibrium biomass may be achieved for a given system as a function of hydraulic detention time and sludge age. This information is utilized in the oxygen requirement expression and is calculated and presented on figure 18. Also on this figure are data points which represent operating conditions as observed in our experimental continuous culture reactors. The data from the experimental reactors, when compared to the theoretically calculated values, exhibit percent errors on the order of two percent to about ten percent, indicating rather good agreement.

FIGURE 17

Calculation of MLSS as a Function of θ and θ_H

FAILED REACTORS

While it is easy to report good data, one can often learn from examining experimental failures.

For reasons unknown, during the course of the study, two reactors failed. One reactor was at a sludge age of 8 days, the other at 15 days; values which are in the region of process stability. Figures 19 and 20 illustrate reactor response with respect to biomass and effluent thiocyanate levels with time. Both figures illustrate steadily decreasing thiocyanate levels down to approximately 50 mg/L and 5 mg/L for the 8 day and 15 day reactors respectively. Biomass levels concurrently continued to rise during this time indicating that an appropriate metabolism-sludge harvest condition was not as yet maintained. For no apparent reason, after 30 to 40 days into the run, the effluent thiocyanate levels began to rise and biomass concentrations began to drop. Sludge wasting at this time was halted in an attempt to conserve biomass, therefore the drop in biomass levels are attributed to sludge losses occurring over the weir due to deflocculation of the sludge.

Figure 19

Figure 20

NITROGEN AND SULFUR BALANCE CONCLUSIONS

In summary, it appears that thiocyanate degrading micro-organisms quantitatively convert the sulfur and nitrogen of an aqueous thiocyanate solution into sulfate and ammonia.

Table 6 and 7 are summaries of nitrogen and sulfur balances for the semi-continuous (batch) and continuous bioreactors. The values listed reflect sulfate and ammonia as end products of SCN biodegradation only.

Figures 21, 22, 23, and 24 are typical results (of reactor #3) from which typical data as shown above are obtained.

Figure 31 shows sulfur recovery plotted against sludge age. Sulfur recovery is presented as a ratio of sulfate-sulfur measured in the effluent to thiocyanate-sulfur which was removed within the biological reactor. A correlation between sulfur recovery and sludge age shows an average recovery of 96.3%, with a standard deviation of 7.6%. This indicates as summarized above, that essentially all of the sulfur contained in the biologically degraded thiocyanate has been converted to sulfate. No other sulfur species were measured

TABLE 6 Summary of Data from Batch Reactor Study

Temp. = $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$

$\text{SCN}_{\text{effluent}} = 0 \text{ mg/L}$

Hydraulic Detention Time = 2 days

Sludge Age (days)	$\text{NH}_3\text{-N}$ (mg/L) $\pm \sigma / \text{NH}_3\text{-N}$	$\text{SO}_4\text{-S}$ (mg/L) $\pm \sigma / \text{SO}_4\text{-S}$	cell- N_{eff} (mg/L)	%N Rec.	%S Rec.	SVI (cc/g)
5	777.7 $\pm 7.5\%$	1480.6 $\pm 6.9\%$	14.01	109.4	89.5	32.9
10	604.4 $\pm 18.5\%$	1671.9 $\pm 6.1\%$	8.61	84.7	101.0	-
10	951.3 $\pm 19.8\%$	2088.5 $\pm 5.8\%$	12.18	99.7	94.6	26.2
15	727.5 $\pm 13.5\%$	1578.4 $\pm 5.8\%$	8.78	101.7	95.4	30.9
15	952.7 $\pm 18.9\%$	2047.1 $\pm 5.0\%$	14.13	100.1	92.8	24.2

TABLE 7 Summary of Data from Continuous Reactor Study

Temp. = $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$ $\text{SCN}_{\text{influent}} = 1000 \text{ mg/L}$ Hydraulic Detention Time = 1 day

Sludge Age (days)	$\overline{\text{SCN}}_{\text{eff}}$ (mg/L) $\pm \sigma / \text{SCN}$	$\overline{\text{NH}_3\text{-N}}$ (mg/L) $\pm \sigma / \text{NH}_3\text{-N}$	$\overline{\text{SO}_4\text{-S}}$ (mg/L) $\pm \sigma / \text{SO}_4\text{-S}$	cell- N_{eff} (mg/L)	VSS_{eff} (mg/L)	%N Rec.	%S Rec.
6.7	$2.1 \pm 46\%$	$226 \pm 13\%$	$499 \pm 5.1\%$	12.2	18	98.9	90.6
8.2	$6.8 \pm 93\%$	$233 \pm 15.6\%$	$435 \pm 10.7\%$	14.9	26	103.4	79.3
10.3	$8.8 \pm 104\%$	$240 \pm 10.1\%$	$480 \pm 7.4\%$	9.5	13	104.1	87.7
15.0	$1.5 \pm 77.9\%$	$229 \pm 5.8\%$	$520 \pm 5.1\%$	5.1	-	97.1	94.3
15.1	$2.0 \pm 69.3\%$	$241 \pm 8.2\%$	$530 \pm 5.7\%$	6.4	22	102.9	93.6
16.2	$1.0 \pm 69.7\%$	$245 \pm 5.6\%$	$570 \pm 6\%$	9.7	18	105.5	103.5
16.3	$11.3 \pm 59\%$	$182 \pm 3\%$	$572 \pm 4.4\%$	7.0	13	79.3	104.9
17.1	$1.7 \pm 52.8\%$	$244 \pm 6.3\%$	$541 \pm 7.2\%$	4.8	20	103.4	98.3
17.1	$1.3 \pm 62\%$	$215 \pm 9.4\%$	$608 \pm 5.3\%$	9.5	13	93.2	110.3
152.0	$1.4 \pm 46\%$	$260 \pm 1.5\%$	$562 \pm 3.3\%$	1.6	15	108.7	101.9
216.6	$1.2 \pm 62\%$	$251 \pm 1.4\%$	$553 \pm 5.1\%$	1.5	14	108.9	100.4

that contributed to this recovery.

Figure 24 shows nitrogen recovery plotted against sludge age. Nitrogen recovery is presented as a ratio of effluent ammonia-nitrogen plus cell-nitrogen (from the daily wasting of mixed liquor suspended solids) to the thiocyanate-nitrogen which was removed within the reactor. A correlation between nitrogen recovery and sludge age shows an average recovery of 100.1% with a standard deviation of 8.4%.

Nitrogen was found to account for 10.4% of cell weight. The nitrogen present in the cells discarded daily from the reactor run at a pH of 5.0 accounted for about 4% of the nitrogen recovery, which, when added to the effluent ammonia-nitrogen, raised the overall nitrogen recovery to 93.2%. The reactor run at a pH of 8.0 exhibited overall low nitrogen recovery (79.2%, 3.0% of which was cell-nitrogen). The reason may be partially due to ammonia stripping to the atmosphere during aeration at this pH.

Nitrite-nitrogen, nitrate-nitrogen, and cyanide-nitrogen were all found to be present in negligible quantities in the effluents of biological degradation of aqueous thiocyanate. Thus, nitrification of the formed ammonia (to NO_2 and NO_3) did not occur.

PHYSICAL APPEARANCE OF SLUDGE SYSTEM

It was observed, during the course of experimentation, that the color of the microorganisms was affected by the pH under which they operated. Cultures at a lower pH of 5.0 to 6.0 exhibited a caramel-colored floc, and had a very soft, almost slimy texture. As the pH was moved up to 8.0, the culture turned, in appearance, to a very pale yellow color. The texture was that of small granules of sand.

No apparent reason can be given for this change in color and texture. The low VSS/SS ratio observed in the reactor run at a pH of 8.0 indicates that a considerable non-volatile fraction existed in the solids of this reactor.

SLUDGE SETTLING CHARACTERISTICS

Table 8 presents data for the sludge volume index, (SVI), for thiocyanate degrading organisms under varying sludge ages and pH values. While pH did not appear to have an effect on the SVI, the higher sludge ages resulted in a relatively higher sludge volume index.

Sludge Volume Index values in the range of 50-150 cc/g indicate a good settling sludge in activated sludge processes, (39) but this range varies with the characteristics and concentration of the mixed liquor suspended solids (39). Lower values can

TABLE 8

Sludge Volume Index for Thiocyanate
Degrading Organisms

Sludge Age (days)	pH	SVI. (cc/g)
5	7.29	32.9
10	7.59	26.2
15	7.51	30.9
15	7.71	24.2
16.2	6.0	47.6
16.3	8.0	21.8
17.1	5.0	40.6
152	7.0	74.5
216.6	7.0	48.3

indicate a bulking sludge.

Settling velocities were very difficult to obtain with this particular sludge due to the fact that upon proceeding with the test, the major proportion of the sludge settled within seconds. In addition, the sludge-liquid interface was almost impossible to determine during that time.

Overall, the settling characteristics of thiocyanate degrading organisms were excellent, with slightly better results obtainable at higher sludge ages. It must be noted, however, that relatively pure cultures were under investigation in this study, and differing results may be encountered in the field.

SPECIFIC CONCLUSIONS

1. Thiocyanates are seen as a pollution parameter of significance in coal conversion wastewaters influencing phenolic biodegradation and servicing as an indicator for biological process control.

2. Quantification of biokinetics for thiocyanate degradation have been developed. These kinetics follow a substrate inhibition pattern. Analysis of biokinetics indicates that operation at sludge ages of less than six days may lead to significant process instabilities.
3. Quantification of thiocyanate biokinetics indicates a maximum in SCN specific removal rates at about 470 mg/L with decreasing rates at increasing SCN levels. Caution should be expected in the discharge of SCN laden wastewaters from sulfur removal processes into biological reactor systems for coal conversion or coke plant wastewater treatment.
4. Utilizing experimental results, the critical sludge age for SCN biodegradation was found to be 4.14 days.
5. Thiocyanate biodegradation leads to a residual sulfate and ammonia in the liquid effluent. While low level discharges of sulfate should not pose severe environmental difficulties, low level discharges of ammonia may result in conflicts with pollution control agencies. As an example, for the steel industry best available control technology pipe line effluent limitations for total ammonia are in the neighborhood of 10 mg/L.
6. Continuous culture systems operated at a pH between

6 and 7 show virtually complete thiocyanate removal at influent thiocyanate levels of 1000 mg/L. However, continuous culture systems operated at a pH of 5 or 8 indicate poor thiocyanate removal ability and some degree of process instability.

APPENDIX A-1

Semi-Continuous (Batch) Reactor Data

TABLES A-1 to A-5

TABLE A-1

Daily Operational Data for Batch Reactor 1

Influent SCN = 1500 mg/L Temp. = 22°C $\pm$ 2°C				Sludge Age = 15 days Day 1 = 9/20/78			
DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
1	7.39	0	1638	1333	81	658	--*
2	7.41	0	--	--	--	--	--
3	7.67	0	--	--	--	658	--
4	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--
6	7.94	0	--	--	--	--	--
7	7.54	0	--	--	--	822	--
8	7.84	0	--	--	--	--	--
9	7.36	95	1416	1232	87	--	--
10	7.54	0	--	--	--	--	--
11	7.82	0	--	--	--	--	--
12	7.54	0	--	--	--	--	--
13	8.02	0	--	--	--	--	--
14	7.43	0	1490	1312	88	637	--
15	7.92	0	--	--	--	--	--
16	7.56	0	--	--	--	781	--
17	7.91	0	1192	1088	91	--	--
18	7.54	0	--	--	--	--	--
19	7.65	0	--	--	--	--	--
20	7.87	0	--	--	--	--	--
21	7.22	0	--	--	--	--	1716
22	7.21	0	--	--	--	670	--
23	7.34	0	--	--	--	740	--
24	7.79	0	1344	1194	89	576	--
25	7.26	--	--	--	--	--	--
26	7.60	--	--	--	--	--	--
27	7.70	0	--	--	--	--	--
28	7.65	0	1248	1036	83	535	--
29	7.56	0	--	--	--	--	--
30	6.85	0	--	--	--	514	--
31	6.95	0	--	--	--	--	--
32	6.93	0	--	--	--	--	--
33	7.04	0	--	--	--	--	--
34	8.08	0	1344	1112	83	781	--
35	7.49	0	--	--	--	--	--
36	8.02	0	--	--	--	--	--
37	7.83	0	--	--	--	--	1619
38	7.81	0	1352	1108	82	--	--

TABLE A-1(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
39	8.14	0	--	--	--	--	--
40	7.97	0	--	--	--	--	--
41	7.88	0	--	--	--	--	--
42	7.97	0	--	--	--	--	--
43	7.80	0	--	--	--	--	--
44	7.92	0	--	--	--	--	--
45	7.87	0	--	--	--	--	1652
46	7.63	0	1444	1220	84	--	--
47	7.85	0	--	--	--	--	--
48	7.74	0	--	--	--	--	--
49	7.58	0	--	--	--	--	--
50	7.55	0	1605	1332	83	--	1619
51	7.38	0	--	--	--	--	--
52	7.30	0	--	--	--	--	--
53	7.27	0	--	--	--	--	--
54	7.29	0	--	--	--	--	--
55	7.33	0	--	--	--	--	--
56	7.07	0	--	--	--	--	--
57	7.32	0	--	--	--	--	1619
58	7.92	0	--	--	--	--	--
59	7.89	0	1604	1320	82	--	--
60	7.85	0	--	--	--	--	--
61	8.11	0	--	--	--	--	--
62	8.12	0	--	--	--	691	--
63	7.93	0	--	--	--	773	--
64	7.97	0	--	--	--	--	1544
65	8.03	0	--	--	--	--	--
66	7.81	0	--	--	--	--	--
67	7.80	0	1732	1508	87	--	1686
68	7.66	0	--	--	--	--	--
69	7.64	0	--	--	--	--	--
70	7.23	0	--	--	--	--	1686
71	7.49	0	1704	1414	83	--	--
72	7.46	0	--	--	--	--	--
73	7.36	0	--	--	--	790	--
74	7.27	0	--	--	--	--	--
75	7.23	0	--	--	--	--	--
76	7.30	0	--	--	--	--	--
77	7.05	0	--	--	--	--	--
78	7.15	0	--	--	--	773	1619
79	7.14	0	1664	1414	85	--	--
80	7.12	0	--	--	--	--	--
81	7.21	0	--	--	--	--	--
82	7.45	0	--	--	--	--	--
83	7.35	0	--	--	--	--	1585

TABLE A-1(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
84	7.46	0	--	--	--	707	--
85	7.46	0	--	--	--	--	--
86	7.72	0	1774	1352	76	--	1619
87	7.66	0	--	--	--	--	--
88	7.33	0	--	--	--	--	--
89	7.57	0	--	--	--	--	--
90	7.65	0	--	--	--	757	1485
91	7.56	0	--	--	--	--	--
92	7.61	0	--	--	--	--	--
93	7.63	0	--	--	--	--	--
94	7.72	0	1702	1334	78	--	--
95	7.70	0	--	--	--	--	--
96	7.72	0	--	--	--	--	--
97	7.81	0	--	--	--	--	--
98	7.78	0	--	--	--	--	--
99	7.84	0	--	--	--	806	--
100	7.85	0	--	--	--	--	--
101	7.88	0	1366	964	71	--	--
102	7.88	0	--	--	--	--	--
103	7.86	0	--	--	--	--	--
104	7.74	0	--	--	--	--	--
105	7.68	0	--	--	--	--	--
106	7.89	0	--	--	--	872	--
107	7.88	0	1336	1036	78	--	--
108	7.90	0	--	--	--	--	--
109	7.89	0	--	--	--	--	--
110	7.74	0	--	--	--	--	--
111	7.81	0	--	--	--	822	1502
112	7.61	0	1496	1294	86	--	--
113	7.76	0	--	--	--	--	--
114	7.69	0	--	--	--	--	--
115	7.70	0	--	--	--	--	--
116	7.50	0	--	--	--	--	--
117	7.10	0	--	--	--	822	1652
118	7.30	0	1722	1204	70	--	--
119	7.25	0	--	--	--	--	--
120	7.45	0	--	--	--	--	--
121	7.25	0	--	--	--	855	1469
122	7.30	0	1564	1428	91	--	--
123	7.20	0	--	--	--	--	--
124	7.25	0	--	--	--	--	--
125	6.90	0	--	--	--	773	1469
126	7.15	0	--	--	--	--	--
127	7.25	0	--	--	--	--	--
128	7.15	0	--	--	--	--	--

TABLE A-1(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁻ -S (mg/L)
129	7.15	0	--	--	--	--	--
130	7.05	0	--	--	--	--	--
131	7.20	0	--	--	--	--	--
132	7.20	0	--	--	--	--	--
133	7.00	0	1638	1364	83	822	1435
134	6.95	0	--	--	--	--	--
135	7.30	0	--	--	--	--	--
136	7.55	0	--	--	--	--	--
137	7.25	0	--	--	--	--	--
138	7.50	0	--	--	--	--	--
139	7.60	0	--	--	--	674	1435
140	7.25	0	--	--	--	--	--
141	7.35	93	--	--	--	--	--
142	7.25	0	--	--	--	--	--
143	7.40	0	--	--	--	--	--
144	7.40	0	--	--	--	--	--
145	7.45	0	--	--	--	--	--
146	7.35	41	--	--	--	--	--
147	7.25	0	--	--	--	576	--
148	7.35	0	--	--	--	--	--
149	7.40	0	--	--	--	--	--
150	7.25	0	1572	1512	96	--	--
151	7.30	0	--	--	--	--	--
152	7.40	0	--	--	--	--	--
153	7.60	0	--	--	--	--	--
154	7.30	0	--	--	--	--	--
155	7.35	0	--	--	--	--	--
156	7.25	0	--	--	--	--	--
157	7.25	0	--	--	--	--	--
158	7.25	0	--	--	--	--	--
159	7.30	0	--	--	--	757	--
160	7.40	0	--	--	--	--	--
161	7.30	0	1454	1228	84	--	--
162	7.30	0	--	--	--	--	--
163	7.30	0	--	--	--	--	--
164	7.35	0	--	--	--	--	--
165	7.25	0	--	--	--	--	--
166	7.35	0	--	--	--	--	--
167	7.45	0	--	--	--	--	--
168	7.35	0	--	--	--	--	--
169	7.35	0	--	--	--	--	--
170	7.40	0	--	--	--	--	--
171	7.45	0	--	--	--	--	--
172	7.40	0	--	--	--	--	--
173	7.40	0	--	--	--	--	--

TABLE A-1 (cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ²⁻ -S (mg/L)
174	7.40	129	--	--	--	--	--
175	7.35	0	--	--	--	--	--
176	7.35	0	--	--	--	--	--
177	<u>7.30</u>	<u>102</u>	<u>1576</u>	<u>1328</u>	<u>84</u>	<u>--</u>	<u>--</u>
178	7.25	131	--	--	--	--	--
179	7.30	0	--	--	--	--	--
180	7.30	36	--	--	--	--	--
181	7.20	238	--	--	--	--	--
182	7.20	0	--	--	--	--	--
183	7.25	0	--	--	--	--	--
184	7.25	0	--	--	--	--	--
185	7.15	0	--	--	--	--	--
186	7.15	0	--	--	--	--	--
187	7.15	167	--	--	--	--	--
188	7.25	0	--	--	--	--	--
189	7.15	0	--	--	--	--	--
190	7.15	0	--	--	--	--	--
191	7.15	0	--	--	--	--	--

* indicates no data taken

** indicates steady-state period

TABLE A-2

Daily Operational Data for Batch Reactor 2A

Influent SCN = 1500 mg/L Temp. = 22°C $\pm$ 2°C				Sludge Age = 10 days Day 1 = 9/20/78			
DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
1	7.45	115	1432	1174	82	740	--
2	7.26	0	--	--	--	--	--
3	7.92	0	--	--	--	617	--
4	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--
6	7.45	300	--	--	--	--	--
7	7.08	525	--	--	--	411	--
8	7.14	345	--	--	--	--	1308
9	6.92	0	864	716	83	--	--
10	7.15	225	--	--	--	--	--
11	7.24	45	--	--	--	--	--
12	7.25	225	--	--	--	--	--
13	7.43	100	--	--	--	329	--
14	7.54	50	592	514	87	514	--
15	7.35	380	--	--	--	239	--
16	7.23	0	--	--	--	308	--
17	7.56	0	656	578	88	--	--
18	7.89	0	--	--	--	--	--
19	8.10	0	--	--	--	--	--
20	8.07	0	--	--	--	247	--
21	7.83	25	330	277	84	--	1569
22	7.77	75	--	--	--	600	--
23	7.88	25	--	--	--	658	--
24	7.62	0	740	668	90	473	--
25	7.78	--	--	--	--	--	--
26	7.73	--	--	--	--	--	--
27	7.85	0	--	--	--	--	--
28	7.81	0	752	532	71	452	--
29	7.70	0	--	--	--	--	--
30	7.57	0	--	--	--	493	--
31	7.45	0	--	--	--	--	--
32	7.38	0	--	--	--	--	--
33	7.80	0	--	--	--	--	--
34	8.29	0	1020	880	86	740	--
35	8.01	0	--	--	--	--	--
36	7.99	0	--	--	--	--	--
37	7.93	0	--	--	--	--	1786
38	7.79	0	970	794	82	--	--

TABLE A-2(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
39	7.95	0	--	--	--	--	--
40	8.02	0	--	--	--	--	--
41	7.91	0	--	--	--	--	--
42	7.78	0	--	--	--	--	--
43	7.88	0	--	--	--	--	--
44	7.81	0	--	--	--	--	--
45	7.82	0	--	--	--	--	1752
46	7.80	0	1120	934	83	--	--
47	7.97	0	--	--	--	--	--
48	7.79	0	--	--	--	--	--
49	7.52	0	--	--	--	--	--
50	7.48	0	1103	927	84	--	1702
51	7.43	0	--	--	--	--	--
52	7.36	0	--	--	--	--	--
53	7.29	0	--	--	--	--	--
54	7.27	17	--	--	--	--	--
55	7.17	0	--	--	--	--	--
56	7.58	0	--	--	--	--	1585
57	7.83	0	--	--	--	--	--
58	7.66	0	--	--	--	--	--
59	7.66	0	1176	956	81	--	--
60	7.19	13	--	--	--	--	--
61	7.24	99	--	--	--	--	--
62	6.90	466	--	--	--	609	--
63	6.92	11	--	--	--	658	--
64	7.01	0	--	--	--	--	1510
65	7.34	0	--	--	--	--	--
66	7.15	0	--	--	--	--	--
67	7.04	0	--	--	--	--	1752
68	7.06	0	--	--	--	757	--
69	7.21	0	--	--	--	--	--
70	6.99	0	--	--	--	--	1719
71	7.13	0	1102	930	84	--	--

TABLE A-3

Daily Operational Data for Batch Reactor 2B

Influent SCN = 1500 mg/L Temp. = 22°C ± 2°C							
Sludge Age = 5 days Day 1 = 11/30/78							
DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
1	7.19	0	--	--	--	--	--
2	7.28	0	--	--	--	822	--
3	7.01	0	--	--	--	--	--
4	7.03	0	--	--	--	--	--
5	6.80	790	--	--	--	--	--
6	6.98	0	--	--	--	--	--
7	6.97	500	--	--	--	551	1335
8	6.98	0	634	516	81	--	--
9	7.30	0	--	--	--	--	--
10	6.76	0	--	--	--	--	--
11	6.90	57	--	--	--	--	--
12	6.97	39	--	--	--	--	1585
13	6.80	95	--	--	--	658	--
14	6.98	0	--	--	--	--	--
15	7.15	117	704	652	93	--	1519
16	7.23	107	--	--	--	--	--
17	7.23	0	--	--	--	--	--
18	7.37	0	--	--	--	--	--
19	7.25	0	--	--	--	757	1519
20	7.27	0	--	--	--	--	--
21	7.33	0	--	--	--	--	--
22	7.44	0	--	--	--	--	--
23	7.51	0	932	832	89	--	--
24	7.47	0	--	--	--	--	--
25	7.14	0	--	--	--	--	--
26	7.32	0	--	--	--	--	--
27	7.74	0	--	--	--	--	--
28	7.38	35	--	--	--	806	1552
29	7.43	0	--	--	--	--	--
30	7.49	344	782	708	91	--	--
31	7.30	0	--	--	--	--	--
32	7.53	0	--	--	--	--	--
33	7.73	0	--	--	--	--	--
34	7.36	197	--	--	--	--	--
35	7.50	0	--	--	--	822	1369
36	7.42	125	804	708	88	--	--
37	7.45	70	--	--	--	--	--
38	7.33	88	--	--	--	--	--

TABLE A-3(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
39	7.35	0	--	--	--	--	--
40	7.85	0	--	--	--	773	1402
41	7.20	0	802	700	87	--	--
42	7.43	275	--	--	--	--	--
43	6.95	0	--	--	--	--	--
44	7.60	0	--	--	--	--	--
45	6.80	313	--	--	--	--	--
46	6.80	100	--	--	--	674	1318
47	7.30	0	742	653	88	--	--
48	7.05	0	--	--	--	--	--
49	7.05	189	--	--	--	--	--
50	7.05	0	--	--	--	806	1585
51	6.95	164	705	620	88	--	--
52	6.90	45	--	--	--	--	--
53	6.85	360	--	--	--	--	--
54	7.15	0	--	--	--	658	1352
55	6.90	285	--	--	--	--	--
56	6.90	158	--	--	--	--	--
57	6.95	200	--	--	--	--	--
58	6.95	328	--	--	--	--	--
59	6.95	395	--	--	--	--	--
60	6.95	138	--	--	--	--	--
61	6.95	570	--	--	--	--	--
62	7.05	0	308	262	85	354	668
63	7.35	304	--	--	--	--	--
64	7.15	0	--	--	--	--	--
65	7.20	260	--	--	--	--	--
66	7.35	190	--	--	--	--	--
67	8.00	-	--	--	--	--	--
68	7.90	240	--	--	--	576	1152
69	7.75	0	--	--	--	--	--
70	7.20	700	--	--	--	--	--
71	6.95	0	--	--	--	--	--
72	7.40	300	--	--	--	--	--
73	7.85	200	--	--	--	--	--
74	7.55	340	--	--	--	--	--
75	7.65	355	--	--	--	--	--
76	7.40	360	--	--	--	329	634
77	7.60	310	--	--	--	--	--
78	7.60	345	--	--	--	--	--
79	7.15	0	--	--	--	--	--
80	7.95	145	--	--	--	--	--
81	7.50	430	--	--	--	--	--
82	7.30	0	--	--	--	--	--
83	7.70	275	--	--	--	--	--

TABLE A-3(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁻ -S (mg/L)
84	7.45	400	--	--	--	--	--
85	7.25	145	--	--	--	--	--
86	7.20	275	--	--	--	--	--
87	7.45	0	--	--	--	--	--
88	7.45	500	--	--	--	337	367
89	7.30	750	--	--	--	--	--
90	7.30	185	444	336	76	--	--
91	7.30	355	--	--	--	--	--
92	7.40	130	--	--	--	--	--
93	7.25	235	--	--	--	--	--
94	7.15	285	--	--	--	--	--
95	7.20	105	--	--	--	--	--
96	7.20	400	--	--	--	--	--
97	7.25	295	--	--	--	--	--
98	7.25	300	--	--	--	--	--
99	7.30	375	--	--	--	--	--
100	7.25	285	--	--	--	--	--
101	7.25	285	--	--	--	--	--
102	7.25	200	--	--	--	--	--
103	7.30	455	--	--	--	--	--
104	7.25	310	--	--	--	--	--
105	7.25	328	--	--	--	--	--
106	7.25	355	372	300	81	--	--
107	7.25	355	--	--	--	--	--
108	7.20	355	--	--	--	--	--
109	7.25	275	--	--	--	--	--
110	7.25	400	--	--	--	--	--
111	7.25	320	--	--	--	--	--
112	7.30	380	--	--	--	--	--
113	7.45	267	--	--	--	--	--
114	7.40	225	--	--	--	--	--
115	7.45	0	--	--	--	--	--
116	7.50	145	--	--	--	--	--
117	7.60	130	--	--	--	--	--
118	7.60	190	--	--	--	--	--
119	7.35	362	--	--	--	--	--
120	7.40	-	--	--	--	--	--

TABLE A-4

Daily Operational Data for Batch Reactor 3

Influent SCN = 2000 mg/L
Temp. = 22°C ± 2°C

Sludge Age = 15 days
Day 1 = 9/20/78

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
1	7.14	0	2404	1990	83	946	--
2	7.07	0	--	--	--	--	--
3	7.08	0	--	--	--	740	--
4	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--
6	7.70	65	--	--	--	--	--
7	8.17	95	--	--	--	822	--
8	7.80	0	--	--	--	--	--
9	7.92	0	2558	2328	91	--	--
10	8.00	0	--	--	--	--	--
11	7.87	0	--	--	--	--	--
12	7.95	0	--	--	--	--	--
13	8.02	0	--	--	--	--	--
14	7.69	0	2668	2276	85	658	--
15	7.39	0	--	--	--	--	--
16	4.86	0	--	--	--	822	--
17	5.85	65	2184	2000	92	--	--
18	7.06	0	--	--	--	--	--
19	7.41	0	--	--	--	--	--
20	7.58	0	--	--	--	--	--
21	7.09	0	2110	1751	83	--	2136
22	7.47	0	--	--	--	650	--
23	7.43	0	--	--	--	822	--
24	7.81	0	2366	1806	76	740	--
25	7.09	--	--	--	--	--	--
26	7.13	--	--	--	--	--	--
27	6.97	0	--	--	--	--	--
28	7.02	0	2466	2047	83	--	--
29	6.90	0	--	--	--	--	--
30	6.65	0	--	--	--	637	--
31	6.89	0	--	--	--	--	--
32	7.23	0	--	--	--	--	--
33	7.48	0	--	--	--	--	--
34	7.34	0	2544	2112	83	822	--
35	6.77	0	--	--	--	--	--
36	7.31	0	--	--	--	--	--
37	7.26	0	--	--	--	--	2153
38	7.27	0	2768	2297	83	--	--

TABLE A-4(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁼ -S (mg/L)
39	7.43	0	--	--	--	--	--
40	7.42	0	--	--	--	--	--
41	7.60	0	--	--	--	--	--
42	7.42	0	--	--	--	--	--
43	7.22	0	--	--	--	--	--
44	7.74	0	--	--	--	--	--
45	7.86	0	--	--	--	--	2128
46	7.92	0	2800	2168	77	--	--
47	8.08	0	--	--	--	--	--
48	8.06	0	--	--	--	--	--
49	8.02	0	--	--	--	--	--
50	8.18	0	2867	2205	77	--	2121
51	8.20	0	--	--	--	--	--
52	8.24	0	--	--	--	--	--
53	8.19	0	--	--	--	--	--
54	8.26	0	--	--	--	--	--
55	8.26	0	--	--	--	--	--
56	8.31	0	--	--	--	--	--
57	8.24	0	--	--	--	--	2036
58	8.36	0	--	--	--	--	--
59	8.30	0	2536	2105	83	--	--
60	8.26	0	--	--	--	--	--
61	8.40	0	--	--	--	--	--
62	8.43	0	--	--	--	954	--
63	8.23	0	--	--	--	1020	--
64	8.18	0	--	--	--	--	2043
65	8.26	0	--	--	--	--	--
66	8.30	0	--	--	--	--	--
67	8.25	0	2288	1926	84	--	2036
68	8.08	0	--	--	--	--	--
69	7.25	0	--	--	--	--	--
70	7.04	0	--	--	--	--	2153
71	7.78	0	2034	1688	83	--	--
72	7.28	0	--	--	--	--	--
73	7.03	0	--	--	--	1086	--
74	7.96	0	--	--	--	--	--
75	7.93	0	--	--	--	--	--
76	7.80	0	--	--	--	--	--
77	7.86	0	--	--	--	--	--
78	8.05	0	--	--	--	987	2186
79	7.99	0	2326	1774	76	--	--
80	7.95	0	--	--	--	--	--
81	8.03	0	--	--	--	--	--
82	7.88	0	--	--	--	--	--
83	7.93	0	--	--	--	--	1936

TABLE A-4 (cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁻ -S (mg/L)
84	7.87	0	--	--	--	938	--
85	7.96	0	--	--	--	--	--
86	7.60	0	1784	1574	88	--	2186
87	7.48	0	--	--	--	--	--
88	7.42	0	--	--	--	--	--
89	7.84	0	--	--	--	--	--
90	8.03	0	--	--	--	1053	1903
91	8.00	0	--	--	--	--	--
92	8.06	0	--	--	--	--	--
93	8.09	0	--	--	--	--	--
94	8.11	0	2474	2174	88	--	--
95	8.08	0	--	--	--	--	--
96	8.20	0	--	--	--	--	--
97	8.25	0	--	--	--	--	--
98	8.30	0	--	--	--	--	--
99	8.19	0	--	--	--	1217	--
100	8.24	0	--	--	--	--	--
101	8.18	0	2470	2008	81	--	--
102	8.22	0	--	--	--	--	--
103	8.21	0	--	--	--	--	--
104	8.25	0	--	--	--	--	--
105	8.17	0	--	--	--	--	--
106	8.11	0	--	--	--	1217	1811
107	8.10	0	2646	2178	82	--	--
108	8.06	0	--	--	--	--	--
109	7.98	0	--	--	--	--	--
110	8.07	0	--	--	--	--	--
111	8.13	0	--	--	--	1151	2053
112	8.01	0	2684	2190	82	--	--
113	8.15	0	--	--	--	--	--
114	7.96	0	--	--	--	--	--
115	7.99	0	--	--	--	--	--
116	7.90	0	--	--	--	--	--
117	7.90	0	--	--	--	1119	1936
118	7.90	0	2734	2130	78	--	--
119	7.80	0	--	--	--	--	--
120	7.70	0	--	--	--	--	--
121	7.65	0	--	--	--	1151	2036
122	7.60	0	2404	2228	93	--	--
123	7.50	0	--	--	--	--	--
124	7.50	0	--	--	--	--	--
125	7.70	0	--	--	--	1069	2036
126	7.70	0	--	--	--	--	--
127	7.65	0	--	--	--	--	--
128	7.45	0	--	--	--	--	--

TABLE A-4(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
129	7.45	0	--	--	--	--	--
130	7.35	0	--	--	--	--	--
131	7.90	0	--	--	--	--	--
132	7.85	0	--	--	--	--	--
133	7.65	0	2356	1922	82	1151	--
134	7.60	0	--	--	--	--	--
135	7.40	0	--	--	--	--	--
136	7.40	0	--	--	--	--	--
137	7.25	0	--	--	--	--	--
138	7.50	--	--	--	--	--	--
139	7.90	0	--	--	--	954	1969
140	7.35	0	--	--	--	--	--
141	7.70	0	--	--	--	--	--
142	7.25	0	--	--	--	--	--
143	7.40	0	--	--	--	--	--
144	7.70	0	--	--	--	--	--
145	7.75	0	--	--	--	--	--
146	7.85	0	--	--	--	--	--
147	7.55	0	--	--	--	822	2036
148	7.60	0	--	--	--	--	--
149	7.50	0	--	--	--	--	--
150	7.45	0	2498	2073	83	--	--
151	7.45	0	--	--	--	--	--
152	7.55	0	--	--	--	--	--
153	7.35	130	--	--	--	--	--
154	7.35	0	--	--	--	--	--
155	7.40	0	--	--	--	--	--
156	7.55	0	--	--	--	--	--
157	7.35	0	--	--	--	--	--
158	7.40	0	--	--	--	--	--
159	7.40	0	--	--	--	1003	--
160	7.40	0	--	--	--	--	--
161	7.30	0	2516	1944	77	--	--
162	7.35	0	--	--	--	--	--
163	7.35	0	--	--	--	--	--
164	7.35	0	--	--	--	--	--
165	7.35	0	--	--	--	--	--
166	7.35	0	--	--	--	--	--
167	7.35	0	--	--	--	--	--
168	7.35	0	--	--	--	--	--
169	7.30	0	--	--	--	--	--
170	7.20	134	--	--	--	--	--
171	7.25	360	--	--	--	--	--
172	7.35	220	--	--	--	--	--
173	7.35	120	--	--	--	--	--

TABLE A-4(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁻ -S (mg/L)
174	7.40	500	--	--	--	--	--
175	7.30	378	--	--	--	--	--
176	7.30	295	--	--	--	--	--
177	7.30	400	2066	1582	77	--	--
178	7.20	210	--	--	--	--	--
179	7.30	0	--	--	--	--	--
180	7.45	0	--	--	--	--	--
181	7.40	0	--	--	--	--	--
182	7.30	0	--	--	--	--	--
183	7.20	-	--	--	--	--	--
184	7.40	0	--	--	--	--	--
185	7.70	0	--	--	--	--	--
186	7.65	0	--	--	--	--	--
187	7.95	0	--	--	--	--	--
188	7.80	0	--	--	--	--	--
189	7.85	0	--	--	--	--	--
190	7.65	0	--	--	--	--	--
191	7.70	0	--	--	--	--	--

TABLE A-5

Daily Operational Data for Batch Reactor 4

Influent SCN = 2000 mg/L Temp. = 22°C ± 2°C				Sludge Age = 10 days Day 1 = 9/20/78			
DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ²⁻ -S (mg/L)
1	8.29	0	--	--	--	822	--
2	8.17	0	--	--	--	--	--
3	8.17	0	--	--	--	--	--
4	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--
6	8.67	0	--	--	--	--	--
7	8.34	0	--	--	--	864	--
8	8.61	0	--	--	--	--	--
9	8.46	0	--	--	--	--	--
10	8.46	0	--	--	--	--	--
11	8.51	0	--	--	--	--	--
12	8.57	0	--	--	--	--	--
13	8.60	0	--	--	--	--	--
14	8.50	0	1128	902	80	666	--
15	7.86	125	--	--	--	--	--
16	8.17	0	--	--	--	781	--
17	7.51	0	1134	896	79	--	--
18	7.05	140	--	--	--	--	--
19	7.28	0	--	--	--	--	--
20	6.88	0	--	--	--	--	--
21	6.96	0	--	--	--	--	2170
22	6.97	65	--	--	--	--	--
23	6.91	0	--	--	--	740	--
24	7.03	0	1248	922	74	699	--
25	7.07	--	--	--	--	--	--
26	6.81	--	--	--	--	--	--
27	6.77	0	--	--	--	--	--
28	7.11	0	1242	1026	83	--	--
29	7.37	0	--	--	--	--	--
30	7.21	0	--	--	--	658	--
31	6.81	0	--	--	--	--	--
32	6.84	0	--	--	--	--	--
33	7.26	0	--	--	--	--	--
34	7.47	0	1392	1054	76	822	--
35	7.07	0	--	--	--	--	--
36	7.64	0	--	--	--	--	--
37	7.56	0	--	--	--	--	2220
38	7.18	0	1278	1038	81	--	--

TABLE A-5(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
39	7.14	0	--	--	--	--	--
40	7.19	0	--	--	--	--	--
41	7.36	0	--	--	--	--	--
42	7.48	0	--	--	--	--	--
43	7.57	0	--	--	--	--	--
44	7.66	0	--	--	--	--	--
45	7.83	0	--	--	--	--	2153
46	7.42	0	1592	1170	73	--	--
47	7.67	0	--	--	--	--	--
48	7.60	0	--	--	--	--	--
49	7.32	0	--	--	--	--	--
50	7.30	0	1702	1345	79	--	2186
51	7.26	0	--	--	--	--	--
52	7.27	0	--	--	--	--	--
53	7.30	0	--	--	--	--	--
54	7.41	0	--	--	--	--	--
55	7.46	0	--	--	--	--	--
56	7.46	0	--	--	--	--	--
57	7.54	0	--	--	--	--	2128
58	7.55	0	--	--	--	--	--
59	7.45	15	1698	1358	80	--	--
60	7.25	0	--	--	--	--	--
61	7.50	0	--	--	--	--	--
62	7.52	0	--	--	--	987	--
63	7.44	0	--	--	--	1020	--
64	7.34	0	--	--	--	--	2220
65	7.18	0	--	--	--	--	--
66	7.22	0	--	--	--	--	--
67	7.16	0	1684	1318	78	--	2153
68	7.05	0	--	--	--	822	--
69	7.05	0	--	--	--	--	--
70	6.92	0	--	--	--	--	2036
71	7.12	0	1450	1160	80	--	--
72	6.90	0	--	--	--	--	--
73	6.91	0	--	--	--	1151	--
74	7.36	0	--	--	--	--	--
75	7.64	0	--	--	--	--	--
76	7.53	0	--	--	--	--	--
77	7.50	0	--	--	--	--	--
78	7.61	0	--	--	--	987	2220
79	7.42	0	--	--	--	--	--
80	7.59	0	--	--	--	--	--
81	7.46	0	--	--	--	--	--
82	7.54	0	--	--	--	--	--
83	7.52	0	--	--	--	--	2069

TABLE A-5 (cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
84	7.45	0	--	--	--	938	--
85	7.40	0	--	--	--	--	--
86	7.46	0	1656	1330	80	--	2153
87	7.49	0	--	--	--	--	--
88	7.26	0	--	--	--	--	--
89	7.44	0	--	--	--	--	--
90	7.46	0	--	--	--	1151	1936
91	7.43	0	--	--	--	--	--
92	7.48	0	--	--	--	--	--
93	7.53	0	--	--	--	--	--
94	7.54	0	1580	1380	87	--	--
95	7.51	0	--	--	--	--	--
96	7.42	0	--	--	--	--	--
97	7.56	0	--	--	--	--	--
98	7.66	0	--	--	--	--	--
99	7.67	0	--	--	--	1250	2153
100	7.57	0	--	--	--	--	--
101	7.65	0	1518	1236	81	--	--
102	7.71	0	--	--	--	--	--
103	7.70	0	--	--	--	--	--
104	7.80	0	--	--	--	--	--
105	7.80	0	--	--	--	--	--
106	7.69	0	--	--	--	1250	1903
107	7.65	0	1454	1163	80	--	--
108	7.70	0	--	--	--	--	--
109	7.73	0	--	--	--	--	--
110	7.50	0	--	--	--	--	--
111	7.63	0	--	--	--	1184	1969
112	7.66	0	1504	1278	85	--	--
113	7.87	0	--	--	--	--	--
114	7.66	0	--	--	--	--	--
115	7.80	0	--	--	--	--	--
116	7.80	0	--	--	--	--	--
117	7.80	0	--	--	--	1053	2153
118	7.85	0	1450	1160	80	--	--
119	7.90	0	--	--	--	--	--
120	7.85	0	--	--	--	--	--
121	7.85	0	--	--	--	1151	--
122	7.95	0	1408	1154	82	--	--
123	7.85	0	--	--	--	--	--
124	7.95	0	--	--	--	--	--
125	8.05	0	--	--	--	1020	1836
126	8.05	0	--	--	--	--	--
127	7.95	0	--	--	--	--	--
128	7.95	0	--	--	--	--	--

TABLE A-5(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
129	7.85	0	--	--	--	--	--
130	7.85	0	--	--	--	--	--
131	7.90	0	--	--	--	--	--
132	7.90	0	--	--	--	--	--
133	7.80	0	1390	1062	76	1151	1903
134	7.75	0	--	--	--	--	--
135	7.75	0	--	--	--	--	--
136	7.70	0	--	--	--	--	--
137	7.50	0	--	--	--	--	--
138	7.80	0	--	--	--	--	--
139	7.90	0	--	--	--	921	--
140	7.70	0	--	--	--	--	--
141	7.55	0	--	--	--	--	--
142	7.75	0	--	--	--	--	--
143	7.80	0	--	--	--	--	--
144	7.85	0	--	--	--	--	--
145	7.50	310	--	--	--	--	--
146	7.80	0	--	--	--	--	--
147	7.50	0	--	--	--	691	--
148	7.45	0	--	--	--	--	--
149	7.45	0	--	--	--	--	--
150	7.55	0	1508	1284	85	--	--
151	7.50	0	--	--	--	--	--
152	7.60	0	--	--	--	--	--
153	7.70	0	--	--	--	--	--
154	7.30	0	--	--	--	--	--
155	7.50	0	--	--	--	--	--
156	7.80	0	--	--	--	--	--
157	7.50	0	--	--	--	--	--
158	7.50	0	--	--	--	--	--
159	7.60	0	--	--	--	1003	2120
160	7.60	0	--	--	--	--	--
161	7.50	0	1502	1360	91	--	--
162	7.40	0	--	--	--	--	--
163	7.40	0	--	--	--	--	--
164	7.45	0	--	--	--	--	--
165	7.50	0	--	--	--	--	--
166	7.30	0	--	--	--	--	--
167	7.60	0	--	--	--	--	--
168	7.35	0	--	--	--	--	--
169	7.45	0	--	--	--	--	--
170	7.35	0	--	--	--	--	--
171	7.35	0	--	--	--	--	--
172	7.15	107	--	--	--	--	--
173	7.20	180	--	--	--	--	--

TABLE A-5(cont.)

DAY No.	pH	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)
174	7.30	335	--	--	--	--	--
175	7.25	330	--	--	--	--	--
176	7.25	320	--	--	--	--	--
177	7.30	125	1272	1018	80	--	--
178	6.95	0	--	--	--	--	--
179	7.75	0	--	--	--	--	--
180	7.50	0	--	--	--	--	--
181	7.65	0	--	--	--	--	--
182	7.25	0	--	--	--	--	--
183	7.35	740	--	--	--	--	--
184	7.55	345	--	--	--	--	--
185	7.60	262	--	--	--	--	--
186	7.65	0	--	--	--	--	--
187	7.60	930	--	--	--	--	--
188	7.60	120	--	--	--	--	--
189	7.60	360	--	--	--	--	--
190	7.60	670	--	--	--	--	--
191	7.60	-	--	--	--	--	--

APPENDIX B

Continuous Culture Raw Reactor Data

TABLES B-1 to B-11

TABLE B-1

Daily Operational Data for Continuous Reactor 1

Influent SCN = 1000 mg/L Temp. = 22°C $\pm$ 2°C					pH = 7.0 Sludge Age = 8.2 days Day 1 = 3/29/79		
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	0	454	390	86	--	--	--
2	0	--	--	--	--	--	--
3	206	--	--	--	--	--	--
4	295	--	--	--	--	--	--
5	0	786	352	45	--	--	--
6	0	--	--	--	--	--	--
7	0	--	--	--	--	--	--
8	24	570	428	75	--	--	--
9	31	--	--	--	--	--	--
10	50	--	--	--	--	--	--
11	93	--	--	--	--	--	--
12	132	--	--	--	--	--	--
13	186	536	426	79	--	--	--
14	276	--	--	--	--	--	--
15	327	--	--	--	--	--	--
16	275	--	--	--	--	--	--
17	310	--	--	--	--	--	--
18	345	--	--	--	--	--	--
19	335	--	--	--	--	--	--
20	353	496	451	91	--	--	--
21	395	--	--	--	--	--	--
22	-	--	--	--	--	--	--
23	-	--	--	--	--	--	--
24	465	--	--	--	--	--	--
25	405	272	248	91	--	--	--
26	405	--	--	--	--	--	--
27	395	--	--	--	--	--	--
28	388	--	--	--	--	--	--
29	355	284	258	91	--	--	--
30	210	--	--	--	--	--	--
31	135	338	280	83	--	--	--
32	90	--	--	--	--	--	--
33	48	516	480	93	--	--	--
34	19	--	--	--	--	--	--
35	22	--	--	--	--	--	--
36	8	696	650	93	--	--	--
37	6	--	--	--	--	--	--
38	11	--	--	--	--	--	--

TABLE B-1 (cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	12	--	--	--	--	--	--
40	8	--	--	--	--	--	--
41	5	962	866	90	--	--	--
42	7	--	--	--	--	--	--
43	7	--	--	--	--	--	--
44	4	--	--	--	--	--	--
45	3	--	--	--	--	--	--
46	5	--	--	--	--	--	--
47	6	--	--	--	--	--	--
48	3	1064	968	91	--	--	--
49	7	--	--	--	--	--	--
50	6	--	--	--	--	--	--
51	7	--	--	--	--	--	--
52	-	--	--	--	--	--	--
53	665	--	--	--	--	--	--
54	580	--	--	--	--	--	--
55	0	--	--	--	263	517	--
56	70	--	--	--	--	--	--
57	22	--	--	--	--	--	--
58	10	--	--	--	--	--	--
59	-	--	--	--	--	--	--
60	-	--	--	--	--	--	--
61	3.5	--	--	--	--	--	--
62	12	1024	932	91	--	--	--
63	5	--	--	--	280	401	--
64	4.5	1052	940	89	--	--	--
65	9	--	--	--	214	367	--
66	92	--	--	--	--	--	--
67	154	--	--	--	--	--	--
68	6	--	--	--	--	467	--
69	32	1246	1190	96	--	--	--
70	12	--	--	--	222	441	--
71	49	--	--	--	--	--	--
72	20	1352	1230	91	206	457	--
73	8	--	--	--	--	--	--
74	1	--	--	--	--	--	--
75	0	--	--	--	222	457	--
76	0	1394	1316	94	--	--	--
77	4.5	--	--	--	--	--	--
78	27	--	--	--	--	--	--
79	47	1592	1288	81	206	474	--
80	10	--	--	--	--	--	--
81	25	--	--	--	--	--	--
82	13	--	--	--	214	367	--
83	-	1530	1448	95	--	--	--

TABLE B-1(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
84	2	--	--	--	--	--	--
85	3	--	--	--	206	387	--
86	9	--	--	--	--	--	--
87	2	--	--	--	--	--	--
88	0	--	--	--	--	--	--
89	2	1500	1434	96	329	401	--
90	3	--	--	--	--	--	--
91	1.5	1440	1256	87	222	401	--
92	1.5	--	--	--	--	--	--
93	3	1434	1352	94	222	474	--
94	8	--	--	--	--	--	--
95	5	--	--	--	--	--	--
96	<u>4.5</u>	1394	1269	91	<u>222</u>	<u>474</u>	--
97	12	--	--	--	--	--	--
98	31	1274	1168	92	214	457	--
99	15	--	--	--	--	--	--
100	60	1172	1104	94	197	401	--
101	117.5	--	--	--	--	--	--
102	84	--	--	--	--	--	--
103	8.5	<u>1132</u>	<u>1084</u>	96	222	441	--
104	60	--	--	--	--	--	--
105	173	1026	952	93	161	347	<u>26</u>
106	276	--	--	--	--	--	--
107	296	--	--	--	158	294	--
108	200	--	--	--	--	--	--
109	236	--	--	--	--	--	--
110	-	--	--	--	--	--	--
111	-	--	--	--	--	--	--
112	260	988	928	94	155	327	--
113	264	--	--	--	--	--	--
114	251	942	812	86	155	327	--
115	227	--	--	--	--	--	--
116	108	--	--	--	--	--	--
117	38	966	864	89	206	441	--
118	54	--	--	--	--	--	--
119	127	876	760	<u>87</u>	197	401	--
120	200	--	--	--	--	--	--
121	270	--	--	--	173	387	--

TABLE B-2

Daily Operational Data for Continuous Reactor 3

Influent SCN = 1000 mg/L Temp. = 22°C $\pm$ 2°C pH = 7.0 Sludge Age = 15 days Day 1 = 6/27/79							
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	425	978	702	72	127	294	--
2	100	--	--	--	--	--	--
3	2	1036	836	81	230	584	--
4	4	--	--	--	--	--	--
5	3	--	--	--	--	--	--
6	1.5	--	--	--	239	621	--
7	1.5	--	--	--	--	--	--
8	1.5	934	822	88	230	567	--
9	1.5	--	--	--	--	--	--
10	0	866	724	84	214	511	--
11	1	--	--	--	--	--	--
12	1	--	--	--	--	--	--
13	1.5	842	678	81	230	511	--
14	0.5	--	--	--	--	--	--
15	12	798	682	85	206	511	--
16	5	--	--	--	--	--	--
17	0	840	722	86	239	474	--
18	1.5	--	--	--	--	--	--
19	5	--	--	--	--	--	--
20	-	--	--	--	--	--	--
21	-	--	--	--	--	--	--
22	1	854	738	86	222	547	--
23	1.5	--	--	--	--	--	--
24	1	778	661	85	222	511	--
25	1.5	--	--	--	--	--	--
26	1.5	--	--	--	--	--	--
27	1.5	862	726	84	239	511	--
28	1	--	--	--	--	--	--
29	2	896	746	83	247	531	--
30	1.5	--	--	--	--	--	--
31	1	908	776	85	247	547	--
32	1	--	--	--	--	--	--
33	2	--	--	--	--	--	--
34	1.5	934	794	85	222	494	--

TABLE B-3

Daily Operational Data for Continuous Reactor 4

Influent SCN = 1000 mg/L Temp. = 22°C ± 2°C		pH = 7.0		Sludge Age = 6.7 days Day 1 = 7/28/79			
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	238	--	--	--	--	--	--
2	184	--	--	--	--	--	--
3	206	--	--	--	148	387	--
4	251	--	--	--	--	--	--
5	242	696	630	91	173	387	--
6	235	--	--	--	--	--	--
7	282	616	524	85	161	347	--
8	328	--	--	--	--	--	--
9	270	--	--	--	--	--	--
10	235	516	442	86	173	294	--
11	302	--	--	--	--	--	--
12	330	482	412	85	148	294	--
13	384	--	--	--	--	--	--
14	552	480	416	87	122	294	--
15	476	--	--	--	--	--	--
16	475	--	--	--	--	--	--
17	378	512	446	87	164	327	--
18	3	--	--	--	--	--	--
19	298	428	370	86	173	367	--
20	330	--	--	--	--	--	--
21	346	506	436	86	145	327	--
22	288	--	--	--	--	--	--
23	120	--	--	--	--	--	--
24	1.5	762	662	87	263	494	--
25	1	--	--	--	--	--	--
26	2	796	693	87	214	494	8
27	1.5	--	--	--	--	--	--
28	4	844	748	89	197	494	--
29	-	--	--	--	--	--	--
30	-	--	--	--	--	--	--
31	-	--	--	--	--	--	--
32	1	--	--	--	214	547	--
33	33	--	--	--	--	--	--
34	90	--	--	--	--	--	--
35	54	712	612	86	189	474	32
36	86	--	--	--	--	--	--
37	2	--	--	--	--	--	--
38	-	--	--	--	--	--	--

TABLE R-3(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	--	--	--	--	--	--	--
40	2	1142	1038	91	247	514	16
41	3	--	--	--	--	--	--
42	<u>3</u>	1078	938	87	<u>255</u>	<u>474</u>	<u>--</u>
43	50	--	--	--	--	--	--
44	97	--	--	--	--	--	--
45	111	948	864	91	222	401	--
46	157	--	--	--	--	--	--
47	212	908	790	87	173	367	--
48	220	--	--	--	--	--	--
49	282	<u>842</u>	<u>736</u>	<u>87</u>	164	334	--
50	240	--	--	--	--	--	--
51	240	--	--	--	--	--	--
52	280	694	586	84	161	367	--
53	298	--	--	--	--	--	--
54	350	604	516	85	138	294	18
55	413	526	470	89	--	--	--
56	435	500	416	83	122	254	--
57	395	--	--	--	--	--	--
58	485	--	--	--	--	--	--
59	500	348	324	93	87	220	--
60	533	340	298	88	--	--	--
61	548	388	338	87	82	220	--
62	665	--	--	--	--	--	--

TABLE B-4

Daily Operational Data for Continuous Reactor 5

Influent SCN = 1000 mg/L Temp. = 22°C ± 2°C		pH = 7.0		Sludge Age = 10.3 days Day 1 = 7/31/79			
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	1.5	--	--	--	--	--	--
2	1	1056	818	77	247	494	--
3	1	--	--	--	--	--	--
4	1	1074	846	79	247	494	--
5	1	--	--	--	--	--	--
6	4	--	--	--	--	--	--
7	3	1086	954	88	255	441	--
8	4.5	--	--	--	--	--	--
9	2	1110	990	89	255	511	--
10	19	--	--	--	--	--	--
11	90.5	1138	930	82	222	457	--
12	46	--	--	--	--	--	--
13	7	--	--	--	--	--	--
14	14	1166	952	82	255	421	--
15	375	--	--	--	--	--	--
16	2	1072	934	87	222	--	--
17	104	--	--	--	--	--	--
18	184	1012	920	91	--	421	--
19	174	--	--	--	--	--	--
20	60	--	--	--	--	--	--
21	6	--	--	--	255	531	--
22	4	--	--	--	--	--	--
23	9	--	--	--	214	474	10
24	29	--	--	--	--	--	--
25	32	1264	1132	90	189	461	--
26	-	--	--	--	--	--	--
27	-	--	--	--	--	--	--
28	-	--	--	--	--	--	--
29	60	--	--	--	206	494	--
30	189	1080	826	76	--	--	--
31	130	--	--	--	--	--	--
32	130	1174	986	84	--	--	12
33	140	--	--	--	--	--	--
34	76	--	--	--	--	--	--
35	-	--	--	--	--	--	--
36	-	--	--	--	--	--	--
37	2	1214	1020	84	263	527	14
38	22	--	--	--	--	--	--

TABLE B-4(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	5	1236	1038	84	263	494	--
40	10	--	--	--	--	--	--
41	11	--	--	--	--	--	--
42	<u>19</u>	<u>1138</u>	<u>864</u>	<u>76</u>	<u>263</u>	<u>494</u>	--
43	87	--	--	--	--	--	--
44	120	1086	646	59	214	457	<u>16</u>
45	120	--	--	--	--	--	--
46	120	1054	904	86	222	441	--
47	94	--	--	--	--	--	--
48	86	--	--	--	--	--	--
49	82	956	822	86	239	494	--
50	101	--	--	--	--	--	--
51	181	906	720	79	206	457	10

TABLE B-5

Daily Operational Data for Continuous Reactor 6

Influent SCN = 1000 mg/L Temp. = 22°C ± 2°C pH = 7.0 Sludge Age = 15.1 days Day 1 = 9/28/79							
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	112	916	766	84	255	457	--
2	4	--	--	--	--	--	--
3	4	--	--	--	--	--	--
4	2	838	729	87	222	494	--
5	2	--	--	--	--	--	--
6	1	940	824	88	230	514	16
7	1	--	--	--	--	--	--
8	1	928	800	86	247	534	--
9	3	--	--	--	--	--	--
10	2	--	--	--	--	--	--
11	1.5	1022	848	83	239	494	--
12	1.5	--	--	--	--	--	--
13	1	1020	864	85	255	534	--
14	6	--	--	--	--	--	--
15	1.5	1064	910	86	230	541	--
16	6	--	--	--	--	--	--
17	1.5	--	--	--	--	--	--
18	1.5	1020	924	91	263	547	--
19	3	--	--	--	--	--	--
20	1	1138	990	87	189	534	30
21	1	--	--	--	--	--	--
22	1	1132	998	88	255	494	--
23	1	--	--	--	--	--	--
24	--	--	--	--	--	--	--
25	1.5	1164	998	86	239	601	--
26	1.5	--	--	--	--	--	--
27	1.5	1182	1002	85	239	547	22
28	1	--	--	--	--	--	--
29	1	1150	1032	90	263	547	--
30	3	--	--	--	--	--	--
31	1.5	--	--	--	--	--	--
32	1	1242	1110	89	255	494	--
33	1.5	--	--	--	--	--	--
34	1.5	1262	1076	85	255	547	--
35	2	--	--	--	--	--	--
36	2	--	--	--	--	--	--
37	--	--	--	--	--	--	--
38	--	--	--	--	--	--	--

TABLE B-5(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁼ -S (mg/L)	VSS _{eff} (mg/L)
39	1.5	--	--	--	--	--	--
40	1.5	--	--	--	--	--	--
41	3	--	--	--	--	--	--
42	23.5	--	--	--	--	--	--
43	4.5	--	--	--	--	--	--
44	1.5	--	--	--	--	--	--
45	4	--	--	--	--	--	--
46	3	--	--	--	--	--	--

TABLE B-6

Daily Operational Data for Continuous Reactor 7

Influent SCN = 1000 mg/L				pH = 7.0		Sludge Age = 17.1 days	
Temp. = 22°C ± 2°C						Day 1 = 9/28/79	
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	550	320	260	81	87	200	--
2	510	--	--	--	--	--	--
3	325	--	--	--	--	--	--
4	162	594	500	84	189	441	--
5	6	--	--	--	--	--	--
6	1.5	758	690	91	230	534	12
7	3	--	--	--	--	--	--
8	1	796	728	91	247	494	--
9	4	--	--	--	--	--	--
10	2	--	--	--	--	--	--
11	1.5	932	802	86	239	514	--
12	1	--	--	--	--	--	--
13	1	936	808	86	255	587	16
14	1	--	--	--	--	--	--
15	1.5	914	800	88	230	619	--
16	4	--	--	--	--	--	--
17	2.5	--	--	--	--	--	--
18	1.5	878	802	91	255	584	--
19	1.5	--	--	--	--	--	--
20	1	942	760	81	206	514	--
21	1.5	--	--	--	--	--	--
22	1	902	848	94	255	567	--
23	1.5	--	--	--	--	--	--
24	--	--	--	--	--	--	--
25	3	836	786	94	239	527	--
26	1.5	--	--	--	--	--	--
27	1	930	834	90	255	494	32
28	1.5	--	--	--	--	--	--
29	1	754	716	95	255	507	--
30	3	--	--	--	--	--	--
31	2.5	--	--	--	--	--	--
32	1.5	1000	886	87	255	547	--
33	1	--	--	--	--	--	--
34	1.5	1022	818	80	255	547	--
35	2.5	--	--	--	--	--	--
36	2.5	--	--	--	--	--	--
37	--	--	--	--	--	--	--
38	--	--	--	--	--	--	--

TABLE B-6(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁼ -S (mg/L)	VSS _{eff} (mg/L)
39	12	--	--	--	--	--	--
40	4	--	--	--	--	--	--
41	27	--	--	--	--	--	--
42	22	--	--	--	--	--	--
43	3	--	--	--	--	--	--
44	3	--	--	--	--	--	--
45	6	--	--	--	--	--	--
46	0	--	--	--	--	--	--

TABLE B-7

Daily Operational Data for Continuous Reactor 8

Influent SCN = 1000 mg/L Temp. = 22°C ± 2°C pH = 7.0 Sludge Age = 152 days Day 1 = 11/13/79							
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	97	--	--	--	--	--	--
2	35	--	--	--	--	--	--
3	1	--	--	--	--	--	--
4	1	1158	860	74	255	567	46
5	25	--	--	--	--	--	--
6	3	--	--	--	--	--	--
7	1	1244	938	75	255	567	24
8	1	--	--	--	--	--	--
9	4	1316	1196	91	288	621	23
10	4	--	--	--	--	--	--
11	19	--	--	--	--	--	--
12	9	--	--	--	--	--	--
13	18	--	--	--	--	--	--
14	62	1586	1282	81	230	534	19
15	47	--	--	--	--	--	--
16	46	--	--	--	--	--	--
17	106	--	--	--	--	--	--
18	102	1770	1528	86	230	534	32
19	95	--	--	--	--	--	--
20	73	--	--	--	--	--	--
21	44	1782	1584	89	263	534	10
22	125	--	--	--	--	--	--
23	120	--	--	--	--	--	--
24	65	--	--	--	--	--	--
25	16.5	1972	1786	91	263	567	18
26	2.5	--	--	--	--	--	--
27	3	--	--	--	--	--	--
28	1.5	2120	1906	90	263	584	17
29	1.5	--	--	--	--	--	--
30	1.5	--	--	--	--	--	--
31	1	2320	1906	82	263	547	8
32	1.5	--	--	--	--	--	--
33	--	--	--	--	--	--	--
34	1.5	--	--	--	--	--	--
35	1.5	2530	2194	87	255	527	36
36	1.5	--	--	--	--	--	--
37	1	2614	2138	82	263	567	20
38	1.5	--	--	--	--	--	--

TABLE B-7 (cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	1.5	--	--	--	--	--	--
40	2.5	--	--	--	--	--	--
41	1.5	--	--	--	--	--	--
42	1.5	2978	2516	84	263	584	8
43	--	--	--	--	--	--	--
44	1.5	3080	2649	86	263	547	16
45	1.5	--	--	--	--	--	--
46	1	--	--	--	--	--	--
47	--	--	--	--	--	--	--
48	1	--	--	--	--	--	--
49	0	--	--	--	--	--	--
50	1.5	3032	2608	86	255	567	9
51	1	--	--	--	--	--	--
52	1	--	--	--	--	--	--
53	<u>0</u>	<u>3372</u>	<u>2830</u>	<u>84</u>	<u>255</u>	<u>567</u>	<u>6</u>
54	--	--	--	--	--	--	--
55	1.5	--	--	--	--	--	--
56	1.5	--	--	--	--	--	--
57	0	3490	3156	90	--	--	--
58	2.5	--	--	--	--	--	--
59	1	--	--	--	--	--	--
60	1	3794	3434	91	--	--	--
61	--	--	--	--	--	--	--
62	1.5	--	--	--	--	--	--
63	1.5	--	--	--	--	--	--

TABLE B-8

Daily Operational Data for Continuous Reactor 9

Influent SCN = 1000 mg/L Temp. = 22°C $\pm$ 2°C pH = 7.0 Sludge Age = 216.6 days Day 1 = 11/13/79							
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	119	--	--	--	--	--	--
2	95	--	--	--	--	--	--
3	41	--	--	--	--	--	--
4	2	1460	1324	91	255	534	28
5	14	--	--	--	--	--	--
6	31	--	--	--	--	--	--
7	36	1676	1424	85	239	514	16
8	65	--	--	--	--	--	--
9	108	1784	1608	90	239	474	13
10	118	--	--	--	--	--	--
11	97	--	--	--	--	--	--
12	110	--	--	--	--	--	--
13	133	--	--	--	--	--	--
14	146	2080	1832	88	214	494	13
15	152.5	--	--	--	--	--	--
16	133.5	--	--	--	--	--	--
17	157	--	--	--	--	--	--
18	194	2370	1978	83	206	421	18
19	150	--	--	--	--	--	--
20	148	--	--	--	--	--	--
21	119	2366	2116	89	239	474	12
22	125	--	--	--	--	--	--
23	104	--	--	--	--	--	--
24	21	--	--	--	--	--	--
25	6	2640	2250	85	263	584	30
26	4.5	--	--	--	--	--	--
27	2	--	--	--	--	--	--
28	1.5	2682	2402	90	263	567	20
29	1	--	--	--	--	--	--
30	4	--	--	--	--	--	--
31	1.5	3032	2604	86	255	584	5
32	1.5	--	--	--	--	--	--
33	--	--	--	--	--	--	--
34	1.5	--	--	--	--	--	--
35	1	3278	2878	88	263	527	16
36	1	--	--	--	--	--	--
37	1	3402	2900	85	263	527	8
38	1	--	--	--	--	--	--

TABLE B-8(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	1	--	--	--	--	--	--
40	1	--	--	--	--	--	--
41	1	--	--	--	--	--	--
42	1	3862	3360	87	263	601	7
43	--	--	--	--	--	--	--
44	1	4098	3374	82	263	527	18
45	1	--	--	--	--	--	--
46	1	--	--	--	--	--	--
47	--	--	--	--	--	--	--
48	1	--	--	--	--	--	--
49	0	--	--	--	--	--	--
50	1.5	3746	3148	84	255	547	20
51	1	--	--	--	--	--	--
52	1	--	--	--	--	--	--
53	<u>0</u>	<u>3928</u>	<u>3586</u>	<u>91</u>	<u>263</u>	<u>547</u>	<u>18</u>
54	--	--	--	--	--	--	--
55	65	--	--	--	--	--	--
56	1	--	--	--	--	--	--
57	0	4038	3636	90	--	--	--
58	1.5	--	--	--	--	--	--
59	1.5	--	--	--	--	--	--
60	2.5	4380	3922	90	--	--	--
61	--	--	--	--	--	--	--
62	1	--	--	--	--	--	--
63	1	--	--	--	--	--	--

TABLE B-9

Daily Operational Data for Continuous Reactor 10

Influent SCN = 1000 mg/L Sludge Age = 16.2 days
 Temp. = 22°C ± 2°C pH = 6.0 Day 1 = 1/15/80

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	165	--	--	--	--	--	--
2	48	--	--	--	--	--	--
3	1.5	--	--	--	--	--	--
4	1.5	--	--	--	--	--	--
5	1	--	--	--	--	--	--
6	1.5	--	--	--	--	--	--
7	0	1746	1606	92	255	607	20
8	1.5	--	--	--	--	--	--
9	0	--	--	--	--	--	--
10	1.5	1626	1431	88	280	607	14
11	1	--	--	--	--	--	--
12	1	--	--	--	--	--	--
13	1	--	--	--	--	--	--
14	1	1576	1402	89	239	571	30
15	1	--	--	--	--	--	--
16	0	--	--	--	--	--	--
17	1	1508	1352	90	222	467	30
18	1	--	--	--	--	--	--
19	0	--	--	--	--	--	--
20	1.5	--	--	--	--	--	--
21	1	1464	1262	86	239	537	20
22	0	--	--	--	--	--	--
23	1	--	--	--	--	--	--
24	0	1408	1196	85	255	607	14
25	0	--	--	--	--	--	--
26	1.5	--	--	--	--	--	--
27	0	--	--	--	--	--	--
28	1	1528	1342	88	239	571	--
29	1.5	--	--	--	--	--	--
30	1	--	--	--	--	--	--
31	1	1674	1473	88	247	557	9
32	1	--	--	--	--	--	--
33	2	--	--	--	--	--	--
34	1	--	--	--	--	--	--
35	1.5	1734	1494	86	239	571	7
36	1.5	--	--	--	--	--	--
37	0	--	--	--	--	--	--
38	0	1780	1506	85	239	571	7

TABLE B-9(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ ⁼ -S (mg/L)	VSS _{eff} (mg/L)
39	1.5	--	--	--	--	--	--
40	1	--	--	--	--	--	--
41	0	--	--	--	--	--	--
42	0	1914	1686	88	239	571	16
43	0	--	--	--	--	--	--
44	0	--	--	--	--	--	--
45	1	1908	1679	88	255	587	11
46	1	--	--	--	--	--	--
47	1.5	--	--	--	--	--	--
48	1	--	--	--	--	--	--
49	2.5	1960	1702	87	239	587	14
50	1.5	--	--	--	--	--	--
51	1.5	--	--	--	--	--	--
52	1.5	2006	1786	89	230	571	22
53	1.5	--	--	--	--	--	--
54	1	--	--	--	--	--	--
55	1.5	--	--	--	--	--	--
56	1.5	1894	1618	85	255	574	33
57	<u>3</u>	<u>1890</u>	<u>1663</u>	<u>88</u>	<u>--</u>	<u>--</u>	<u>--</u>

TABLE B-10

Daily Operational Data for Continuous Reactor 11

Influent SCN = 1000 mg/L Temp. = 22°C ± 2°C pH = 8.0 Sludge Age = 16.3 days Day 1 = 1/15/80							
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	143	--	--	--	--	--	--
2	68	--	--	--	--	--	--
3	1.5	--	--	--	--	--	--
4	1.5	--	--	--	--	--	--
5	1.5	--	--	--	--	--	--
6	1.5	--	--	--	--	--	--
7	0	1994	1826	92	255	571	14
8	1.5	--	--	--	--	--	--
9	1.5	--	--	--	--	--	--
10	2	1834	1558	85	263	537	16
11	3	--	--	--	--	--	--
12	3	--	--	--	--	--	--
13	4	--	--	--	--	--	--
14	10	1914	1668	87	230	537	14
15	4	--	--	--	--	--	--
16	7.5	--	--	--	--	--	--
17	7	1834	1662	91	214	451	13
18	28	--	--	--	--	--	--
19	50	--	--	--	--	--	--
20	46	--	--	--	--	--	--
21	47	1794	1518	85	206	501	10
22	68	--	--	--	--	--	--
23	68	--	--	--	--	--	--
24	116	1668	1388	83	214	524	4
25	84	--	--	--	--	--	--
26	133	--	--	--	--	--	--
27	165	--	--	--	--	--	--
28	188	1496	1252	84	189	394	1
29	298	--	--	--	--	--	--
30	270	--	--	--	--	--	--
31	237	1506	1172	78	164	334	13
32	346	--	--	--	--	--	--
33	325	--	--	--	--	--	--
34	310	--	--	--	--	--	--
35	350	1518	1032	68	143	310	1
36	390	--	--	--	--	--	--
37	150	--	--	--	--	--	--
38	1	1842	1272	69	230	557	4

TABLE B-10(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	6	--	--	--	--	--	--
40	2	--	--	--	--	--	--
41	4.5	--	--	--	--	--	--
42	1.5	1840	1340	73	230	524	12
43	1.5	--	--	--	--	--	--
44	6	--	--	--	--	--	--
45	15	1802	1228	68	239	524	12
46	20	--	--	--	--	--	--
47	38	--	--	--	--	--	--
48	102	--	--	--	--	--	--
49	106	1876	1184	63	214	451	4
50	89	--	--	--	--	--	--
51	103	--	--	--	--	--	--
52	75	1814	1228	68	206	487	16
53	57	--	--	--	--	--	--
54	44	--	--	--	--	--	--
55	18	--	--	--	--	--	--
56	16.5	1942	1266	65	239	574	22
57	11	--	--	--	--	--	--
58	1	--	--	--	--	--	--
59	8	1784	1224	69	230	592	20
60	49	--	--	--	--	--	--
61	32	--	--	--	--	--	--
62	54	--	--	--	--	--	--
63	56	1638	1144	70	222	554	18
64	114	--	--	--	--	--	--
65	114	--	--	--	--	--	--
66	44.5	--	--	--	214	537	8
67	132	--	--	--	--	--	--
68	244	--	--	--	--	--	--
69	295	--	--	--	--	--	--
70	340	1612	1046	65	132	354	0
71	380	--	--	--	--	--	--
72	250	--	--	--	--	--	--
73	300	1360	986	73	127	310	9
74	285	--	--	--	--	--	--
75	310	--	--	--	--	--	--
76	355	--	--	--	--	--	--
77	335	1334	940	70	122	334	13
78	355	--	--	--	--	--	--
79	390	--	--	--	--	--	--
80	420	1646	1002	61	112	334	26
81	420	--	--	--	--	--	--
82	355	--	--	--	--	--	--
83	453	--	--	--	--	--	--

TABLE B-D(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
84	453	1320	782	59	99	310	8
85	485	--	--	--	--	--	--
86	460	--	--	--	--	--	--
87	470	1040	758	73	95	284	16
88	500	--	--	--	--	--	--
89	500	--	--	--	--	--	--
90	515	--	--	--	--	--	--
91	530	960	632	66	82	220	19
92	510	--	--	--	--	--	--
93	555	--	--	--	--	--	--
94	595	942	586	62	72	267	4
95	565	--	--	--	--	--	--
96	550	--	--	--	--	--	--
97	550	--	--	--	--	--	--
98	525	1046	654	63	90	240	23
99	493	--	--	--	--	--	--
100	295	--	--	--	--	--	--
101	510	818	600	73	82	220	17
102	525	--	--	--	--	--	--
103	510	--	--	--	--	--	--
104	530	--	--	--	--	--	--
105	550	912	596	65	82	240	--
106	530	--	--	--	--	--	--
107	548	--	--	--	--	--	--
108	530	1138	608	53	76	215	--
109	515	--	--	--	--	--	--
110	525	--	--	--	--	--	--
111	-	--	--	--	--	--	--
112	475	--	--	--	--	--	--
113	550	--	--	--	--	--	--
114	525	1054	594	56	61	240	--
115	515	--	--	--	--	--	--
116	475	--	--	--	--	--	--
117	530	--	--	--	--	--	--
118	-	--	--	--	--	--	--
119	525	--	--	--	--	--	--
120	485	--	--	--	--	--	--
121	470	1576	734	47	82	287	--
122	460	--	--	--	--	--	--
123	420	--	--	--	--	--	--
124	415	--	--	--	--	--	--
125	-	--	--	--	--	--	--
126	360	--	--	--	--	--	--
127	305	--	--	--	107	--	--
128	295	--	--	--	--	--	--

TABLE B-10(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
129	222.5	1378	790	57	95	451	14
130	225	--	--	--	--	--	--
131	220	--	--	--	--	--	--
132	-	--	--	--	--	--	--
133	-	--	--	--	--	--	--
134	1	--	--	--	--	--	--
135	175	--	--	--	--	--	--
136	215	1498	872	58	121	447	4
137	215	--	--	--	--	--	--
138	175	--	--	--	--	--	--
139	-	--	--	--	--	--	--
140	16	--	--	--	--	--	--
141	6	--	--	--	--	--	--
142	7	1748	968	55	181	554	--
143	4.5	--	--	--	--	--	--
144	-	--	--	--	--	--	--
145	-	--	--	--	--	--	--
146	5	--	--	--	--	--	--
147	8	1710	1056	62	189	--	--
148	0	--	--	--	--	--	--
149	4.5	--	--	--	--	--	--
150	7	--	--	--	--	--	--
151	-	--	--	--	--	--	--
152	-	--	--	--	--	--	--
153	-	--	--	--	--	--	--
154	-	--	--	--	--	--	--
155	11.5	--	--	--	--	--	--
156	11	--	--	--	--	--	--
157	7	--	--	--	181	607	9
158	5	--	--	--	173	--	--
159	-	--	--	--	--	--	--
160	7	--	--	--	--	--	--
161	7	--	--	--	--	--	--
162	8	--	--	--	--	--	--
163	19	--	--	--	--	--	--
164	-	1571	1162	74	189	574	--
165	39	--	--	--	--	--	--
166	20	--	--	--	--	--	--
167	-	--	--	--	--	--	--
168	17	--	--	--	--	--	--
169	20	--	--	--	--	--	--
170	13	--	--	--	--	--	--
171	-	1659	1194	72	181	554	--
172	-	--	--	--	--	--	--
173	18	--	--	--	--	--	--

TABLE B-10(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
174	-	--	--	--	--	--	--
175	16.5	--	--	--	--	--	--
176	25	--	--	--	--	--	--
177	<u>20</u>	<u>1602</u>	<u>1116</u>	<u>70</u>	<u>181</u>	<u>574</u>	<u>16</u>
178	-	--	--	--	--	--	--
179	0	--	--	--	--	--	--

TABLE B-11

Daily Operational Data for Continuous Reactor 12

Influent SCN = 1000 mg/L Temp. = 22°C ± 2°C		pH = 5.0		Sludge Age = 17.1 days Day 1 = 3/12/80			
DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
1	1	--	--	--	--	--	--
2	1	1736	1502	87	239	562	31
3	1.5	--	--	--	--	--	--
4	317.5	--	--	--	--	--	--
5	1.5	--	--	--	--	--	--
6	0	--	--	--	143	357	--
7	1	--	--	--	--	--	--
8	1.5	--	--	--	--	--	--
9	2	1502	1208	80	230	584	32
10	1	--	--	--	--	--	--
11	1.5	--	--	--	--	--	--
12	1	--	--	--	--	--	--
13	1	1646	1242	75	230	607	--
14	1	--	--	--	--	--	--
15	1.5	--	--	--	--	--	--
16	1	1688	1400	83	239	607	16
17	1.5	--	--	--	--	--	--
18	1.5	--	--	--	--	--	--
19	1.5	--	--	--	--	--	--
20	1.5	1676	1440	86	230	644	22
21	1.5	--	--	--	--	--	--
22	1	--	--	--	--	--	--
23	1	1844	1594	86	230	574	22
24	1	--	--	--	--	--	--
25	1	--	--	--	--	--	--
26	1.5	--	--	--	--	--	--
27	1.5	1856	1526	82	214	554	6
28	1.5	--	--	--	--	--	--
29	2.5	--	--	--	--	--	--
30	1.5	1876	1618	86	239	628	--
31	2.5	--	--	--	--	--	--
32	3	--	--	--	--	--	--
33	1.5	--	--	--	--	--	--
34	1.5	2014	1670	83	239	587	17
35	1.5	--	--	--	--	--	--
36	2.5	--	--	--	--	--	--
37	133.5	1772	1514	85	206	537	5
38	2.5	--	--	--	--	--	--

TABLE B-11(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
39	3	--	--	--	--	--	--
40	2.5	--	--	--	--	--	--
41	3	1856	1600	86	239	587	17
42	1.5	--	--	--	--	--	--
43	1.5	--	--	--	--	--	--
44	3	1846	1614	87	239	644	13
45	2.5	--	--	--	--	--	--
46	1.5	--	--	--	--	--	--
47	1	--	--	--	--	--	--
48	1	1756	1544	88	230	607	--
49	1	--	--	--	--	--	--
50	0	--	--	--	--	--	--
51	1	1754	1502	86	222	607	--
52	1	--	--	--	--	--	--
53	0	--	--	--	--	--	--
54	-	--	--	--	--	--	--
55	1	--	--	--	--	--	--
56	0	--	--	--	--	--	--
57	1	1880	1610	86	189	607	--
58	1	--	--	--	--	--	--
59	0	--	--	--	--	--	--
60	1	--	--	--	--	--	--
61	-	--	--	--	--	--	--
62	1	--	--	--	--	--	--
63	1	--	--	--	--	--	--
64	0	1884	1648	87	214	628	--
65	1.5	--	--	--	--	--	16
66	2.5	--	--	--	--	--	--
67	2.5	--	--	--	--	--	--
68	-	--	--	--	--	--	--
69	0	--	--	--	--	--	--
70	1	--	--	--	193	--	--
71	1	--	--	--	--	--	--
72	0	1968	1796	91	181	644	10
73	2.5	--	--	--	--	--	--
74	1	--	--	--	--	--	--
75	-	--	--	--	--	--	--
76	-	--	--	--	--	--	--
77	1	--	--	--	--	--	--
78	1	--	--	--	--	--	--
79	0	1962	1692	86	191	--	6
80	1	--	--	--	--	--	--
81	1.5	--	--	--	--	--	--
82	-	--	--	--	--	--	--
83	1.5	--	--	--	--	--	--

TABLE B-11(cont.)

DAY No.	SCN _{eff} (mg/L)	MLSS (mg/L)	MLVSS (mg/L)	VSS/SS (%)	NH ₃ -N (mg/L)	SO ₄ -S (mg/L)	VSS _{eff} (mg/L)
84	0	--	--	--	--	--	--
85	1	1990	1734	87	206	628	--
86	1	--	--	--	--	--	--
87	-	--	--	--	--	--	--
88	-	--	--	--	--	--	--
89	2	--	--	--	--	--	--
90	2	1850	1646	89	206	--	--
91	1.5	--	--	--	--	--	--
92	1.5	--	--	--	--	--	--
93	1	--	--	--	--	--	--
94	-	--	--	--	--	--	--
95	-	--	--	--	--	--	--
96	-	--	--	--	--	--	--
97	-	--	--	--	--	--	--
98	1	--	--	--	--	--	--
99	0	--	--	--	--	--	--
100	0	1786	1368	77	188	644	7
101	<u>0</u>	<u>--</u>	<u>--</u>	<u>--</u>	<u>193</u>	<u>--</u>	<u>--</u>
102	-	--	--	--	--	--	--
103	1	--	--	--	--	--	--
104	1	--	--	--	--	--	--
105	1	--	--	--	--	--	--

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