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Comparison of the PACT™ and Activated Sludge Processes, for the Treatment of a Kraft Pulp Mill Wastewater

by

Darrell Ball

A M.Sc. Thesis

submitted to the School of Graduate Studies and Research in partial fulfillment of the requirements for the Master of Environmental Engineering Degree

University of Ottawa

Ottawa, Ontario

Canada

December, 1995

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Abstract

This study has compared the conventional activated sludge process to the Powdered Activated Carbon Treatment (PACT™) process for the treatment of a bleached kraft mill effluent. The PACT™ process involves the addition of powdered activated carbon (PAC) to the aeration basin of an activated sludge system. Powdered activated carbon has a very high surface area and is able to adsorb large amounts of hydrophobic compounds, such as organochlorines. This process was selected because it was likely to increase the removals of toxins including adsorbable organics halides (AOX) and because it had not been evaluated for this type of wastewater. Bench scale continuous flow reactors, with internal sludge recycle, were used in this study. The design and process control parameters varied included hydraulic retention time, solids retention time and powdered activated carbon dose. PAC doses of 0.1 - 1.0 g/L were used.

Four feeds were used in this study, which were collected at different times, from a bleached kraft pulp mill batch operation. Their compositions were very different. Furthermore, probably because of degradation in the barrels, during freezing and thawing, the feed to a given reactor varied, during the steady - state period.

The PACT™ systems were found to yield only small increases in SCOD and DOC removals over the activated sludge systems. Little or no improvement was found for Microtox toxicity and $SBOD_5$ removals, by addition of PAC to the aeration basin. $SBOD_5$ removals were close to 100 %, for all control activated sludge and PACT™ reactor runs. The addition of PAC resulted in significant increases in SAOX removal. Solids retention time, in the range of 7 to 25 days, was found to have little or no impact on the removals of any of the parameters tested for.

Two conceptual models for effluent SCOD prediction, were developed and tested. The models used a zero order biodegradation rate constant, lumped the stripping removal component into the biodegradation term and described adsorption by either the Langmuir or Freundlich isotherm. The conceptual models yielded fairly good predictions. The Lankford and Miller empirical model (1987), also incorporated some sensitivity to feed variability, in addition to HRT, influent SCOD and carbon dose, in predicting effluent SCOD concentration. This model was found to be the best predictor (slightly better than the conceptual models) of effluent SCOD, yielding a 30 % global mean absolute percent error.

The Dec, 31 1999 AOX limit of 0.8 kg/air dried metric tonne (ADMT) was met by both activated sludge and PACT™ systems for two feeds, both of which had low calculated TAOX concentrations compared to those reported in the literature. For a third feed batch, both the activated sludge and PACT™ systems did not meet the limit.

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GLOSSARY

a	fraction of biomass digested
b	Langmuir adsorption model constant (L/mg substrate)
b_d	fraction of PAC digested
C_D	powdered activated carbon dose (g or mg PAC/L feed)
EFFTSS	effluent total suspended solids (mg TSS/L)
EFFVSS	effluent volatile suspended solids (mg VSS/L)
F	volumetric flowrate (L/d)
F_h	volumetric flowrate (L/hr)
F_w	wastage flow from the aeration basin (L/d)
HRT	hydraulic retention time (hours)
k	maximum substrate utilization per unit time per unit VSS (mg COD/(mg VSS*d))
k_d	endogenous decay coefficient (mg VSS/mg COD)
k_i	adsorption constant in Lankford and Miller model (L/mg PAC)
k_{bio}	maximum substrate utilization in A.S. control (mg TOC/(mg VSS*d)
$\hat{k}_{bio}$	modified maximum substrate utilization in A.S. control (L/(d*mg VSS))
k_R	maximum substrate utilization in PACT™ reactor (mg TOC/(mg VSS*d)
K	Freundlich constant (mg SCOD/mg PAC)
K1	concentration of suspended solids that was solubilized in a PACT™ sample (mg/L)
K_A'	Freundlich model constant for a linear isotherm (L/mg PAC)
K_{AP}	apparent first order rate constant (1/d)
K_b	biodegradation rate coefficient (mg TOC/(mg VSS*hour))
K_{BD}	first order biodegradation rate constant (1/d)
K_{Db}	zero order biodegradation rate constant (mg/(L*d))
K_{gb}	biodegradation rate coefficient (mg TOC/(mg VSS*L*hour)) in Garcia - Orozco model
K_{gbn}	DNOC biodegradation rate coefficient (mg DNOC/(mg VSS*L*hour)) in Garcia - Orozco model
K_{OBa}	adsorption kinetic coefficient in O'Brien's model (L/(mg PAC*d))
K_{OBb}	biodegradation coefficient in O'Brien's model (L/(mg VSS*d))
K_{OBs}	stripping coefficient in O'Brien's model (1/d)
K_p	biosorption equilibrium constant (L/(mg VSS))
K_{Ra}	adsorption rate constant in Robertaccio's model (L/(mg PAC*d))
K_s	half velocity constant (mg COD/L)
m	proportionality constant (L/mg PAC)
MC	mass of carbon (g)
MLCSS	mixed liquor carbon suspended solids (mg PAC/L)
MLNCSS	mixed liquor non - carbon suspended solids (mg TSS/L)
MLTSS	mixed liquor total suspended solids (mg TSS/L)
n	Freundlich constant (dimensionless)
NB	non - biodegradable TOC (mg TOC/L)

q	equilibrium PAC loading (mg substrate/mg PAC)
Q	composite constant $(Q_{Max}/24)$(L/mg PAC)
Q_{max}	maximum loading of PAC in Langmuir model (mg substrate/mg PAC)
r_A	mass flow for adsorption (mg/d)
r_{Ra}	rate of adsorption in Robertaccio's model (mg/(L*d))
r_{tu}	utilization rate of total substrate (mg COD/(L*d))
R_{BS}	biosorption rate (mg/d)
R_{gb}	rate of TOC biodegradation in Garcia - Orozco model (mg TOC/(L*hour))
R_{gbn}	rate of DNOC biodegradation in Garcia - Orozco model (mg DNOC/(L*hour))
R_{OBa}	adsorption rate in O'Brien's model (mg/d)
R_{OBb}	biodegradation rate in O'Brien's model (mg/d)
R_{OBs}	stripping rate in O'Brien's model (mg/d)
S	degradable SCOD (mg COD/L)
SRT	solids retention time (d)
S_b	effluent substrate concentration from A.S. in Lankford and Miller model (mg TOC/L)
S_e	effluent substrate concentration (mg/L)
S_i	influent substrate concentration (mg/L)
S_{ge}	effluent TOC concentration (mg TOC/L)
S_{g0}	influent TOC concentration (mg TOC/L)
S_{Re}	amount of substrate adsorbed, at any time, expressed as solution concentration (mg TOC/L)
S_{Re}^*	equilibrium amount of substrate adsorbed, expressed as solution concentration (mg TOC/L)
S_p	pseudo concentration (mg TOC/L)
S_t	total effluent COD concentration (mg COD/L)
t	time (days)
TC	temperature correction factor $(1.04^{(T-20^\circ C)})$
TSS	total suspended solids (mg TSS/L)
U	specific utilization (mg COD/(mg VSS*d))
V	volume (L)
VSS	volatile suspended solids (mg VSS/L)
w	wastage rate (mg TSS/d)
X	mixed liquor VSS concentration (mg VSS/L mixed liquor)
X_0	VSS concentration at time zero (mg VSS/L mixed liquor)
X_t	VSS concentration at time t (mg VSS/L mixed liquor)
Y	yield coefficient (mg VSS/mg COD)
α_R	proportionality constant (mg TOC*L/(mg VSS*mg PAC*d))
α_R^*	proportionality constant (L^2/(mg VSS*mg PAC*d))
Δs	A.S. effluent biodegradable TOC - PACT™ effluent biodegradable TOC (mg TOC/L)
Θ	hydraulic retention time (days)

Abbreviations

ADMT	air dried metric tonne
AOX	adsorbable organic halide
A.S.	activated sludge
ASB	aerated stabilization basin
BKME	bleached kraft mill effluent
BOD_5	5 day biochemical oxygen demand
CM	completely mixed
COD	chemical oxygen demand
DNOC	4,6 - dinitro - o - cresol
DOC	dissolved organic carbon
E.A.	extended aeration
EFFTSS	effluent total suspended solids
EFFVSS	effluent volatile suspended solids
EPA	environmental protection agency
GAC	granular activated carbon
GC	gas chromatography
HRT	hydraulic retention time
MEP	metabolic end product
MISA	municipal industrial strategy for abatement
MLCSS	mixed liquor carbon suspended solids
MLNCSS	mixed liquor non - carbon suspended solids
MLTSS	mixed liquor total suspended solids
MLVSS	mixed liquor volatile suspended solids
MS	mass spectroscopy
OUR	oxygen uptake rate
PAC	powdered activated carbon
PACT™	powdered activated carbon treatment
SAOX	soluble adsorbable organic halide
$SBOD_5$	soluble 5 day biochemical oxygen demand
SCOD	soluble chemical oxygen demand
TAOX	total adsorbable organic halide
$TBOD_5$	total 5 day biochemical oxygen demand
TCOD	total chemical oxygen demand
TOC	total organic carbon
SRT	solids retention time
THF	tetrahydrofuran
UV	ultraviolet radiation

1. Introduction

The use of chlorine containing compounds in the bleaching process is responsible for biorefractory chlorinated compounds in pulp and paper mill effluents. These include chlorinated phenols, chlorinated veratroles, chlorinated guaiacols and chlorinated catechols (Murray and Richardson, 1993) which are frequently measured as adsorbable organic halides (AOX). These biorefractory chlorinated organics are chronically toxic (Murray and Richardson, 1993). They have demonstrated high mutagenic capacity (and therefore potentially carcinogenic capacity) in bacteria and yeast (Murray and Richardson, 1993). The Ministry of the Environment of Ontario estimates 90% of the organochlorines discharged into the Great Lakes and Ontario waterways originate from the Pulp and Paper sector (Ministry of the Environment of Ontario, 1993a). Two other significant pollutants from pulp mills are fatty and resin acids, which are natural components of wood resins (Murray and Richardson, 1993 and McCubbin Consultants, 1992). These compounds have demonstrated high acute and chronic toxicity towards fish (McCubbin Consultants, 1992).

Especially strict environmental standards exist in Ontario (Canada) by virtue of the Clean Water Regulation for the Pulp and Paper Sector, issued under the Municipal Industrial Strategy for Abatement (MISA) (Ministry of the Environment of Ontario, 1993b). As of Dec. 31, 1995, the AOX emission limit will be 1.5 kg/air dried metric tonne (ADMT) of pulp. This decreases to 0.8 kg/ADMT on Dec.31, 1999 and to zero detectable by 2002. In addition, the 1995 limits for the five day biochemical oxygen demand (BOD_5) and toluene are 85% lower than the 1990 limits; phenol and chloroform limits are 88% and 96% lower, respectively. This results in monthly limits of 2.91 - 5.0 kg/(ADMT) for BOD_5, 0.0001 - 0.0002 kg/(ADMT) for toluene, 0.0002 - 0.0004 kg/(ADMT) for phenol and 0.001 - 0.002 kg/(ADMT) for chloroform. Furthermore, MISA requires effluents to have no acute toxicity effects on rainbow trout and Daphnia magna (Ministry of the Environment of Ontario, 1993b).

The Powdered Activated Carbon Treatment, PACT™, process has been successfully used to treat many different types of industrial wastewaters (Hutton, 1978), however it has not been thoroughly evaluated for pulp and paper wastewaters. This Zimpro patented process involves the combination of activated carbon adsorption (strictly, chemical or physical adsorption) with an activated sludge process (biological treatment) (Meidl, 1990). Due to the powdered activated carbon (PAC) additions, the PACT™ process generally has higher organics removals than the activated sludge process (Hutton, 1978). Also, it is more stable and more resistant to toxic shocks (Hutton, 1978). Thus, the PACT™ process may be a good option for the treatment of bleached kraft mill effluent (BKME).

1.1 Objectives

The main objectives of this thesis are as follows. First, to assess and compare the pollutant and toxicity removal of the activated sludge process and the PACT™ process, for a bleached kraft mill wastewater. This will be achieved via a series of steady - state bench scale reactor runs. Second, to model the performance of these two processes.

2. Literature Review

The following discussion of the pertinent literature can be divided into three main topics. These are i) comparison of the PACT™ process with the activated sludge process, with and without post treatment by granular activated carbon (GAC) columns, ii) models for the PACT™ process and iii) conventional biological treatment of bleached kraft mill effluent (BKME).

2.1 System Descriptions and Process Control Parameters

Diagrams of the activated sludge and PACT™ processes can be found in Figure 2-1 and Figure 2-2. The difference between the two systems is that the PACT™ system has powdered activated carbon added to the aeration basin. Activated carbon has a very high surface area (about 1000 m^2/g) which gives it the ability to adsorb substantial quantities of many organic compounds.

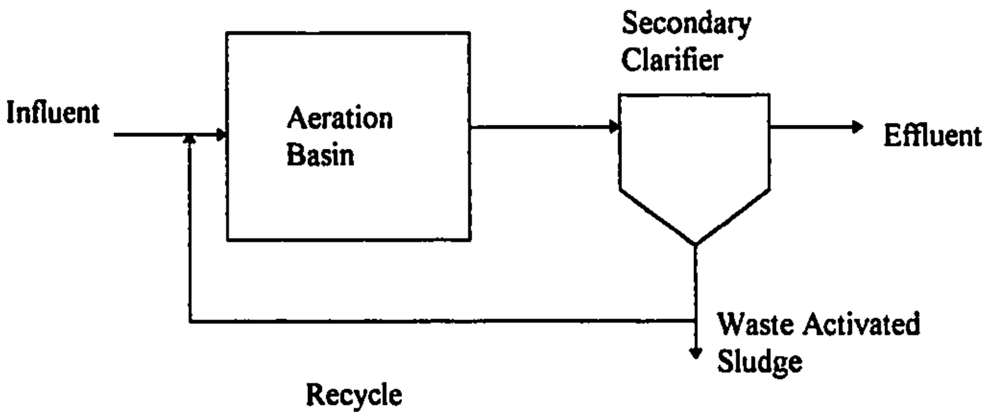

Figure 2-1: General Diagram of the Activated Sludge Process

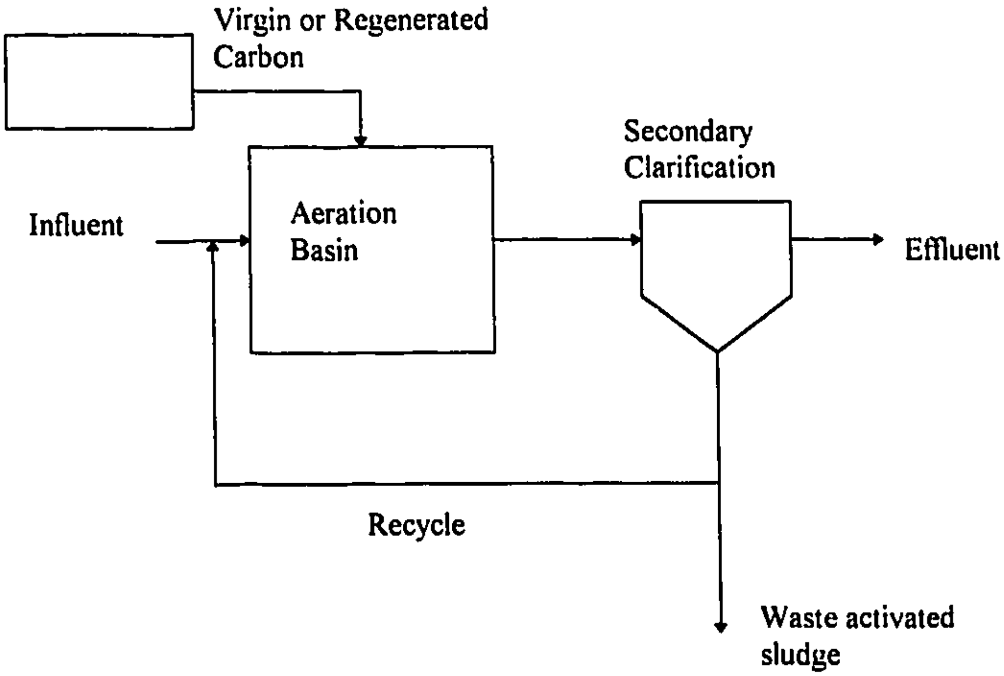

Figure 2-2: General Diagram of the PACT™ Process

The main design variable for the activated sludge process is the hydraulic retention time (HRT) (hours). The process control parameters for the activated sludge process include 2 independent variables. These can be solids retention time (SRT) (days) and recycle solids concentration. The PACT™ process has one additional process control parameter, PAC dose (C_D) (mg PAC/L of feed). Two dependent parameters, mixed liquor total suspended solids (MLTSS) (mg/L) and mixed liquor carbon suspended solids (MLCSS) (mg/L) are also relevant, but they are a function of SRT, HRT and C_D.

Hydraulic retention time (HRT) (hours) is defined as:

$$HRT = V / F_h \qquad \textbf{2-1}$$

where V = active volume of the reactor (L) and F_h = volumetric flowrate to the reactor (L/hour).

Solids retention time (SRT) is defined by the following relation:

$$SRT = \frac{(MLTSS * V)}{W} \qquad \textbf{2-2}$$

where W is the wastage rate of total suspended solids (mg TSS/d), which includes biomass, inert solids and PAC, from the reactor. This includes loss through the effluent and purposeful removal of mixed liquor to maintain a given SRT.

The PAC dose is given by:

$$C_D = {}^{MC}\!\!\Big/\!{}_{(F_h * 24)} \qquad \textbf{2-3}$$

where MC is the mass of carbon added per day (mg PAC/d).

MLCSS is estimated by

$$MLCSS = \frac{C_D * SRT}{{}^{HRT}\!/\!{}_{24}} \qquad \textbf{2-4}$$

2.2 Comparison of the PACT™ and Activated Sludge Processes

Some of the frequently cited advantages of the PACT™ process over conventional activated sludge are: i) improved chemical oxygen demand (COD) and total organic carbon (TOC) removal; ii) dampening of shock loads by adsorption of toxic organics and some toxic heavy metals; iii) enhanced color removal by adsorption of dyes; iv) better removal of slowly/non-biodegradable and/or toxic substances; v) enhanced nitrification; vi) reduced aerator foaming due to adsorption of detergents; vii) improved sludge settleability and dewatering; viii) suppressed stripping of volatiles; and ix) resistance to reduced treatment efficiency at lower temperatures or from long idle periods for batch systems (Hutton, 1978, Weber and Matsumoto, 1987). These advantages are discussed in greater detail below.

It should be noted that there are increased costs associated with the use of a PACT™ system. These include PAC purchase costs, PAC regeneration costs and possibly increased sludge handling costs.

2.2.1 COD and TOC Removal

There are numerous studies that indicate superior COD and TOC removal by PACT™ systems compared to the conventional activated sludge system, but not significantly better BOD_5 removal (Table 2-1). The percent COD, TOC and BOD_5 removals of the PACT™ systems were higher than those of the activated sludge controls. The mean COD removal of the PACT™ systems was 13 % higher and ranged from 2 - 25 %. The mean TOC removal of the PACT™ systems was 9 % higher and ranged from 1.5 -

43 %. The mean BOD_5 removal of the PACT™ systems was 3 % higher and ranged from 0.2 - 10 %. The average removals of the activated sludge systems were 79 %, 69 % and 96 %, respectively.

These findings indicate that the activated sludge process is able to remove most of the biodegradable organics as indicated by the high BOD_5 removals. However the higher COD and TOC removals of the PACT™ systems, compared to the activated sludge controls, might indicate the PACT™ system is able to remove additional non - biodegradable material including possibly some of the metabolic end products (MEPs).

Wastewater Type and System Size	C_D (g/L)	Influent COD (mg O_2/L)	Influent TOC (mg C/L)	Influent BOD_5 (mg O_2/L)	% COD removal by A.S.	% COD removal by PACT™	% TOC removal by A.S.	% TOC removal by PACT™	% BOD_5 removal by A.S.	% BOD_5 removal by PACT™	Reference
Oil Refinery; 792 L/hr	0.002	214 (s)	59 (s)		68.2	79.4	64.4	78.0			Grieves et al., 1980
Shale Oil; pilot scale	4.26	23700	4950 (s)	6220	64.4	89.4	39.6	83.2	89.5	99.6	Dietrich et al., 1988
Dye & Pigments; 6.9 L/hr	1	1260 (s)	635 (s)		74	96	64	87			Shaul et al., 1983
Chemical; 0.59 L/hr	0.65	10230	2965	4035	97.1	99.0	97.8	99.2	99.6	99.7	Rollins et al., 1982
Chemical; 0.9 L/hr	0.1		153				69.3	86.3			Hutton, 1981
Pharmaceutical ; 11.8 L/hr	0.1		387				72.4	89.7			Kincannon and Esfandi,1981
Pharmaceutical ; 3.6 L	0.2 - 1.2	5240 3850(s)		2810	87.5 - 89.8 87.1 - 88.3	92.1 - 96.8 90.5 - 96.7			99.6	99.8	Osantowski et al., 1987
Coal Lique-faction 0.25 L/hr	0.4	1120	386	511	69	90	74	92	95	98	Kaczmarek and Robertaccio, 1983
Coal Gas., 0.056 - 0.125 L/hr	1.8	1570			83.6	93.0					Randall et al., 1984
Cr(VI) containing (15mg/L), 0.3 L/hr	0.2	453 (s)			85	96					Lee et al., 1989

Table 2-1: Examples of COD, TOC and BOD_5 Removals using the PACT™ Process Compared to the Activated Sludge (A.S.) Process

* s for influent indicates soluble basis

2.2.2 System Stability

System stability refers to the maintenance of system performance during transient periods of high toxin or organic loading.

Adams (1973) reported on the performance of a 1.4 mgd municipal plant, receiving 70% of its flow from a textile dying and finishing mill. The median BOD_5 treatment efficiency increased from 72% to 89% upon the addition of a 22.5 mg/L PAC dose. The difference in overall performance was attributed to superior PACT™ results during periods of shock load and hence was viewed as a case of increased system stability of the PACT™ process.

Rizzo (1976) described a 1.1 mgd plant treating refinery wastewater. The frequency distribution for % BOD removal essentially flattened out with a 9 ppm C_D, from a previously sigmoidal shape (Figure 2-3), which showed increased stability by adding PAC.

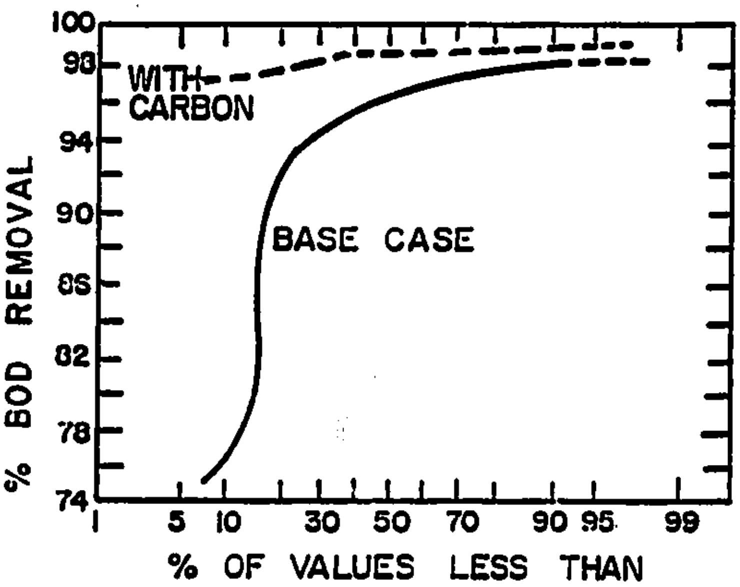

Figure 2-3: Effect of a 9 ppm Carbon Dose on Effluent BOD_5, for an Oil Refinery Wastewater (after Rizzo, 1976)

Grieves et al. (1980) compared the treatment of oil refinery wastewater by a control activated sludge unit and a PACT™ pilot plant, during periods of upset. Periods of upset were defined as those with soluble chemical oxygen demand (SCOD) effluent values in the 90 - 98 % cumulative probability range. Figure 2-4 shows that the SCOD effluent levels for the PAC A unit were about 35 % lower than those of the SA activated sludge control unit.

Another study using various phenol shock loadings of a bacterial population, fed glucose as substrate, showed that pulse addition of PAC allowed for continued operation of a reactor, even during shock loading of 1000 mg/l phenol. Without PAC addition, it was shown the reactor failed (Nayar and Sylvestor, 1979).

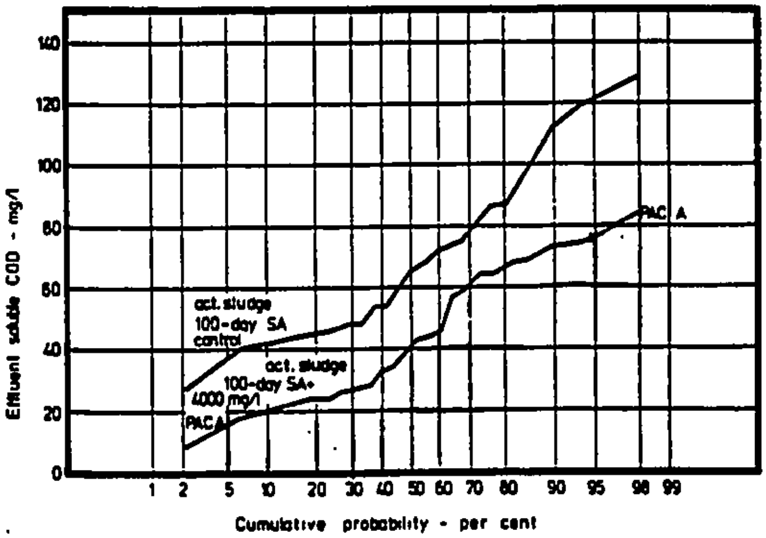

Figure 2-4: Effluent SCOD with (curve PAC A) and without PAC Addition, for an Oil Refinery Wastewater (after Grieves et al., 1980)

2.2.3 Color Removal

Color often results from compounds with conjugate double bond structures and aromatic compounds. Such chemicals are often quite non - polar and hence well adsorbed onto activated carbon. Some examples of enhanced color removal by the PACT™ process can be found in Table 2-2. Differences in color removal were very large; removals were increased 2 - 4 times with the addition of PAC. In one case, the activated sludge process resulted in an increase in color, presumably due to metabolic end products (MEPs).

Wastewater	C_D (g/L)	Influent Color (APHA units)	% removal by A.S.	% removal by PACT™	Reference
Dye and Pigments	1	1340	34	98	Shaul et al.,1983
Chemical	0.1	1640	22.0	80.8	Hutton, 1981
Pharmaceutical	0.1	4648	46.3	94.9	Kincannon, 1981
Coal - Gasification	1.8	1080	- 55	88.4	Randall et al., 1984

Table 2-2: Examples of Enhanced Color Removal by the PACT™ Process over the Activated Sludge Process

2.2.4 Removal of Toxic and/or Slowly/Non-Biodegradable Substances

Table 2-3 demonstrates the superior removal afforded by the PACT™ process as compared to the activated sludge process, in terms of priority pollutants, toxic metals and generic toxicity. For the cases presented, PACT™ removal of organics was generally found to be greater than 89 %, while corresponding organics removal in the activated sludge system ranged from 0 to 97 %, with a mean of about 50 %. Metals removal in the activated sludge process, in the examples presented, averaged 37 %, while in the PACT™ units, the removals averaged 68 %, on average.

Two additional studies on the ability of the PACT™ system to remove toxicity are worth highlighting. The first study showed a better ability on the part of the PACT™ system to remove toxicity even when COD removals approximated those of the activated sludge process (Wong and Maroney, 1990). A refinery wastewater was treated by pilot plant extended aeration (E.A.) and PACT™ systems. The E.A. system had an SRT of 20 days and an HRT of 24 hours, while the PACT™ system had an SRT of 10 days and an HRT of 12 hours, with a PAC dose of 0.075 g/L. Both systems had COD removal of about 74 %. However, the PACT™ system produced effluent which yielded 95 - 100 % sickleback and trout survival while the E.A. effluent had 0 % survival. Ammonia, cyanide, phenol and heavy metal effluent concentrations were such that the authors did not consider them as causes of the toxicity, although synergistic effects were not contemplated. A possible reason for these results is the adsorption of some oxidized MEPs, that react poorly in the COD test, hence the similar COD removals.

The second study involved treatment of a raw neutralized pharmaceutical wastewater via the PACT™ and A.S. systems (Osantowski et al., 1987). During one test period, carbon dosages of 0.2 and 0.7 g/L of Westvaco Nuchar SA - 15 were used while during the second test period 0.4 and 1.2 g/L carbon dosages were used. Toxicity was assessed using Ceriodaphnia dubia. Both the PACT™ and A.S. control systems reduced the wastewater toxicity. The PACT™ effluent had equal or greater toxicity than the control effluent, contrary to expectations. Adsorption of toxins onto the carbon and subsequent desorption from small carbon particles present in the effluent and thus present in the toxicity assay was assumed to be the cause for these unusual results. Filtering through a 0.45μm filter was suggested as a measure that might yield the expected greater reduction in toxicity, for the PACT™ system.

Waste-water	C_D (g/L)	Pollution Parameter	Influent Concentrat - ion	% removal by A.S.	% removal by PACT™	Reference
Dye and Pigments	1	Chromium	0.93 mg/L	64.5	77.4	Shaul et al., 1983
Dye and Pigments	1	Lead	0.94 mg/L	65.6	82.8	Shaul et al., 1983
Dye and Pigments	1	D. magna (48 hr, EC_{50})	12%	74	87	Shaul et al., 1983
Chemical	0.1 0.25 0.5	Copper	0.41 mg/L	12	56 83 90	Lankford, 1990
Chemical	0.1 0.25 0.5	Nickel	0.52 mg/L	33	48 54 56	Lankford, 1990
Cr(VI) containing W.W.	0.2	Chromium	15 mg/L	9	41	Lee et al., 1989
Chemical	0.1	Organic Chlorine	5.08 mg/L	82	98	Rollins, 1982
Chemical	0.1	Phenol	8.1 mg/L	97.3	99.9	Rollins, 1982
Shale Oil Retort	4.26	Phenols	71.4 mg/L	96	99.7	Dietrich et al., 1988
Shale Oil Retort	4.26	Cyanide	60.1 mg/L	34.6	98.8	Dietrich et al., 1988
Shale Oil Retort	4.26	Thio-cyanate	191.7 mg/L	0	91.5	Dietrich et al., 1988
Oil Refinery	4	Phenols	0.98 mg/L	94	96.5	Grieves et al., 1980
Chemical	0.1	2,4 - dinitro - phenol		0	96.6	Hutton , 1981
Chemical	0.1	1,3-dichloro-benzene		71	91.3	Hutton , 1981
Chemical	0.1	pentachloro -phenol		35	89	Hutton , 1981
Chemical	0.1	4,6 - dinitro-o-cresol		0	93	Hutton , 1981

Table 2-3: Examples of Enhanced Removal of Specific Organics, Metals and Generic Toxicity by the PACT™ Process as Compared to the Activated Sludge Process

2.2.5 Nitrification Performance

The advantage of PAC addition, in terms of increased nitrification, is unclear in the literature, since there are not many studies that use comparable activated sludge controls. Some researchers have found marginal increased nitrification (Dehnert and Weisberg, 1978) and others significant increased nitrification (Black and Andrews, 1977) with PAC addition. However, others have found equal nitrification (Grieves et al., 1977; Grieves et al., 1980) and poorer nitrification (Grieves et al., 1980; Randall et al., 1984) with PAC addition to the activated sludge process.

In one other study, a series of batch tests were conducted to determine the role of adsorption of inhibitors onto PAC, in the enhancement of nitrification, using unacclimated sludge (Ng and Stenstrom, 1987). The source of the sludge was a bench scale continuous flow reactor with a SRT of 9 days and a HRT of 8 hours which was fed a synthetic mixture of glucose, of unspecified concentration, and 50 mg/L of ammonia nitrogen. In the batch tests, ammonia was added to bring its concentration to between 40 and 50 mg N /L and the pH was adjusted to 7.2 - 7.4. Ammonia is essentially non - adsorbable, in this pH range, since the predominant form is NH_4^+. All inhibitors were added in separate tests. Phenol and aniline were used as adsorbable inhibitors while ethanol and cyanide were used as non - adsorbable inhibitors. The concentrations used corresponded to 75% or greater inhibition of nitrification. The carbon used was Westvaco Nuchar SA - 15. Ammonia conversion in the controls was between 5 and 70 %. For the non - adsorbable inhibitors, little decrease in inhibition was found, using carbon doses of 0.5 - 4 g/L. The runs with the adsorbable inhibitors showed between 75 - 97% increased nitrification with the addition of the PAC and the improvements were apparent within 1 - 2 hours.

2.2.6 Foaming

The suppression of foaming, caused by aeration of wastewater containing surfactants, can be a significant cost of treatment plant operation. Adams (1973) reports on a 0.3 mgd cotton finishing plant using $108,000 worth of defoamer per year (early 1970's). At 60 ppm C_D, defoamer was not needed, which resulted in a saving of $100,000 per year. Dejohn and Black (1977) report similar savings at a refinery wastewater treatment facility. Another study using large pilot plants treating oil refinery wastewater found that the addition of 20 mg/L of PAC eliminated all foaming while the control units had to be skimmed daily (Grieves et al., 1980).

2.2.7 Sludge Settling Velocity and Dewaterability

The addition of PAC particles might help form denser and larger floc particles. These particles settle faster and the sludge formed might dewater more easily than sludge without PAC. These are often - cited advantages of the PACT™ process. The improved settling can help give the PACT™ system greater stability.

Secondary clarifier solids loading rates for PACT™ systems are typically much higher (100 - 125 $lb/ft^2/d$) than for conventional activated sludge (20 - 40 $lb/ft^2/d$) (Meidl, 1990).

At the DuPont Chambers Works chemical manufacturing plant, Meidl (1982) found that PAC additions decreased the SVI from 388 ml/g to 29 ml/g. It should be noted that SVI values are affected by mixed liquor suspended solids concentrations, which increased from 7 g/L to 15 g/L.

2.2.8 Stripping of Volatiles

A number of studies have shown reduced stripping of volatile organics in continuous flow steady - state tests with the PACT™ process as compared to the activated sludge process (O'Brien, 1992, Weber et al., 1987, Stover et al., 1985). Compounds that have been shown to be stripped less in the PACT™ process include 1,2 dichloroethane, chloroethane, chloromethane, chloroform, methylene chloride, chlorobenzene, toluene, ethylbenzene, xylenes, benzene, 1,2 dichlorobenzene, 1,2,4- trichlorobenzene and lindane. It was noted by Weber et al. (1987) that biodegradable compounds were stripped to the same extent in the PACT™ and activated sludge processes. Depending on the specific application this may not always be true, but the trend is clear and not unexpected because biodegradable compounds are often taken up by cells quickly before stripping can occur to any significant extent.

2.2.9 Impact of Lower Temperatures and Long Idle Periods for Batch Systems

Lower temperature can decrease pollutant removal efficiencies (Metcalf and Eddy, 1991). Long idle periods for batch reactor systems can also decrease pollutant removal efficiencies, by causing a loss of microbial acclimatization (Weber and Matsumoto, 1987). Weber and Matsumoto (1987) compared the effect of low temperature and long idle periods on the performance of intermittently operated, lab scale, activated sludge and PACT™ sequencing batch reactors (SBRs). The wastewater used was groundwater collected near a hazardous waste facility. Using carbon doses of 1 to 5 g/L, the PACT™ system yielded effluents with 40 to 75 % lower COD and TOC concentrations as compared to the activated sludge control. The poorer performance by the activated sludge control was attributed to the extended idle periods (13 and 20 days) and/or low temperature (5°C or 15°C).

In order for the longer lag period or lower temperature activated sludge controls to achieve the same soluble COD removal as the shorter idle period (6 days) or higher temperature (25°C) activated sludge controls, respectively, the aeration periods needed to be extended to 24 hours from 12 hours.

2.2.10 Comparison Summary

Given its many advantages, the PACT™ process is an important alternative process for industrial wastewater treatment.

2.3 Comparison of the PACT™ Process and the Activated Sludge Process followed by GAC Columns

The main advantage of the use of GAC columns is that they use activated carbon more efficiently than the PACT™ process because they remove more pollutants per unit weight. In GAC columns, the saturated activated carbon is in equilibrium with the influent, while PAC in the PACT™ process, will be in equilibrium with a lower concentration, the PACT™ system effluent. An alternative to the PACT™ process is the activated sludge process followed by a GAC column. This configuration allows for most of the biodegradable compounds to be degraded in the activated sludge process and hence not use active sites on the GAC that could otherwise be used for non - biodegradable compounds. This also results in less clogging of the GAC column than when a column precedes the activated sludge process.

Generally an activated sludge system followed by GAC yields slightly lower effluent water quality parameter concentrations than the PACT™ system but it is often more expensive. The GAC column can adsorb essentially all adsorbable compounds before it becomes saturated while the PACT™ system activated carbon will be, at best, in equilibrium with the effluent. A completely mixed PACT™ system even with a high carbon dose may not be capable of achieving very low effluent concentrations. Another advantage to the use of GAC can be noted. PAC particles can settle poorly and end up in the effluent (Benedek, 1980).

There are six advantages of the PACT™ process over the activated sludge process followed by GAC. Firstly, there is a decreased chromatographic effect and this can decrease the economical advantage of using GAC columns (Hutton, 1981; Meidl, 1990; Grieves et al., 1980, Ying, 1989). A chromatographic effect involves desorption of compounds from GAC when the concentration of the feed decreases. The effect can also be observed when competitive adsorption causes displacement of previously adsorbed compounds. Under shock load the PACT™ process may retain biodegradable compounds on the carbon, to be desorbed and degraded at a later time. In the same situation, an activated sludge system might not remove part of the biodegradable organics which increases the organic load on the GAC column. These organics would occupy sites on the GAC, possibly allowing more non - biodegradable compounds to pass through the GAC column into the effluent. There will not necessarily be a lower effluent concentration than with the PACT™ system.

Secondly, clogging in GAC columns can occur, even if the columns follow activated sludge systems. This biological growth related clogging is less for columns following activated sludge systems because most biodegradable compounds will have been removed and the effluent is settled in the secondary clarifier. This clogging can result in short circuiting and dead volume, which results in inefficient use of the GAC. Third, the PAC has faster adsorption kinetics due to its smaller particle size (Schultz, 1982), which helps decrease the efficiency advantage of GAC. Fourth, PAC is cheaper than GAC. Fifth, there is greater flexibility in terms of carbon dosage when using PAC. Sixth, there is essentially no pressure drop in PACT™ systems, as there is associated with GAC columns (Schultz, 1982). Some examples of cheaper PACT™ systems compared to an activated sludge system followed by a GAC column are discussed below.

Using primary effluent from DuPont's Chambers Works chemical manufacturing plant (soluble TOC of 170 mg/L), the PACT™ system was compared, at the lab scale, to an activated sludge system followed by two GAC carbon columns in series (Hutton, 1981). At the breakthrough point for TOC (above 40 mg C/L) and color (600 APHA units), which occurred together, column 1 had used a carbon dose of 140 mg/L while the PACT™ reactor used a carbon dose of 100 mg/L. Up to the breakthrough point, the average TOC was 17.8 mg/L in the effluent from column 1 while it was 21.1 mg/L from the PACT™ reactor. Furthermore, both systems were removing 30 of the 36 priority pollutants present, with 85% or greater efficiency.

Hutton (1981) stated that the PACT™ reactor was more economical based on its lower carbon usage rate. However, activated sludge with GAC post treatment achieved slightly higher removals. As discussed earlier, there will be a maximum degree of removal that may be achieved by a PACT™ system which an activated sludge system with GAC post treatment can exceed (Narbaitz, 1995). However, the chromatographic effect observed in GAC columns tends to negate this advantage. Not dealt with were possible differential carbon regeneration costs for PAC as opposed to GAC, column costs, carbon slurry make - up tank costs for the PACT™ system and possible differential maintenance costs.

A SBR (sequencing batch reactor) followed by a carbon column system was compared to a SBR/PAC system, treating a combined wastewater, consisting of hazardous landfill leachate and an undefined wastewater (Ying, 1989). Carbon regeneration was not considered. For a flow of 144000 L/d, the SBR/PAC process was found to be cheaper by

$44,000 per year, than the corresponding SBR/GAC system, taking all costs into consideration. The difference was shown to be due to carbon savings, as a result of activated carbon, in the GAC column, being used to adsorb biodegradable compounds, that could not be removed by the activated sludge system. This advantage was also noted in another source (Meidl, 1990).

A pilot scale oil refinery wastewater treatability study compared the PACT™ process to an activated sludge process followed by GAC columns (Grieves et al., 1980). Sludge ages of 10, 50 and 100 days were investigated. The influent SCOD and DOC were 214 mg/L and 59 mg/L, respectively. For flows of 2 mgd to 20 mgd, the PACT™ process was found to be more economical than an activated sludge system followed by GAC, except when effluent concentrations below 30 mg/L SCOD or 10 mg/L DOC were required.

2.4 Comparison of PACT™ and GAC followed by an Activated Sludge System

Another alternative to the PACT™ and activated sludge systems is the use of a granular activated carbon column before a conventional activated sludge system. GAC columns may in some extreme cases need to be put before activated sludge systems if the toxicity of the feed is too high for the PACT™ system to tolerate (Narbaitz, 1995). However this situation is not common. Sometimes pH adjustment, extraction and oil removal would conceivably also be required.

There are three advantages of the PACT™ system over a GAC column followed by an activated sludge unit. First, if the feed contains biodegradable compounds, substantial microbial growth will occur in the column (Benedek, 1980). Microbial growth can eventually lead to short circuiting and/or dead volume unless there are frequent backwashings, which is expensive. Secondly, with the PACT™ process, lower concentrations of biodegradable compounds will adsorb (adsorption is generally faster than biodegradation (Schultz, 1982)) occupying carbon sites that would otherwise be destined for non - biodegradable compounds (Meidl, 1990; Ying, 1989). Thirdly, the chromatographic effect, is a much greater problem with a GAC column (Hutton, 1981; Meidl, 1990; Grieves et al., 1980).

2.5 PACT™ Process Mechanisms

In order to interpret the results of any PACT™ experiment, knowledge of the potential mechanisms at work is required. It should be remembered that, like the activated sludge process, the main removal mechanism for the PACT™ process is biodegradation. This is evident from the very high BOD_5 removals and somewhat lower COD and TOC removals by PACT™ units, as discussed in Section 2.2.1. The potential mechanism(s) of PAC enhancement of an activated sludge system can be divided into two groups - those operative at steady - state as well as under dynamic conditions and those only operative under dynamic conditions.

2.5.1 Mechanisms Operative Under All Conditions

There are six subgroups of potential mechanisms involved. These include enhanced bioactivity, slow contact degradation, biological regeneration, MEP adsorption, substrate adsorption and improved floc separation.

2.5.1.1 Enhanced Bioactivity

In order to investigate the possibility of enhanced bioactivity existing, oxygen uptake rates (OUR), with and without PAC, have been measured. No increase in OUR was found in parallel activated sludge and PACT™ reactors (Scaramelli and DiGiano, 1973). This result holds even though no correction was made for adsorption of O_2 by activated carbon. Activated carbon has been shown to adsorb O_2 in the range of 10 - 40 g/kg (Prober et al., 1975).

Robertaccio (1976) presumed that enhanced bioactivity exists for both phenol and isopropyl alcohol substrates, however, he did not have direct proof. This result is in disagreement with other studies using a phenol substrate (Schultz, 1982, Nayar and Sylvestor, 1979). Schultz (1982) has offered direct evidence against enhanced bioactivity, for a phenol substrate.

Schultz (1982) has found no increased bioactivity using PACT™ compared to conventional activated sludge, with a phenol substrate. The evolved CO_2, produced from the biodegradation of phenol, which contained radiolabelled carbon, was used as a measure of bioactivity. Another study that used 6 biodegradable compounds, in addition to some classified as non - biodegradable, found no increased removal of the biodegradable compounds, upon addition of 100 mg/L of PAC, at steady - state (Weber et al., 1987).

The strongest evidence against enhanced bioactivity may come from the numerous steady - state continuous flow studies that indicate the PACT™ system shows no significantly increased BOD_5 removal compared to the activated sludge system (see Section 2.2.1). It is unlikely that all the systems involved were underloaded to such an extent that enhanced bioactivity was not evident because of underloading. Such results speak against any form of enhanced bioactivity.

Seven mechanisms have been proposed to explain enhanced bioactivity. The mechanisms proposed in the literature are : 1) concentration enhancement, 2) increased exoenzyme presence, 3) increased mass transfer, 4) toxicity protection, 5) greater diversity of microbes, 6) increased mass of microbes and 7) concentration of oxygen near microbes. Under steady - state conditions, the literature indicates that enhanced bioactivity appears to be unlikely.

2.5.1.1.1 Concentration Enhancement

Concentration enhancement refers to the concentrating of substrate on the carbon surface, such that the bacteria on the surface are exposed to a higher substrate concentration and hence have a higher rate of substrate utilization. This mechanism rests on the fact that the rate of adsorption is generally faster than the rate of biological assimilation (Schultz, 1982). Some of the evidence against concentration enhancement is found in the Enhanced Bioactivity general discussion (Section 2.5.1.1). Furthermore, Benedek (1980) points out, it is more likely for carbon adsorption to decrease the relevant concentration for bacterial attack : the liquid phase concentration. Thus the rate of biodegradation will be slower or the same, as without the activated carbon. Schultz (1982) showed phenol needed to desorb in order for biodegradation to occur, which speaks against the concentration enhancement theory, since the concentration of substrate on the PAC had no enhancement effect.

Most bacteria have diameters of 0.5 μm or more (Brock and Madigan, 1988). Hence, the opportunity for bacteria to colonize the majority of the PAC surface, which is the internal surface, given that PAC pore sizes vary from 0.01 to 0.1 μm (Perrotti and Rodman, 1973), is low.

2.5.1.1.2 Increased Exoenzyme Presence

Enhanced bioactivity may be mediated by the presence of additional exoenzymes on the PAC particles which would not be present in a standard activated sludge system (Benedek, 1980). The argument against increased exoenzyme presence can be found in the Enhanced Bioactivity general discussion (Section 2.5.1.1).

2.5.1.1.3 Increased Mass Transfer

The above discussion of concentration enhancement assumes that the reaction rate is not mass transfer limited, as is often the case with fixed films (Schultz, 1982).

Robertaccio (1976) has claimed to have identified increased mass transfer as one of the explanations for enhanced bioactivity. Since carbon particles adsorb substrate in their vicinity, Robertaccio speculated that a higher concentration gradient is generated, that increases mass transfer into bacteria living on the carbon particle surface. This has been refuted, at least for phenol (Schultz, 1982).

2.5.1.1.4 Toxicity Protection

Although it has been shown that the PACT™ process is better than the activated sludge process in terms of priority pollutant removal at steady - state, it has not been demonstrated that reduced toxicity towards the microbes in the process is a significant cause of these additional removals. Given enough time, bacteria can become not only resilient but capable of degrading many substrates (Brock and Madigan, 1988). For toxins that cannot be degraded resilience can be quite high (Brock and Madigan, 1988). Adsorbed microbes have less area exposed for toxin transport and have less need for basic maintenance energy and therefore more energy available for combating toxin effects. However, if a steady - state process exists, these advantages can be greatly reduced by acclimatization.

The bulk of the evidence against reduced toxicity being an important mechanism, at steady - state, comes from the evidence against enhanced bioactivity in general.

2.5.1.1.5 Greater Diversity of Microbes

Upon addition of a great amount of solid surface, in the form of PAC, it seems clear that the proportion of certain microbes favouring a solid surface for growth would increase. The question is whether this will make a difference in treatment efficiency, in a significant number of cases. Robertaccio (1976) has found that the biological utilization of the adsorbed substrates - phenol and isopropyl alcohol was increased, by the presence of PAC (i.e. enhanced bioactivity), while there was no enhancement for the non-adsorbed substrate, acetic acid. If the advantage of the PACT™ process was derived from a greater diversity of microbes, then why should this advantage be realized for adsorbed substrate but not for non - adsorbed substrate. However, this is circumstantial evidence and cannot stand alone.

Further limited evidence against increased diversity of microbes associated with an aerobic stationary fixed film compared to conventional activated sludge comes from a study treating paper manufacturing (no pulping or bleaching on site) wastewater via the Acticontact Process (Fein et al., 1993). The Acticontact process is an aerobic process involving an upflow packed bed biofilter operating in the plug flow mode. The species diversity of the macroflora and microflora were found to be similar to that found in a well-run activated sludge system. No comment on the relative numbers of the species present was made. Furthermore, how specific these results are to the wastewater and other operating conditions, is unknown.

Additional arguments against this potential mechanism, for specific pollutants, can be found in the Enhanced Bioactivity general discussion.

2.5.1.1.6 Increased Mass of Microbes

There is evidence for (Kalinske, 1972) and against (Scaramelli and DiGiano, 1973; DeWalle and Chian, 1977) increased biomass with the addition of carbon to an activated sludge system. The data for either case is within the coefficient of variation of TSS measurements, i.e. 10% (Schultz, 1982).

2.5.1.1.7 Concentration of Oxygen

It appears that oxygen is chemisorbed on PAC (AWWA Committee Report, 1981), and hence, is not available for utilization even when and where oxygen is limiting. In one study, only 5% of adsorbed oxygen could be desorbed (Prober et al., 1975). Hence, if oxygen and PAC interact, the interaction is not likely to favor enhanced bioactivity.

The above discussion demonstrates the lack of importance of the enhanced bioactivity mechanism, during steady - state periods, in increased performance by the PACT™ process. However, there may be cases when the reduction of toxicity below a critical level can occur, with the addition of PAC, to an activated sludge system. Five other possible mechanisms, slow contact degradation, biological regeneration, MEP adsorption, substrate adsorption and improved floc separation are discussed below.

2.5.1.2 Slow Contact Degradation

This mechanism as explained by Flynn (1975) involves the degradation of recalcitrant compounds by virtue of bacteria being exposed to them, for extended periods.

No conceptual explanations of this mechanism have been proposed (Schultz, 1982), thus it is difficult to evaluate.

2.5.1.3 Biological Regeneration

At steady - state, biological regeneration of carbon is not possible since there is no net driving force away from the carbon, which would permit desorption. However, this is not the case under unsteady - state conditions. Practical (but not absolute) steady - state often does exist.

2.5.1.4 MEP Adsorption

Metabolic end products (MEPs) include glycocalyx polysaccharides, polypeptides, remnants of dead cells, and metabolites. Studies have shown that MEP can be the major component of activated sludge effluent (Kim et al., 1976; Daigger and Grady, 1977). Thus the adsorption of MEP may be a mechanism responsible for the higher COD and TOC removals by PACT™ systems. Residual organics from a simple substrate feed can be quite recalcitrant to biodegradation; 75 % resistance, at an SRT of 30 days, has been found (Schultz, 1982). The capacity of activated carbon to adsorb MEPs appears to vary. Using single carbon doses and simple degradable substrates, one study found 16 - 40 % MEPs adsorption (Martin and Iwugo, 1980) and another 75% MEPs adsorption (Schultz, 1982). Also, Schultz found that although 20% of the non - adsorbed MEP could be degraded only 4% of the adsorbed MEP was degraded. Hence bioregeneration of adsorbed MEP, under dynamic conditions, may not be significant. However, MEP adsorption and its subsequent removal during sludge wasting is a valid mechanism for the enhanced performance of PACT™ systems. However, competitive adsorption with MEP may lead to less substrate (from the influent) adsorption (Narbaitz, 1995).

Two studies have shown that adsorbability (tendency to adsorb) of MEP increased as SRT increased (Kim et al., 1976; Dewalle et al., 1977).

Lee et al. (1989) demonstrated some possible mechanisms for increased pollutant removal offered by the use of PAC. Two lab scale, completely mixed, continuous-flow reactors with internal recycle were run, at 4, 7 and 10 days SRT with 15 mg/L Cr(VI) in the influent; the HRT was 11 hours and the carbon dose 0.2 g/L. Steady - state data were generated. The glucose used for COD loading is negligibly adsorbed by PAC (Dewalle et al., 1977). The PACT™ system was found to provide 96 % COD removal efficiency compared to 85 % for the activated sludge control, possibly due to MEP adsorption. Furthermore, as the sludge age was increased from 4 to 10 days, the control showed either small or no improvement in Cr(VI) removal while the PACT™ reactor showed an increase in efficiency from 24 % to 41 %. The authors explained the Cr(VI) removals by the greater PAC concentration and hence greater adsorption, at the higher sludge ages. The yield coefficient and maximum substrate removal constant increased with the presence of PAC.

2.5.1.5 Increased Adsorbable Substrate Removal

Adsorption onto activated carbon and removal via wasting may be a factor for biodegradable and/or non - biodegradable substrate. At a given organic loading and SRT, a system's biodegradation capacity may be insufficient to remove all the biodegradable substrate, in which case the PAC may serve to remove some of it. For biodegradable substrate, this is likely a minor removal mechanism (Benedek, 1980). Though adsorption is usually faster than biodegradation (Schultz, 1982), the biodegradable substrate concentration in the effluent is low therefore the biodegradable substrate adsorbed onto PAC is expected to be low (Benedek, 1980). However, this will depend on the substrate's affinity to the particular PAC (Narbaitz, 1995). The contribution of irreversibly PAC adsorbed substrate will depend on the adsorbent and adsorbate.

2.5.1.6 Better Floc Separation

It is expected that flocs that include PAC particles will be denser than those without PAC, so they should settle faster and thicken more. No examples of superior performance by the PACT™ system over the activated sludge system could be clearly identified as being solely attributable to better floc separation. However, there may be some cases when this occurs since lower SVIs and higher secondary clarifier solids loading rates can be attained with the PACT™ system (Meidl, 1990; Meidl, 1982). However, solids loss in the effluent may be greater due to loss of PAC particles that have not been colonized by bacteria. Additionally, increased anoxic conditions in some parts of the secondary clarifier, as a result of increased solids content, may lead to denitrification and rising sludge in some cases. This might result in poorer treatment than a corresponding activated sludge system. However, there have been no such observations reported.

2.5.2 Mechanisms Operative Under Dynamic Conditions Only

In addition to the mechanisms found to be reasonable above, under dynamic conditions, biological regeneration becomes more important. Numerous batch studies, which are necessarily unsteady - state, investigated biological regeneration. Schultz (1982) has found complete desorption of phenol from PAC (Westvaco Nuchar SA - 15), with associated bioregeneration. The degree to which desorption is possible depends on the activated carbon source and the adsorbate, as some compounds adsorb irreversibly, in some sites (Narbaitz, 1995).

Other work with phenol pre-loaded carbon has shown regeneration (Benedek, 1980). This was indicated by greater total oxygen consumption, up until the point of substrate limitation in the oxygen consumption curve, in the flask containing PAC compared to the flask lacking PAC. The initial liquid phase concentrations were equal. Fifty percent bioregeneration of PAC was found in this case. Robertaccio (1976) used repeated feeding to show complete regeneration of carbon using phenol. Hence biological regeneration would appear to be a reasonable concept, under dynamic conditions, when the liquid phase concentration is allowed to drop below adsorption equilibrium concentration.

Toxicity protection becomes much more important under unsteady - state conditions, for example, with the use of an unacclimated microbial population. It has been shown that pulse addition of PAC allowed for continued operation of a continuous reactor even during shock loading of 1000 mg/l phenol. Without PAC, it was shown the reactor would fail (Nayar and Sylvestor, 1979).

Ng and Stenstrom (1987) examined possible mechanisms for enhanced nitrification, in a batch study, for a PACT™ system compared to an activated sludge system. Adsorbable and non - adsorbable nitrification inhibitors were tested with an unacclimated sludge. Decreased inhibition of nitrification was noted after addition of 0.5 - 4 g/L PAC for the adsorbable inhibitors (Ng and Stenstrom, 1987). Since the decreased inhibition occurred after 1 - 2 hours, enhanced nitrifier growth, concentration of trace nutrients on the surface of the PAC and heterotroph acclimatization were ruled out as the possible mechanisms for the observed enhanced nitrification. Furthermore, since decreased inhibition was a function of PAC dose, for adsorbable inhibitors only, enhanced nitrifier growth and concentration of trace nutrients on the PAC are unlikely. Additionally, since adsorbed trace nutrients are not available to the microbes until desorption, little enhancement should be expected due to any adsorption of trace nutrients. The adsorption of adsorbable inhibitors was found to be the reason for the increased nitrification in the PACT™ system. Higher PAC doses showed greater improvement. Furthermore, there appeared to be a critical PAC dose, corresponding to a critical inhibitor concentration, above which the inhibition decreased at a high rate.

Also, adsorption of substrate and removal with the PAC may become more important under shock loads. However, it may also become less important when the feed concentration decreases and biological regeneration increases in importance.

2.5.3 Conclusions about Potential Mechanisms

The main organic removal mechanism in the PACT™ process is biodegradation. Two additional mechanisms are likely to be important, in continuous flow units under steady - state conditions : substrate adsorption and MEP adsorption. Bleached kraft mill effluent (BKME) contains many biorefractory compounds and hence adsorption of these compounds will probably be significant. However, enhanced bioactivity may also be important. Since real wastewater treatment systems do not operate under steady - state conditions, bioregeneration and toxicity protection are possible significant mechanisms for yielding better performance of the PACT™ process compared to the activated sludge process.

2.6 Modelling of the PACT™ Process

There have been numerous attempts at modelling the PACT™ process. Five models will be discussed here - the Garcia - Orozco model, the O'Brien model, Robertaccio's model, an enhanced apparent rate constant model and an enhanced effluent quality model. The Flynn model (1975) is not discussed, since no explanation for it's underlying concept, is available (Schultz, 1982).

2.6.1 The Garcia-Orozco Approach

Twenty litre continuous flow, complete-mixed reactors were used in a steady - state study by Garcia-Orozco et al. (1986). The synthetic wastewater was composed of dextrose, peptone and 4,6 dinitro-o-cresol (DNOC). The removals of both TOC and DNOC, a U.S. EPA priority pollutant, were modelled. Although acetone was used to dissolve DNOC, its contribution was minimized, by the experimental conditions. TOC and DNOC stripping were assumed to be essentially zero.

The general equation used for the TOC rate of removal by biodegradation was

$$R_{gb} = K_{gb}X\left(\left(S_{ge} / S_{go}\right) - y\right)^{n} \qquad \textbf{2-5}$$

where R_{gb} is the rate of biodegradation (mg TOC/(L*hour)), K_{gb} is the biodegradation rate coefficient (mg TOC/(mg VSS*L*hour), S_{ge} is the effluent TOC concentration (mg TOC/L), S_{g0} is the influent TOC concentration (mg TOC/L), y is the non - biodegradable fraction in the effluent, n is an empirical constant and X is the average biomass concentration (mg VSS/L). It was not stated whether the VSS concentration included the PAC concentration. The increase in biodegradable TOC removal of the PACT™ system, Δs (mg/L), was assumed to be given by:

$$\Delta s = \frac{\alpha C_D{}^{\beta}}{SRT^{\gamma}} \qquad \textbf{2-6}$$

where C_D is the PAC dose (mg PAC/L feed) , α, β and γ are empirical constants and SRT is the solids retention time (d). This assumes that the PACT™ and activated sludge systems, were equivalent in terms of an increase in biodegradable TOC removal, as the sludge age approaches infinity.

The above approach also allows for the calculation of the non - biodegradable fraction, y, which was assumed to vary with the amount of PAC present. This was done by assuming n = 1 at low S_{ge}/S_{go}, in equation 2-5. By plotting R_{gb}/X against S_{ge}/S_{go} - y, K_{gb} and y can be found, from the slope and intercept. The non - biodegradable fraction could have been modelled as a constant. If this fraction was assumed to be constant, it could have been found from a proper control experiment. The biodegradation rate coefficient was also assumed to vary with the carbon dose. The steady -state mass balance was given as follows:

$$F\left(S_{go} - S_{ge}\right) = VR_{gb} + Fq\ C_D \qquad \text{2-7}$$

where F_h is the flowrate (L/hour), V is the volume of the reactor (L) and q is the carbon adsorption capacity for the TOC (mg TOC/mg PAC). The value of q was estimated (method unknown) and was neglected. The assumption of a negligible q did not consider MEP adsorption and hence may be invalid.

The fit was quite good for the two carbon doses investigated (70 mg/L and 175 mg/L), however only four points at four different sludge ages were used. Since these are the same four points used to calibrate the model this exercise amounts to simulation. In Figure 2-5, the lines represent the model.

The method used for the modelling of the DNOC removal utilized equation 2-7 with $R_{gbn} = K_{bn}X$ (i.e. zero order), where R_{gbn} is the rate of DNOC biodegradation (mg DNOC/(L*hour)) and K_{bn} is the DNOC biodegradation rate coefficient (mg DNOC/(mg VSS*L*hour)). This is not unexpected for a compound present in small quantities compared to the total substrate and where toxicity was determined not to be a factor, at the concentrations present. This is because the reaction order is based on the total substrate. The presence of PAC was assumed not to affect the biodegradation rate of DNOC.

The removal due to adsorption was given as $Fq_{DNOC}\ C_D$, where q_{DNOC} is the adsorption capacity for DNOC (mg DNOC/mg PAC), which is reasonable assuming adsorption equilibrium is attained. It should be stressed that equilibrium may not be attained for compounds which adsorb very slowly. However, within 8 hours, at least 70 % of the equilibrium capacity of most synthetic organic compounds will be attained (Narbaitz, 1995). If the variety and proportion of non - biodegradable compounds does not change significantly over the SRT, HRT and C_D ranges used, then a pseudo q (representing a fraction of the equilibrium q) may be relatively constant over the operating condition ranges used.

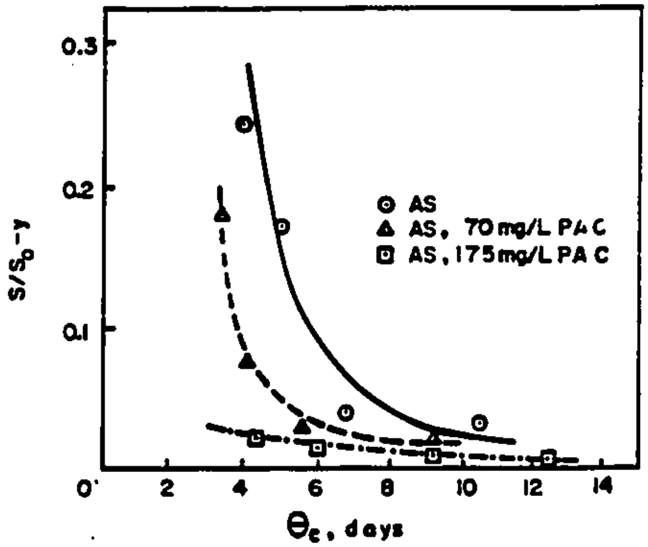

Figure 2-5: Garcia-Orozco Model Fit for 4 SRTs and 3 Carbon Doses (Including 0) (after Garcia - Orozco et al., 1986)

2.6.2 The O'Brien Model

This model for a completely mixed system assumes first order removal by stripping, biodegradation and carbon adsorption, with biosorption being lumped into biodegradation (O'Brien, 1992). The model was developed using three reactors; one in which only stripping occurred, one in which biodegradation and stripping occurred and one in which carbon adsorption and stripping occurred. The model was calibrated for analysis of 18 specific compounds which are U.S. EPA priority pollutants. The feed was wastewater from the DuPont chemical manufacturing facility, Chambers Works, spiked with 18 priority pollutants.

Specifically, the removal rate expressions are:

$$R_{OBs} = K_{OBs} S_e V \tag{2-8}$$

$$R_{OBb} = K_{OBb} S_e X V \tag{2-9}$$

$$R_{OBa} = K_{OBa} S_e * MLCSS * V \tag{2-10}$$

where R_{OBs} is the stripping rate (mg compound/day), R_{OBb} is the biodegradation rate (mg compound/day), R_{OBa} is the PAC adsorption rate (mg compound/day), K_{OBs} is the stripping constant (day^{-1}), K_{OBb} the biodegradation constant (L*mg VSS^{-1}*day^{-1}), K_{OBa} the carbon adsorption kinetic coefficient (L*mg PAC^{-1}*day^{-1}), V the volume (L), X the mixed liquor biomass volatile suspended solids (VSS) concentration (mg VSS/L), S_e the effluent and reactor concentration of the compound of interest (mg compound/L) and MLCSS is the mixed liquor powdered activated carbon (PAC) concentration (mg PAC/L).

The steady - state mass balance equation is

$$(FS_i - FS_e) - R_{OBs} - R_{OBb} - R_{OBa} = 0 \tag{2-11}$$

where F is the flowrate (L/d), S_i is the influent concentration (mg compound/L). Upon substitution of equations 2-8, 2-9 and 2-10 into equation 2-11, the following is arrived at

$$(FS_i - FS_e) - K_{OHs} S_e V - K_{OHb} S_e X V - K_{OBa} * MLCSS * S_e V = 0 \qquad \textbf{2-12}$$

Hence the relevant design equation is

$$S_e = \frac{S_i}{1 + K_{OHs} * \Theta + K_{OHb} * X * \Theta + K_{OBa} * SRT * C_D} \qquad \textbf{2-13}$$

where Θ is the hydraulic retention time (days) and SRT is the solids retention time (days).

Problems with the evaluation of the stripping coefficient have been pointed out by Kuo and Hashman (1994). The observed stripping was shown to be greater than the theoretical calculated value for many of the compounds studied. This was attributed to possible errors in the experimental setup, including insufficient time allowed for dissolution of compounds and an increase in temperature from the location of spiking of compounds to the stripping tank.

Kuo and Hashman (1994) also pointed out that another expression for adsorption is FC_Dq, where F is the flowrate (L/d), C_D is the activated carbon dose (mg/L feed) and q is the assumed equilibrium loading on the PAC (mg compound/mg PAC). If the analyte concentration is low and the isotherm is linear, as assumed by O'Brien, then

$$q = K'_A S_e \qquad \textbf{2-14}$$

where K_A' is the Freundlich model constant for a linear isotherm (L/mg PAC). Equation 2-14 is the Freundlich relationship with an exponent of one. Hence, the following mass flow is arrived at

$$R_{OBa} = K_A' S_e F C_D \tag{2-15}$$

rather than the rate based expression

$$R_{OBa} = K_{OBa} S_e * MLCSS * V \tag{2-10}$$

where K_A' is an equilibrium constant (L/mg PAC) and K_{OBa} is a rate constant ($L*mg^{-1}*day^{-1}$). When using PAC dose, as in equation 2-15, the associated volume element should therefore be the flowrate, in order to have a rate term. This steady - state expression is in agreement with that used in another source (Weber et al., 1987). The active sites added in the PAC dose are occupied by the time of the next carbon dosing, at steady - state.

If equilibrium were not established or close to being established, in the lowest SRT used, then the free accessible active sites will not be the same for a given C_D and different SRTs. It should also be remembered that MLCSS active site concentration will change with the HRT, SRT and carbon dose. Therefore a single proportionality factor, K_{OBa} in O'Brien's model, may not properly account for adsorption.

It has been shown by Robertaccio (1976) that carbon in the PACT™ process may be colonized to approximately the same extent, despite that the PAC to biomass ratio ranged from 0.5 to 7.8. The question of carbon active site distribution changing with time

(SRT) spent in the reactor by virtue of differential colonization should be addressed. A higher SRT may increase colonization. SRT may also have an effect on the inherent adsorbability of cell fragments, which are part of MEPs, with a higher SRT increasing adsorbability (Kim et al., 1976). Given that SRT and MEP adsorbability may be related, the use of SRT in an adsorption expression is a possibility. Additionally, a reduction in active adsorption sites, by this mechanism, may be considered a hindrance to desired adsorption of some influent compounds, through competition with MEPs. Hence the effect of SRT on adsorption should be divided into an effect on MEPs adsorption and an effect on influent compound adsorption.

The method of incorporation of biosorption into the same expression for biodegradation might have been inherently incorrect, because the two removal mechanisms have different forms. The form of the biodegradation rate proposed by O'Brien is given below :

$$R_{OBb} = K_{OBb} S_e X V \qquad \textbf{2-16}$$

while the form of the biosorption rate should be similar to that of carbon adsorption rate to give

$$R_{BS} = K_p S_e X F_w \qquad \textbf{2-17}$$

(from Weber et al., 1987), where R_{BS} has units of mg/d, F_w is the wasting flow from the aeration basin (L mixed liquor/day) and K_p is the biosorption equilibrium constant (L/mg

VSS). F_w is independent of V. However, it has been shown that biosorption is usually small compared to carbon adsorption, which may mask the error (Weber et al., 1987).

The general method O'Brien used to generate the model parameters, independent of the above concerns, is also problematic. The stripping coefficient was evaluated first and assumed not to vary when biodegradation and/or adsorption was present. However K_s is dependent on Henry's law coefficient, as well as surface tension, bubble size, aeration air flowrate and temperature (Kuo and Hashman, 1994). Surface tension and bubble size might be affected by the presence of biomass and/or PAC. These effects, however, may be minor.

Another paper also demonstrated the use of a separately calculated stripping coefficient, in order to calculate the biodegradation factor, by linear regression (Weber et al., 1987). Perhaps this simplification did not introduce much error if there was little interaction between the biodegradation and stripping coefficients. This should not be confused with interaction between the stripping and biodegradation mechanisms which is probably more significant.

O'Brien (1992) also evaluated the biodegradation coefficient separately from the adsorption coefficient, but both in the presence of stripping. The model generated was checked against the PACT™ reactor, operating at the same conditions and receiving the same feed. Any disagreement between the actual PACT™ reactor and the model prediction removal results was assumed to be due to toxicity protection offered by the PAC being present. This was corrected for by modifying the adsorption coefficient. This is partially data fitting since the adsorption and biodegradation rates are of different forms. The model parameters are best evaluated simultaneously using nonlinear regression.

Additionally, the feed and operating conditions were the same in the PACT™ reactor used to test the model and the reactors used to calibrate the model. Ideally, the model should have been tested using conditions fairly different than those used for its calibration. The criteria used to assess goodness of fit was that the difference between the experimental data and the model data was within one standard deviation of the spread of the experimental values for that data point. This may be a poor criterion, especially if the experimental and analytical variations are large.

Two of the compounds could only be evaluated on a greater than removal basis, because the effluent concentrations were below their analytical detection limits (Table 2-4). The removals were close to 100% for most of the compounds which makes validation of the model structure difficult. Models are not very sensitive at these high percentage removals.

Compound	Predicted % Removal	Actual % Removal
1,2 - dichloroethane	89.7	97.7
chloroethane	96.9	97.5
chloromethane	97.8	96.8
chloroform	94.3	87.6
methylene chloride	92.5	85.9
chlorobenzene	96.9	96.5
toluene	99.1	97.8
ethyl benzene	97.6	97.5
xylenes	93.4	96.3
benzene	97.7	97.6
1,2 - dichlorobenzene	95.0	99.2
phenol	99.5	>99.0
4 - nitrophenol	99.0	99.5
2 - nitrophenol	98.9	90.6
2,4 - dinitrotoluene	99.0	97.2
2,6 - dinitrotoluene	84.0	92.4
nitrobenzene	99.6	99.9
naphthalene	96.9	>97.0
4,6 - dinitro-o-cresol	80.6	83.0

Table 2-4: Comparison of Predicted Removals and Actual Removals using the O'Brien PACT™ system Model, for Dupont's Chambers Works Feed (after O'Brien, 1992)

2.6.3 Robertaccio's Model

This model was developed and tested using batch experiments with three substrates (acetic acid, isopropyl alcohol and phenol) individually and together (Robertaccio, 1976).

The model used Monod kinetics, Freundlich isotherms and a rate of adsorption term of the form:

$$r_{Ra} = K_{Ra}\left(S^{*}_{Re} - S_{Re}\right)C_D \qquad \textbf{2-18}$$

where r_{Ra} has the units mg/(L*d), K_{Ra} is the adsorption rate constant (L*mg PAC^{-1}*d^{-1}), S_{Re}^{*} is the equilibrium amount of substrate adsorbed expressed as solution concentration (mg TOC/L), S_{Re} is the weight of substrate adsorbed at any time, expressed as solution concentration (mg/L) and C_D is the PAC dose (mg PAC/L feed). A concept of pseudo concentration was used. Pseudo concentration was defined as the sum of the actual concentration in solution and the concentration that would result if the adsorbed substrate were in solution. Adsorption equilibrium was assumed to be fast and hence the adsorbed substrate was determined by measuring the solution concentration. Hence the determination of a rate constant is not required for this term. The maximum substrate utilization rate was assumed to be linearly related to the effective PAC dose.

$$k_R = k_{bio} + \alpha_R M_e \qquad \textbf{2-19}$$

where k_{bio} is the maximum substrate utilization in the activated sludge controls (mg TOC/(mg VSS * d); M_e is the effective carbon dose, which was found to be about 70% of the carbon dose (mg PAC/L feed), due to blockage of PAC active sites by biomass; α_R is a proportionality constant (mg TOC * L/(mg VSS * mg PAC * d)); and k_R is the maximum substrate utilization in the PACT™ systems. It is important to point out that k_R and k_{bio} are with respect to pseudo concentration. This model states that the biodegradation rate is increased by the presence of the carbon.

Two rate equations were used for substrate utilization. The first is:

$$\frac{dS_p}{dt} = -k_{bio}X_t \qquad \textbf{2-20}$$

where S_p is the pseudo concentration or the equivalent solution concentration of the amount of substrate in the system, at any time (mg TOC/L) and X_t is the VSS concentration at any time in the batch test (mg VSS/L mixed liquor). The above equation arises from the Monod model assuming the substrate concentration is much greater than that yielding the half maximum rate.

An autocatalytic reaction (in which the product of the reaction, microbes, serve as catalyst for the reaction) assumption leads to the following equation

$$\frac{dS_p}{S_{p,0}dt} = \hat{k_{bio}}X_t \qquad \textbf{2-21}$$

where $S_{p,0}$ is the pseudo concentration, at time zero (mg TOC/L) and $\hat{k_{bio}}$ is a modified biodegradation constant, $k_{bio}/S_{p,0}$ (L/(mg VSS * d)).

Using equation 2-19, 2-20, the definition of pseudo concentration and a temperature correction factor, the following equation can be derived

$$S_{p,t} = S_{s,0} + M_e k_1 S_{s,0}^{1/k_2} + \left[1 - e^{\left\{(k_{bio}+\alpha_R M_e)\Theta^{T-20} Y t\right\}}\right]\frac{X_0}{Y} \qquad \textbf{2-22}$$

Using equation 2-21, Robertaccio arrived at the following equation

$$S_{p,t} = S_{s,0} + M_e k_1 S_{s,0}^{1/k_2} + \left[1 - e^{\left\{S_{p,0}\left(\hat{k}_{bio} + \alpha_R'' M_e\right)\Theta^{T-20} Y t\right\}}\right]\frac{X_0}{Y} \qquad \text{2-23}$$

where $S_{p,t}$ is the pseudo concentration at time t (mg TOC/L), $S_{p,0}$ is the pseudo concentration at time 0, $S_{s,0}$ is the dissolved concentration at time 0 (mg TOC/L), α_R" is a modified enhancement coefficient, equal to $\alpha_R/S_{p,0}$ (L^2/(mg VSS * mg PAC * d)), X_0 is the biomass concentration at time zero (mg VSS/L mixed liquor); t is the time of the test (d); Θ is the temperature coefficient, k_1 is a Freundlich constant, $1/k_2$ is a Freundlich exponent; and Y is the yield coefficient (mg VSS/mg substrate).

The model prediction of solution and pseudo concentrations for the adsorbable substrates - isopropyl alcohol and phenol, using the model, were quite good. The model predictions using the phenol substrate are shown in Figure 2-6. A large data set was used to calibrate the model, while the data points in Figure 2-6 represent a small portion of the observed data. The calibration and verification data sets should have been different.

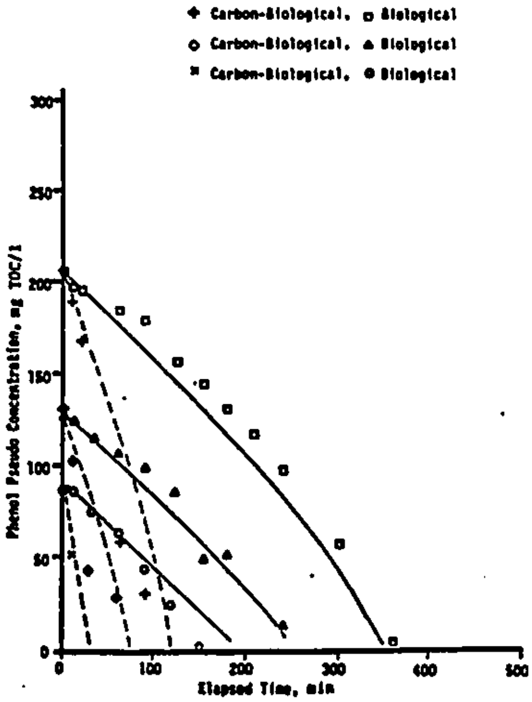

Figure 2-6: Model Predictions of the Rate of Phenol Disappearance (model is shown as lines) (after Robertaccio, 1976)

If adsorption equilibrium is fast or relatively fast, the good model predictions would not be surprising. Whether the good predictions would be obtained for longer time periods of colonization of the PAC is unknown. Competition with MEP for adsorption sites could limit the model's predictive ability, under other conditions. No explanation was offered as to why acetic acid, the non - adsorbable substrate, was not predicted well.

The assumption of linear enhancement of the substrate utilization rate constant (equation 2-19) with increasing effective carbon dose was statistically verified for the phenol data. There was insufficient data to conduct a statistical analysis for the other substrates. Given that this is a single compound and verification, under different operating conditions and/or using different compounds was not carried out, the validity of this part of the model would seem to be debatable.

This model rests on the concept of enhanced bioactivity. The author suggested an altered microbial population as the specific form of enhanced bioactivity. However, the data presented did not rule out the possibility of reduced toxicity.

2.6.4 An Enhanced Apparent Rate Constant Model

This model was developed using an aggregate measure of waste strength, TOC (Hamoda and Fahim, 1984) and data from batch testing. The feed was primary municipal effluent. The following rate equation was used:

$$S_e = S_i e^{-K_{AP} t} \qquad \textbf{2-24}$$

where S_e is the TOC concentration (mg C/L) after time t (d), S_i is the TOC concentration at time zero and K_{AP} is the apparent first order rate constant (d^{-1}), with carbon present. Based on their experiments, the following empirical relationship was found

$$K_{AP} = K_{BD}(1 + m * MLCSS) \qquad \textbf{2-25}$$

where MLCSS is the charcoal adsorbent concentration of mixed liquor (mg PAC/L), K_{BD} is the first order biodegradation rate constant (d^{-1}) and m is a proportionality constant (L/mg PAC). This relationship is HRT and SRT dependent, so MLCSS could be replaced with the carbon dose (see equation 2-4). Four points were used in the fitting of the model. It was noted that the model was verified using another data set.

When the adsorbent concentration is zero, equation 2-24 reduces to

$$S_e = S_0 e^{-K_{BD}t} \qquad \textbf{2-26}$$

This equation does not consider non - biodegradable TOC. S_e and S_0 should be S_e - NB and S_0 - NB, where NB is the non - biodegradable TOC (mg C/L)

Unlike Robertaccio's model, the rate constants are with respect to the soluble phase. Adsorption of non - biodegradable substances and/or reduced toxicity were offered as explanations for the high apparent rate constant, which are reasonable.

2.6.5 An Enhanced Effluent Quality Model

Another model was developed by Lankford and Miller (1987), using continuous flow lab - scale reactors with internal and external recycle, treating a complex chemical wastewater. Organics were measured in terms of TOC. The proposed relationship is

$$S_e = S_b e^{(-k_i C_D)} \qquad \textbf{2-27}$$

where S_e is the effluent TOC concentration from the PACT™ reactor (mg C/L), S_b is the effluent TOC concentration from the activated sludge control (mg C/L), C_D is the carbon dose (mg PAC/L feed), and k_i is termed the adsorption constant (L/mg PAC) (its value is carbon and substrate dependent). This relationship allows for the prediction of the carbon dose required to bring the effluent concentration to a given value. The model did very well in predicting the performance of a PACT™ reactor based on the performance of a parallel activated sludge control (Figure 2-7).

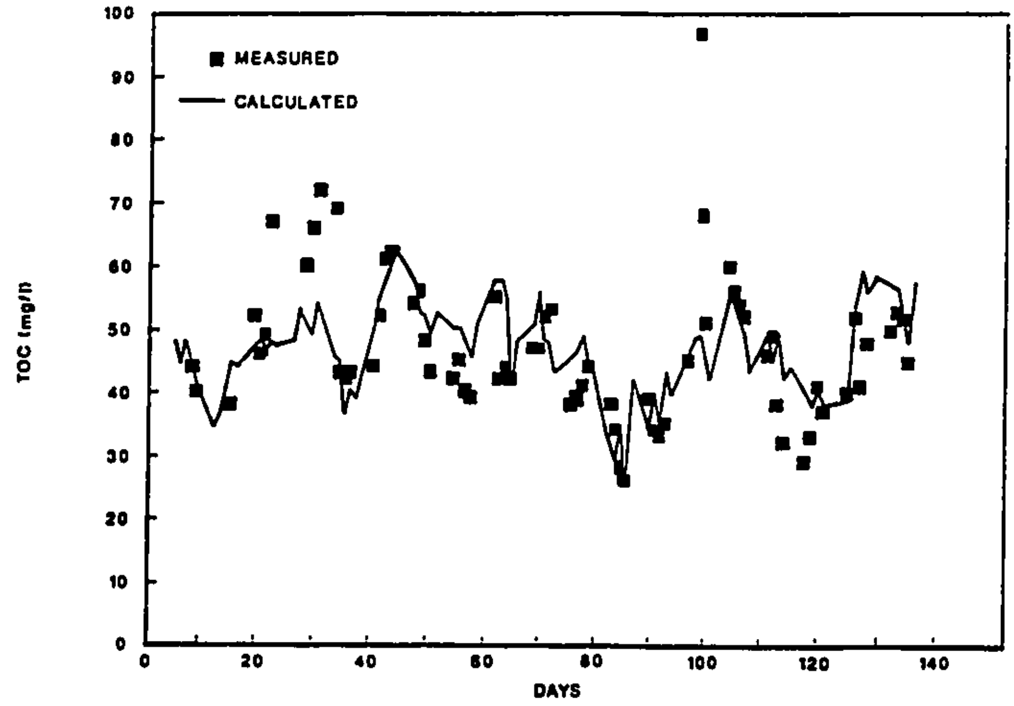

Figure 2-7: Measured and Calculated Data for a PACT™ Reactor using the Enhanced Effluent Quality Model (Model is shown as a line) (after Lankford and Miller, 1987)

The gross adsorption of MEP and/or influent compounds, exclusive of other possible dependent mechanisms, is a possible explanation for such a model having a good predictive ability.

2.7 Treatment of Kraft Pulp Mill Wastewater

2.7.1 Introduction

Pulping, or the separation of wood into individual fibers suitable for paper making, can be done mechanically, chemically or a combination of the two. Kraft pulping is the dominant chemical pulping process in Ontario and the rest of the world (McCubbin Consultants, 1992). The fibers produced from this process are long and therefore have high strength. Most of this pulp is bleached, with Cl_2 or ClO_2, to produce a high quality paper. Since some lignin remains with the fibers, after the pulping, many toxic, persistent and bioaccumulative organochlorine compounds (often measured as AOX) are formed during bleaching of the fibers. Some typical characteristics of bleached kraft mill effluent (BKME) are shown in Table 2-5; $TBOD_5$ is total BOD_5, TCOD is total COD, DOC is dissolved organic carbon and TAOX is total adsorbable organic halides.

Parameter	Mean	Range
$TBOD_5$	255 mg O_2/L	124 - 453 mg O_2/L
TCOD	685 mg O_2/L	628 - 742 mg O_2/L
DOC	390 mg C/L	178 - 850 mg C/L
TAOX	-	21 - 152 mg Cl/L

Table 2-5: Some General Characteristics of BKME

2.7.2 Traditional Biological Treatment

Biological treatment of pulp mill wastewaters usually involves one or more of the following processes - activated sludge systems, aerobic stabilization basins and facultative stabilization basins. Anaerobic/aerobic lagoon combinations have been used, as well.

2.7.2.1 Typical COD, BOD$_5$ and DOC Data for BKME

TBOD$_5$ for BKME has been found to vary between 124 and 453 mg O$_2$/L (Haberl et al., 1991, Cecen et al., 1992, Oleszkiewicz et al., 1992). Conventional biological treatment of BKME generally yields 90 %+ TBOD$_5$ and 5 day soluble biochemical oxygen demand (SBOD$_5$) removals (Haberl et al., 1991, Cecen et al., 1992, Tomar and Allen, 1991). Typical TCOD in BKME is in the range of 628 - 742 mg O$_2$/L (Randle et al., 1991; Hall and Randle, 1992 and Haberl et al., 1991). TCOD removals for BKME usually do not exceed 50 - 60 % (Haberl et al., 1991; Cecen et al., 1992; Randle et al., 1991 and Hall and Randle, 1992). One study found no trend with respect to SRT between 5 and 15 days or temperature between 10 and 25 °C and TCOD removal (Randle et al., 1991). SCOD measurements, in the literature, are somewhat lacking.

The DOC of BKME has been found to vary between 178 and 850 mg C/L, with a mean of about 390 mg C/L. DOC removals for BKME, using aerated lagoons and activated sludge systems, are usually 33 % or less (Cecen et al., 1992, Tomar and Allen, 1991, Oleszkiewicz et al., 1992) but a study of an activated sludge system found removals of 49 % (Jokela et al., 1993).

2.7.2.2 Typical AOX Removals

Stricter regulations with respect to AOX discharges has led to a focusing of much of the research on AOX removal.

Typical AOX concentrations in BKME are in the range 21 - 152 mg Cl/L (Gergov et al., 1988; Tomar and Allen, 1991; Hall and Randle, 1992; Randle et al., 1991; Jokela et al., 1993 and Haberl et al., 1991). The treatment efficiencies with respect to total AOX for activated sludge range from 19 to 65 %, but are generally between 30 and 65 % (Gergov et al., 1988; Jokela et al., 1993; Hall and Randle, 1992; Randle et al., 1991; Haberl et al., 1991 and Saunamaki et al., 1991). This corresponds to effluents with a range of AOX of 11.7 - 81.5 mg Cl/L. Lagoons generally achieve somewhat lower total AOX removals, between 10 and 50 % (Gergov et al., 1988; Tomar and Allen, 1991; Hall and Randle, 1992; Randle et al., 1991 and Bryant et al., 1987).

Jokela et al. (1993) found better total AOX removal (58 - 66 % AOX removal) with a lab scale anaerobic/aerobic lagoon combination compared to activated sludge plants (19 -55 %). However, given that the mills associated with these treatment systems were quite different, including different feeds and bleach sequences, the above comparisons are not direct comparisons of performance.

2.7.2.3 AOX Removal Mechanisms

There appears to be no agreement on which mechanisms have the most influence on AOX removal. In one lab - scale study treating simulated BKME, a facultative stabilization basin (FSB) and an aerobic stabilization basin (ASB) yielded total median

AOX removals of 43% and 40% respectively while A.S. only had a 22% removal efficiency (Hall and Randle, 1992). SRT was varied from 5 to 15 days. It was concluded that the difference could be attributed to the higher HRT of the ASB and FSB.

This study demonstrated that the biosorption step was not as important as others have thought (Bryant et al., 1988). This was indicated by the poor AOX removals by the activated sludge process, despite the higher sludge wastage rate compared to the ASB and the FSB. No more than 5 % of the AOX removed was by adsorption onto sludge (Hall and Randle, 1992). In addition, it was found that an anaerobic zone, not present in the ASB, was unnecessary for AOX removal, contrary to other research (Bryant et al., 1987). Hall and Randle (1992) found that the volatilized AOX was 0.5 % of influent AOX. Another study also showed low purgeable AOX, 3 - 8 % (Bryant et al., 1987).

Randle et al. (1991) treated simulated BKME with an activated sludge system, a facultative stabilization pond and an aerobic stabilization basin. They found less than 10 % of the AOX was bound to the sludge, 1 % volatilized and 67 - 96 % biodegraded. Another study, using an aerated stabilization pond, with 7 days HRT, for treating pre - settled BKME, also showed biological activity to be the major removal mechanism for AOX (Tomar and Allen, 1991).

Oleszkiewicz et al. (1992) studied BKME wastewater treatment via seven different treatment trains consisting of an aerated lagoon followed by either an aerobic sequencing batch reactor (SBR) or another aerated lagoon of HRT 1.5 days. Each train ended with a 1.5 day HRT facultative lagoon. AOX removals, across the whole process trains, ranged from 21 to 30 %. Biodegradation was found to be the predominant mechanism of AOX removal. Oleszkiewicz et al. (1992) claimed that biosorption was a significant mechanism of removal, although it was not quantified. Two pairs of reactors were compared, two at 10 days SRT and two at 40 days SRT. Of each pair, one had a lower HRT than the other. The lower HRT systems showed better removals. This points to adsorption onto wastage sludge as an important removal mechanism.

Stuthridge and McFarlane (1994) have found initial adsorption to be the most important factor in AOX removal. Stuthridge and McFarlane (1994) reported on a mixing zone/aerated lagoon system treating chlorination stage bleaching effluent with general pulping wastewater (alkali extraction stage bleaching effluent and foul condensates are treated in another system). Unfiltered wastewater samples from the aerated lagoon, including suspended bacteria, pulping fibers and limerock fines were analyzed for total organic halide (TOX) (American Public Health Association et al., 1992). TOX is essentially the same type of measurement as AOX except it is carried out on the entire sample and not just what can be adsorbed by an activated carbon microcolumn. In the 3.3 hour HRT mixing zone there was a TOX removal of 46 %. Stuthridge and McFarlane (1994) claimed that this was achieved via adsorption onto the limerock fines (36 %), adsorption onto microbes (6 %) and adsorption onto pulp fibers (4 %). The entire process including the aerated lagoon, removed a total of 65 % of the TOX. Via analysis of the sludge and mass balancing, it was determined that 99 % of the TOX was eventually mineralized. This high degree of mineralization, 82 - 100 %, was also shown in other studies (Bryant et al., 1987 and Saunamäki et al., 1991).

The removal of AOX and chlorinated phenolics, via activated sludge, has been found to be better at HRT > 9 hours and SRT > 10 days (Rempel et al., 1992). A higher HRT yields less sludge. As the rate of biosorption equals the rate of wastage of the biosolids from the system times the contaminant concentration of the biosolids, the role of biosorption decreases in importance, with increasing HRT. In addition, a higher SRT yields a higher active biomass endogenous decay coefficient (Grady and Roper, 1974). Hence both a higher HRT and a higher SRT contribute to a lower net sludge production rate. A mass balance indicated that biosorbed AOX was no more than a few percent of the total reduction across the activated sludge plant (Rempel et al., 1992).

The research to date has not shown a single AOX removal mechanism, either biodegradation or adsorption, to be the most important, in all cases.

2.7.2.4 AOX and Toxicity Relationships

Some important points regarding AOX, specific groups of AOX and toxicity can be mentioned. One study of BKME, from a modern mill, treated by an activated sludge system, found that although AOX removal was 48 - 65 %, chlorophenolics removal was 75 -95 % and the effluent contained less than 0.001 kg of chloroacetones/ADMT and less than 0.004 kg of chloroform/ADMT (Gergov et al., 1988). The removal of small and therefore potentially toxic components of AOX, such as chlorophenols and chloroacetones is most beneficial. Daphnia toxicity tests, from the same study, showed they were not correlated to chlorinated compound content in the effluent. Furthermore, the activated sludge effluent was nontoxic and nonmutagenic, to Daphnia, although the effluent AOX concentration was 16.3 - 81.5 mg/L.

It has been reported that the concentration of chlorinated compounds is not related to either effluent or sediment toxicity (Craig et al., 1990). However, the complement of low molecular mass (< 1000 M.W.) chlorinated compounds has been correlated to acute and chronic toxicity (Bryant and Amy, 1989).

2.7.2.5 AOX Size Fractions and Removals

Low molecular mass chlorinated compounds (<1000 M.W.) comprise about 45 % of the total AOX (Tomar and Allen, 1991) in BKME. It has been reported that the removal of low molecular mass chlorinated compounds range from 43 - 60 % while the corresponding removal for high molecular mass compounds (> 100000 M. W.) was only 20 % in an aerated lagoon (Aprahamian and Stevens, 1990). It was hypothesized that this was due to the greater ability of the small molecules to traverse the biological membranes of the microbes.

Tomar and Allen (1991) found that the removal of total AOX and filtered AOX (1.2 μm filter) to be essentially the same, at 33.5 %, in their study of aerated lagoon treatment of settled BKME. Therefore < 1.2 μm AOX removal efficiencies might be interpreted as total AOX, if no secondary settling is involved (Tomar and Allen, 1991). It should be noted that the particle sizes that can be filtered can vary with the matrix, since blinding of filters can control separation.

2.7.2.6 AOX Groupings

Other researchers have described three groups of chlorinated compounds in BKME. These include AOX (organic halide adsorbable to activated carbon) extractable with tetrahydrofuran (THF), AOX not extractable with THF, and NOX (organic halide not adsorbable to activated carbon) extractable with tetrahydrofuran (Jokela et al., 1993). AOX extractable with THF was found to be almost totally recalcitrant. Since NOX/Extractable compounds were found to be highly biodegradable, it was concluded that it's omission from the AOX parameter, as a measure of chlorinated compound content, is not significant. The more non - polar a compound is, the easier it is for it to traverse a biological membrane (Brock and Madigan, 1988). Therefore, considering a given group of compounds that are equally degradable once they are within a microbe, the non - polar members of this group are more likely to be biodegraded. The low biodegradability of the non - extractable AOX fraction was attributed to the high polarity of this AOX fraction. Furthermore, the AOX/non - extractable fractions recalcitrance was not found to be related to the degree of chlorination (Jokela et al., 1993) or size. This is contrary to other studies (Murray and Richardson, 1993 and McCubbin Consultants, 1992).

2.7.2.7 AOX and TOC Relationships

Some studies have observed that the ratio of the mass of organic carbon removed to the mass of organic chlorine removed was constant at 0.125 g Cl/g C (Aprahamian and Stevens, 1990; Tomar and Allen, 1991). It was noted that this indicates the removal of carbon and chlorine is via the same mechanism. Tomar and Allen noted that since chlorinated compounds would tend to be more biologically recalcitrant than non - chlorinated compounds that physical and chemical mechanisms of removal must be the most important for AOX. However Bryant et al. (1987) found a ratio of 0.18 g Cl/g C. It would seem likely that the organic carbon removed/organic chlorine removed ratio of 0.125 g Cl/g C found by the above two groups of researchers is simply coincidence.

2.7.2.8 SRT and HRT Effects on AOX Removals

The effect of SRT in a lab scale activated sludge system, in treating a filtered simulated combined BKME, at an HRT of 10.4 hours, was investigated by Randle et al. (1991). AOX removal remained at about 32 %, regardless of the SRT, for the range of 5 to 15 days, at 10 and 25 °C. In the same study, an aerobic stabilization basin, yielded about 45 % AOX removal for the same SRTs. The higher removal of AOX in the aerobic stabilization basin may have been due to higher contact time since it had a higher HRT and HRT = SRT.

2.7.2.9 Temperature Effect on AOX Removal

Randle et al. (1991) showed that for temperatures from 10 to 40 °C, using lab scale systems, that AOX removal in the activated sludge and aerobic stabilization basin systems was best at 25 °C. Removal was the highest at 25 °C, possibly because of physical biosorption. Physical adsorption is favored at low temperature given that it is an exothermic equilibrium process (Narbaitz, 1995). Within a fairly wide temperature range aerobic processes are faster at higher temperature (Metcalf and Eddy, 1991). Hence, an intermediate temperature might not be unexpected to yield the highest AOX removal.

2.7.3 Adsorption of AOX from Biologically Treated BKME

The use of color absorption at 436 nm (color$_{436}$) and UV absorption at 254 nm (UV$_{254}$) were found to be good and rapid tests for the estimation of AOX in biologically treated BKME (Cecen, 1993). The adsorptivity of different activated carbons for biologically treated BKME was assessed using these parameters (Cecen, 1993). The type of activated carbon was found to be much less important than the dose, for removal of color$_{436}$ and UV$_{254}$.

2.7.4 Advanced and Conventional Treatment Compared

The treatment of kraft pulp bleaching effluents by activated sludge, in a study by Haberl et al. (1991), yielded 30 - 40 % removal of total COD and 20 - 30- % removal of total AOX while BOD$_5$ removals were greater than 90 %. Precipitation/coagulation using lime resulted in removals of 40% total COD and 50 % total AOX. Precipitation/coagulation using lime, followed by activated sludge increased the total COD removals to 70 - 80 %. The lime doses used were very high (2 - 3 g/L). Biological treatment followed by ozone, at 1.7 mg/L, resulted in 98 % removal of AOX from C - stage bleaching effluent. However, this option was considered expensive. Furthermore, γ radiation was found not to add much to ozonation effectiveness, except possibly at low doses. Also it was found not to be economically feasible to use an activated carbon column following activated sludge, for bleaching effluent (Haberl et al., 1991). No explanation was provided for this conclusion.

In another study, bleaching effluent from the last bleaching stage (COD of 1102 - 2850 mg O_2/L, BOD_5 of 205 - 470 mg O_2/L, AOX of 79 - 170 mg Cl/L and TOC of 355 - 970 mg/L) was treated via activated sludge (Çeçen et al., 1992). The COD removal was between 17 and 50 %, the AOX removal was between 10 and 30 % and the BOD_5 removal greater than 90 %. Precipitation/coagulation following biological treatment increased the removals to greater than 90 % for both total AOX and total COD. The best coagulant tested was $FeCl_3$ at 400 mg/L.

2.7.5 PACT™ Application to Kraft Pulp Mill Wastewater Treatment

There has been one application of the PACT™ process to a kraft pulp mill wastewater, to date (Verreault and Depuydt, 1992). Cooking liquor (used in the pulping operation) from the Domtar Fine Papers mill, Beauharnois, Quebec, was treated with a full scale (56000 L/d) batch PACT™ process. This wastewater had a mean COD of 18000 - 25000 mg O_2/L, a mean BOD_5 of 9000 - 10000 mg O_2/L and a pre - neutralized pH of approximately 13. Using a PAC dose of 1.2 g/L, COD and BOD_5 removals were found to be 90 - 92 % and 98 % +, respectively. However, no chlorine had been added to the wastewater, since cooking of the pulp occurs before bleaching. Hence, it is quite different from a typical whole BKME. Therefore, little information concerning the treatment of whole BKME, can be gleamed from this study.

2.8 Toxicity : Measurement and Correlations to other Parameters

Toxicity can be detected by lower COD and TOC removals. Toxicity has also been measured by alga, daphnia (water flea), trout toxicity and Microtox tests (Firth and Backman, 1990). The Microtox test measures the decrease in light output from the bacterium, Photobacterium phosphorum, before and after exposure to a toxin. Some general points regarding toxicity need to be addressed. Firstly, toxicity removal and COD and/or TOC removal do not necessarily correspond. The reasons for this include the fact that intermediate products or end products of a biological degradation sequence may be more toxic than the starting compound (Brenner et al., 1993; Chudoba, 1985). Secondly, synergism, positive or negative, of toxic compounds is another important factor (Brenner et al., 1993). Thirdly, the adsorption of toxic compounds is often greater, percentage wise, than the activated carbon adsorption of TOC (Brenner et al., 1993). This is not unexpected when it is noted that biological membranes, whether phospholipid based or otherwise, are hydrophobic (Brock and Madigan, 1988) and the degree of adsorptivity, onto activated carbon, is proportional to the compound's hydrophobicity (Weber et al., 1987). Hence, hydrophobic compounds, which can penetrate membranes and interfere with cell functioning are preferentially adsorbed by activated carbon. Toxicity is dependent on the biological system involved. There is a large number of examples that show that what is toxic to one organism may not be toxic to another organism, at a given concentration (Murray and Richardson, 1993). Hence if a surrogate parameter for toxicity is to be used it must be correlated to an intrinsically meaningful and/or regulated measure of toxicity.

For kraft pulp mill wastewater and treated effluents there is little agreement on the correlation between AOX and trout acute toxicity. One study found lower molecular weight (<1000) AOX and total BOD_5 to be the best predictors of Rainbow trout toxicity, with correlations of 0.8 and 0.94, respectively, for untreated BKME (Firth and Backman, 1990). Elsewhere, the complement of low molecular mass (< 1000 M.W.) chlorinated compounds, in influent and effluent has been correlated to acute and chronic toxicity (Bryant and Amy, 1989). It has also been reported that the concentration of chlorinated compounds is not related to either effluent or sediment toxicity (Craig et al., 1990).

At least five studies have noted the elimination or virtual elimination of acute toxicity with the application of secondary treatment (Jokela et al., 1993; Rempel et al., 1992; Firth and Backman, 1990; Craig et al., 1990; Gergov et al., 1988).

A Microtox toxicity EC_{50} of 35 % (35 % concentration causes a 50 % decrease in light output by the Microtox test bacteria), for primary treated BKME, was found by Firth and Backman (1990).

2.9 Literature Review Summary

The PACT™ process has been evaluated using many different wastewaters, including cooking liquor from a kraft pulp mill. The PACT™ process generally yielded higher organics removal than the activated sludge process. However, the PACT™ process has not been tested on whole BKME. Since the PACT™ process is probably well suited to such a wastewater, which contains large amounts of slowly/non - biodegradable and toxic substances (Murray and Richardson, 1993), investigation of an application of the PACT™ process to BKME treatment is warranted. The comparison will be conducted using a series of continuous flow, bench scale, activated sludge and PACT™ reactors. Comparison between the two systems will be made, under steady - state conditions.

3. Experimental

Six lab scale reactors were run in parallel to compare the PACT™ system to the activated sludge system, in treating settled BKME. Parallel operation is essential to clearly identify differences in treatment efficiency as well as to model the effect of HRT, SRT and carbon dose on process efficiency. The following section is divided in four parts - wastewater characteristics, reactor configuration and operation, operating conditions and methods for analysis of samples.

3.1 Wastewater Characteristics

Whole mill wastewater, from the Maclaren Kraft pulp mill in Thurso, Quebec was used as a typical example of a kraft mill effluent. The mill uses a furnish (wood used as feed for the process) of approximately 10 % softwood. The mill uses a wet drum debarking process, which results in more effluent compared to a dry debarking process (McCubbin Consultants Inc., 1992). Chlorine dioxide is substituted in excess of 70 % for molecular chlorine; the bleaching sequence being DEDED (i.e. D = chlorine dioxide; E = caustic extraction). Furthermore, advanced technologies, such as extended cooking or oxygen delignification (McCubbin Consultants Inc., 1992) have yet to be applied to the mill.

The wastewater was collected in 45 gallon plastic drums and stored at -20°C until used. Raw wastewater was collected on July 13, 1994, Nov. 10, 1994, February 2, 1995 and March 22, 1995. Approximately 35 barrels were collected each of the first three trips and 12 barrels during the last occasion. The number of barrels collected during the first three trips was limited by the available space at the Department of Civil Engineering's cold storage room. Although the four trips yielded four different feeds, which prevented some comparisons from being made, the very large volume of wastewater required for these experiments made it impossible to operate otherwise. Upon thawing, wastewater was settled and stored at 1°C until being fed to the reactors. Phosphorus and nitrogen were added in a mass ratio of TCOD:N:P of 100:5:1, respectively. NH_4Cl and KH_2PO_4 (reagent grades, Canlab, Ottawa) were used as nitrogen and phosphorus sources, respectively. For 4 of the runs with feed batch # 1, yeast extract (Canlab, Ottawa) was periodically added in the amount of 12.5 mg/L of feed, as a trace nutrient source. This was subsequently discontinued.

3.2 Reactor Configuration and Operation

Experiments were conducted in six Plexiglass bench top continuous flow activated sludge systems, each with a 5.0 L complete mixed (CM) aeration section and a 2.2 L clarifier zone. A movable baffle separated the CM zone from the clarifier zone, in the reactor. Internal recycle of sludge was in effect. A diagram of the three reactor configurations used can be found in Figure 3-1.

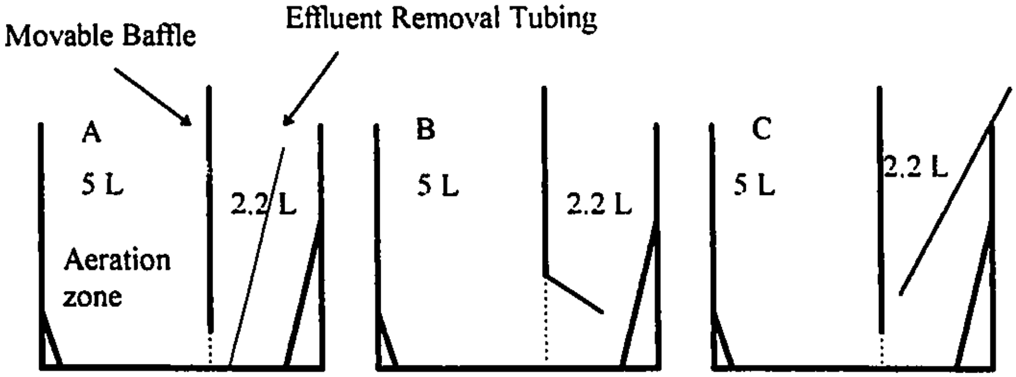

Figure 3-1: Reactor Configurations used in study

The reactors were approximately 22.5 cm in length, 15.7 cm in width and 27 cm in height. Effluent removal was via tubing extending from the bottom of clarifier to the liquid surface in the clarifier (Figure 3-1A). Three configurations were used in order to limit solids loss in the effluent. Solids loss in the effluent caused difficulty in maintaining a target SRT. In order to maintain all the PAC in suspension, very intensive mixing was required, which caused some mixing in the clarifier section. Mixing of all the reactor contents was carried out upon solids sampling and wasting. Accordingly, active volume was taken as the total volume, including the clarifier volume.

The reactors were seeded with a mixture of sludge from a nearby municipal activated sludge treatment plant (Robert O. Picard Wastewater Treatment Facility, Ottawa) and a detention pond located at the Thurso Kraft pulp mill. Although the feed was continuous, sludge wasting and PAC addition were batch mode (once per day). The PAC used was Calgon - WPX (Calgon, Pittsburgh, PA), which is a standard PACT™ grade. The PAC was added as a slurry in about 200 ml of effluent to the CM zone after daily sludge wasting, from the CM zone. SRT was calculated from the following equation.

$$SRT = \frac{MLTSS * V}{F_w * MLTSS + (F - F_w) * EFFTSS} \qquad \text{3-1}$$

where F is the flowrate (L/day), MLTSS is the mixed liquor suspended solids (mg/L), EFFTSS is the effluent suspended solids (mg/L), F_W is the wastage flowrate (L mixed liquor/d) and SRT has the units of days. Wasted mixed liquor was replaced with effluent, hence the term $(F-F_w)*EFFTSS$.

The quantity of sludge wasted was based on the previous 3 day composite MLTSS and effluent suspended solids (EFFTSS) measurements. The target flow and target SRT were also used to yield the following equation

$$F_W = \frac{MLTSS * V - EFFTSS * F * SRT}{SRT * (MLTSS - EFFTSS)} \qquad \text{3-2}$$

Dissolved oxygen was maintained above 4 mg/L for all runs, except for the 7.8 hour HRT, 7.4 days SRT control run, for which the dissolved oxygen fell to between 0.5 and 1.0 mg/L for the last 3 days of the run.

Due to plant operation, feed batches 3 and 4 were acidic (pH 3) and basic (pH 10) at times. pH adjustment was carried out for feed batches # 3 and # 4, during the steady - state periods, using concentrated reagent grade H_2SO_4 (Canlab, Ottawa, Canada) and reagent grade KOH (Canlab, Ottawa).

In obtaining a feed sample, an aliquot was taken from the refrigerated feed reservoir. Effluent samples were taken from the effluent accumulated over the previous day. Samples for SCOD and solids (mixed liquor and effluent) were collected, acidified to pH 2, with concentrated reagent grade H_2SO_4 (Canlab, Ottawa, Canada) and refrigerated at 1 °C. For SCOD samples, solids were removed by centrifugation (model RC5C, Sorvall Instruments, DuPont, Toronto, Canada) and the supernatants were frozen. The analysis of daily samples of suspended solids and SCOD was not considered feasible, due to time limitations. The identification of a possible anomaly in reactor operation was considered easier with the compositing of samples rather than with periodic sampling. With periodic sampling, an anomaly could have occurred but yet have remained unnoticed. The measurement frequencies for the water quality parameters measured are given in Table 3-1.

Water Quality Parameter	Feed Batch 1 Runs	Feed Batch 2 Runs	Feed Batch 3 Runs	Feed Batch 4 Runs
pH	3 recorded measurements	Every 1 to 3 days	Every 1 to 3 days	Every 1 to 3 days
Temperature	3 recorded measurements	Every 1 to 3 days	Every 1 to 3 days	Every 1 to 3 days
Dissolved Oxygen	Intermittent	Intermittent	Intermittent	Intermittent
MLTSS	Every 1 to 3 days	Every day as a 1 to 3 day composite	Every day as a 1 to 3 day composite	Every day as a 1 to 2 day composite
EFFTSS	Every 1 to 3 days	Every day as a 1 to 3 day composite	Every day as a 1 to 3 day composite	Every day as a 1 to 2 day composite
MLVSS	Every 1 to 3 days, for controls	Every day as a 1 to 3 day composite, for controls	scattered and unreliable measurements	scattered and unreliable measurements
EFFVSS	Every 1 to 3 days, for controls	Every day as a 1 to 3 day composite, for controls	scattered and unreliable measurements	scattered and unreliable measurements
SCOD	Every 1 to 3 days	Every day as a 1 to 3 day composite	Every day as a 1 to 3 day composite	Every day as a 1 to 2 day composite
DOC	one 3 day composite	one 3 day composite	one 3 day composite	one 3 day composite
SAOX	non - comparable feed and effluent measurements	one 3 day composite	one 3 day composite	one 3 day composite
$SBOD_5$	one 3 day composite	one 3 day composite	one 2 day composite	one 3 day composite
$TBOD_5$	one 3 day composite, for 2 reactors	not measured	one 2 day composite	one 3 day composite
Microtox Toxicity	one 3 day composite	one 3 day composite	one 3 day composite	one 3 day composite
Specific Organics	not measured	one 3 day composite	one 3 day composite (feed only)	one 3 day composite (feed only)

Table 3-1: Sampling Frequency for Water Quality Parameters, near or during the Steady - State Period

3.3 Operating Conditions Investigated

The feed batches corresponding to the target operating conditions for SRT, HRT and PAC dose, for this study, are shown in Table 3-2. The runs of each feed batch were conducted in parallel, in the order of feed batch 1, 2, 3 and 4. The range of SRTs and HRTs chosen corresponded to common ranges found in the literature (Randle et al., 1991). Low HRTs were avoided because of the large volume of wastewater required to obtain steady - state values. The carbon doses used were chosen based on common doses found in the literature (Hutton, 1978) and specifically the work of Verreault and Depuydt (1992), on the treatment of a Kraft pulp mill wastewater, via the PACT™ process.

	HRT = 5.8 hours		HRT = 11.5 hours					HRT = 34.6 hours	
SRT (d)	$C_D = 0$	$C_D =$ 0.5 g/L	$C_D = 0$	$C_D =$ 0.1 g/L	$C_D =$ 0.2 g/L	$C_D =$ 0.5 g/L	$C_D =$ 1.0 g/L	$C_D = 0$	$C_D =$ 1.0 g/L
7.2	4	4	2 3	2	2	3	3	1	1
14.4			2	2		3		1	1
21.6			2					1	1

Table 3-2: Feed Batches Corresponding to Target Operating Conditions

The # corresponds to the feed batch used during the steady - state period, for those runs, as follows: 1 - Nov. 10, 1994; 2 - July 13, 1994; 3 - Feb. 2, 1995; 4 - March 22, 1995

A new set of operating conditions was allowed to operate for a minimum time of three sludge ages. Upon identification of steady - state, which was defined as operation over at least one week where reactor SCOD and TSS fluctuate evenly about mean values, an average of the pollution parameters was generated.

3.4 Methods Used for Analysis of Samples

Soluble samples refer to that which passes a 1.2 µm glass fibre filter (Whatman GF/C, Canlab, Ottawa, Canada), using vacuum filtration, for all parameters except SCOD, DOC and Microtox, for which solids separation was conducted by centrifugation at 27500 relative centrifugal force for 20 minutes, followed by decanting (Kennedy, 1994). Filtration was not used to prepare for all parameter measurements because of the added time and expense that would have been involved.

MLTSS and EFFTSS were measured as that material which is retained on a 1.2 µm GF/C filter. Volatile solids were determined by heating to 500 °C for 30 minutes. SCOD, TCOD, $SBOD_5$, $TBOD_5$ and DOC were measured according to Standard Methods (American Public Health Association et al., 1992), sections 5220 C (closed reflux/titrimetric), 5220 C, 5210 B (Combustion-Infrared), 5210 B and 5310 B, respectively. The DOC measurement instrument was a Dohrmann TOC analyzer (model DC-190, Rosemont, California), operated at 550 °C, using an autoinjector and a sample size of 50 µl.

Specific organics were determined by gas chromatography (model 3400, Varian, Palo Alto, California)/mass spectroscopy (Saturn II, ion trap, Varian, Palo Alto, California) (GC/MS). Phenol, 2 - chlorophenol, 2,4 - dichlorophenol, 2,4,6 - trichlorophenol, pentachlorophenol, naphthalene and camphene were considered compounds of interest, for BKME (McCubbin Consultants Inc., 1992). The U.S. EPA 625 method was used. The column used was a DB-5 (Varian, Palo Alto, California). The carrier gas was helium at 5 ml/minute. Concentration to 1/1000th of the original volume was effected, using evaporation. The method uses methylene chloride (Optima grade, Fisher, Ottawa) as the extraction solvent. The sample was acidified to pH 2 with 50 % H_2SO_4 (Anachemia, Montreal, Canada) prior to extraction of the acid fraction and the pH was brought to 12, using 50 % NaOH (Anachemia, Montreal, Canada) before extraction of the base - neutral fraction. Before extraction, a surrogate, pentafluorophenol, (reagent grade, Aldrich, Milwaukee, Wisconsin) is added in known amounts, in order to determine the efficiency of the extraction procedure for the acid extractable compounds of interest. The surrogate for the base - neutral extractables was 4,4' difluorobiphenyl (reagent grade, Aldrich, Milwaukee, Wisconsin).

The following acid extractables were analyzed for : 4 - chloro - 3 - methylphenol, 2 - chlorophenol, 2,4 - dichlorophenol, 2,4 - dimethylphenol, phenol, 2,4,6 - trichlorophenol and pentachlorophenol. The available standard included all these compounds (Product M - 625A, from Accustandard Inc., New Haven, Connecticut). The detection limit for the acid extractables was approximately 3 ppb - 10 ppb.

The library routine of the mass spectrometer was used to search for the base - neutral compounds (base - neutral compounds of environmental significance would be present in kraft pulp mill effluent primarily because of possible use of petroleum products, such as some solvents, except for camphene, which is a constituent of wood extractives).

AOX was measured by Seprotech Laboratories, in Ottawa, Canada, using a Dohrmann TX-20 (Rosemont, California). A 100 ml sample size was used.

Toxicity analyses were performed with the Microtox (model M500, Microbics Corporation, Carlsbad, California) acute toxicity measure. The Microtox test measures the difference in light output by the marine bacterium, Photobacterium phosphoreum, before and after exposure to a potential toxin. There are two common time periods of exposure of the Microtox test bacteria to toxicants before the final light measurement is made - 5 and 15 minutes. The 5 minute values are reported more frequently in the literature. However, the 15 minute values have also been utilized and are the relevant values here, because this study involves a complex waste and because certain toxicants, such as heavy metals, do not fully express their effect until 15 minutes, in the Microtox test (Microbics Corporation, 1992). All values reported in this thesis are at 15 minutes.

The effective concentration at which a 50 % decrease in light output by the bacteria (EC_{50}) occurs, is the standard, but EC_{20} or EC_{10} are more appropriate for low toxicity samples, since they can be more accurately determined (Microbics Corporation, 1992; Binder et al., 1995). EC_{50} and EC_{20} values are reported in this thesis as a percentage of the original sample. For example an EC_{50} of 60 % means that 60 % of the original concentration of a given sample results in a 50 % decrease in light output, by the bacteria, in the Microtox test. An EC_{50} of greater than 100 % means that even the original sample, without dilution, is not toxic enough to produce a 50 % decrease in light output by the Microtox bacteria.

Either the basic test (light output is measured at time 0 and at 5 and 15 minutes for control and test samples) or the 100% test (light output is measured at 5 and 15 minutes, for the control and test samples) protocols were used. Non - standard concentrations (other than those indicated in the manual) of feed or effluent sample were accomplished by increasing the concentration of bacteria for the measurements made before exposure to the toxic wastewater sample.

Mixed liquor activated carbon suspended solids (MLCSS) were measured according to the nitric acid digestion method of Schultz (1982). The nitric acid digestions were carried out in triplicate. The method uses a 1:1 mixture of sample and concentrated nitric acid (15.4 N, reagent grade, Canlab, Ottawa, Canada). The mixture was heated to 90 °C, for two hours. The digested fractions were found by filtering two samples, one untreated and one treated with nitric acid and heat. By subtracting the treated solids weight from the untreated solids weight, the digested amounts were found. For solids measurements, filtration through 1.2 µm GF/C filters were carried out.

In the relations following, a is the fraction of biomass found to be digested from a sample, derived from a non - carbon reactor with similar characteristics (HRT and SRT) to the PACT™ test reactors, b_d is the fraction of PAC found to be digested in a PAC only sample, K1 is the concentration of suspended solids that was solubilized (digested) in a PACT™ sample.

$$MLNCSS + MLCSS = MLTSS \qquad \textbf{3-3}$$

$$a * MLNCSS + b_a * MLCSS = K1 \qquad \textbf{3-4}$$

where MLNCSS is the non - PAC total suspended solids concentration.

Settleability comparisons were also made. SVI is defined as 1000 times the settled volume in ml divided by the MLTSS in mg/L after 30 minutes settling in a 1 L cylinder, with 1 rpm stirring provided (American Public Health Association et al., 1992).

4. Results and Discussion

Four feed batches were used in the experiments for this thesis. As shown in Table 4-1, the feeds were quite different. Hence the presentation of results will be based on the individual feed batch used. The number of analyses used to determine each value is noted in the relevant sections.

4.1 Comparison of the Four Feed Wastewaters

	Feed Batch 1	Feed Batch 2	Feed Batch 3	Feed Batch 4
Mean SCOD (mg O_2/L)	539	344	721	980
Mean DOC (mg O_2/L)	264	177	243	237
Mean $SBOD_5$ (mg O_2/L)	329	195	400	505
Mean Microtox EC_{50} (%)	28	15	14	3
$SBOD_5$/SCOD (3 day composite)	0.55	0.47	0.47	0.53
SCOD/DOC (3 day composite)	2.2	2.3	3.5	4.1
SAOX (mg Cl/L)	11	5	13	12
Mean TCOD (mg O_2/L)	685	379	609	501
Mean $TBOD_5$ (mg O_2/L)	380	-	400	501
Feed TSS (mg/L)	-	46	40	-
Feed VSS (mg/L)	-	35	40	-

Table 4-1: A Comparison of the four feeds used in this study

Note: SAOX is soluble AOX

The TCOD of the feeds, 379, 501, 609 and 685 mg O_2/L are close to typical values found in the literature, 628 - 742 mg O_2/L (Randle et al., 1991; Hall and Randle, 1992; Haberl et al., 1991). The TCOD values of feeds # 3 and # 4 were lower than the corresponding SCOD values, because these TCOD values are means of 2 to 3 samples, while the SCOD values are means of 3 - 17 samples.

Focusing on SCOD and $SBOD_5$, it can be noted that the feed strength increases in the following order - batch 2, batch 1, batch 3 and batch 4. The $SBOD_5$/SCOD ratio, for which a higher value indicates a more easily biodegradable sample, was similar for all feeds. The Microtox results showed that all the feeds were toxic. The strongest feeds, in terms of SCOD and $SBOD_5$ (excluding feed 2) were most toxic, since the EC_{50} was lower, as measured by the Microtox test. The EC_{50} of 3 % for batch # 4 feed, means a solution containing 3 % of batch # 4 wastewater caused the light emissions from the standard bioluminescent bacteria to be reduced by 50 %.

The DOC concentrations were similar except for batch 2, for which it was somewhat lower. The DOC concentrations were in the range of values found in the literature, for BKME, of 178 to 850 mg/L (Cecen et al., 1992; Tomar and Allen, 1991; Oleskiewicz et al., 1992).

The SCOD/DOC ratios varied widely, except batches 1 and 2, which were almost identical. Based on the SCOD/DOC ratio, feeds 3 and 4 were much more oxidizable than feeds 1 and 2; feeds 1 and 2 contained more recalcitrant compounds.

The SAOX values, were between 11 and 13 mg Cl/L, except for feed 2, which is 5 mg Cl/L. Typical TAOX values found in the literature are 21 - 152 mg Cl/L and usually greater than 80 % TAOX is SAOX (passes through a 1.2 μm filter) (Tomar and Allen, 1991, Stuthridge and McFarlane, 1994). Hence, the SAOX values appear to be low. The Thurso mill has had an average pulp production of 660 ADMT/d and an average flowrate of 67500 m^3/d, over the last 12 months (Plouffe, 1995), during which, the sampling, for this study, occurred. This translates into 102273 L/ADMT. Hence the Dec. 31, 1995 MISA limit of 1.5 kg Cl/ADMT and the Dec.31, 1999 MISA limit of 0.8 kg Cl/ADMT corresponds to 14.6 mg Cl/L and 7.8 mg Cl/L, respectively.

Looking at the above table it seems fairly obvious that no two feeds can be viewed as similar. Hence any modelling must be restricted to each feed batch separately.

4.2 Reactor Design and Operational Problems

To achieve good mixing and limit formation of a sludge layer on the aeration section bottom of the reactors, mixing was so intense that most of the clarifier was at least partially mixed. To obtain consistent TSS concentration values, supplementary mixing of the contents of the aeration and clarifier sections was implemented, during sampling. Hence, the active volume of the reactors was taken as the total of aeration section and clarifier section volumes.

The operation of the PACT™ reactors, using feed batch 1, with high PAC dose (1 g/L carbon dose), was found to be most problematic. Thick sludge blankets were often present in the aeration and clarifier zones. This sometimes was associated with floating sludge (possibly due to denitrification (Metcalf and Eddy, 1991)). When a higher organic loading was applied, in relation to the carbon dose used (which was the case for all subsequent runs), it appears enough biomass was present to incorporate much of the PAC within the flocs, lowering it's scour velocity and thus alleviating the aeration zone sludge blanket problem. More careful control of reactor operation was carried out for groups 2, 3 and 4. In future studies, intermittent mixing may also alleviate an excessive sludge blanket problem. If higher HRT studies were to be examined, a batch mode of operation would be recommended.

Because of the vigorous (especially in the PACT™ reactors) and variable mixing used during reactor operation, solids loss in the effluent was probably mainly determined by the mixing intensity in each reactor. Additionally, the three reactor designs used (Figure 3-1) likely caused some variation in effluent solids concentration. Furthermore, the internal sludge recycle used in these experiments is not used in full scale activated sludge systems, in which a separate clarifier is used. Hence, effluent solids concentrations were not considered indicative of any advantages or disadvantages, the PACT™ system may have with respect to the activated sludge system, in terms of limiting effluent solids loss.

Since waste solids flow is related to effluent solids flow, it is likely the relative waste solids flows, of activated sludge and PACT™ systems, found in this thesis, would be different from full scale versions of the two wastewater treatment systems. Hence, some caution should be taken in comparing activated sludge and PACT™ waste solids flows. Although waste solids flows of PACT™ systems are expected to usually exceed those of corresponding activated sludge systems (Meidl, 1982), most of the additional solids are expected to be PAC and most of the PAC (approximately 95 %) is expected to be regenerated, by application of heat (Meidl, 1982). Wet air regeneration is one of the options for the regeneration process (Meidl, 1982).

Variation in the flowrate, delivered by the peristaltic pumps used, caused some deviation from target HRTs. Variable solids loss in the effluent contributed to the deviation of SRTs from their target values.

Some difficulty was experienced in determining the active volume, and therefore the HRT and SRT, of the reactors used (Figure 3-1).

To reduce the difficulty in determining active volume, and therefore HRT and SRT, it is recommended that, for future studies, the volume of the aeration basin should be increased to 20 L. Figure 4-1 shows a potentially better design. This is because active volume could be estimated with a smaller error. Furthermore, the bottom of the clarifier section should be slanted to prevent a significant sludge blanket from developing in the clarifier. A minimum sludge blanket is required in separate clarifier systems in order to assure a minimum recycle concentration, however it is not required in the systems used here because internal recycle was used. A disadvantage to using this design, with a minimum clarifier volume and a large height to minimize disturbances of the upper clarifier section, is the large volume of wastewater required to operate at practical HRTs.

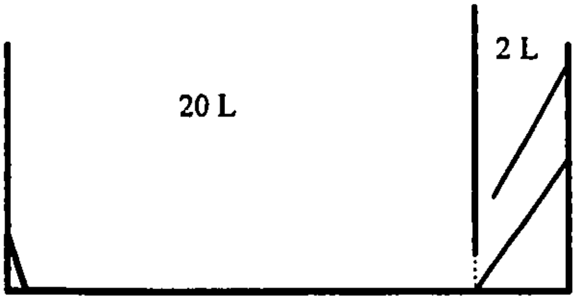

Figure 4-1: Proposed Reactor Design for Future Studies

4.3 Runs with the Batch # 1 Feed

It should be noted that although the same feed batch was used for all the runs of this group, different reactors reached steady-state more quickly than others. This resulted in some reactors being converted to new operating conditions faster than others. As a result of degradation of the feed during the freezing process (the contents of some barrels were above 15 °C, for a week or more), the runs of group 1 experienced slightly different feeds during steady-state.

Table 4-2 indicates the actual mean HRTs, SRTs and carbon doses used for this group of runs, during the steady - state periods (see Appendix A). However, for comparisons, the values of these parameters are approximated by the mean values : HRT 36.5 hours, SRTs 7.2, 13.4 and 23.4 days and carbon doses 0 or 1 g/L. The mean mixed liquor total suspended solids concentrations, during the steady - state periods, are also shown.

Reactor	HRT (hours)	SRT (days)	Carbon Dose (g/L)	MLTSS (mg/L)
1	39.9	7.6	0	487
2	34.8	6.9	1.01	5930
3	38.1	13.3	0	747
4	36.1	13.6	1.06	9659
5	34.6	21.4	0	1170.8
6	35.5	25.3	0.95	14124.4

Table 4-2: Actual HRTs, SRTs and Carbon Doses used and Associated MLTSS, for the First Group of Runs

The nitric acid digestion method of Schultz (1982) yielded MLCSS values that were generally quite close to values calculated from the carbon dose, SRT and HRT, as can be seen from Table 4-3. This gives some credibility to wasting and SRT calculation being based on TSS and not microbial VSS.

Feed Source	SRT (days)	HRT (hours)	Carbon Dose (g/L)	MLCSS Analyzed (mg/L)	MLCSS Calculated (mg/L)	% Error relative to analyzed value
Feed 1	6.9	34.8	1.01	4948	4806	2.8
Feed 1	13.6	36.1	1.06	8255	9584	16.1

Table 4-3: MLCSS Determined by Nitric Acid Digestion and Calculated from Theory

The corresponding temperatures and pHs in effect for this set of runs are shown in Table 4-4.

Reactor	Mean Temperature (°C)	pH Range
1	17.8	-
2	18.35	5.29 - 7.05
3	17.8	5.73 - 6.68
4	17.25	5.52 - 6.95
5	17.8	5.11 - 6.8
6	17.8	5.95 - 7.03

Table 4-4: Temperatures and pHs in effect for the runs with Batch Feed # 1

The temperatures were not significantly different and probably had little effect on any comparisons made. pH did at times dip below 6 but this was not noted to have had any significant effect on either the TSS concentrations or the SCOD removals. Filamentous growth was not a problem at steady - state for any of the runs, even with the occasional low pH values, observed in reactors 2 and 5. The pH of activated sludge systems are usually in the range of 6 to 8. No corrections were made for temperature variation or pH.

The MLTSS, feed SCOD and effluent SCOD variations over time for the 21.4 day SRT control activated sludge reactor are shown in Figure 4-2. Steady-state was considered to be the period after day 10. It should be noted that the reactor was running with these specific operating conditions, for 50 days prior to day 1 in this figure. Furthermore, all runs of this group, as all other groups, lasted at least 3 sludge ages. Even though the organic loading varied during the steady-state period (therefore strictly pseudo steady - state) the effluent concentration remained approximately constant. The variation in feed concentration may have been due to degradation of some of the feed during freezing, which often required 10 - 14 days. After defrosting, each barrel provided approximately 6 days of feed for this set of runs and some degradation is presumed to have occurred in the barrels during this time, as well. The relatively constant effluent concentration (common for most reactor runs) may have been due to underloading of the system (in terms of biodegradable substrate for control reactors and COD for PACT™ reactors).

Figure 4-3 shows the MLTSS, feed SCOD and effluent SCOD progressions for the 25.3 day SRT, 0.95 g/L PACT™ reactor. The whole period shown was taken as the steady-state period. Day 1 was 50 days after the reactor had started running. The large variation in MLTSS, as shown in Figure 4-3, occurred because proper mixing of the reactor during sampling was not achieved until the later part of the steady - state period. The PAC sludge was found to be difficult to keep in suspension, probably due to the high PAC dose.

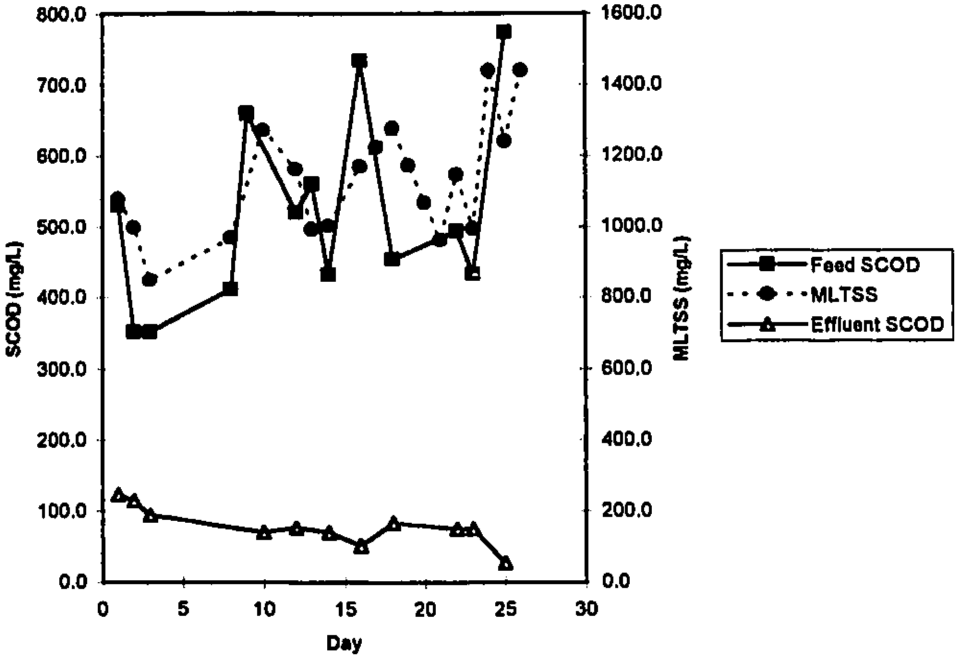

Figure 4-2: MLTSS, Feed SCOD and Effluent SCOD Progressions for the 21.4 day SRT Control Reactor, for Batch 1 (HRT = 34.6 hrs)

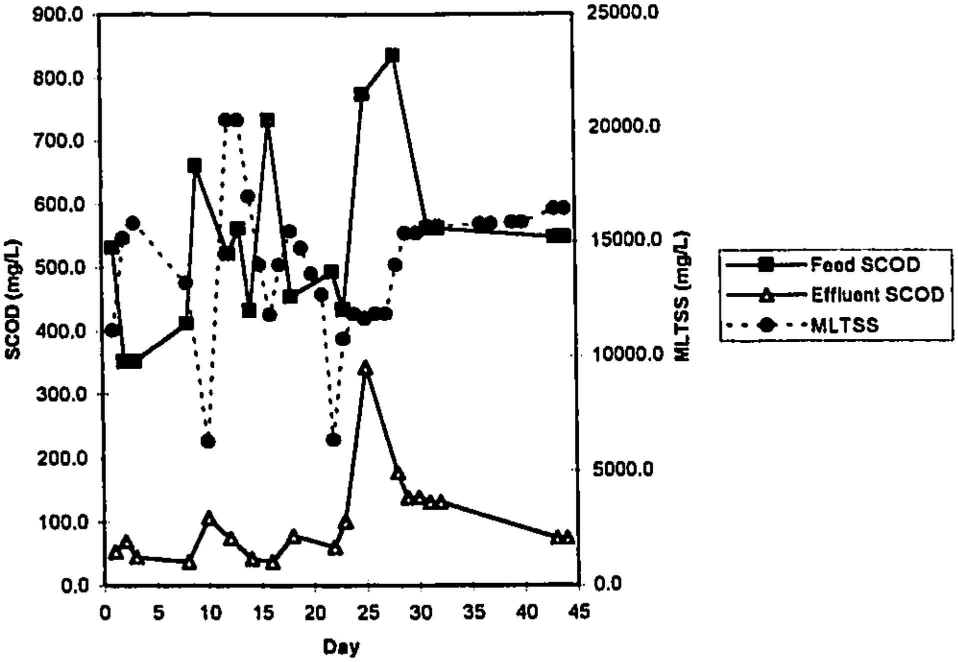

Figure 4-3: MLTSS, Feed SCOD and Effluent SCOD Progressions for the 25.3 day SRT PACT™ Reactor, 0.95 g/L Carbon Dose, for Batch 1 (HRT = 35.5 hrs)

Figure 4-4 shows the steady - state SCOD removal results, at 36.5 hours HRT, for SRTs between 7.25 and 23.4 days. For each operating condition, feed and effluent values are based on 3 - 17 values, at steady - state. Usually 6 - 8 samples for both feed and effluent were analyzed. The steady - state SCOD feed strength for a given reactor varied between 494 and 577 mg O_2/L, with a mean of 539 mg O_2/L for all reactor runs. Ammonia oxidation in the chemical oxygen demand test was very unlikely, since given the amount of Hg^{2+} available (added as $HgSO_4$) to precipitate any Cl^- ion (necessary for ammonia oxidation in the COD test) present, as a result of chlorinated compound bleaching agent use. Hg^{2+} would be in excess (American Public Health Association et al, 1992).

Effluent SCOD values are based on samples drawn from a bucket which accumulated the previous day's flow. Feed SCOD values correspond the previous day, in relation to the effluent values. If the feed sample, taken on the same day as a given effluent sample, corresponds to a just replenished feed reservoir, then the feed sample from the previous day was necessarily used in conjunction with the effluent sample, from the present day, to calculate a removal efficiency. However, if a feed sample was not taken on the previous day but the feed reservoir still contained refrigerated feed from the previous day, then the present day feed sample was used in conjunction with the present day effluent sample, to calculate a removal efficiency. The removals were calculated by computing efficiencies for each pair of feed and effluent SCOD values and then generating a mean from these values. This method of calculating removals is used throughout the thesis, for all water quality parameters.

The control reactors had a range of SCOD removal of 66.8 - 76.0 %, while the 1 g/L PACT™ reactors had a range of SCOD removal of 70.2 - 84.6 %. The 13.5 day SRT control and PACT™ runs seem to be out of step with the other runs, yielding a lower removal than the 7.25 and 23.4 days SRT runs. This may be the result of the variability of biological systems or the wastewater used. The control reactor SCOD removals are higher than the TCOD removals cited in the literature of 50 to 60 % (Haberl et al., 1991; Cecen et al., 1992; Randle et al., 1991 and Hall and Randle, 1992). However, in general, SCOD removals are expected to be higher than TCOD removals.

Comparing control and PACT™ reactors, at the same SRT, the PACT™ reactor seemed to yield better SCOD removal, however all 95% confidence intervals do overlap.

It can be noted that the confidence intervals for the PACT™ reactors were always narrower than the corresponding controls, which suggests an enhanced stability offered by the PAC.

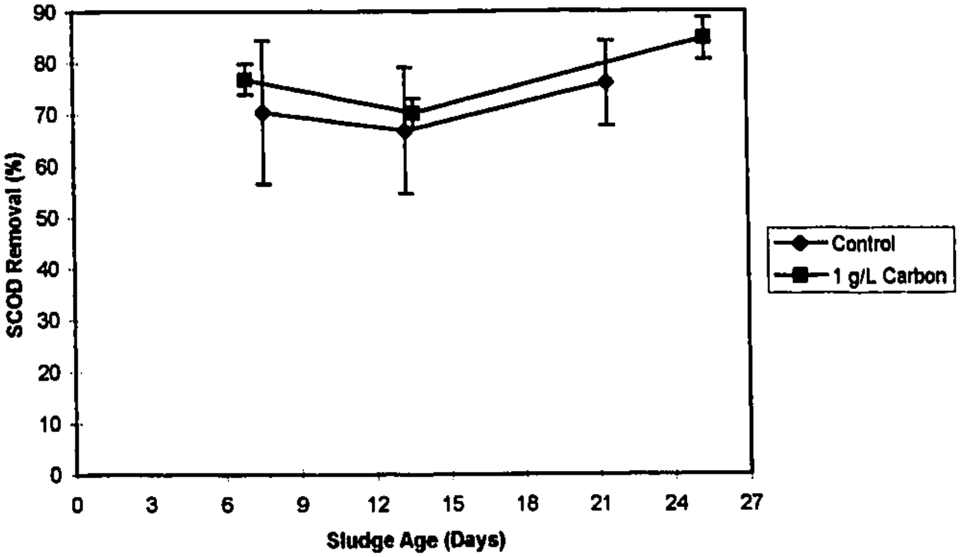

Figure 4-4: SCOD Removal Results and their 95 % Confidence Limits, for the Nominal 36.5 hours HRT runs

For both the control activated sludge and 1 g/L carbon dose PACT™ reactors there appeared to be a slight increase in SCOD removal with higher sludge age. It is expected that treatment efficiency should increase (lower effluent concentration) with increasing sludge age, for conventional activated sludge systems (Lawrence and McCarty, 1970). For conventional activated sludge systems the biodegradable soluble effluent concentration (S, (mg SCOD/L)) is a function of kinetic coefficients and the sludge age

(Lawrence and McCarty, 1970), as shown in equation 4-1. It is important to note the magnitudes of the kinetic coefficients (Metcalf and Eddy, 1991).

$$S = \frac{K_s(1 + SRT * k_d)}{SRT(Yk - k_d) - 1} \qquad \text{4-1}$$

where Y is the yield coefficient (mg microbes/mg SCOD), k is the maximum rate of substrate utilization (1/d), k_d is the endogenous decay coefficient (1/d) and K_s is the half velocity constant (mg SCOD/L).

The reduction in S with increasing SRT occurs because of increased biomass concentration, at high sludge ages. However, biomass activity may remain the same with increasing sludge age, as shown by Grady and Roper (1974). If the treatment system is not stressed, then even a low SRT may result in essentially all biodegradable substrate removal (Lawrence and McCarty, 1970). Hence, S may be relatively independent of SRT, within a range of SRT.

Furthermore, the development by Lawrence and McCarty (1970) does not consider MEPs. Using data from the literature, Daigger and Grady (1977) have developed a model taking into account MEP formation. The model also considers that a higher biodegradable feed concentration may result in an increased biodegradable effluent (non - MEP) concentration (contrary to Lawrence and McCarty, 1970) which is often found (Daigger and Grady, 1977). The model demonstrates that there are times when SCOD effluent concentration might actually be expected to increase (presumably slightly) with increasing sludge age. The model assumes there is an optimum sludge age, at which MEP formation is a minimum, for a given influent.

The mean SCOD removal of the three controls was 71 % '/. 3.6 % (95 % confidence), while the mean SCOD removal of the three PACT™ reactors was 77 % '/. 1.9 % (95 % confidence). Hence, there appears to be a small difference in SCOD removal between PACT™ and control reactors.

Figure 4-5 shows the DOC removal results from the 36.5 hours HRT runs. The feed DOC varied from 217.4 - 312.1 mg C/L, with a mean of 264 mg C/L, for the 3 analyses of feed carried out, each, in triplicate (i.e. three times). Each effluent sample (one for each reactor run) was analyzed three times using a 3 day composite, from the steady - state period. The PACT™ reactors all yielded approximately 83 % removal while the control reactors attained about 70 % DOC removal. The DOC removals of the control reactors were much higher than the literature values, for secondary treatment of BKME, which were usually less than 33 % (Cecen et al., 1992, Tomar and Allen, 1991, Oleszkiewicz et al., 1992). The removal differences between this study and the literature studies may have been due to bleach sequence, furnish and other mill operating conditions differences. The 7.6 day SRT control DOC result is not available, due to lack of sample. The advantage of using PAC is large, in terms of DOC removal, of organic carbon associated with influent compounds and/or MEP.

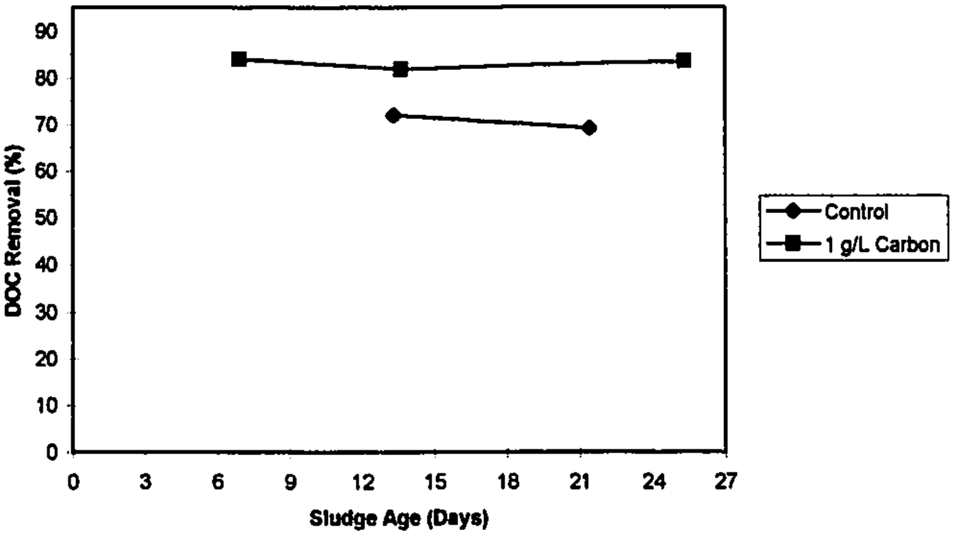

Figure 4-5: DOC Removal Results for nominal 36.5 hours HRT Runs

The ($SCOD_{IN}$ - $SCOD_{OUT}$)/(DOC_{IN} - DOC_{OUT}) ratio yields some information about the oxidation state of the compounds removed. The higher the ratio, the more oxidizable (or at least potentially) the compound. Table 4-5 shows the SCOD/DOC ratios for some common substances. If they were to be completely oxidized to CO_2 or otherwise removed, then the measured SCOD/DOC ratios for these compounds would be the same as the ($SCOD_{IN}$ - $SCOD_{OUT}$)/(DOC_{IN} - DOC_{OUT}) ratios. The value of 2.4 for the ($SCOD_{IN}$ - $SCOD_{OUT}$)/(DOC_{IN} - DOC_{OUT}) ratio for the 13.3 day SRT control (Table 4-6) is partially understandable given that the theoretical and measured SCOD/DOC ratios for sucrose are about 2.67 and 2.44. Glucose and other sugars will have the same theoretical ratio and will have similar measured ratios. Cellulose is polymerized glucose and hemicellulose is a polymer of glucose, mannose, xylose and other sugars.

The high value of 3.3 for the 21.4 day SRT control might be explained by oxidation of highly reduced lipids (Brock and Madigan, 1988), which are somewhat more difficult to degrade than carbohydrates (Metcalf and Eddy, 1991). Lipids would be present as MEPs, derived from biological membranes, from dead microbes, produced in the reactor. The value of 2.4 for the 13.3 day SRT control may be lower than the 21.4 day SRT control value because of variability of biological systems. The low ($SCOD_{IN}$ - $SCOD_{OUT}$)/(DOC_{IN} - DOC_{OUT}) ratios, in Table 4-6 , for the PACT™ reactors indicate that in addition to the more oxidizable compounds removed by the activated sludge system, the PACT™ system also removes less oxidizable compounds, presumably through adsorption.

Substance	SCOD/DOC (Calculated)	SCOD/DOC (Measured)
Acetone	3.56	2.44
Sucrose	2.67	2.44
Benzene	3.34	0.84
Pyridine	3.33	0
Benzoic Acid	2.86	2.9
Phenol	3.12	2.96
chlorophenol	3.7	-
dichlorophenol	4.0	-
Ethanol	4.0	3.35

Table 4-5: SCOD/DOC Ratios for some common compounds (Adapted from Eckenfelder, 1980)

SRT (days)	Carbon Dose (g/L)	$\frac{(SCOD_{IN} - SCOD_{OUT})}{(DOC_{IN} - DOC_{OUT})}$
13.3	0	2.4
21.4	0	3.3
6.9	1.01	1.96
13.6	1.06	1.96
25.3	0.95	2.1

Table 4-6: $(SCOD_{IN} - SCOD_{OUT})/(DOC_{IN} - DOC_{OUT})$ ratios for 36.5 hours HRT Runs

The average $SBOD_5$ results can be found in Figure 4-6. Feed and effluent values were based on a 3 day composite sample, measured in 3 - 6 replicates. The feed $SBOD_5$ samples analyzed during the steady - state period varied from 285 - 355 mg O_2/L and the $SBOD_5$/SCOD ratios were 0.46 - 0.66, with a mean of 0.55. This range is close to the ratio of 0.42, found in the literature, for BKME (Hall and Randle, 1992; Randle et al., 1991). The $SBOD_5$ removal results, at 36.5 hours HRT, indicate 97.5 - 98.7 % removal, for all reactor runs tested. Given the large experimental error (a coefficient of variation of around 15 %) (American Public Health Association et al., 1992) of the BOD test, this means all runs had the same $SBOD_5$ removals. Hence a 13.3 day SRT and a 36 hour HRT (HRT, in addition to SRT, can be important in real processes) is sufficient to remove all the biodegradable content of the waste. This is consistent with the literature which finds very high BOD_5 removals for BKME, in A.S. and aerated lagoon systems. The $SBOD_5$ removal results possibly indicate that the SCOD removal results are not likely due to enhanced bioactivity but rather adsorption of MEP and/or recalcitrant influent SCOD.

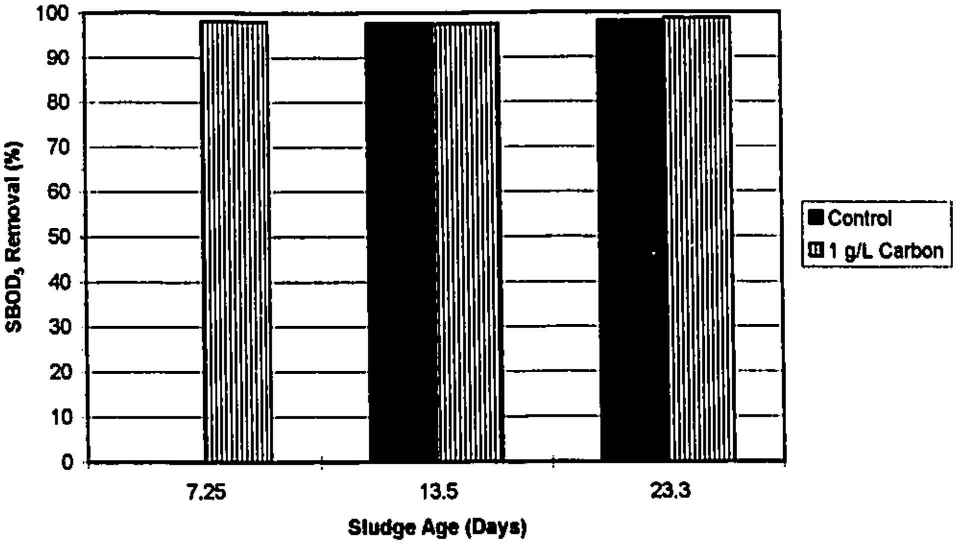

Figure 4-6: $SBOD_5$ Removal Results for nominal 36.5 hours HRT Runs

All Microtox results (feeds and effluents) are based on a 3 day composite measured once. The feed samples of this group of runs appeared different in terms of Microtox results (Table 4-7). If the 95 % confidence intervals are considered, two of the feed samples can be differentiated in terms of toxicity. This might have been due to some degradation that has taken place during freezing, that produced some inhibitory MEPs (Chudoba, 1985). The feeds had EC_{50}s of about 20 - 60 %, which agree with the literature (Firth and Backman, 1990), for the most part. The value at 60 % has a lower toxicity than might be expected but its 95 % confidence interval is large and hence this EC_{50} may actually be lower than 60 % (i.e. more toxic).

For low toxicity samples, the EC_{20} or EC_{10} value is a better choice than the EC_{50} value (Microbics Corporation, 1992, Binder, 1995). The reason is that the EC_{50} estimation may only be practically done by extrapolation (Microbics Corporation, 1992), rather than interpolation. The uncertainty in estimating a value is greater for an extrapolation rather than an interpolation (Hamilton, 1992). The EC_{20} values for the effluent samples of this group of runs could not be statistically calculated, since only, at most, 2 valid points were obtained for the effluent sample analyses.

All the effluent EC_{50}s were over 100 %. This is also in agreement with the literature in that even conventional activated sludge, for the most part, has been found to yield complete removal of toxicity using conventional toxicity measures, such as the 96 hour acute trout toxicity assay (Craig et al., 1990; Firth and Backman, 1990; Jokela et al., 1993; Gergov et al., 1988; Rempel et al., 1992).

	EC_{50} (%)		EC_{20} (%)	
Sample Source	Mean	95 % Confidence Interval	Mean	95 % Confidence Interval
Feed	61.0	8.5-438.0	27.3	9.8-75.8
13.3 day SRT Control	> 100	-	-	-
21.4 day SRT Control	>100	-	-	-
Feed	36.3	27.6-47.7	9.4	7.5-11..8
6.9 day SRT with 1 g/L C_D	>100	-	-	-
13.6 day SRT with 1 g/L C_D	>100	-	-	-
Feed	20.6	19.4-21.8	7.1	6.5-7.7
25.3 day SRT with 1 g/L C_D	>100	-	-	-

Table 4-7: Microtox Results at 36.5 hours HRT

It was suspected that the feed SAOX samples of this group might have been partially degraded. Furthermore, some of the SAOX samples tested did not correspond in terms of feed and effluent. Therefore, the results are presented in Appendix B.

Table 4-8 shows the total suspended solids exit flows, in waste and effluent streams, for PACT™ and activated sludge reactors. Because of the method of operation of the reactors, it might be misleading to compare effluent solids loss, for PACT™ and activated sludge systems. TSS loss in the effluent was high compared to the 1995 MISA lower limit of 4.57 kg TSS/ADMT (Ministry of the Environment of Ontario, 1993b), for one control reactor and all the PACT™ reactors. This was due to the intensive mixing used, especially for the PACT™ reactors. The effluent contained between 28 mg/L (0.14 g/d) and 560 mg/L (2.8 g/d). This translates into 2.9 to 58 kg TSS/ADMT, respectively, for a plant water usage of 102273 L/ADMT (Plouffe, 1995).

Waste solids flows, for PACT™ reactors, were expected to be much greater than the waste solids flows for the controls, at the same sludge age. This was found to be the case, as waste solids flows for the PACT™ reactors were approximately 16 times those of the controls, for the same SRT. This is reasonable given that the MLTSS of the PACT™ reactors was approximately 13 times that of the corresponding control reactors. Most of this additional mass flow would be expected to be PAC.

SRT (d)	C_D (g/L)	Waste (g/d)	% of Total to Waste	Effluent (g/d)	% of Total to Effluent
7.6	0	0.39	74	0.14	26
6.9	1.01	5.3	85	0.90	15
13.3	0	0.25	61	0.16	39
13.6	1.06	4.2	86	0.70	14
21.4	0	0.19	37	0.32	63
25.3	0.95	3.6	56	2.8	44

Table 4-8: Total Suspended Solids Loss in Waste and Effluent Streams, for the First Group of Runs, at 36.5 hours HRT

Feed and effluent samples were not analyzed for specific organics because of inadvertent sample depletion.

In summary, for this set of runs, with an HRT of 36.5 hours, SRTs, in the range of 7.25 - 23.4 days, had a very small effect on the SCOD, $SBOD_5$ and DOC removals. $SBOD_5$ removal was found to be near 100 %, for all control and PACT™ runs. The PACT™ systems were consistently better than the control activated sludge systems in terms of SCOD and DOC removal, i.e. 4 - 8 % and 9 - 14 % better, respectively. The additional removals might have been the result of gross MEP and/or influent compound adsorption. Complete Microtox toxicity removal was achieved even in the activated sludge systems.

4.4 Runs with the Batch # 2 Feed

The main feature for this set of runs was that the HRT was reduced from approximately 36.5 hours to 11.3 hours. In addition, for this group of runs, PAC doses of

0.1 and 0.2 g/L were used. There were two reasons for decreasing the carbon dose from 1 g/L. First, to determine the sensitivity of BKME treatment efficiency to PAC dose. Secondly, it was hoped that the lower PAC doses would alleviate some of the problems experienced in fluidizing all the PAC present, some of which would form a layer at the bottom of the aeration zone during operation.

The actual mean HRTs, SRTs and PAC doses used for this group of runs, during the steady - state period, are shown in Table 4-9. For comparisons, HRT and SRTs are approximated by their means, HRT = 11.4 hours, SRTs = 7.3, 16.8 and 23.8 days. The PAC doses were 0, 0.1 or 0.2 g/L. The average mixed liquor total suspended solids, during the steady - state period can also be found in the same table.

Reactor	HRT (Hours)	SRT (days)	PAC Dose (g/L)	MLTSS (mg/L)
1	11.3	7.3	0	1846
2	11.6	7.3	0.1	3789
3	11.3	7.2	0.2	5413
4	11.3	18.5	0	2990
5	11.5	15.0	0.1	5375
6	11.3	23.8	0	3468

Table 4-9: Actual HRTs, SRTs and Carbon doses used and associated MLTSS, for the second group of runs

The nitric acid digestion method of Schultz (1982) yielded MLCSS values (Table 4-10) that were close to values calculated from the carbon dose*SRT/HRT. This good correlation between calculated and analyzed MLCSS was similar to the corresponding result using feed batch 1. This gives added credibility to wasting and SRT calculation being based on TSS and not microbial VSS.

Feed Source	SRT (days)	HRT (hours)	Carbon Dose (g/L)	MLCSS Analyzed (mg/L)	MLCSS Calculated (mg/L)	% Error relative to analyzed value
Feed 2	7.3	11.6	0.096	1676	1450	13.5
Feed 2	7.2	11.3	0.194	3096	2967	4.2
Feed 2	15.0	11.5	0.098	2912	3068	5.0

Table 4-10: MLCSS Determined by Nitric Acid Digestion and Calculated from Theory

The corresponding temperatures and pHs for this group of runs can be found in Table 4-11. There was a 2 °C range in temperatures for this set of runs. This was not considered significant. pH did at times fall to low values during the steady - state period, but no correlation to reduced SCOD treatment efficiency and/or filamentous growth was noted.

Reactor	Temperature Range (°C)	pH Range
1	17.3 - 17.5	5.93 - 6.7
2	16.5 - 16.6	5.75 - 6.43
3	16.9 - 17.1	5.63 - 6.91
4	15.5 - 15.6	5.51 - 5.76
5	17 - 17.2	5.24 - 6.09
6	15.5 - 15.6	5.84 - 6.33

Table 4-11: Temperatures and pHs Associated with the Second Group of Runs

Figure 4-7 and Figure 4-8 present solids and SCOD data collected for two of the reactors in this group of runs. For the 7.3 day SRT control, steady - state was taken to begin at day 23. Day 12 was taken as the beginning of steady - state for the 7.2 day SRT

PACT™ reactor with 0.2 g/L PAC dose. Although feed SCOD varied significantly (due to possible degradation in the barrels, during freezing and thawing), there was little variation in effluent SCOD. Almost all of the data points shown are results of three day composites. Equal volumes of sample were collected for each of three days, placed in the same container and mixed. The composite sample was drawn from this container. For these results, the middle day has been plotted.

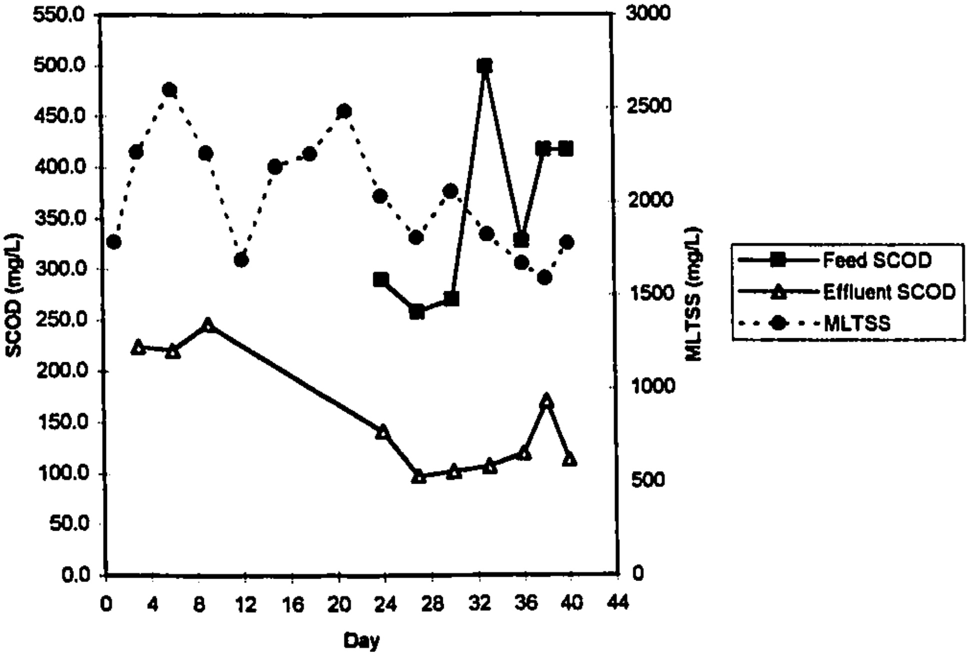

Figure 4-7: MLTSS, Feed SCOD and Effluent SCOD Progressions for the 7.3 day SRT Control Reactor, using Batch 2 (HRT = 11.3 hrs)

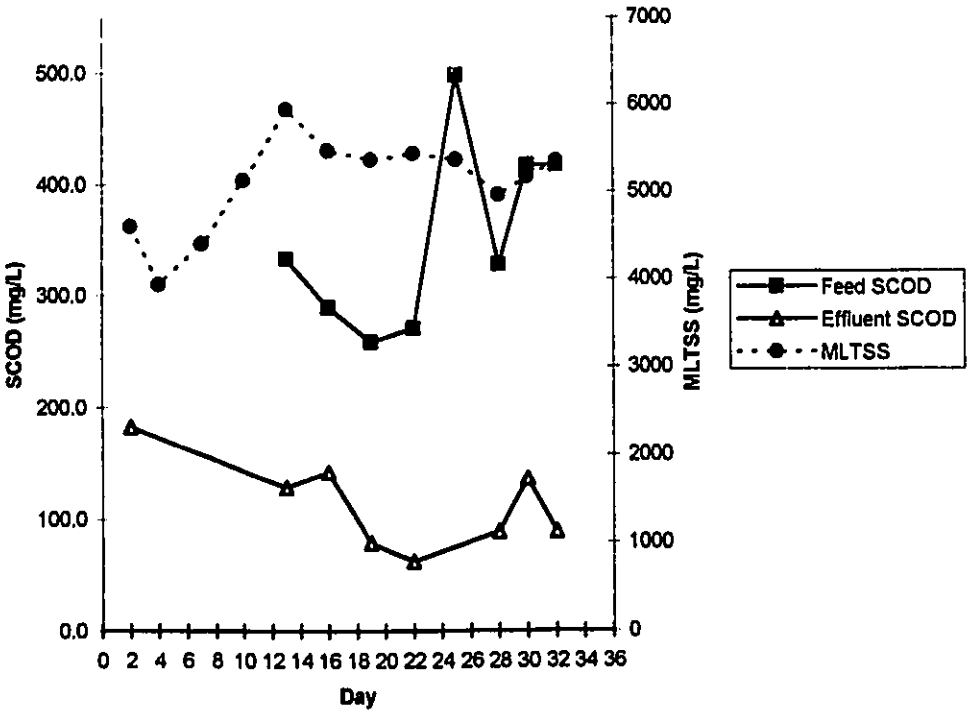

Figure 4-8: MLTSS, Feed SCOD and Effluent SCOD Progressions for the 7.2 day SRT PACT™ Reactor with 0.2 g/L Carbon Dose, using Batch 2 (HRT = 11.3 hrs)

Table 4-12 contains the SCOD removal results for this group of runs, at 11.4 hours HRT. The results were based on 5 - 7 three day composite samples. The feed sample from the previous day, in relation to the effluent sample, was used in calculating removals, for this group of runs and the two subsequent groups of runs. Removal efficiencies were found by calculating individual removal efficiencies for each feed and effluent pair and then computing an average from these values. This method of calculating efficiency is used throughout the thesis, for all water quality parameters. The three control reactors had a SCOD removal efficiency of 65 $^{+}/_{-}$ 2 %. From Table 4-12 and Figure 4-9 it can be noted that sludge age, between 7.3 and 23.8 days, had little effect on SCOD removal for the control activated sludge reactors.

For conventional activated sludge, there is often an increase in SCOD treatment efficiency with increasing sludge age (Lawrence and McCarty, 1970). When sludge age has little effect on treatment efficiency, the systems may be understressed, in terms of biodegradable organic loading. Thus, biodegradation beyond 65 % SCOD removal may be limited, for this feed. There is also evidence, using municipal waste, that the active biomass concentration can remain the same as the sludge age is increased from 7.3 to 23.8 days, at least (Grady and Roper, 1974). This might also result in increased SRT not resulting in increased treatment efficiency.

	% SCOD Removals					
SRT	Control		0.1 g/L C_D		0.2 g/L C_D	
(Days)	Mean (%)	95 % C.I.	Mean (%)	95 % C.I.	Mean (%)	95 % C.I.
7.3	63.9	59.6-68.2	65.4	59.8-71.0	70.1	66.2-74.0
16.8	66.7	62.7-70.7	64.4	55.2-73.6	-	-
23.8	64.0	58.9-69.1	-	-	-	-

Table 4-12: SCOD Removal Results at 11.4 hours HRT, using Batch 2

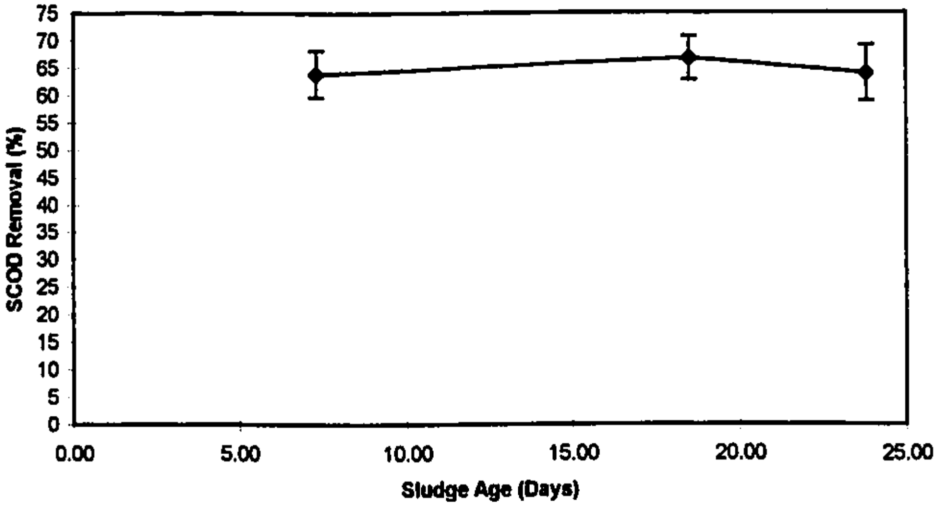

Figure 4-9: SCOD Removal Results for nominal 11.4 hours HRT Control Activated Sludge Reactors, using Feed Batch #2

The PACT™ system with a C_D of 0.1 g/L had essentially the same SCOD removal as the controls (Table 4-12). The mean feed SCOD concentration was 344 mg/L $^+/_-$ 44 mg/L (95 % confidence). As can be seen from Figure 4-10, the three runs at 7.3 days SRT showed a trend of increasing SCOD removal with increasing PAC dose from 0 to 0.2 g/L. The small increase of 6.2 %, yielding 70.1 %, at 0.2 g/L PAC dose was found to be statistically significant at the 95 % confidence level compared to the control, using a t test of the differences of the efficiencies of SCOD removal, over a common 17 day period of steady - state operation.

This calculation was done as follows. For each common day of operation, for the two reactors being compared, an efficiency of SCOD removal was calculated. The differences in efficiency (negative or positive) between the two reactors, with reference to one reactor, were calculated. An average difference was calculated from these values. From the average difference, a sample standard deviation was calculated for the differences in efficiency. For the calculation of the t statistic, the average difference replaces the difference between means, in the standard paired t test.

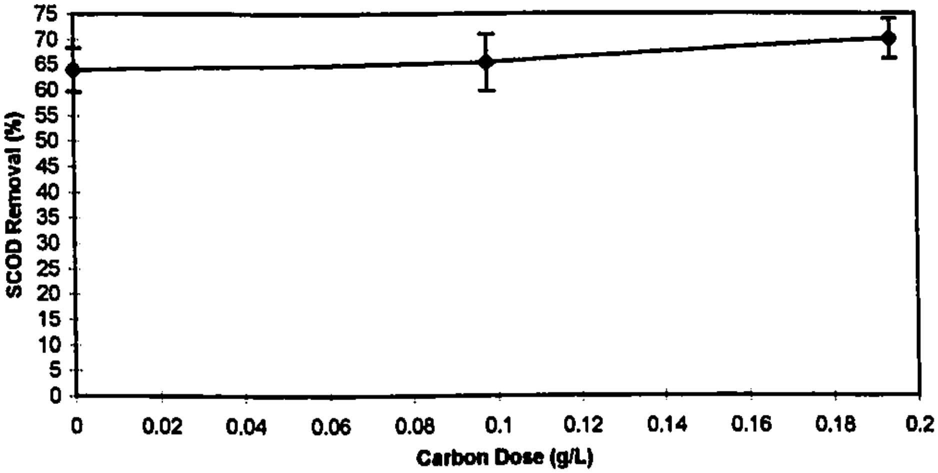

Figure 4-10: SCOD Removal Results as a Function of Carbon Dose for Nominal 11.4 Hours HRT and 7.3 Days SRT Runs, using Feed Batch # 2

At higher sludge ages than those tested for, potential slower growing microbes may be able to degrade some of the more recalcitrant compounds. These compounds would not be utilized otherwise (i.e. be considered biorefractory).

Table 4-13 shows the DOC removal results for this series of runs at 11.4 hours HRT. All results are based on single 3 day composites, measured in triplicate. A mean feed strength of 176.6 $^+/_-$ 9.0 mg C/L was used. Table 4-13 displays the relationship of DOC removal efficiency to carbon dose, at an SRT of 7.3 days. Removal efficiency between 69-76 % was found for all of these runs. There appears to have been little effect in the range of carbon doses of 0 to 0.2 g/L. Given these small differences in removal, the post - biodegradation organics appear not to be very adsorbable.

Table 4-13 shows the effect of sludge age on DOC removal for the control activated sludge reactors. The anomalous low DOC removal, of about 62 % at 16.8 days compared to the removals of 76.3 % at 23.8 days SRT and 75 % at 7.3 days SRT, might be attributed to high variability associated with biological systems. As was found for the SCOD, for this group of runs and the SCOD and DOC, for the runs using feed batch # 1, SRT, within the range tested, had little effect on removal efficiency. Table 4-13 may indicate less adsorption of DOC, for the 0.1 g/L C_D, at the higher SRT of 16.8 days compared to 7.3 day SRT or possibly biological system variability. More extensive sampling would have clarified the relationship between DOC removal and SRT.

SRT	Mean % DOC Removal		
(days)	Control	0.1 g/L C_D	0.2 g/L C_D
7.3	74.8	72.2	69.0
16.8	61.8	65.7	-
23.8	76.3	-	-

Table 4-13: Mean DOC Removal Results at 11.4 hours HRT, using Batch 2

Table 4-14 indicates the $(SCOD_{IN} - SCOD_{OUT})/(DOC_{IN} - DOC_{OUT})$ ratio for this group of runs. The values, between 2.3 and 2.7, are not unexpected for the controls, given the high cellulose and hemicellulose feed. It might have been expected that the PACT™ reactors yield lower ratios than the control reactors. However, given, the marginal results of increased SCOD and DOC removal, at these lower carbon doses, the similar $(SCOD_{IN} - SCOD_{OUT})/(DOC_{IN} - DOC_{OUT})$ ratios for PACT™ and activated sludge systems might have been expected. The results indicate that the non - biodegradable organics in the feed are not very adsorbable.

SRT (days)	Carbon Dose (g/L)	$\frac{(SCOD_{IN} - SCOD_{OUT})}{(DOC_{IN} - DOC_{OUT})}$
7.3	0	2.3
18.5	0	2.7
23.8	0	2.4
7.3	0.1	2.6
7.2	0.2	2.7
15.0	0.1	2.5

Table 4-14: $(SCOD_{IN} - SCOD_{OUT})/(DOC_{IN} - DOC_{OUT})$ ratios at 11.4 hours HRT, using Batch 2

Table 4-15 shows that $SBOD_5$ removal, for a feed strength of 195 '/. 21.6 mg O_2/L, was 94.8 - 95.9 % for all runs in this group. These values are all based on one three day composite, measured three times. As for the group 1 runs, removal of $SBOD_5$ by conventional activated sludge was near 100 %. This is consistent with the literature (Haberl et al., 1991, Cecen et al., 1992, Tomar and Allen, 1991). The $SBOD_5$/SCOD ratio of the feed was found to be 0.47, which is close to the value found for the group 1 runs.

SRT	Mean % $SBOD_5$ Removal		
(Days)	Control	0.1 g/L C_D	0.2 g/L C_D
7.3	95.4	94.8	95.6
16.8	95.6	95.2	
23.8	95.9		

Table 4-15: $SBOD_5$ Removal Results at 11.4 hours HRT, using Batch 2

The Microtox toxicity of the feed wastewater for this set of runs was EC_{50} = 15.4 % (Table 4-16). This indicates somewhat greater toxicity than found in the literature for BKME (EC_{50} = 25 % (Firth and Backman, 1990)). The effluents demonstrated essentially all greater than 100 % EC_{50}s. The 23.8 day SRT control and the 7.3 day PACT™ reactor with a 0.1 g/L carbon dose had EC_{50}s less than 100 %, but are not considered reliable given their wide 95 % confidence intervals. The EC_{20} or EC_{10} value is more appropriate for low toxicity samples (Binder, 1995; Microbics Corporation, 1992), because they can be more accurately determined. The EC_{20} values, associated with these runs, are 53 % or greater, considering the 95 % confidence intervals. Therefore, it is likely that the EC_{50} values (which should be greater than the EC_{20} values) are actually greater than 100 % or close to 100 %. Considering the wide confidence intervals, for the runs of this group, it is impossible to establish that the various reactor runs performed differently, in terms of toxicity removal.

Sample Source	EC$_{50}$ (%)		EC$_{20}$ (%)	
	Mean	95 % Confidence	Mean	95 % Confidence
Feed	15.4	13.8-17.1	3.7	2.9-4.7
7.3 day SRT Control	> 100	48.9-295.6	87.8	66.1-116.6
18.5 day SRT Control	>100		78.0	68.8-88.4
23.8 day SRT Control	87.6	32.1-229.1	87.6	62.4-123.0
7.3 day SRT with 0.1 g/L C$_D$	52.4	2.1-1280.0	94.0	52.7-167.4
15.0 day SRT with 0.1 g/L C$_D$	>100			
7.2 day SRT with 0.2 g/L C$_D$	>100		116.7	0.65-20881

Table 4-16: Microtox Results at 11.4 hours HRT, using Batch 2

Table 4-17 presents the soluble AOX (SAOX) removal efficiency data for this group of runs with a feed strength of 5.2 mg Cl/L (0.5 kg Cl/ADMT). All samples are based on a single three day composite. If a settled wastewater soluble AOX were 5.2 mg Cl/L, assuming 80 % of total AOX is soluble, then the total AOX in the influent would be 6.5 mg Cl/L. This is below the current MISA limit of 24.3 mg Cl/L, the Dec.31, 1995 MISA limit of 14.6 mg Cl/L (1.5 kg Cl/ADMT) and the Dec.31, 1999 MISA limit of 7.8 mg Cl/L (0.8 kg Cl/ADMT) (Section 4.1).

SRT	Mean % SAOX Removal		
(Days)	Control	0.1 g/L C_D	0.2 g/L C_D
7.3	15.4	17.3	32.7
16.8	11.5	26.7	
23.8	15.4		

Table 4-17: SAOX Removal Efficiencies at 11.4 hours HRT, using Feed Batch #2

From Table 4-17, it can be seen that the SAOX removals for the control reactors were lower than typical total AOX removals found in the literature, 19 - 65 % (Tomar and Allen, 1991, Randle et al., 1991, Haberl et al., 1991, Hall and Randle, 1992, Jokela et al., 1993). Since the influent concentration of SAOX was one third of the lowest SAOX influent values found in the literature (16 mg Cl/L), assuming 80 % of total AOX is soluble (Tomar and Allen, 1991), the kinetics of AOX removal may be substantially slower, than those in effect for the literature studies reviewed.

Table 4-17 indicates that SRT had little effect on SAOX removal for the control activated sludge reactors, which is consistent with the literature (Randle et al., 1991). Figure 4-11 indicates the superior removal of SAOX offered by the presence of carbon. At 7.3 days SRT, the removal increased to 32.7 % from 15.4 %, on the addition of 0.2 g/L carbon.

Table 4-17 also indicates that at 16.8 days SRT, the removal increased to 26.7 % from 11.5 %, on the addition of 0.1 g/L carbon. The higher removal associated with the addition of PAC, at the 16.8 day SRT, might indicate that there is less competitive adsorption at the 16.8 day SRT compared to the 7.3 day SRT. Alternatively, the SAOX might have been converted into a more adsorbable form. Experimental error may also be a factor, as the result is based on one analysis. Increased adsorption capacity is likely the cause for increased removal at the higher carbon dose, at 7.3 days SRT. Therefore, PAC additions to activated sludge systems may help in reaching stringent AOX standards. SAOX is expected to be completely removed by adsorption, given sufficient adsorption capacity. Possible explanations for the SAOX removal results being less than 100 % are insufficient adsorption capacity, competitive adsorption and operating at a pH at which some chlorinated compounds are ionized and therefore much less adsorbable.

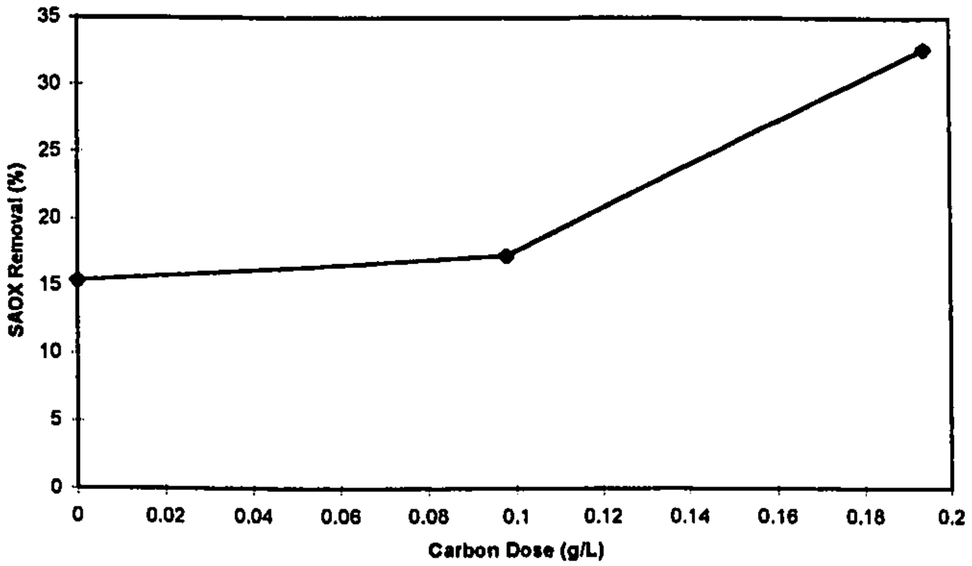

Figure 4-11: SAOX Removal as a function of Carbon Dose for 7.3 day SRT Reactor Runs, using Batch 2

Table 4-18 shows the sludge volume index results for the 7.3 days SRT runs. The lower the SVI, the better the settleability (Metcalf and Eddy, 1991). Table 4-18 and Figure 4-12 show the decrease in SVI accompanying an increase in carbon dose. The largest decrease occurs with the first 0.1 g/L carbon dose. The SVI of the control was excellent at 22 ml/g. Another bench scale study by Wessberg et al. (1994) tested BKME which used chlorine dioxide and oxygen bleaching. They reported an SVI of 25 ml/g at approximately 6.5 days SRT and 20 ml/g at approximately 13.5 days SRT. These SRTs were estimated, from the data given, assuming a yield coefficient of 0.6 g VSS/g BOD_5 and an endogenous decay coefficient of 0.06/d (Metcalf & Eddy, 1991).

Period	Carbon Dose (g/L)	MLTSS (mg/L)	Settled Volume (ml)	SVI (ml/g)	Critical SVI Factor	SVI Factor
Day 1	0	2480	55	22.2		
Day 1	0.096	4800	81	16.9	0.52	0.76
Day 1	0.194	5640	66	11.7	0.44	0.53
Day 2	0	2260	49	21.7		
Day 2	0.096	5120	78	15.2	0.44	0.70
Day 2	0.194	6100	67	11.0	0.37	0.51
Mean	0	2370	52	22.0		
Mean	0.096	4960	79.5	16.0	0.48	0.73
Mean	0.194	5870	66.5	11.3	0.40	0.51

Table 4-18: Settleability Results for the 7.3 days SRT Runs, using Batch 2

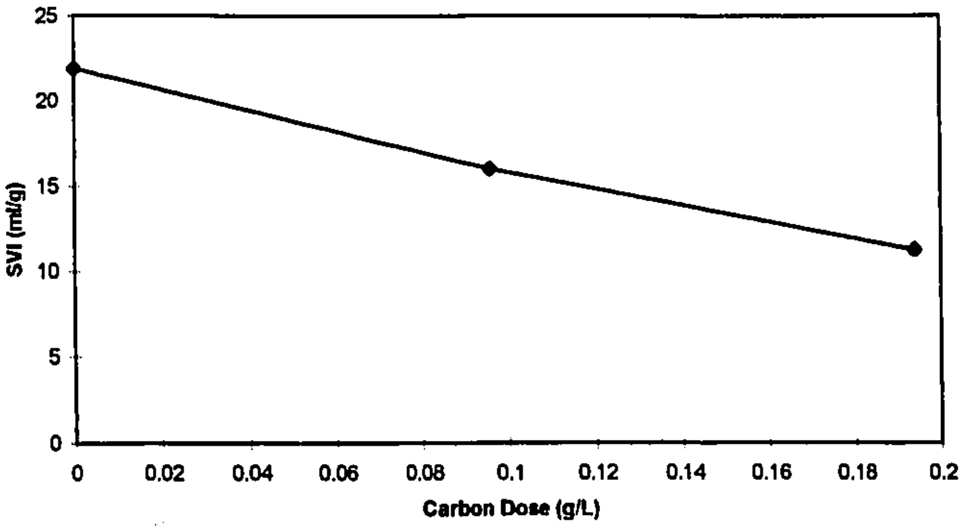

Figure 4-12: The Effect of Carbon Dose on SVI at 7.3 days SRT and 11.4 hours HRT, using Batch 2

Although SVI might be a useful parameter at a given plant, it is difficult to compare between plants since the characteristics of the feed and other conditions differ. Furthermore the MLTSS may differ. In the SVI test, 1 L of mixed liquor is placed in a one L cylinder and allowed to settle for 30 minutes, with one rpm mixing provided. SVI is defined by the following equation

$$SVI = \frac{settled\ volume(ml)}{MLTSS(g/L)*1\,L} \qquad \text{4-2}$$

The addition of PAC results in a more concentrated MLTSS. Hence, the recycle sludge stream to a PACT™ reactor, as opposed to an activated sludge reactor, must have a higher TSS concentration, for the same recycle flow. Therefore, it seems unreasonable to compare SVIs with and without PAC. To determine if there is a real advantage by using PAC, it might be better to introduce a critical SVI factor which is the MLTSS of the control divided by the MLTSS of the PACT™ reactor, which can be found in Table 4-18. If the SVI factor (i.e. the SVI of the PACT™ reactor divided by the SVI of the control reactor) is less than the critical SVI factor, then the PAC additions may have a truly positive effect on settling. However the SVI factor was found to be consistently higher than the corresponding critical SVI factor (Table 4-18). Therefore based on this criterion, the addition of carbon is not considered to be advantageous in terms of increased settleability, for BKME, under the conditions of this set of runs.

It should be recognized that solids flux analysis is more appropriate to the above analysis, but the data required for its use was not collected.

Table 4-19 shows the mean total suspended solids exit flows, in the waste and effluent streams, for the PACT™ and activated sludge reactors. To generate these values (as well those for the other groups of runs), daily flows were calculated and then an average of these values was computed. None of the effluent TSS losses met the 1995 MISA limit. However, because of the method of operation of the reactors, it would likely be misleading to compare effluent TSS losses, for PACT™ and activated sludge systems, to each other or to the MISA limit. The waste solids mass flowrates, for the PACT™ reactors, using relatively low carbon doses, were two to three times that of the controls, at the same sludge age. However, most of this additional waste mass flow would be expected to be PAC.

SRT (d)	C_D (g/L)	Waste (g/d)	% of Total to Waste	Effluent (g/d)	% of Total to Effluent
7.3	0	4.9	78	1.4	22
7.3	0.096	10.9	92	0.9	8
7.2	0.194	15.0	89	1.8	11
18.5	0	2.3	44	2.9	56
15.0	0.098	3.9	48	4.2	52
23.8	0	1.6	53	1.4	47

Table 4-19: Total Suspended Solids Loss in Waste and Effluent Streams, for the Second Group of Runs, at 11.4 hours HRT

The feed and effluents of this group of runs were analyzed by GC/MS. 4 - chloro - 3 - methylphenol, 2 - chlorophenol, 2,4 - dichlorophenol, 2,4 - dimethylphenol, phenol, 2,4,6 - trichlorophenol and pentachlorophenol were searched for but could not be detected. The detection limit was 3 - 10 ppb.

Studies using feed batch # 2 indicate that low carbon doses of 0.1 and 0.2 g/L yielded small increases of SCOD removal but significant increases in SAOX removal. The results for DOC were unclear. Calculated total AOX in the settled influent would meet the Dec. 31, 1999 MISA limit of 0.8 kg Cl/ADMT. SRT in the range of 7.3 - 23.8 days, as was the case for the runs using feed batch # 1, was found to have little effect on SCOD, DOC or SAOX removal. $SBOD_5$ removals were close to 100 % for all control and PACT™ runs, as was the case using feed batch # 1. Microtox results showed essentially total removal of toxicity for both activated sludge control and PACT™ reactor runs.

4.5 Runs with the Batch # 3 Feed

For this group of runs an HRT of 11.5 hours, was maintained. The carbon doses were however increased to get clearer results with respect to any advantages that the PACT™ process may have in treating BKME. Table 4-20 indicates the actual mean HRTs, SRTs and carbon doses used for this group of runs. For comparison purposes, the HRTs are designated as 11.5 hours, the SRTs as 7.6 and 14.2 days and the carbon doses as 0, 0.5 or 1.0 g/L. The mean mixed liquor total suspended solids, during the steady - state period, are also shown.

Reactor	HRT (hours)	SRT (days)	Carbon Dose (g/L)	MLTSS (mg/L)
1	11.5	8.4	0	3229
2	11.5	7.3	0.50	11230
3	11.6	7.4	1.0	18479
4	11.4	14.2	0.50	22077

Table 4-20 Actual HRTs, SRTs and carbon doses used and associated MLTSS, for the third group of runs

The temperature for all runs was within a 1.3°C range (Table 4-21), which was deemed to be acceptable. The pH dropped as low as 5.6, at certain times (Table 4-21) but appeared not to have any noticeable effect on SCOD removal efficiency or solids levels. The feed for this group of runs was, at times, particularly acidic and basic, because of variation between barrels. The variation was possibly due to discharge of chlorination and extraction stage solutions, of the bleach plant, somewhat separately and hence pH adjustment was necessary. The pH in the reactors was low towards the end of the steady -

state period, when samples were taken for $SBOD_5$, SAOX, DOC and specific organics. However, given the steady solids and SCOD removal data, it is unlikely that there was much effect on reactor performance.

Reactor	Temperature Range (°C)	pH Range
1	16.7 - 17.0	5.7 - 7.85
2	17.5 - 17.8	5.67 - 7.87
3	18	5.61 - 7.95
4	17.6 - 18.0	5.76 - 7.81

Table 4-21: Temperatures and pHs associated with the third group of runs

Figure 4-13 and Figure 4-14 depict the MLTSS, feed SCOD and effluent SCOD versus time for the 8.4 day SRT control and the 7.4 day SRT PACT™ reactor, with a 1.0 g/L carbon dose, respectively. Day 8 was taken as the beginning of the steady - state periods. Two and three day composite samples were measured, however only the middle or last day of each composite is shown in Figure 4-13 and Figure 4-14. For both reactors the effluent SCOD was fairly constant during the steady - state period despite large changes in the influent SCOD. Organic underloading of the systems was indicated since even though the feed strength varied, the effluent SCOD remained the same. It can be noted that the PACT™ reactor MLTSS was much more stable than the control reactor MLTSS.

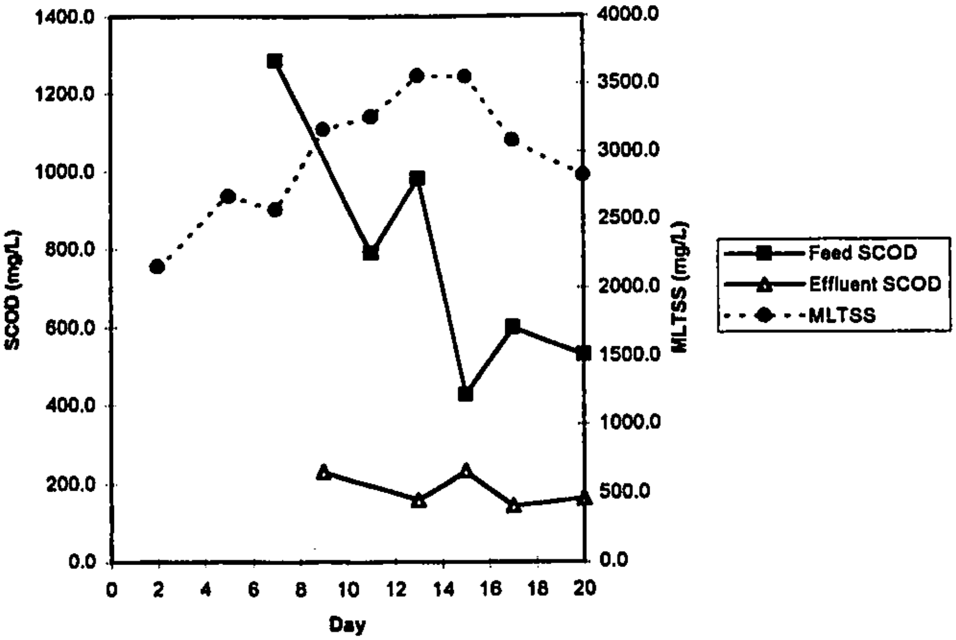

Figure 4-13: MLTSS, Feed SCOD and Effluent SCOD Progressions for the 8.4 day SRT Control Reactor, using Batch 3 (HRT = 11.5 hrs)

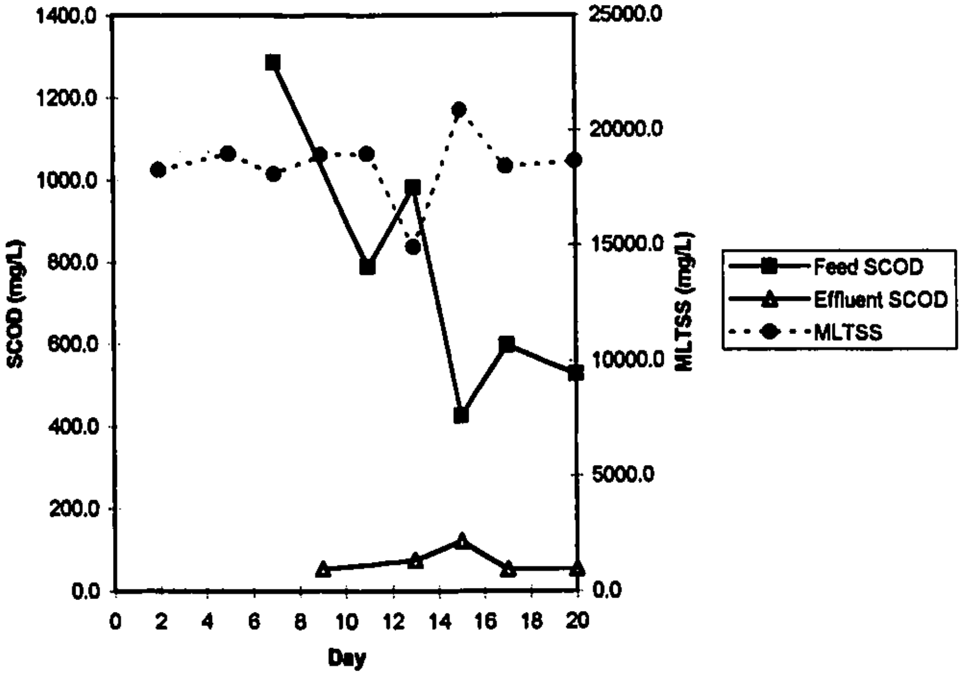

Figure 4-14: MLTSS, Feed SCOD and Effluent SCOD of the 7.4 day SRT PACT™ Reactor with 1.01 g/L Carbon Dose, using Batch 3 (HRT = 11.6 hrs)

Table 4-22 presents the SCOD removal results, at 11.5 hours HRT, for the runs of this group. The values presented are based on 4 two day composites and 1 three day composite. The influent SCOD was 721.3 ⁺/- 165.7 mg/L. Figure 4-15 shows the effect of carbon dose, from 0 to 1.0 g/L, at 7.2 - 7.6 days SRT on the efficiency of SCOD removal. The control reactor yielded 74.2 % removal while the 0.5 g/L carbon dose reactor 81.2 % removal and the 1.0 g/L C_D reactor 90.2 % removal. The same trend was found using feed batch # 2, which had similar operating conditions, with respect to the effect of carbon dose, as shown in Figure 4-15. However Figure 4-15 also demonstrates the differences in the two feeds, particularly by the different SCOD removal results for the controls.

	% SCOD Removal					
SRT	Control		0.5 g/L C_D		1.0 g/L C_D	
(Days)	Mean (%)	95 % C.I.	Mean (%)	95 % C.I.	Mean (%)	95 % C.I.
7.6	74.2	70.4-78.0	81.2	78.5-83.9	90.2	88.4-92.0
14.2			83.0	80.0-86.0		

Table 4-22: SCOD Removal Results at 11.5 hours HRT, using Feed Batch # 3

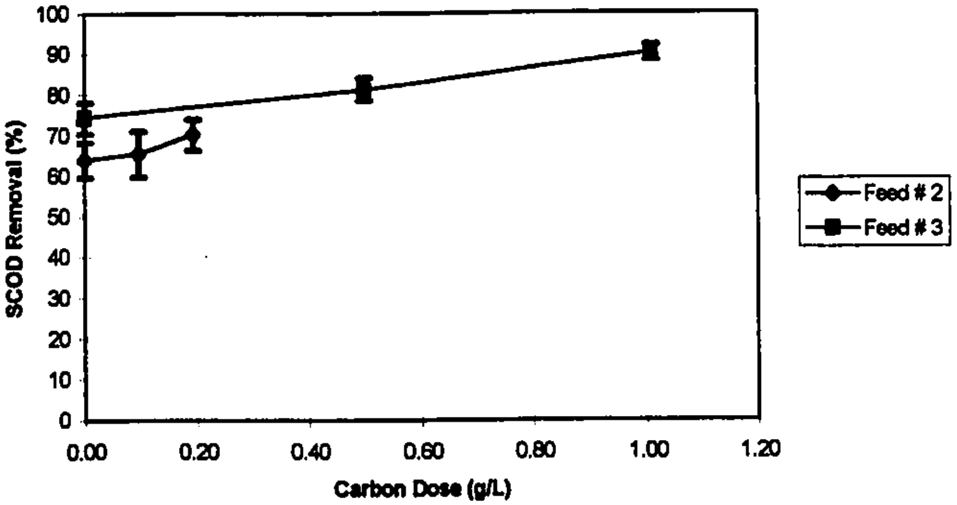

Figure 4-15: SCOD Removal for nominal 11.5 hours HRT and 7.2 - 7.6 days SRT, using Batches 2 and 3 (95 % confidence intervals are shown)

Within the range of SRT, of 7.3 - 14.2 days, it appears that SRT had little effect on SCOD removal, at the operating conditions of these runs (Table 4-22). Approximately 82 % SCOD removal was obtained using a 0.5 g/L carbon dose for both the 7.6 and 14.2 day SRTs.

Table 4-23 gives the DOC removal results for the runs of this group, using an average feed strength of 243.0 ⁺/₋ 4.6 mg C/L. The DOC removal efficiencies demonstrate the same trend as the SCOD results. All values are based on a single 3 day composite, analyzed in triplicate (i.e. measured 3 times). Figure 4-16 shows the impact of carbon dose on the removal of DOC. The effect was greater at these higher carbon doses than it was using the lower carbon doses of the second group of runs. Table 4-23 suggests a lack of importance of sludge age, in the removal of DOC, at least within the SRT range tested.

SRT	Mean % DOC Removal		
(Days)	Control	0.5 g/L C_D	1.0 g/L C_D
7.6	74.8	84.0	92.7
14.2		80.6	

Table 4-23: DOC Removal Results at 11.5 hours HRT, using Batch 3

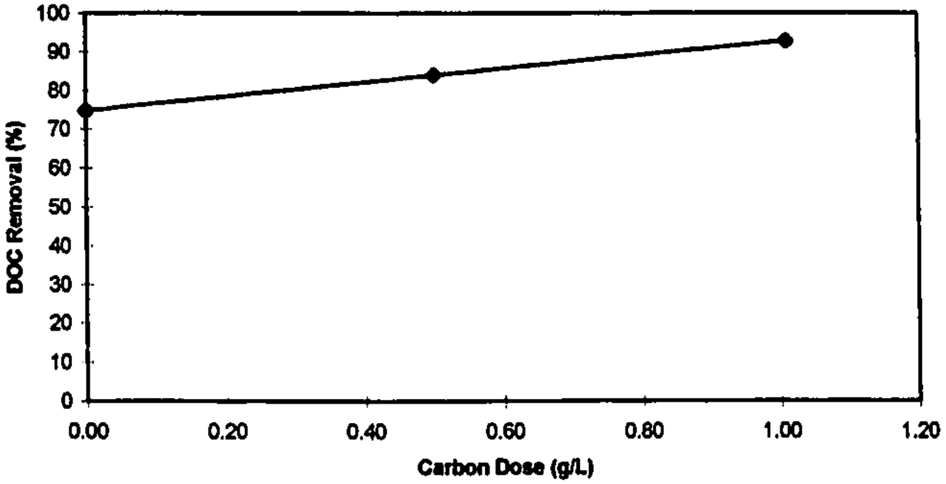

Figure 4-16: DOC Removal for nominal 11.5 hours HRT and 7.6 days SRT, using Feed Batch #3

Table 4-24 shows a similar trend as was found for the runs using feed batch # 2 for the ratio ($SCOD_{IN}$ - $SCOD_{OUT}$)/(DOC_{IN} - DOC_{OUT}). Feed batch 2 yielded a range of ratios of 2.3 to 2.7, while feed batch 3 yielded a range of 2.2 to 2.3. All values are based on a single 3 day composite sample measured in triplicate. The compounds removed by adsorption appear to have had a SCOD/DOC ratio of 2.3, which was the expected ratio using biological treatment, alone, for this feed (with high concentration of cellulose and hemicellulose).

SRT (days)	Carbon Dose (g/L)	$\frac{(SCOD_{IN} - SCOD_{OUT})}{(DOC_{IN} - DOC_{OUT})}$
8.37	0	2.2
7.26	0.50	2.2
7.37	1.0	2.3
14.2	0.50	2.3

Table 4-24: $(SCOD_{IN} - SCOD_{OUT})/(DOC_{IN} - DOC_{OUT})$ ratios at 11.5 hours HRT, using Feed Batch # 3

Table 4-25 shows the $SBOD_5$ removal results for this group of runs, with an average feed concentration of 400 +/- 20 mg O_2/L. All feed and effluent values were based on a single 2 day composite sample, measured using 3- 6 replicate analyses. The feed $SBOD_5$/SCOD ratio was found to be 0.47, which is in the same range found for the groups 1 and 2 runs.

The $SBOD_5$ removals for the 7.6 days SRT reactors were very high; about 99 % in all cases. The 14.2 day SRT run only yielded 80 % removal. The pH of the effluent from this reactor increased during the two days $SBOD_5$ sample was collected. Thus the reactor may have been in a state of unusual stress during this time, for unknown reasons. Therefore, it is expected that if the $SBOD_5$ analysis was done with effluent collected earlier, the same results would have been obtained as at 7.6 days SRT. The reactor was not run longer because of lack of feed.

SRT	Mean % $SBOD_5$ Removal			Mean % $TBOD_5$ Removal		
(Days)	Control	0.5 g/L C_D	1.0 g/L C_D	Control	0.5 g/L C_D	1.0 g/L C_D
7.6	98.4	98.8	99.0	98.3	98.0	98.6
14.2		80.2			76.7	

Table 4-25: $SBOD_5$ and $TBOD_5$ Removal Results at 11.5 hours HRT, using Feed Batch #3 (Feed $SBOD_5$ = Feed $TBOD_5$ = 400 +/- 41 mg/L)

The $TBOD_5$ removal results, in Table 4-25, are essentially the same as for the $SBOD_5$ values, taking into account the variability of the BOD_5 test. The feed strength was the same as for $SBOD_5$. This points to very little degradable VSS remaining in the influent after settling.

Table 4-26 presents the Microtox data for this group of runs. Feed and effluent values were determined from single 3 day composites and a single analysis. The feed Microtox result, EC_{50} = 13.7 %, for this group of runs, at 11.5 hours HRT, indicates somewhat greater toxicity than found in the literature but was similar to the feed used for the second group of runs. The effluents yielded EC_{50}s that were essentially all greater than 100 %. An EC_{50} value of greater than 100 % implies that a higher concentration of toxins, than present in the original sample, is required to decrease the light output of the Microtox bacteria by 50 %. The 8.4 day SRT control and the 7.3 day PACT™ reactor with a 0.5 g/L carbon dose had EC_{50}s less than 100 %, but these values had wide 95 % confidence intervals that included 100 %. It is likely the EC_{50}s associated with these runs were actually greater than or close to 100 %. Given the closeness of the EC_{20} values for this group of runs and the width of the affiliated 95 % confidence intervals, it is impossible to differentiate between the various reactor runs, as for the first two groups of runs.

Sample Source	EC_{50} (%)		EC_{20} (%)	
	Mean	95 % Confidence	Mean	95 % Confidence
Feed	13.7	7.4-25.2	4.1	2.0-8.5
8.2 day SRT Control	74.5	25.6-216.6	45.8	20.3-103.6
7.2 day SRT with 0.5 g/L C_D	90.5	59.8-137.0	41.7	31.9-54.5
7.4 day SRT with 1.0 g/L C_D	>100		46.0	34.8-60.9
14.2 day SRT with 0.5 g/L C_D	>100			

Table 4-26: Microtox Results at 11.5 hours HRT using Feed Batch #3

The SAOX removal results, with an average a feed concentration of 13.1 mg Cl/L, are presented in Table 4-27. All feed and effluent values were based on single measurements, of a two day composite. At 7.6 days SRT, there was a trend of increasing SAOX removal with increasing carbon dose (Figure 4-17), possibly due to increased adsorption capacity or kinetics. Although for feed batch # 2, there was also an increase in SAOX removal with increasing carbon dose, the form of the increase was sharper than for the runs using feed batch # 3 (Figure 4-17). This suggests a difference between the two feeds.

For the 14.2 days SRT and 0.5 g/L carbon dose reactor, there was an anomalous result. This was likely due to stress experienced by this reactor, during the sampling for SAOX. Similar anomalous poor performance, of this reactor, was also observed in terms of SCOD, BOD_5 and DOC. SCOD removal dropped from a steady 80 % to 65 %, during this time.

The influent total AOX can be estimated, as per the calculation in Section 4.1, as 16.4 mg Cl/L. Assuming all solid AOX is removed by flocculation and coagulation, the total AOX in the effluent, from all reactors, would meet the 1999 MISA limit of 7.8 mg Cl/L. The highest effluent TAOX was estimated to be 6.6 mg Cl/L. If the solid AOX were removed at the same efficiency as the SAOX, then the highest TAOX effluent, of the healthy 7.6 day SRT reactors, would be 7.8 mg Cl/L, the 1999 MISA limit. PAC additions could help meet this future standard.

SRT	Mean % SAOX Removal		
(Days)	Control	0.5 g/L C_D	1.0 g/L C_D
7.6	52.7	67.2	77.1
14.1		49.6	

Table 4-27: SAOX Results at 11.5 hours HRT, using Feed Batch #3

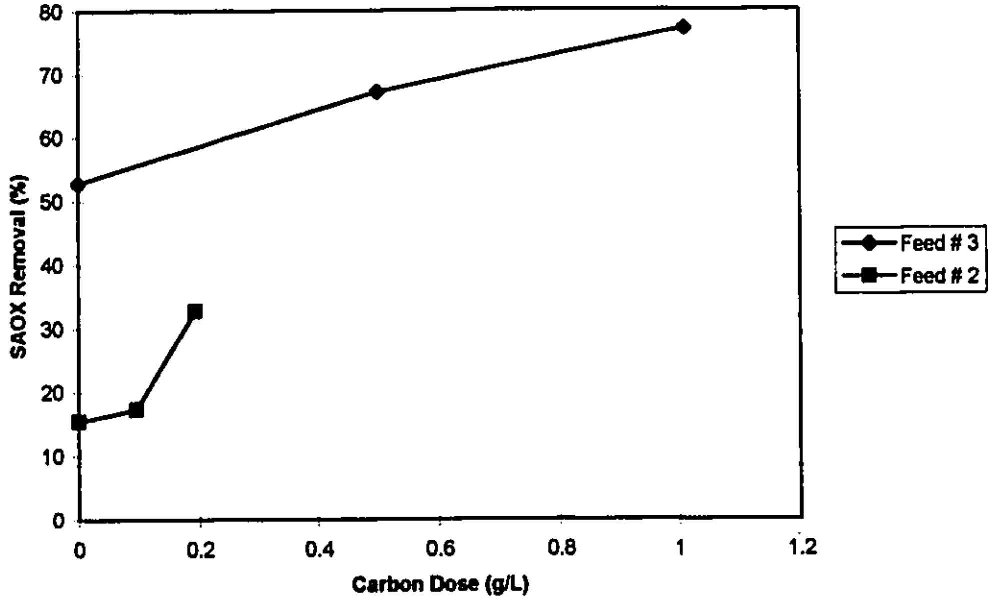

Figure 4-17: SAOX Removal as a function of Carbon Dose for the 7.6 day SRT Reactor Runs, using Feed Batches 2 and 3

Table 4-28 gives the sludge volume index results for the 7.6 days SRT runs. This table shows a decrease in SVI accompanying an increase in carbon dose. The largest decrease occurs with the first 0.5 g/L carbon dose added. The SVI of the control (70.2 ml/g) was moderate when one compares it to the previous set of runs (22 ml/g) and the literature (20 - 25 ml/g) (Wessberg et al., 1994).

Period	Carbon Dose (g/L)	MLTSS (mg/L)	Settled Volume (ml)	SVI (ml/g)	Critical SVI Factor	SVI Factor
Day 1	0	2822	182	64.5		
Day 1	0.5	10643	149	14.0	0.27	0.22
Day 1	1.01	18588	158	8.5	0.15	0.13
Day 2	0	2556	194	75.9		
Day 2	0.5	9730	144	14.8	0.26	0.19
Day 2	1.01	17529	149	8.5	0.15	0.11
Mean	0	2689	188	70.2		
Mean	0.5	10186	146	14.4	0.26	0.21
Mean	1.01	18059	154	8.5	0.15	0.12

Table 4-28: Settleability Results for the 7.6 days SRT Runs, using Batch 3

Figure 4-18 shows that large decreases in SVI were associated with the addition of carbon at 0.5 and 1 g/L doses. The largest decrease accompanies the 0.5 g/L carbon dose. This is the same trend as found using feed batch # 2. Table 4-28 shows that the mean SVI factors are lower than the critical SVI factors. Thus, for this feed batch, there was an increase in settleability associated with the addition of PAC, beyond that expected from an increase in MLTSS.

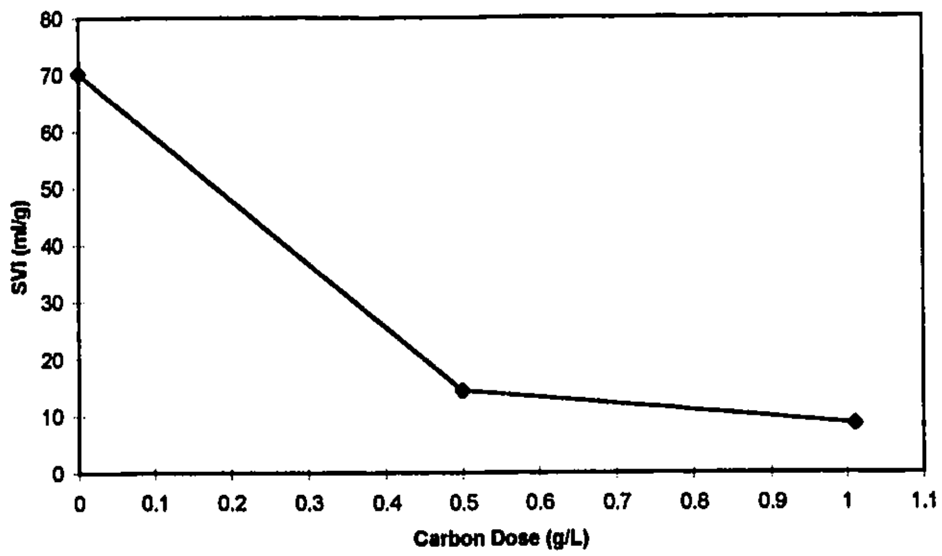

Figure 4-18: The Effect of Carbon Dose on SVI for the 7.6 Days SRT runs

Table 4-29 shows the mean total suspended solids exit flows, in the waste and effluent streams, for the PACT™ and activated sludge reactors. Daily mass flows were calculated, from volumetric flowrate and concentration data and then an average of these values was computed. Effluent TSS flows did not meet the 1995 MISA TSS upper limit of 7.9 kg TSS/ADMT; this was caused by intensive mixing in the clarifier zones of the reactors. Because of the method of operation of the reactors, it would likely be misleading to compare effluent solids loss, for PACT™ and activated sludge systems. The waste TSS flows, for the PACT™ reactors, using relatively high carbon doses, were four to six times that of the control, at the same sludge age, as expected.

SRT (d)	C_D (g/L)	Waste (g/d)	% of Total to Waste	Effluent (g/d)	% of Total to Effluent
8.4	0	7.3	82	1.6	18
7.3	0.50	31.9	94	2.0	6
7.4	1.0	49.2	90	5.4	10
14.2	0.497	29.5	86	4.7	14

Table 4-29: Total Suspended Solids Loss in Waste and Effluent Streams, for the Third Group of Runs, at 11.5 hours HRT

The feed of this group of runs was analyzed by GC/MS. 4 - chloro - 3 - methylphenol, 2 - chlorophenol, 2,4 - dichlorophenol, 2,4 - dimethylphenol, phenol, 2,4,6 - trichlorophenol and pentachlorophenol were searched for but could not be detected.

The results from this group of runs clearly show the advantages of the PACT™ process. At 7.6 days SRT, SCOD removal was increased from 74.2 % to 90.2, DOC removal was increased from 74.8 to 92.7 % and SAOX removal was increased from 52.7 to 77.1 %, using a carbon dose of 1 g/L. Calculated total AOX of all treated effluents would meet Dec. 31, 1999 MISA limits. Therefore PAC additions would not be required to meet this future standard. SRT did not affect SCOD removal. The $SBOD_5$ and $TBOD_5$ removals were 98 - 99 % for all runs, except the upset 14.1 day SRT run. The PACT™ reactor effluents all had essentially EC_{50} of greater than 100 %.

4.6 Runs with the Batch # 4 Feed

For this group of runs the HRT was lowered from 11.4 to about 7 hours in order to stress the systems. A carbon dose of 0.5 g/L was chosen because it was feared that for higher PAC doses, at the lower HRT (therefore higher SRT/HRT concentration ratio) the mixed liquor would be so thick as to inhibit mixing. The target HRT was 5.8 hours but because of a feed pump failure the control reactor had an HRT of 7.8 hours. Table 4-30 presents the actual HRTs, SRTs and carbon doses used for this group of runs. However, for comparisons HRTs are designated as 6.8 hours, SRT 7.3 days and carbon doses 0 and 0.5 g/L. The mixed liquor total suspended solids, during the steady - state period, are also indicated.

Reactor	HRT (hours)	SRT (days)	Carbon Dose (g/L)	MLTSS (mg/L)
1	7.8	7.4	0	5104
2	5.7	7.1	0.494	23068

Table 4-30: Actual HRTs, SRTs and Carbon Doses used and Associated MLTSS, for the Fourth Set of Runs

The temperatures and pHs associated with this group of runs, given in Table 4-31, were deemed to be acceptable. The temperatures of the two reactors were close to one another and representative of temperatures used in biological treatment. pH was within the usual range of 6 to 8 for an activated sludge system.

Reactor	Temperature Range (°C)	pH Range
1	18.5 - 20.0	6.9 - 7.42
2	19.0 - 20.0	6.08 - 7.00

Table 4-31: Tempertures and pHs Associated with the Fourth Group of Runs

Figure 4-19 and Figure 4-20 present the MLTSS, feed SCOD and effluent SCOD progressions for the control and PACT™ reactors. Some of the values shown in these figures are based on the analysis of 2 day composite samples. In these cases, only the second day of the composites are shown in the figures. The feed SCOD variability was possibly predominately due to different initial microbial loads in the barrels. Although the feed SCOD varied, the effluent SCOD of the PACT™ reactor was quite steady. This exemplifies one of the main advantages of the PACT™ system - steady performance under variable loading and stressed conditions (Hutton, 1978).

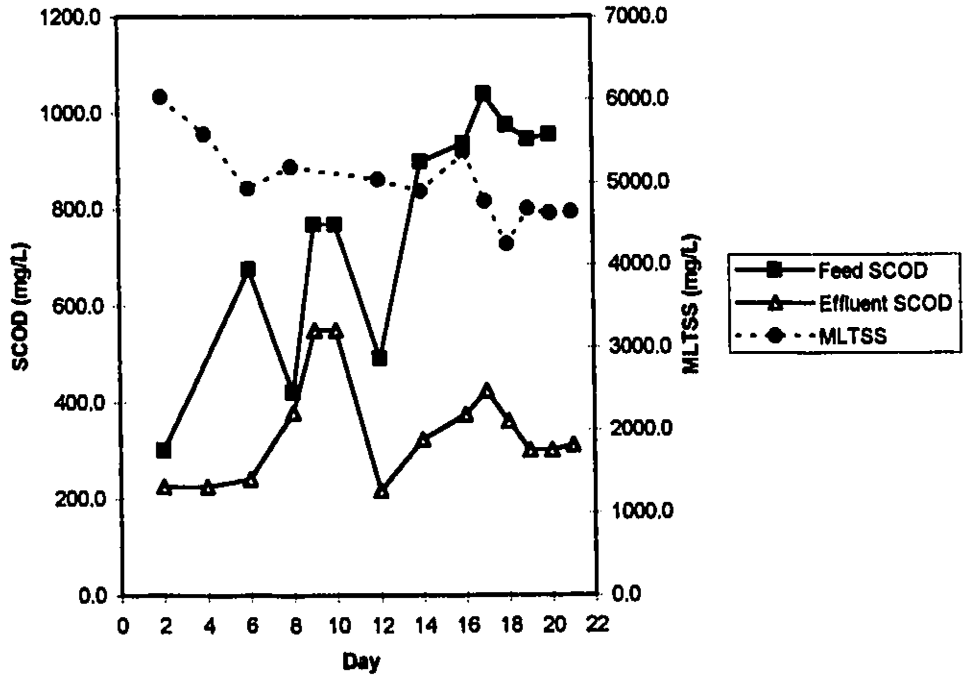

Figure 4-19: MLTSS, Feed SCOD and Effluent SCOD Progressions for the Control Reactor, using Batch 4

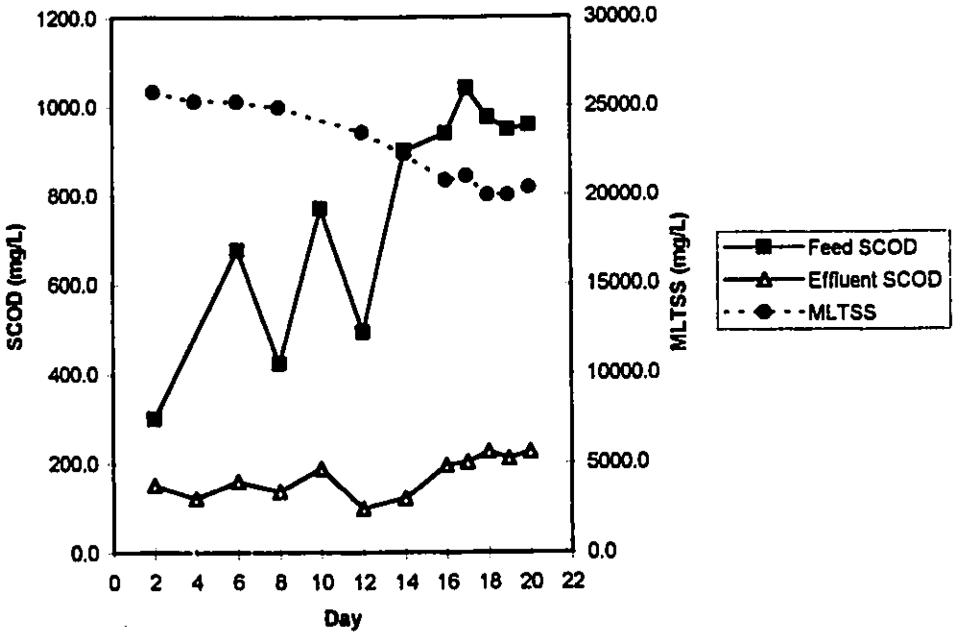

Figure 4-20: MLTSS, Feed SCOD and Effluent SCOD Progressions for the PACT™ Reactor, using Batch 4

It must be noted that while the MLTSS progressions for the two reactor runs show that a steady - state was reached, the SCOD data show steady - state being reached only at the end of the runs. Ideally the runs would have been continued for another couple of days, but the feed had run out.

Table 4-32 contains the mean % SCOD, DOC, $SBOD_5$ and $TBOD_5$ removals from the two runs at nominal 6.8 hours HRT and 7.3 days SRT. One run was operated as a control while the other had a carbon dose of 0.5 g/L.

The SCOD removal results were based on 4 samples, collected during the steady - state period. The SCOD removal for the 0.5 g/L carbon dose reactor was about 77 % while the control reactor had a removal of about 68 %. The 95 % confidence intervals did not overlap. This may point to a small non - biodegradable but adsorbable complement, for this feed. Insufficient adsorption capacity or kinetics may have limited the extent of adsorption.

Table 4-32 points to very little difference between control and PACT™ reactor DOC removal, with about 64 % DOC removal in both cases. The higher ($SCOD_{IN}$ - $SCOD_{OUT}$)/(DOC_{IN} - DOC_{OUT}) ratio associated with the 0.494 g/L carbon dose reactor (4.9) compared to the control reactor (4.2) is contrary to what might be expected. When activated carbon removes (through adsorption) some SCOD contributing compounds, all of the DOC associated with these compounds is also removed. In contrast, when biological action oxidizes compounds, the DOC associated with these compounds may not be removed (as CO_2). Hence, the above anomalous result may be due to the variability of biological systems.

The $SBOD_5$/SCOD ratio for this feed was found to be 0.53, similar to feed batch # 1, 0.55. Table 4-32 indicates greater than 96 % removal for $SBOD_5$ and greater than 92 % removal for $TBOD_5$, for both reactors. These $SBOD_5$ removal values were very similar to the steady - state values for the other runs, indicating near 100 % $SBOD_5$ removal. The complement of solid BOD_5 in the feed was small compared to the $SBOD_5$.

SAOX results showed a great improvement for the PACT™ reactor, 35.3 %, compared to the control, 21.6 % (Table 4-32). The influent total AOX was calculated (Section 4.1) to have been 14.5 mg Cl/L. If it is assumed solid AOX was removed at the same efficiency as the SAOX, then the control had an effluent with 11.4 mg Cl/L while the

PACT™ reactor effluent had 9.4 mg Cl/L. Hence the PACT™ and control reactors did not meet the 7.8 mg Cl/L Dec. 31, 1999 MISA limit.

Parameter	Feed Strength	Carbon Dose (g/L)	Mean Removal (%)	C.I. (+/-)
SCOD	980.0 +/- 67 mg O_2/L	0	67.6	65.1-70.2
		0.5	76.8	73.6-80.0
DOC	236.6 +/- 23 mg C/L	0	65.7	-
		0.5	63.3	-
$SBOD_5$	505.0 +/- 23 mg O_2/L	0	97.9	-
		0.5	96.7	-
$TBOD_5$	501.0 +/- 32 mg O_2/L	0	92.8	-
		0.5	95.2	-
$\frac{(SCOD_{IN} - SCOD_{OUT})}{(DOC_{IN} - DOC_{OUT})}$	-	0	4.2 (ratio)	-
	-	0.5	4.9 (ratio)	-
SAOX	11.6 mg Cl/L	0	21.6	-
		0.5	35.3	-

Table 4-32: Water Quality Parameter Removals for Nominal 6.8 Hours HRT and 7.3 Days SRT Runs, using Batch 4

Table 4-33 presents the Microtox data from the runs at 6.8 hours HRT. Notably, the feed toxicity was found to be extremely high, 3.1 %. The effluents had EC_{50}s of 44.4 % for the control and 65.5 % for the PACT™ reactor, that indicate they were significantly more toxic than the effluents from the first three groups of runs, which had or are presumed to have had EC_{50}s slightly below or greater than 100 %. The results also indicate that the PACT™ reactor yielded less toxicity than the control under this stressed condition of low HRT and high organic loading. Apparently some toxic compounds could not be degraded but could be adsorbed.

Sample Source	EC_{50} (%)	95 % Confidence Interval	EC_{20} (%)	95 % Confidence Interval
Feed	3.1	3.0-3.3	0.97	0.88-1.07
7.2 day SRT Control	44.4	37.4-52.8	14.7	8.4-25.8
7.2 day SRT with 0.5 g/L C_D	65.5	50.7-84.5	36.8	25.2-53.8

Table 4-33: Microtox Results at 5.8 hours HRT, using Batch 4

Table 4-34 shows the mean total suspended solids exit flows, in the waste and effluent streams, for the PACT™ and activated sludge reactors. The method of operation of the reactors did not permit a meaningful comparison, in terms of effluent TSS loss, between the PACT™ and activated sludge reactors. Because of the mode of operation of the reactors, the effluent TSS far exceeded the 1995 MISA TSS upper limit of 7.9 kg TSS/ADMT. The waste solids flows, for the PACT™ reactor, was ten times that of the control, as expected.

SRT (d)	C_D (g/L)	Waste (g/d)	% of Total to Waste	Effluent (g/d)	% of Total to Effluent
7.4	0	9.6	47	10.9	53
7.1	0.494	97.3	83	20.1	17

Table 4-34: Total Suspended Solids Loss in Waste and Effluent Streams, for the Fourth Group of Runs, at 6.8 hours HRT

The feed of this group of runs was analyzed by GC/MS. 4 - chloro - 3 - methylphenol, 2 - chlorophenol, 2,4 - dichlorophenol, 2,4 - dimethylphenol, phenol, 2,4,6 - trichlorophenol, pentachlorophenol were searched for but could not be detected (detection limit 3 - 10 ppb). Naphthalene and camphene also could not be detected.

For the fourth group of runs, the PACT™ reactor yielded 9 % higher SCOD removal than the control. The increase in SCOD removal was similar to the increase found using the third feed batch, comparing the same SRT and carbon dose PACT™ and control reactor pairs. SAOX results showed a greater removal in the PACT™ reactor, with an additional 14 % removal, as compared to the control, with 21.6 % removal. The PACT™ and control reactors did not meet the Dec. 31, 1999 MISA AOX limit. Additionally, Microtox results showed better performance for the PACT™ reactor, EC_{50} = 65.5 % (effluent), compared to the control reactor, EC_{50} = 44.4 % (effluent), using a very toxic feed (EC_{50} = 3 %), at a low HRT.

4.7 Summary of the Four Groups of Runs

Four different feeds of bleached kraft mill effluent were used for 8 control activated sludge and 10 PACT™ reactor runs. Carbon doses of 0.1 to 1.0 g/L were used. SRT, in the range of 7 - 25 days, for HRTs in the range of 11 - 40 hours, has shown to have little effect on SCOD, $SBOD_5$, DOC and AOX (AOX was measured for 3 of the feeds) removals, for both control activated sludge and PACT™ reactors.

$SBOD_5$ was removed to 95 % or greater efficiency, in all the runs. Hence, given the analytical error involved in the $SBOD_5$ test, there was no difference between control and PACT™ $SBOD_5$ removals. These results agreed with the literature, for other wastewaters.

Microtox toxicity removal was close to 100 % or greater, for all control activated sludge and PACT™ reactor run effluents, for 3 of the feed batches. For the fourth feed batch, the PACT™ system yielded a slightly better Microtox toxicity removal compared to the control.

SCOD removal for the control runs was found to be in the range of 64 to 74 %. With the addition of 0.2 to 1.0 g/L carbon dose, SCOD removal was increased by 6 to 16 %, respectively.

SAOX removal for the control runs was found to be 15 to 53 %. The corresponding PACT™ reactors, with 0.2 to 1.0 g/L carbon dose, yielded 18 to 24 % higher SAOX removals. Calculated TAOX, for all PACT™ and activated sludge system effluents, for two of the three feed batches tested, were below the Dec. 31, 1999 MISA limit of 0.8 kg Cl/ADMT. The control and PACT™ runs, of the other feed batch which was tested for SAOX, did not meet the limit. Since the MISA best available technology (McCubbin Consultants, 1992) recommends activated sludge as the only external treatment, the above result is not surprising. The treatment of the fourth feed batch, which was quite toxic, indicated that activated sludge treatment may not be sufficient to reach the 1999 MISA limit.

Simple adsorption of influent compounds and/or MEPs was the likely mechanism of PACT™ increased performance over the activated sludge system, in this study, as suggested by the similar BOD_5 removals for PACT™ and control systems. However, enhanced bioactivity could not be ruled out.

4.8 Kinetics Results

The kinetic coefficients, the yield coefficient and the endogenous decay coefficient as well as a model for the rate of substrate utilization were determined, for the control activated sludge system. It is likely that stripping of SCOD was very small (Droste, 1995). Furthermore, biosorption of SCOD was likely minor (Weber et al., 1987; Dewalle et al., 1977) and was therefore combined with biodegradation of SCOD.

4.8.1 Y and k_d Determination

For the determination of Y, the yield coefficient and k_d, the endogenous decay coefficient, a total COD balance was performed, using single three day composite samples, collected during the steady state period, for the group 2 control reactors. Three points, with 3 different SRTs, were used for the determination of Y and k_d. The temperature in all reactors was approximately 16.2 ⁺/₋ 1°C.

The following equation (Metcalf and Eddy, 1991) was regressed using the Excel 5.0c regression Data Analysis tool:

$$\frac{1}{SRT} = Y * U - k_d \qquad \text{4-3}$$

where U is the specific utilization rate (mg substrate/(mg VSS*d)) and is defined as

$$U = \frac{(S_i - S_t)}{(X * \Theta)} = \frac{r_{tu}}{X} \qquad \text{4-4}$$

where S_i is the influent total COD concentration (mg COD/L), S_t is the total effluent COD concentration, r_{tu} is the utilization rate of total substrate (mg COD/(L*d)) and X is the non - inert VSS concentration (mg VSS/L). Average waste flows, average effluent flows, average mixed liqour SCOD concentrations and average effluent SCOD concentrations were determined. From these values, a flowrate weighted average of the waste and effluent SCOD concentrations was found.

To estimate the active biomass VSS, inert VSS in the influent must be subtracted from the MLVSS. This was done as follows. The estimation was based on 93 % degradation of influent solids BOD_5 (assumed to be due to VSS), using feed batch # 1 runs, for which total BOD_5 was measured, in addition to the $SBOD_5$. Although the four feeds were quite different, they all yielded very similar BOD_5 values. Hence, using feed batch #1 BOD_5 values to predict feed batch #2 BOD_5 values is likely to be acceptable. The influent inert VSS was estimated to have been 7 % of the total influent VSS. The SRT/HRT concentration ratio determines the actual influent inert VSS concentration in the reactors.

The regression of equation 4-3, in finding Y and k_d, yielded a R^2 value of 0.96. Both Y at 0.47 g VSS/g COD and k_d at 0.053/d (Table 4-35) fall in the range commonly found for domestic wastewater (at 20 °C) of 0.4 - 0.6 g VSS/g COD (Grady and Lim, 1980) and 0.025 - 0.075/d (Metcalf and Eddy, 1991). The assumptions that: a) errors have constant variance; b) errors are uncorrelated with each other; and c) errors are normally distributed cannot be verified with the small data set used (Hamilton, 1992, Chapter 4). These assumptions need to be satisfied in order to apply the t test, required to calculate confidence intervals. Hence the calculation of confidence intervals would be inappropriate and possibly misleading (Hamilton, 1992, Chapter 4).

Parameter	Value
Y	0.47 g VSS/g COD
k_d	0.053/d

Table 4-35: Y and k_d determination via total COD balance

4.8.2 Substrate Utilization Rate Expression Determination

The determination of a form for the rate of COD substrate utilization was carried out for the group 1 and group 2 control data. The other groups of data only had one control and were therefore not amenable to the determination of rate constants. The method used for the determination of a rate expression, will be demonstrated for the group 2 data.

In order to estimate the degradable SCOD concentration (at each SRT), the non - biodegradable SCOD concentration (a constant) must be subtracted from the total (degradable and non - degradable) SCOD concentration (at each SRT). The non - degradable SCOD concentration can be estimated as the lowest SCOD concentration attained minus the lowest degradable SCOD concentration attained at the three SRTs. The lowest degradable SCOD concentration was somewhat arbitrarily estimated to be three times the lowest $SBOD_5$ concentration attained at the three SRTs (8 mg/L), namely 24 mg/L, since the factor, 3, has been reported for domestic and industrial wastes (Eckenfelder, 1980). The non - degradable SCOD was found, by this method, to be 88 mg SCOD/L. However, if the lowest degradable SCOD concentration were to have been estimated to be 1 to 5 times the the lowest $SBOD_5$ concentration, the following analysis would be essentially unaffected.

Degradable SCOD values for the effluent are given by S, below. The models tested include Monod, first order in S, first order in X, first order in XS and zero order. All reaction rates were adjusted to 20 °C, using a temperature activity coefficient of 1.04 (Metcalf and Eddy, 1991). The model fits can be found in Table 4-36 and Figure 4-21 - Figure 4-24. Four points (including 0,0) were used except in Figure 4-21 which shows the fitting of the Monod model, which is given below.

$$r_{su} = \frac{kXS}{K_s + S} = \frac{S_i - S_e}{\Theta * TC} \qquad \text{4-5}$$

where r_{su} is the rate of degradable soluble substrate utilization (mg COD/(L*d)), k is the maximum specific substrate utilization rate coefficient (mg COD/(mg VSS*d)), X is the VSS concentration (mg/L), used as an approximation of biomass activity, K_s is the half velocity constant (mg COD/L), Θ is the hydraulic retention time (days) and TC is the temperature correction factor ($1.04^{(T-20°C)}$). A Hanes plot, SX/r_{su} plotted against S, was used. This is considered the best method to plot the Monod equation (Grady and Lim, 1980). k was determined from taking the reciprocal of the slope and K_s was found by noting that the y intercept is K_s times the slope. The best line finds a very low k of 0.22/d and a very low value for K_s of 0.57 mg COD/L.

The first order models all had a poorer fit than the zero order model. This means r_{su} is a constant, k, except at S = 0, where $r_{su} = 0$. A value of k of 574 mg SCOD/(L*d) was found. This can be explained by assuming a Monod model, without X, but with S much higher than the half maximal velocity coefficient, K_s. X, the VSS concentration, may not correlate well with r_{su} because the active biomass concentration is relevant and this may be the same at the different sludge ages investigated (Grady and Roper, 1974). The use of the point (0,0) yields a conservative choice of a zero order model. The inclusion of this point did not present a problem otherwise since confidence intervals were not calculated (Hamilton, 1992).

Rate Model	R^2
Monod	0.13
First Order (S)	0.89
First Order (XS)	0.74
First Order (X)	0.76
Zero Order	0.99

Table 4-36: Rate of Substrate Utilization Models and R^2 values

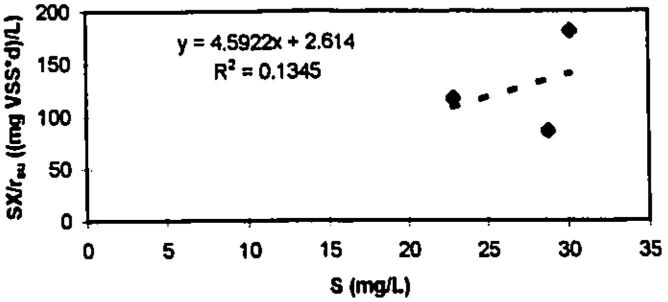

Figure 4-21: Hanes Plot of Monod equation fit to Group 2 Control Reactor SCOD Data

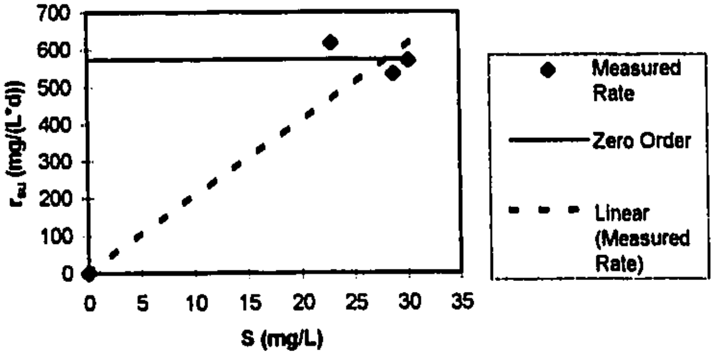

Figure 4-22: First Order (in S) and Zero Order Fits

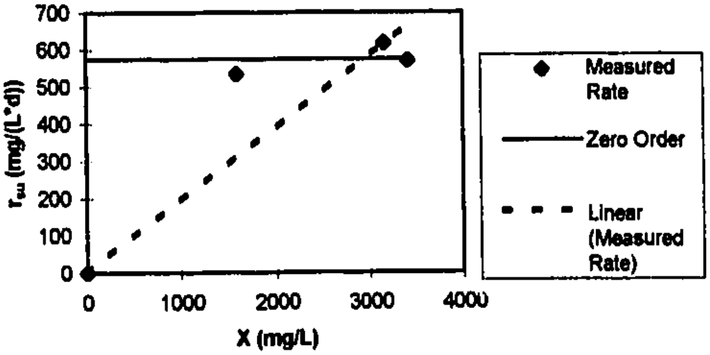

Figure 4-23: First Order (in X) and Zero Order Fits

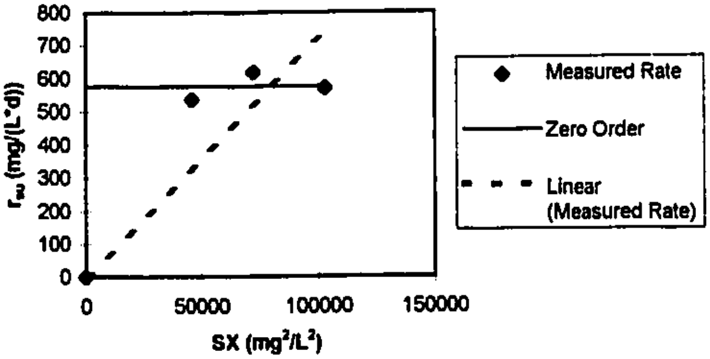

Figure 4-24: First Order (in SX) and Zero Order Fits

The rate expression for the first group of runs was similarly also found to be zero order. The substrate biodegradation rates for the group 3 and group 4 controls were assumed also to be zero order. This assumption was required in order to evaluate the conceptual models to be presented in Chapter 5 and fitted in Chapter 6. Given the rate expressions found for groups 1 and 2, the assumption with respect to groups 3 and 4 was probably reasonable. The non - temperature corrected zero order biodegradation rates are presented in Table 4-37. These rates were used in the models in this non - temperature corrected form. The increasing r_{su} values cannot be attributed to a single factor as many variables changed.

Group	r_{su} (mg SCOD/(L*d))
1	211.4
2	485.3
3	1056.7
4	2261.7

Table 4-37: Zero Order Biodegradation Rates (non - temperature corrected) of the Four Groups of Runs

5. Model Development

Two conceptual models for effluent SCOD prediction (an empirical model will be presented as well) will be developed in this thesis. It is important to note the sequence of events in maintenance of the reactors. After solids and SCOD sampling, sludge wastage was conducted. This was followed by the addition of a PAC slurry, prepared with collected effluent. Thus, when sampling occurred all the PAC had been in the system for at least 1 day. Furthermore, since the minimum SRT was 7.2 days, the substances in the mixed liquor were likely in equilibrium with the MLCSS or nearly so. Schultz (1982) has found mass transfer resistance to limit adsorption, in a PACT™ system. The mass flow for adsorption, r_A (mg/d), can be written as

$$r_A = FC_D q \tag{5-1}$$

where F is the volumetric flowrate (L/d), C_D is the carbon dose (mg PAC/L feed) and q is the equilibrium loading of the carbon (mg SCOD/mg PAC). The mass balance was applied using one day intervals.

Although equation 5-1 is based on a single day PAC dose, rather than MLCSS, at steady - state, it is assumed all the PAC adsorption sites added have been occupied by the time of the next carbon dosing. Adsorption of SCOD by biomass was likely minor (Weber et al., 1987; Dewalle et al., 1977; Randle et al, 1991; Hall and Randle, 1992; Rempel et al,

1992) and was therefore combined with biodegradation. Therefore, equation 5-1 accounts for all or almost all the adsorption taking place.

Both conceptual models used in this thesis start from the steady - state mass balance for substrate (Equation 2-11) (O'Brien, 1992).

$$(FS_i - FS_e) - R_{OBs} - R_{OBb} - R_{OBa} = 0 \qquad \textbf{2-11}$$

The substitution of Equation 5-1 into Equation 2-11 for the adsorption term and assuming a zero order biodegradation term in place of the first order degradation term (since kinetic results yield a zero order form) results in the following expression.

$$(FS_i - FS_e) - R_{OBs} - K_{Db}V - FC_Dq = 0 \qquad \textbf{5-2}$$

where K_{Db} is a zero order biodegradation rate coefficient (mg/(L*d)). It should be noted that the adsorption term above assumes that all the organics can be modelled as a single adsorbate over the operating parameter ranges investigated and assumes that the effects of competitive adsorption are minor. Competitive adsorption, an active area of current research is extremely complex and not well understood even for much simpler systems (Narbaitz, 1995). Thus given our limited knowledge of this topic, at this point, it was hard to justify its inclusion given that it greatly complicates the modelling without necessarily improving its predictions. The complexities of adsorption of influent compounds and MEPs could necessitate the use of a semi - empirical model.

5.1 Conceptual Model 1

From Equation 5-1, assuming adsorption can be described by a Langmuir isotherm, one arrives at

$$r_A = FC_D \frac{Q_{\max} bS_e}{1 + bS_e} \qquad \textbf{5-3}$$

where Q_{max} is the maximum loading of the PAC (mg substrate /mg PAC), b is a constant (L/mg substrate) and S_e is the effluent SCOD concentration. Substituting equation 5-3 into equation 5-2, lumping the stripping removal term into the biodegradation removal term (since stripping is likely to be minor (Metcalf and Eddy, 1991; Hall and Randle, 1992; Bryant et al., 1987; Droste, 1995)) and dividing by F results in the following expression

$$S_i - (K_{Db} * \Theta) - S_e - \frac{Q_{Max} bC_D S_e}{(1 + bS_e)} = 0 \qquad \textbf{5-4}$$

Defining Q (L/mg PAC) as $Q_{max}b$, the following equation is arrived at

$$S_i - K_{Db}\Theta - S_e - \frac{QC_D S_e}{1 + bS_e} = 0 \qquad \textbf{5-5}$$

where Θ is the hydraulic retention time (days).

5.2 Conceptual Model 2

Assuming adsorption can be described by a Freundlich isotherm, the following is obtained

$$r_A = FC_D K S_e^n \qquad \textbf{5-6}$$

where K (mg SCOD/mg PAC) and n (dimensionless) are the Freundlich constants. Substituting equation 5-6 into equation 5-2 and simplifying, the following equation is arrived at

$$S_i - K_{Db}\Theta - S_e - KC_D S_e^n = 0 \qquad \textbf{5-7}$$

In both models SRT is not relevant. If X were to have been retained then SRT would have been implicitly a factor. Another possible effect of SRT is the previously mentioned possible increased adsorbability with increased SRT. This would involve a more complex adsorption term. In addition, there is some evidence that cell fragments, which are considered part of MEPs, are more poorly degraded at higher SRTs (Grady and Roper, 1974). This would be modelled as an additional part of the biodegradation term.

5.3 An Empirical Model

The model suggested by Lankford and Miller (1987), discussed in the literature review, will also be tested for the data generated. The model is expressed by

$$S_e = S_b e^{(-kC_D)} \tag{5-8}$$

where S_e is the effluent concentration from a PACT™ reactor (mg substrate/L), S_b is the effluent strength from the activated sludge control (mg/L) and k is an empirical constant (L/mg PAC). This model was developed at constant HRT and SRT. Given that SRT was found to have little effect on treatment efficiency, the Lankford and Miller model was applied without consideration of the SRT. Furthermore, when there exists more than one control, at different SRTs, an average was generated to find S_b.

The Garcia - Orozco model (1986) was not fitted since the data collected indicated SRT had little effect on treatment efficiency and this model has SRT as a key component. Furthermore this model was developed for a biodegradable substrate and the data indicates that there is very little difference in $SBOD_5$ removal between PACT™ and control reactors. Robertaccio's model (1976) requires the evaluation of Freundlich constants. The appropriate equilibrium experiments, used to obtain the needed constants, were not conducted because of depletion of sample. The enhanced apparent rate constant model (Hamoda and Fahim, 1984) requires rate constant evaluation for PACT™ reactors. Since there is not enough data of the type required, this model could not be evaluated either.

6. Modelling Results

Three models were investigated in this study, as discussed in the previous section. For the runs of feed batch # 1, there were only two carbon doses (including zero) involved, therefore this feed batch was not the best choice for use in calibration of the models. The fourth group of data had only one PACT™ reactor and one control reactor, therefore this group was not a candidate for modelling. Therefore, the models could only be calibrated with the second or third groups of data. An arbitrary (to avoid data fitting) choice of the third group of runs was made. The group 3 data set involved 3 different carbon doses (including 0), 2 different SRTs, with 4 reactor runs. All runs were used to calibrate the three models.

Since three significantly different data points (for the three different carbon doses) were available, 2 parameters could be fit (Hamilton, 1992). The zero order biodegradation rates determined in Section 4.8 (Table 4-37), were used as the biodegradation rate coefficients (K_{Db}s), in the calibration and prediction of the conceptual models.

The models are identified as in Section 5. For identification purposes, conceptual model 1 was shortened to C1 (Eq. 5-5), conceptual model 2 was shortened to C2 (Eq. 5-7) and the empirical model was shortened to E1 (Eq. 5-8).

The use of two different SRTs in calibrating the E1 model was not strictly correct since the model was developed for constant SRT and HRT. However, SRT was found to have little effect on SCOD removal, therefore the use of two different SRTs, for the E1 calibration likely did not introduce much error.

The three non - linear models were calibrated using the non - linear regression routine of Statgraphics Plus 7.0 (Manugistics, 1993, Rockville, Maryland).

Modelling of SAOX will not be presented since not enough data was collected for this parameter, to warrant confirmation of a model structure.

6.1 SCOD Simulation Results

The parameter estimates and residual sum of squares (RSS) values for the three models, for effluent SCOD, can be found in Table 6-1. The simulations of the C1, C2 and E1 models for SCOD, using group 3, can be found in Figure 6-1. The fits appeared to be fairly good. Confidence intervals, based on the t test, were not presented because they are considered to have little meaning for a small data set, such as the one used, for both linear and non - linear regression (Hamilton, 1992). According to Manugistics Inc. (1993) confidence intervals are also inappropriate for the non - linear routine used. The R^2 values calculated by the non - linear routine may also have little meaning (Manugistics Inc., 1993).

The RSS values (calculated by all linear and non - linear regression routines) can be used to differentiate between models. Based on this criterion, model E1 would be considered best since it's RSS was the lowest. Given the limited data, it was difficult to make a clear choice based on RSS (Hamilton, 1992). Due to these simulation comparison difficulties, a comparison of the three models based on simulation capability seemed inappropriate. Hence, all three models were tested for their predictive ability and compared on this basis.

Model	Parameter Values	RSS
C1	Q = 3.89 L/mg PAC b = 0.013 L/mg SCOD	1498
C2	K = 21.5 mg SCOD/mg PAC n = 0.443	1515
E1	k = 0.826 L/mg PAC	237

Table 6-1: Model Calibration Results using the Group 3 SCOD Data

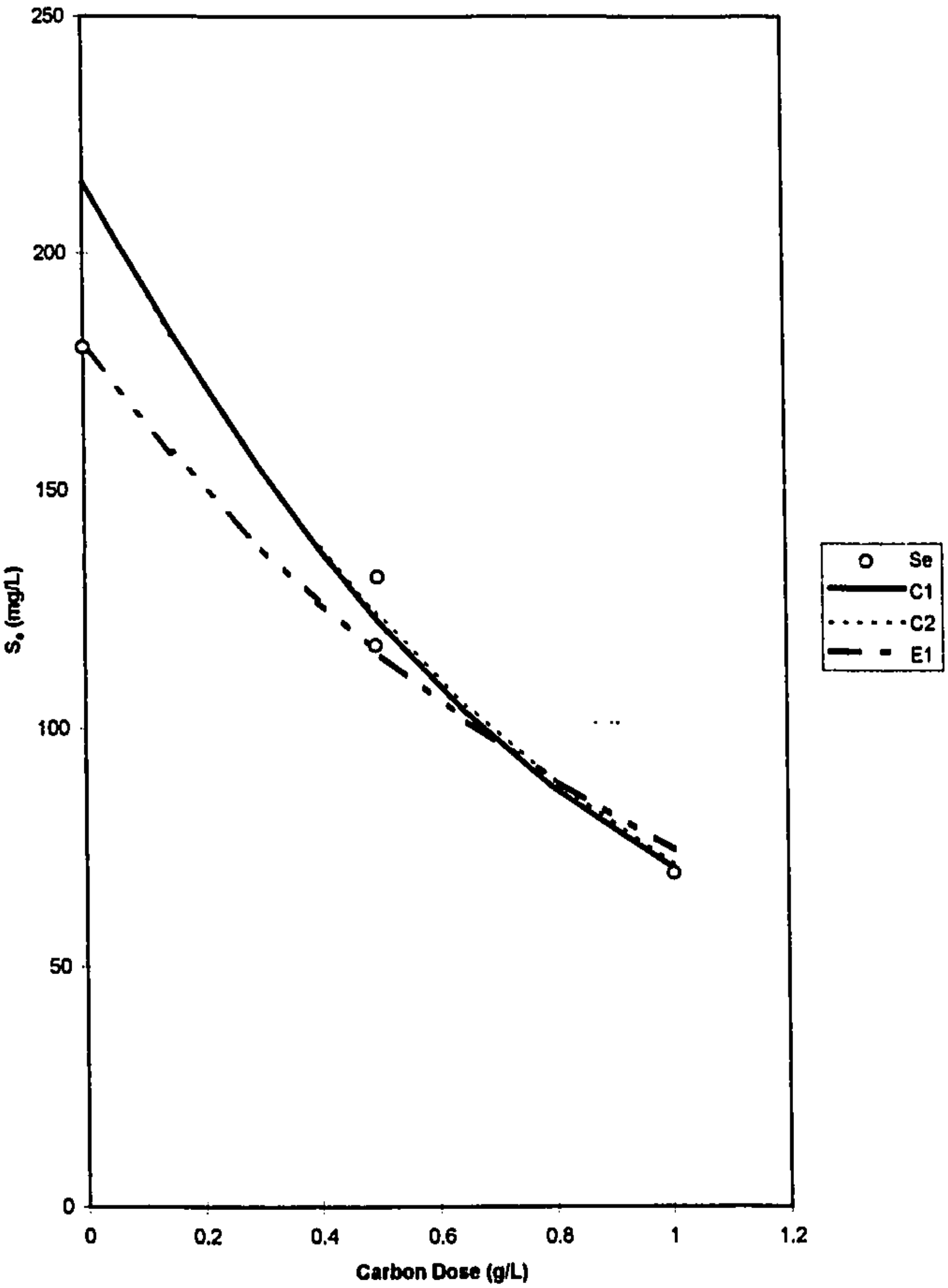

Figure 6-1: C1, C2 and E1 Model Simulations using Group 3 SCOD Data, at 11.5 Hours HRT and with a Mean Influent Feed SCOD of 721 mg/L

6.2 SCOD Predictions

The mean absolute percent error was used as a measure of predictive ability. It is defined as follows

$$MAPE = \frac{\sum_{i=1}^{N} \frac{|S_{ei} - S_{ep}|}{S_{ei}} * 100}{N} \qquad \textbf{6-1}$$

where S_{ei} is the effluent SCOD concentration on measurement day # i, S_{ep} is the steady - state predicted effluent SCOD concentration (mg/L) and N is the number of measurement days for a given reactor run. The global mean absolute percent error is given by

$$GMAPE = \frac{\sum_{i=1}^{NR} MAPE_i}{NR} \qquad \textbf{6-2}$$

where NR is the number of reactor runs considered in the calculation

Table 6-2 shows the mean absolute percent errors and global mean absolute percent errors for the C1, C2 and E1 model predictions of the SCOD effluent data, of the first, second and fourth groups of runs. The models predicted the group 1 effluent SCODs less effectively than the effluent SCODs of the other feed batches. Since feed batch 1 was collected during somewhat anomalous plant operating conditions (Plouffe, 1994), the poorer predictions of the effluent SCOD may not be surprising. Models C1 and C2 were very similar in their predictions, both yielding a global MAPE of approximately 34 %. The predictions might be characterized as fairly good. Figure 6-2 and Figure 6-3 show examples of C1, C2 and E1 model predictions, of steady - state SCOD effluent data, for some runs of feed batches 2 and 4, calibrated with the feed batch # 3 data.

Model E1 yielded slightly better predictions of the effluent SCOD than the conceptual models, with a 30 % global MAPE. This is a good result. considering the complexity of the PACT™ and activated sludge systems and the feed variability.

Models C1 and C2 account for HRT, influent strength and carbon dose. Models C1 and C2 are also sensitive to some feed composition differences, through a variable K_{Dh}. Model E1 implicitly accounts for the effects of HRT, influent concentration, carbon dose and some effects of feed composition differences. It accomplishes this by predicting PACT™ system performance from control activated sludge performance. The reactor runs of the four feed batches were conducted at slightly different temperatures. The operation temperature difference between any two runs was at most 4 °C. The temperature difference was less than 4 °C during much of those runs. Although temperature affects adsorption, this magnitude of temperature difference likely had little effect on the prediction results.

Feed Batch	Influent SCOD (mg/L)	HRT (hrs)	SRT (days)	C_D (g/L)	C1 Mean Absolute % Error	C2 Mean Absolute % Error	E1 Mean Absolute % Error
1	494	39.9	7.6	0	14.9	14.9	
1	577.3	38.1	13.3	0	34.8	34.8	
1	550	34.6	21.4	0	112	112	
1	527.6	34.8	6.9	1.01	34.7	33.8	39.7
1	541.4	36.1	13.6	1.06	54.8	54.3	58.6
1	541.9	35.5	25.3	0.95	47.0	48.3	40.5
2	344	11.3	7.3	0	11.6	11.6	
2	344	11.3	18.5	0	19.6	19.6	
2	344	11.3	23.8	0	20.5	20.5	
2	344	11.6	7.3	0.096	21.7	21.6	19.6
2	344	11.5	15.0	0.098	23.0	22.8	18.4
2	344	11.3	7.2	0.194	21.7	21.7	26.6
4	980	7.8	7.4	0	22.5	22.5	
4	980	5.7	7.1	0.494	43.1	36.4	6.8
Global MAPE					34.4	33.9	30.0

Table 6-2: C1, C2 and E1 Steady - State SCOD Predictions, calibrated with Feed Batch #3

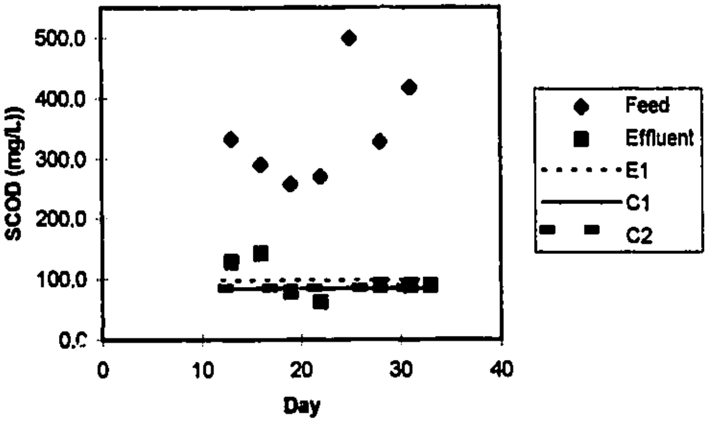

Figure 6-2: C1, C2 and E1 SCOD Model Predictions for the 11.3 Hour HRT, 7.2 Day SRT, 0.194 g/L C_D Reactor, Using Feed Batch # 2 (Mean Influent SCOD = 344 mg/L), Calibrated Using Feed # 3 Data

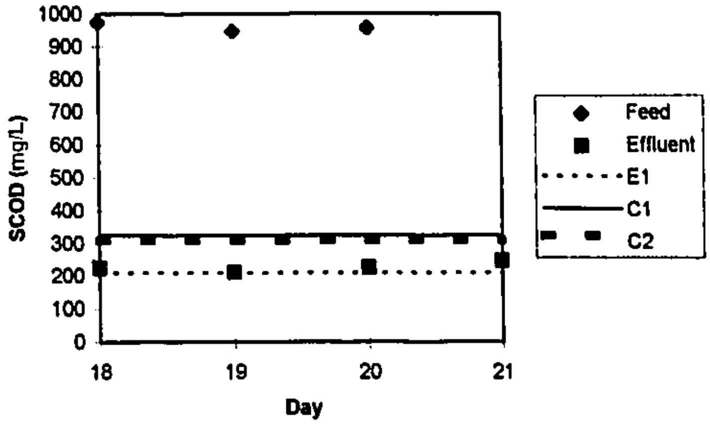

Figure 6-3: C1, C2 and E1 SCOD Model Predictions for the 5.7 Hour HRT, 7.1 Day SRT, 0.494 g/L C_D Reactor, Using Feed Batch # 4 (Mean Influent SCOD = 980 mg/L), Calibrated Using the Feed Batch # 3 Data

6.3 Comments on Modelling

Although, for a given reactor run, there was variability in the feed SCOD, there was little variability in the MLTSS and effluent SCOD values, hence the steady - state assumption was likely a good assumption.

Feed and biological variabilities are two likely causes for the less than excellent effluent SCOD predictive ability of the models. Another problem is that only 3 carbon doses, including zero, were used to calibrate the models. At least 4 carbon doses (including zero), for each of 4 HRTs, for each of 4 feed batches (64 runs) would have been better in modelling the effects HRT, influent SCOD and carbon dose.

Models C1, C2 and E1 point to the carbon acting to simply adsorb MEP and/or influent compounds that would not otherwise be removed. Potential toxicity reduction with respect to the activated sludge microflora, for the PACT™ reactors, was not accounted for. If there were a need to account for such a condition, it would likely involve a fairly complex model, which would require a large amount of data for calibration.

It must be stressed that since competitive adsorption is in effect, the adsorption terms of models C1 and C2 are grossly oversimplified and the existence of a single average adsorbate, over the parameter ranges investigated, was assumed. The Lankford and Miller Model (E1) makes a similar oversimplification. This assumption reduces the complexity of the models and was justified since there were no independent experiments to evaluate an actual larger group of parameters.

7. Conclusions and Recommendations

7.1 Conclusions

This comparison of the activated sludge process and the PACT™ process, for the treatment of BKME, yielded the following conclusions.

1. The large differences among the four batches of wastewater greatly limited the comparisons that could be made among the various runs.
2. The PACT™ process, using carbon doses of 0.1 to 1 g/L, had 0 to 18 percent higher SCOD removals than the conventional activated sludge process, which yielded 64 to 74 % SCOD removal.
3. The PACT™ process yielded little or no improvement compared to the activated sludge process with respect to $SBOD_5$ removals, which were both close to 100 %, for all control and PACT™ reactor runs.
4. Microtox toxicity removal was close to 100 % for the control and PACT™ runs of three of the feed batches. The PACT™ reactor had a slightly higher toxicity removal than the control, for the other feed batch.
5. The addition of PAC yielded significant increases in SAOX removals.
6. Phenol, 4 - chloro, 3 - methylphenol, 2 - chlorophenol, 2, 4 - dichlorophenol, 2, 4, 6 - trichlorophenol and pentachlorophenol were not detected, in concentrations above 10 ppb (the upper bound of the detection limit, in effect), for the three feed batches tested.

7. Both activated sludge and PACT™ systems were able to lower the calculated TAOX to below 0.8 kg Cl/ADMT, the Dec. 31, 1999 MISA limit, for two of the three feed batches tested. This is not surprising given the relatively low calculated TAOX concentrations of the feeds and that the activated sludge process is considered the best available technology by MISA (McCubbin Consultants, 1992). For the other feed batch tested, which was quite toxic to the Microtox test bacteria, both the control and PACT™ reactors did not meet the 1999 MISA limit.
8. SRT had little or no impact, in the range tested of 7 to 25 days, on the water quality parameter removal efficiencies of the PACT™ and control reactors.
9. Two conceptual models for effluent SCOD prediction, were developed and tested. The models used a zero order biodegradation rate constant, lumped the stripping removal component into the biodegradation term and described adsorption by either the Langmuir or Freundlich isotherm. These models incorporated sensitivity to HRT, influent SCOD, carbon dose and feed composition. The models yielded fairly good predictions, with global mean absolute errors of approximately 34 %.
10. The empirical model, for effluent SCOD prediction also incorporated some sensitivity to feed variability, in addition to HRT, influent SCOD and carbon dose. This model predicted PACT™ effluent SCOD concentration from control effluent SCOD concentration. This model was found to be the best predictor of effluent SCOD, yielding a 30 % global mean absolute percent error.

7.2 Recommendations

The recommendations below include both topics for further study and modifications to improve future similar studies.

1. Comparison of the activated sludge and PACT™ processes for a batch mode of operation, in order to have more reliable and trouble free operation.
2. Comparison of the activated sludge process followed by a GAC column and the PACT™ process, in terms of water quality parameter removal efficiencies and associated cost effectiveness.
3. A dynamic lab scale study, preferably located at the plant, investigating the advantage of the PACT™ process over the activated sludge process, under plant discharge variability.
4. Comparison of the activated sludge and PACT™ processes, under lower HRTs and lower SRTs, to stress the systems.
5. An alternative reactor, including a large completely mixed zone compared to the settling zone, should be used in future studies.
6. PAC isotherms should be conducted to permit the testing of some the models discussed.
7. When wastewater is sampled every attempt should be made to prevent it's degradation, by utilizing sufficient heat removal capacity, to accomplish the freezing, as quickly as possible.
8. More intensive sampling during the steady - state period.

8. References

Adams, A.D. Improving Activated Sludge Treatment with Powdered Activated Carbon - Textiles, *6th MidAtlantic Industrial Waste Conference*, Newark, Delaware, November 15, 1973.

American Public Health Association, American Water Works Association and the Water Pollution Control Federation, *Standard Methods for the Examination of Water and Wastewater, 20th Edition*, Port City Press, Baltimore, Maryland, 1992.

Aprahamian, E. (Jr.) and Stevens, S., The Characterization of Organochlorine Compounds (AOX) in Conventional and Modified Kraft Mills, *Tappi Pulping Conference Proceedings*, Toronto, Canada, Vol. 1, pp. 209 - 215, October 1990.

AWWA Research and Technical Practice Committee on Organic Contaminants. An Assessment of Microbial Activity on GAC, *Journal of the American Water Works Association*, Vol. 73, pp. 447, 1981.

Benedek, A., Simultaneous Biodegradation and Activated Carbon Adsorption - A Mechanistic Look, Chapter 11 in *Activated Carbon Adsorption of Organics from the Aqueous Phase Vol. II*, M. J. McGuire and I. H. Suffet, (Eds.), Ann Arbor Science, Ann Arbor, Michigan, pp. 273 - 302, 1980.

Binder, A., Edmunds, L. C., Wilcox, D. R. and Wilks, K. A., Laboratory Treatability and Full Scale Performance of Biotreatment of Pesticide Wastes using Sequencing Batch Reactors (SBR) with PAC, *68th Annual Conference of the Water Environment Federation*, October, 1995.

Black, J. P. and Andrews, J. N., Upgrading Poultry Processing Waste Treatment with Powdered Activated Carbon, *Proceedings of the Fifth Annual Industrial Pollution Conference, sponsored by the Water and Wastewater Equipment Manufacturers Association*, Inc., pp. 309 - 322, April, 1977.

Brenner, A, Belkin, S, Ulitzur, S and Abeliovich, A, Evaluation of Activated Carbon Adsorption Capacity by a Toxicity Bioassay, *Water Research*, Vol. 27, No. 10, pp. 1577-1583, 1993.

Brock, T. D. and Madigan, M. T., *Biology of Microorganisms*, Prentice Hall, Englewood Cliffs, New Jersey, 1988.

Bryant, C.W., Amy, G.L. and Alleman, B.C., Organic Halide and Organic Carbon Distribution and Removal in a Pulp and Paper Wastewater Lagoon, *Journal of the Water Pollution Control Federation*, Vol. 59, No. 10, pp. 890 - 896, 1987.

Bryant, C.W., Amy, G.L., Neill, R. and Ahmad, S., Partitioning of Organic Chlorine between Bulk water and Benthal Interstitial Water through a Kraft Mill Lagoon, *Water Science and Technology*, Vol. 20, No. 1, pp. 73 - 79, 1988.

Bryant, C. W. and Amy, G. L., Seasonal and In-Mill Aspects of Organic Halide Removal by an Aerated Stabilization Basin Treating a Kraft Mill Wastewater, *Water Science and Technology*, Vol. 21, No. 4/5, pp. 231 - 239, 1989.

Cecen, F., Adsorption Characteristics of a Biotreated Pulp Mill Effluent, *Water Science and Technology*, Vol. 28, No. 2, pp. 1 -10, 1993.

Çeçen, F., Urban, W. and Haberl, R., Biological and Advanced Treatment of Sulfate Pulp Bleaching Effluents, *Water Science and Technology*, Vol. 26, No. 1/2, pp. 435 - 444, 1992.

Chudoba, J., Inhibitory Effect of Refractory Organic Compounds Produced by Activated Sludge Micro-Organisms on Microbial Activity and Flocculation, *Water Research*, Vol. 19, No. 2, pp. 197 - 200, 1985.

Craig, G. R., Orr, P. L., Robertson, J. L. and Vrooman, W. M., Toxicity and Bioaccumulation of AOX and EOX, *Pulp and Paper Canada*, Vol. 91, No. 9, pp. 39 -45, 1990.

Daigger, G. T. and Grady, C. P. L., A Model for the Bio - Oxidation Process Based on Product Formation Concepts, *Water Research*, Vol. 11, pp. 1049 - 1057, 1977.

Dehnert, J. F. and Weisberg, E, Biological Surfaces plus Carbon Upgrade Plant Water Treatment, *Oil and Gas Journal*, Vol. 76, No. 2, pp. 87 - 90, 1978.

Dejohn, P.B. and Black, J.P., Treatment of Oil Refinery Wastewaters With Granular and Powdered Activated Carbon, *Proceedings of the Fifth Annual Industrial Pollution Conference, sponsored by the Water and Wastewater Equipment Manufacturers Association*, Inc., pp.173 - 200, 1977.

DeWalle, F. B. and Chian, E. S. K., Biological Regeneration of Powdered Activated Carbon Added to Activated Sludge Units, *Water Research*, Vol. 11, pp. 439-446, 1977.

Dewalle, F. B., Chian, E. S. K. and Small, E. M., Organic Matter Removal by Powdered Activated Carbon Added to Activated Sludge, *Journal of the Water Pollution Control Federation*, Vol. 49, pp. 593 - 599, 1977.

Dietrich, M.J., Copa, W.M., Chowdbury, A.K. and Randall, T.L., Removal of Priority Pollutants from Dilute Wastewater by the PACT™ Treatment Process, *Environmental Progress*, Vol. 7, No. 2, pp. 143 - 149, 1988.

Droste, R. L., Verbal Communication, University of Ottawa, Department of Civil Engineering, 1995.

Eckenfelder, W. Jr., *Principles of Water Quality Management*, CBI Publishing, Boston, Massachusetts, 1980.

Fein, J. E., Omotani, K. and Kantardjieff, A., Aerobic Treatment of a Fine Paper Mill Effluent by the Acticontact Process, *Tappi Environmental Conference Proceedings*, Boston, Massachusetts, pp. 523 - 537, March, 1993.

Firth, B. K. and Backman, C. J., A Comparison of Microtox Testing with Rainbow Trout Acute and Ceriodaphnia Chronic Bioassays Using Pulp and Paper Mill Wastewaters, *Tappi Environmental Conference*, Book 2, pp. 621 - 626, Tappi Press, Atlanta, 1990.

Flynn, B. P., A Model for the Powdered Activated Carbon - Activated Sludge Treatment System, *30th Annual Purdue Industrial Waste Conference*, West Lafayette, In., p.233 - 252, 1975.

Garcia-Orozco, J. H., Fuentes, H. R. and Eckenfelder, W. W. Jr, Modeling and Performance of the Activated Sludge - Powdered Activated Carbon Process in the Presence of 4,6 dinitro-o-cresol, *Journal of the Water Pollution Control Federation*, Vol. 58, No. 4., pp. 320 - 325, 1986.

Gergov, M., Priha, M.,Talka, E., Valttila, O., Kangas, A. and Kukkonen, K., Chlorinated Organic Compounds in Effluent Treatment at Kraft Mills, *Tappi Journal*, pp. 175 - 184, December 1988.

Grady Jr., C. P. L. and Lim, H. C., *Biological Wastewater Treatment, Theory and Application*, P. N. Cheremisinoff (Ed.), Marcel Dekker, Inc., New York, New York, 1980.

Grady, C. P. L. Jr. and Roper, D. R., A Model for the Bio-oxidation Process which incorporates the Viability Concept, *Water Research*, Vol. 8, pp. 471 - 483, 1974.

Graves, J. W. and Joyce, T. W., A Critical Review of the Ability of Biological Treatment Systems to Remove Chlorinated Organics Discharged by the Paper Industry, *Water SA*, Vol. 20, No. 2, pp. 155 - 160, 1994.

Grieves, C. G., Stenstrom, M. K., Walk, J. D. and Grutsch, J. F., Powdered Carbon Improved Activated Sludge Treatment, *Hydrocarbon Process*, Vol. 56, No. 10, pp. 125 - 130, 1977.

Grieves, C.G., Crame, L. W., Venardos, D.G. and Ying, W., Powdered versus Granular Carbon for Oil Refinery Wastewater Treatment, *Journal of the Water Pollution Control Federation*, Vol. 52, No. 3, pp. 483 - 497, 1980.

Haberl, R., Urban, W.,Gehringer, P. and Szinovatz, W., Treatment of Pulp Bleaching Effluents By Activated Sludge, Precipitation, Ozonation and Irradiation, *Water Science and Technology*, Vol. 24, No. 3/4, pp. 229 - 239, 1991.

Hall, E.R. and Randle, W.G., AOX Removal from Bleached Kraft Mill Wastewater: A Comparison of Three Biological Treatment Processes, *Water Science and Technology*, Vol. 26, No. 1/2, pp. 387 - 396, 1992.

Hamilton, L. C., *Regression with Graphics*, A Second Course in Applied Statistics, Wadsworth, Belmont, California, 1992.

Hamoda, M. F. and Fahim, M. A., Enhanced Activated Sludge Waste Treatment by the Addition of Adsorbents, *Environmental Pollution Series A*, Vol. 36, pp. 283 - 294, 1984.

Hutton, D.G., Priority Pollutant Removal: Comparison of the duPont PACT® Process with Activated Sludge Followed by Granular Carbon Columns, in *Application of Adsorption to Wastewater Treatment*, W.W. Eckenfelder, Jr. (Ed.), Enviro. Press, Inc, Nashville, pp. 435 - 471, 1981.

Hutton, D. G., Combined Powdered Activated Carbon - Biological Treatment, *Carbon Adsorption Handbook*, P. N. Cheremisinoff and F. Ellerbusch (Eds.), Ann Arbor Science, Ann Arbor, Michigan, pp. 389 - 447, 1978.

Janeczek Jr, J. and Lamb, J. C., Treatability of a Coal Gasification Wastewater using the Powdered Activated Carbon/Activated Sludge Process, *37th Purdue Industrial Waste Conference*, West Lafayette, In., pp. 497 - 505, 1982.

Jokela, J.K., Laine, M, Ek, M. and Salkinoja-Salonen, M., Effect of Biological Treatment on Halogenated Organics in Bleached Kraft Pulp Mill Effluents Studied by Molecular Weight Distribution Analysis, *Environmental Science and Technology*, Vol. 27, No. 3, pp. 547 - 557, 1993.

Kaczmarek, S. A. and Robertaccio, F. L., EDS Coal Liquefaction Wastewaters : Zero - Discharge Treatability Studies, *38th Purdue Industrial Waste Conference*, West Lafayette, In., pp. 509 - 517, 1983.

Kalinske, A. A., Enhancement of Biological Oxidation of Organic Wastes Using Activated Carbon in Microbial Suspensions, *Water and Sewage Works*, Vol. 119, No. 6, pp. 62 - 64, 1972.

Kennedy, K. J., Verbal Communication, University of Ottawa, Department of Civil Engineering, 1994.

Kim, S. R., Snoeyink, A. M. and Saunders, F. M., Influence of Activated Sludge CRT on Adsorption, *Journal of the Environmental Engineering Division of ASCE*, Vol. 102, pp. 55 - 70, 1976.

Kincannon, D.F., Application of PACT to Industrial Wastewaters, in *Application of Adsorption to Wastewater Treatment*, W.W. Eckenfelder, Jr. (Ed.), Enviro. Press, Inc. Nashville, 1981.

Kincannon, D. F. and Esfandi, A., Performance Comparison of Activated Sludge, PAC Activated Sludge, Granular Activated Carbon and a Resin Column for Removing Priority Pollutants from a Pharmaceutical Wastewater, *35th Purdue Industrial Waste Conference*, Ann Arbor Science Publishers, Inc., Ann Arbor, Mich., pp. 476 - 483, May, 1981.

Kuo, J. F. and Hashman, T., Discussion on Estimation of the Removal of Organic Priority Pollutants by the Powdered Activated Carbon Treatment Process, *Water Environment Research*, Vol. 66, No. 1, pp. 89- 91, 1994.

Lankford, P. W., Powdered Activated Carbon Treatment (PACT®), Chapter 10 in *Toxicity Reduction in Industrial Effluents*, P. W. Lankford and W. W. Eckenfelder, Jr. (Eds.), Van Nostrand Reinhold, New York, 1990.

Lankford, P.W. and Miller, E, Predictive Design Approach for PACT Systems, *Proceeding of the Industrial Wastes Symposium of the 60th Annual Water Pollution Control Federation Conference*, pp. 318 - 331, 1987.

Lawrence, A. W. and McCarty, P. L., Unified Basis for Biological Treatment Design and Operation, *Journal of the Sanitary Engineering Division, ASCE*, Vol. 96, No. SA3, pp. 757 - 778, 1970.

Lee, S. E., Shin, H. S., Paik, B. C., Treatment of Cr(VI)-containing Wastewater by Addition of Powdered Activated Carbon to the Activated Sludge Process, *Water Research*, Vol. 23, No. 1, pp. 67 - 72, 1989.

Manugistics Inc., *Statgraphics Plus 7.0 User and Reference Manuals*, Manugistics Inc., Rockville, Maryland, 1993.

Martin, R. J. and Iwugo, K. O., Studies on Residual Organics in Biological Plant Effluents and their Treatment by the Activated Carbon Adsorption Process, Chapter 16 in *Activated Carbon Adsorption of Organics from the Aqueous Phase Vol. II*, M. J. McGuire and I. H. Suffet (Eds.), Ann Arbor Science Pub., Ann Arbor, Michigan, pp. 385 - 404, 1980.

McCubbin Consultants Inc. for the Ministry of the Environment of Ontario, *MISA, Best Available Technology for the Ontario Pulp and Paper Industry*, Queen's Printer, Toronto, Ontario, PIBS 1847, 1992.

Meidl, J.A., PAC Process, *Water/Engineering & Management*, pp. 33 - 36, June, 1982.

Meidl, J.A., PACT Systems for Industrial Wastewater Treatment, Chapter 2.18 in *Physical/Chemical Processes Innovative Hazardous Waste Treatment Technology Series Vol. 2*, H.M. Freeman (Ed.), Technomic Publishing Inc, Lancaster, PA, pp. 177 - 190, 1990.

Metcalf & Eddy, Inc., *Wastewater Engineering*, Treatment, Disposal and Reuse, G. Tchobanoglous and F. L. Burton (Eds.), McGraw-Hill, Inc., New York, 1991.

Microbics Corporation, *Microtox Manuals for Model M500*, Microbics Corporation, Carlsbad, California, 1992.

Ministry of the Environment of Ontario, *Comprehensive Clean Water Regulation for Ontario's Pulp and Paper Industry*, Queen's Printer, Toronto, Ontario, 00293.NR, February, 1993a.

Ministry of the Environment of Ontario, *Clean Water Regulation : Pulp and Paper Sector*, Queen's Printer, Toronto, Ontario, PIBS 2264E, February, 1993b.

Murray, W.D. and Richardson, M., Development of Biological and Process Technologies for the Pulp Mill Wastes that Pose a Threat to Human Health, *Critical Reviews in Environmental Science and Technology*, Vol. 23, No. 2, pp.157-194, 1993.

Narbaitz, R. M., Verbal Communication, University of Ottawa, Department of Civil Engineering, 1995.

Nayar, S. C. and Sylvestor, N. D., Control of Phenol in Biological Reactors by Addition of Powdered Activated Carbon, *Water Research*, Vol. 13, pp. 201 - 205, 1979.

Ng, A. S. and Stenstrom, M. K., Nitrification in Powdered - Activated Carbon - Activated Sludge Process, *Journal of Environmental Engineering, ASCE*, Vol. 113, No. 6, pp. 1285 - 1301, 1987.

O'Brien, G. J., Estimation of the Removal of Organic Priority Pollutants by the Powdered Activated Carbon Treatment Process, *Water Environment Research*, Vol. 64, No. 7, pp. 877 - 883, 1992.

Oleszkiewicz, J.A., Trebacz, W. and Thompson, D. B., Biological Treatment of Kraft Mill Wastewater, *Water Environment Research*, Vol. 64, No. 6, pp. 805 -810, 1992.

Osantowski, R., Dempsey, C., Gardner, D. and Dostal, K., Biological Treatment of High Strength Wastewater - A Case History using PAC Technology, *Proceedings of the Industrial Wastes Symposium of the 60th Annual Water Pollution Control Federation Conference*, pp. 200 - 225, 1987.

Perotti, A. E. and Rodman, C. A., Enhancement of Biological Waste Treatment by Activated Carbon, *Chemical Engineering Progress*, Vol. 69, No. 11, pp. 63-64, 1973.

Plouffe, E., Employee of the Maclaren kraft mill, in Thurso, written communication, 1994.

Plouffe, E., Employee of the Maclaren kraft mill, in Thurso, spoken communication, 1995.

Prober, R., Pyeha, J. J. and Kidon, W. E., Interaction of Activated Carbon with Dissolved Oxygen, *Journal AIChE*, Vol. 21, No. 6, pp.1200 - 1204, 1975.

Randall, T. L., Canney, P. J., Berndt, C. L., Rollins, R. M. and Soukup, C. L., Bench - Scale Treatment of Lurgi Gasifier and H - Coal Wastewaters by the PACT System, *Environmental Progress*, Vol. 3, No. 4, pp. 237 - 247, 1984.

Randle, W. G., Hall, E. R. and McKinlay, A. Y., Optimization of Biological Treatment Systems for Enhanced Removal of AOX and Chlorophenolic Compounds, *Proceeding of the 1991 Tappi Environmental Conference*, pp. 433 - 443, 1991.

Recktenwalt, M. A., Snoeyink, V. L. and Larson, R. A., Sequential Wet Air Regeneration of PAC from the Powdered Carbon-Activated Sludge Process, *Journal of the Water Pollution Control Federation*, Vol. 60, No. 8, pp. 1439 - 1444, 1988.

Rempel, W., Turk, O. and Sikes, J., Side-by-side Activated Sludge Pilot Plant Investigations Focusing on Organochlorines, *Journal of Pulp and Paper Science*, Vol. 18, No. 3, pp. J77 - J85, 1992.

Rizzo, J.A., Activated Carbon Clears Effluent, *The Oil and Gas Journal*, pp. 52 - 56, May 31, 1976.

Robertaccio, F.L., Powdered Activated Carbon Addition to Biological Reactors, *Doctoral Thesis*, University of Delaware, Newark, Delaware, 1976.

Rollins, M. R., Ellis, C. E. and Berndt, C. L., PACT/Wet Air Regeneration of an Organic Chemical Waste, *37th Purdue Industrial Waste Conference*, Butterworth Publishers, Boston, MA, pp. 1 - 12, May, 1982.

Saunamäki, R., Jokinen, K., Jarvinen, K. and Savolainen, R., Factors Affecting the Removal and Discharge of Organic Chlorine Compounds at Activated Sludge Treatment Plants, *Water Science and Technology*, Vol. 24, No. 3/4, pp. 295 - 307, 1991.

Scaramelli, A. B. and DiGiano, F. A., Upgrading the Activated Sludge System by Addition of Powdered Activated Carbon, *Water and Sewage Works*, Vol. 120, No. 9, pp. 90, 1973.

Schultz, J. R., Pact Process Mechanics, *Doctoral Dissertation*, Clemson University, Clemson, South Carolina, 1982.

Shaul, G. M., Barnett, M. W. and Dostal, K. A., Treatment of Dye and Pigment Processing Wastewater by the Activated Sludge Process, *37th Purdue Industrial Waste Conference*, Butterworth Publishers, Boston, MA, pp. 687 - 689, 1982.

Shaul, G. M., Barnett, M. W., Neiheisel, T. W. and Dostal, K. A., Activated Sludge with Powdered Activated Carbon Treatment of Dye and Pigments Processing Wastewater, *38th Purdue Industrial Waste Conference*, Butterworth Publishers, Boston, MA, pp. 659 - 671, 1983.

Stover, E. L., Fazel, A. and Kincannon, D. F., Powdered Activated Carbon and Ozone - Assisted Activated Sludge Treatment for Removal of Toxic Organic Compounds, *Ozone : Sci. Eng.*, Vol. 7, No. 3, pp. 191 - 203, 1985.

Stuthridge, T.R. and McFarlane, P.N., Adsorbable Organic Halide Removal Mechanisms in a Pulp and Paper Mill Aerated Lagoon Treatment System, *Water Science and Technology*, Vol. 29, No. 5/6, pp. 195 - 208, 1994.

Tomar, P. and Allen, D. G., Removal of Organochlorines from Kraft Pulp Mill Effluent by an Aerated Lagoon, *Water Pollution Research Journal of Canada*, Vol. 26, No. 1, pp. 101 117, 1991.

Verreault, M. and Depuydt, K. T., Biophysical Treatment of Wastewater Papermaking Operations using the PACT™ System, *Tappi Environmental Conference Proceedings*, Richmond, Virginia, Vol. 2, pp. 459 - 467, April, 1992.

Weber, W. J., Jones, B. E. and Katz, L. E., Fate of Toxic Organic Compounds in Activated Sludge and Integrated PAC Systems, *Water Science and Technology*, Vol. 19, pp. 471 - 482, 1987.

Weber, A.S. and Matsumoto, M.R., Feasibility of Intermittent Biological Treatment for Hazardous Wastes, *Environmental Progress*, Vol. 6, No. 3, pp. 166 - 171, 1987.

Wessberg, J., Welander, T. and Jönsson, M., Selector Volume in Pulp and Paper Activated Sludge Wastewater Treatment Plants - Bench Scale and Pilot Plant Studies, *Water Science and Technology*, Vol. 29, No. 5 - 6, pp. 303 - 311, 1994.

Wong, J. M. and Maroney, P. M., Pilot Plant Comparison of Extended Aeration and PACT Toxicity Reduction in Refinery Wastewater, *44th Purdue Industrial Waste Conference*, Butterworth Publishers, Boston, MA, pp. 685 - 693, 1990.

Ying, Wei-Chi, Integrated Treatment of Hazardous Landfill Leachate, Chapter 18 in *Wastewater Treatment Technology*, Vol. 3, Paul N. Cheremisinoff (Ed.), Gulf Publishing Company, Houston, Texas, pp. 515 - 542, 1989.

Appendix A

This appendix contains the daily data from the runs corresponding to the four feed batches. Each table contains the data from a single feed batch. The reactor numbers correspond to the numbering system in the Results and Discussion. The letter i, when present in a cell, signifies a linearly interpolated value.

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 3		1	1600		8500.0		500.0	101.5	698.0		530.1		530.7	180.4
Reactor 3		2	1650	24.5	4825.0	24.5	90.0	103.0	698.0	8.9	602.0		351.6	180.4
Reactor 3		3	1800	25.5	5130.0	25.5	90.0	225.0	550.0	3.1	442.4		351.6	148.6
Reactor 3		4	1450	20.5		20.5	0.0							
Reactor 3		5	1450	24.0	4303.0	24.0	0.0							
Reactor 3		6	1700	26.5		26.5	0.0							
Reactor 3		7												
Reactor 3		8	1650	23.5		23.5	0.0		382.0		338.3		411.3	
Reactor 3		9	1550	23.0	4600.0	23.0	0.0					758.2	659.3	
Reactor 3		10	1650	25.0	5900.0	25.0	500.0	20.0	566.0	10.0	499.1			153.0
Reactor 3		11	1300	20.5	4925.0	20.5	10.0							
Reactor 3		12	1900	30.0	5127.0	30.0	280.0	119.0	510.0	4.1	441.8	560.4	520.9	168.8
Reactor 3		13	1500	20.0	3930.0	20.0	280.0	17.0	424.0	20.3	360.3		560.0	
Reactor 3		14	1600	25.0	4950.0	25.0	300.0	11.0	470.0	16.9		481.3	432.0	153.0
Reactor 3		15	1600	24.0	4750.0	24.0	300.0	34.5						
Reactor 3	Begins	16	1750	25.5	5130.0	25.5	300.0	10.0	670.0	20.6		813.3	733.3	133.3
Reactor 3		17	2050	27.0	5480.0	27.0	300.0	34.5				653.3		
Reactor 3		18	1400	17.5	3800.0	17.5	450.0	24.0	492.0	8.6		493.3	453.3	197.3
Reactor 3		19	1800	28.0	5940.0	28.0	220.0	34.5				500.7		
Reactor 3		20		6.0		6.0	0.0					508.0		
Reactor 3		21	1050	34.5	4170.0	34.5	575.0	27.0	584.0	14.0	493.5	515.7		
Reactor 3		22	1600	29.5	5790.0	29.5	500.0	33.0	820.0	12.4	762.2	523.3	493.3	197.3
Reactor 3		23	1550	23.5	4480.0	23.5	310.0	18.0	864.0	17.8	519.5	543.3	433.3	165.3

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 3		24	1500	23.5	4240.0	23.5	340.0	63.9	938.2	11.6	810.6	763.0		
Reactor 3		25	1650	25.5	5090.0	25.5	310.0	60.0	670.0	10.4	811.0	983.3	773.3	237.3
Reactor 3	Ends	26	1550	23.0	5040.0	23.0	310.0	63.9	938.2	10.9	810.6			
Reactor 3		Mean				38.1			747.1	13.3	701.2	629.7	577.7	186.1
Reactor 4		1	1600		8565.0		500.0	106.5	13384.0		12562.5		530.7	29.2
Reactor 4		2	1650	37.9	4655.0	26.3	500.0	144.0	20696.0	13.9	19410.2		351.6	45.1
Reactor 4		3	1800	35.1	5230.0	24.4	500.0	126.0	16918.0	14.3	15866.0		351.6	29.2
Reactor 4		4	1450	36.3	4065.0	25.2	500.0	108.5	15855.0	11.7				
Reactor 4		5	1450	36.9	4685.0	25.6	500.0	91.0	14792.0	13.7				
Reactor 4		6	1700	34.3	5570.0	23.8	500.0	73.5	13729.0	15.1				
Reactor 4		7												
Reactor 4		8	1650	37.5	4508.0	26.1		56.0	12666.0	353.7	11922.2		411.3	84.9
Reactor 4		9	1550	37.6	4400.0	26.1	500.0	38.5	7692.0	13.3		758.2	659.3	
Reactor 4		10	1650	34.3	5255.0	23.8	500.0	21.0	2718.0	14.0	2501.8			81.8
Reactor 4		11	1300	33.1	4455.0	23.0	500.0	16.0	5656.0	12.0				
Reactor 4		12	1900	34.9	6185.0	24.3	490.0	11.0	8594.0	18.1	7998.1	560.4	520.9	73.8
Reactor 4		13	1500	36.9	3905.0	25.6	500.0	36.0	10912.0	11.7	10210.6		560.0	
Reactor 4		14	1600	34.7	5185.0	24.1	480.0	29.0	5566.0	14.9		481.3	432.0	26.4
Reactor 4		15	1600	39.2	4403.0	27.3	484.0	84.5	5799.0	13.3				
Reactor 4		16	1750	39.0	4705.0	27.1	480.0	23.0	6032.0	15.4		813.3	733.3	29.3
Reactor 4		17	2050	35.8	5430.0	24.9	0.0	84.5	4914.0	86.7				
Reactor 4		18					50.0	84.5	3796.0			493.3	453.3	77.3
Reactor 4		19	1800		4855.0		470.0	84.5	2727.3					

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 4		20					0.0		1658.7					
Reactor 4		21	1050		5495.0		720.0	32.0	590.0		509.8			
Reactor 4		22	1600	35.5	5985.0	24.6	450.0	67.0	15068.0	18.6	15143.3	523.3	493.3	85.3
Reactor 4		23	1550	35.7	4735.0	24.8	260.0	118.0	14820.0	23.8	13905.8	543.3	433.3	61.3
Reactor 4		24	1500	34.8	4865.0	24.2	481.0	137.9	12437.5	13.3	11708.3			
Reactor 4		25	1650	34.5	5315.0	24.0	480.0	96.0	12744.0	14.8		983.3	773.3	117.3
Reactor 4		26	1550	34.8	4765.0	24.1	480.0	137.9	12437.5	13.1	11708.3			
Reactor 4		27					0.0	137.9	12437.5		11708.3			
Reactor 4		28	1600		5364.0		470.0	153.0	8234.0		7735.7	1020.7	834.8	114.8
Reactor 4		29	1600	34.9	4954.0	24.2	470.0	222.0	8932.0	12.4	8223.9			161.7
Reactor 4		30	1467	34.0	4795.0	23.6	470.0	222.0	8932.0	11.8	8223.9			161.7
Reactor 4		31	1767	46.1	4215.0	32.0	405.0	457.0	18230.0	16.2	16691.8	678.3	560.9	130.4
Reactor 4		32	1550	97.0	1620.0	67.4	405.0	457.0	18230.0	15.0	16691.8	678.3	560.9	130.4
Reactor 4		33	2050	38.2	5459.0	26.6	428.0	419.8	14718.0	15.2		684.9		
Reactor 4		34	2078	33.7	5192.0	23.4	360.0	382.5	14718.0	15.0			339.2	96.0
Reactor 4		35	2100	34.1	5112.0	23.7	360.0	345.3	16378.0	15.8			339.2	96.0
Reactor 4		36	2200	32.9	5470.0	22.9	360.0	308.0	18038.0	16.8	16912.3		560.0	153.6
Reactor 4		37	2225	35.0	4995.4	24.3	470.4	308.0	18038.0	13.3	16912.3		560.0	153.6
Reactor 4		38	2175	36.4	4650.4	25.3	470.4	215.5	15679.0	13.4				
Reactor 4		39	2383	34.5	5435.0	24.0	470.4	123.0	13320.0	15.2			608.0	185.6
Reactor 4		40	2225	34.4	4696.0	23.9	470.4	123.0	13320.0	13.2			608.0	185.6
Reactor 4		41	1575	25.5	4939.3	17.7	333.0	172.0	12143.3	13.2				
Reactor 4	Begins	42	1633	34.1	5183 i	23.7	333.0	221 i	10966.67 i	17.1				

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 4		43	1883	35.2	5426.0	24.4	531.0	270.0	9790.0	11.9			547.2	163.2
Reactor 4		44	2400	42.0	5002 i	29.2	582.0	270.0	9790.0	12.4			547.2	163.2
Reactor 4		45	2200	34.6	4577.0	24.0	420.0	218.5 i	8820 i	12.6				
Reactor 4		46	2150	37.4	4523 i	26.0	437.0	167.0	7850.0	13.5			588.8	224.0
Reactor 4		47	1850	33.8	4469.0	23.5	437.0	167.0	7850.0	12.1			588.8	224.0
Reactor 4		48	2000	36.7	4998 i	25.5	437.0	248 i	8431 i	13.4				
Reactor 4		49	2442	37.0	5526.0	25.7	402.0	329.0	9012.0	14.5			566.4	147.2
Reactor 4		50	2367	33.3	5026 i	23.1	402.0							
Reactor 4		51	2316	37.4	4527 i	25.9	402.0	329.0	9614.5 i	13.0			566.4	147.2
Reactor 4		52	2016	37.5	4027.0	26.1	402.0	236.44 i	10217 i	13.0				
Reactor 4		53	2100	52.0	3439.8	36.1	448.0	143.89 i	10819.5 i	15.3				
Reactor 4		54	1235	34.1	3245	23.7	456	51.3	11422.0	9.8			531.2	150.4
Reactor 4		55	1130	32.6	5065	22.7	450	51.3	11422.0	14.6			531.2	150.4
Reactor 4		56	1400	32.5	5909	22.6	479	54.0	9574.0	15.7	13574.0		544.0	128.0
Reactor 4		57	1600	33.2	5645	23.0	480	45.0	9540.0	15.5	8684.0		472.0	147.2
Reactor 4		58	1640	34.3	5125	23.8	474	45.0	9540.0	14.8	8684.0		472.0	147.2
Reactor 4	Ends	59	1350	32.3	4705	22.4	480	45.0	9540.0	12.7	8684.0			147.2
Reactor 4		Mean		36.1	4726.9	25.1			9658.7	13.6			541.4	161.6
Reactor 2		1	1600		7433.0		1000.0	77.5			75.5		530.7	76.9
Reactor 2		2	1650				1000.0	70.0	7176.0	7.4	6670.1		351.6	84.9
Reactor 2		3	1800	43.3	4245.0	30.0	1000.0	50.0	4960.0	7.4	4593.9		351.6	29.2
Reactor 2		4	1450	38.7	3815.0	26.9	1000.0	58.2	5445.5	6.0				
Reactor 2		5	1450	38.0	4551.0	26.4	1000.0	66.3	5931.0	6.9				

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 2		6	1700	35.8	5330.0	24.9	1000.0	74.5	6416.5	7.6				
Reactor 2		7												
Reactor 2		8	1650					82.7	6902.0		6412.1		411.3	
Reactor 2		9	1550	35.0	4730.0	24.3	1000.0	90.8	5778.0	6.5		758.2	659.3	
Reactor 2		10	1650	32.9	5470.0	22.9	1000.0	99.0	4654.0	6.8	4363.8			73.8
Reactor 2		11	1300	30.1	4900.0	20.9	1000.0	57.0	4158.0	5.8				
Reactor 2		12	1900	34.4	6275.0	23.9	1000.0	15.0	3662.0	8.8	3413.4	560.4	520.9	73.8
Reactor 2		13	1500	34.7	4145.0	24.1	1000.0	23.0	3560.0	5.9	3311.6		560.0	
Reactor 2		14	1600	32.6	5515.0	22.7	970.0	31.0	5300.0	7.5		481.3	432.0	42.2
Reactor 2		15	1600	35.4	4875.0	24.6	967.0	67.5	5510.0	7.1				
Reactor 2		16	1750	34.4	5335.0	23.9	970.0	38.0	5720.0	7.7		813.3	733.3	53.3
Reactor 2		17	2050	35.2	5520.0	24.5	970.0	67.5	4675.0	7.8				
Reactor 2		18	1400	33.6	3755.0	23.3	990.0	68.0	3630.0	5.0		493.3	453.3	61.3
Reactor 2		19	1800	33.2	6075.0	23.0	900.0	67.5	3296.7	8.4				
Reactor 2		20					0.0		2963.3					
Reactor 2		21	1050		5525.0		1420.0	32.0	2630.0		2412.1			
Reactor 2		22	1600	35.0	6075.0	24.3	1440.0	97.0	8436.0	5.9	8367.6	523.3	493.3	149.3
Reactor 2		23	1550	38.6	4385.0	26.8	960.0	60.0	5116.0	7.0	4617.9	543.3	433.3	61.3
Reactor 2		24	1500	38.9	4355.0	27.0	960.0	59.6	4293.8	7.0	3982.6			
Reactor 2		25	1650	30.8	5965.0	21.4	940.0	98.0	3868.0	7.2		983.3	773.3	181.3
Reactor 2		26	1550	33.2	4995.0	23.0	950.0	59.6	4293.8	6.9	3982.6			
Reactor 2		27	1400	31.7	5115.0	22.0	950.0	59.6	4293.8	6.7	3982.6			
Reactor 2		28	1600	36.6	5110.0	25.4	900.0	130.0	8200.0	8.1	7486.0	1020.7	834.8	193.0

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 2		29	1600	34.6	4995.0	24.0	900.0	198.0	7514.0	7.1	6812.0			177.4
Reactor 2		30	1500	85.6	1935.0	59.4	900.0	198.0	7514.0	7.4	6812.0			177.4
Reactor 2		31	1783	39.3	4913.0	27.3	890.0	154.0	8350.0	8.3	7546.2	678.3	560.9	161.7
Reactor 2		32	1575	33.5	4715.0	23.2	890.0	154.0	8350.0	6.8	7546.2	678.3	560.9	161.7
Reactor 2	Begins	33	2050	34.9	5933.0	24.2	1077.0	149.5	6630.0	7.3				
Reactor 2		34	2078	34.8	5018.0	24.2	907.0	145.0	6630.0	7.3			339.2	102.4
Reactor 2		35	2100	31.9	5461.0	22.2	907.0	140.5	6275.0	7.2			339.2	102.4
Reactor 2		36	2200	31.8	5655.0	22.1	907.0	136.0	5920.0	7.4	5602.2		560.0	121.6
Reactor 2		37	2225	34.6	5052.0	24.0	936.0	136.0	5920.0	7.1	5602.2		560.0	121.6
Reactor 2		38	2175	35.3	4789.0	24.5	936.0	163.5	5821.0	6.8				
Reactor 2		39	2383	34.9	5378.0	24.2	936.0	191.0	5722.0	7.2			608.0	121.6
Reactor 2		40	2225	34.5	4674.0	24.0	936.0	191.0	5722.0	6.3			608.0	121.6
Reactor 2		41	1575	25.8	4880.0	17.9	663.0	187.3	5681.3	6.5				
Reactor 2		42	1633	34.8	5086 i	24.2	663.0	183.67 i	5640.7 i	9.1				
Reactor 2		43	1883	36.1	5292.0	25.0	1057.0	180.0	5600.0	6.7			547.2	86.4
Reactor 2		44	2400	42.9	4901 i	29.8	1158.0	180.0	5600.0	6.8			547.2	86.4
Reactor 2		45	2200	35.1	4510.0	24.4	791.0	188 i	5516 i	7.2				
Reactor 2		46	2150	39.2	4318 i	27.2	936.0	196.0	5432.0	6.7			588.8	105.6
Reactor 2		47	1850	36.6	4126.0	25.4	936.0	196.0	5432.0	6.0			588.8	105.6
Reactor 2		48	2000	38.8	4736.5 i	26.9	936.0	337.5 i	5408 i	6.5				
Reactor 2		49	2442	38.3	5347.0	26.6	853.0	479.0	5384.0	6.8			566.4	92.8
Reactor 2		50	2367	33.8	4953 i	23.5	853.0	479.0	5384.0	5.7				92.8
Reactor 2		51	2316	37.1	4559 i	25.8	853.0	479.0	5384 i	6.0			566.4	

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 2		52	2016	36.3	4165.0	25.2	853.0	435.67 i	5758.7 i	5.7				
Reactor 2		53	2100	33.8	5285.8	23.5	951.0	392.33 i	6133.3 i	6.1				
Reactor 2		54	1245	33.7	3305	23.4	929	343.5	6466.0	4.4			531.2	134.4
Reactor 2		55	1140	32.9	5015	22.9	930	343.5	6466.0	6.0			531.2	134.4
Reactor 2		56	1415	32.3	5955	22.5	722	92.0	6402.0	10.1			544.0	137.6
Reactor 2		57	1620	32.9	5705	22.8	736	90.0	6597.0	9.7			472.0	137.6
Reactor 2		58	1700	32.4	5515	22.5	935	90.0	6597.0	7.5			472.0	137.6
Reactor 2	Ends	59	1420	35.1	4345.0	24.4	935	90.0	6597.0	6.5				137.6
Reactor 2		Mean		34.8	4930.2	24.2			5930.3	6.9			527.6	115.6
Reactor 1	Begins	1	1600		7626.0		1000.0	32.0	596.0		516.2		530.7	164.5
Reactor 1		2	1650	37.8	4666.0	26.3	1000.0	33.0	652.0	6.2	550.2		351.6	172.5
Reactor 1		3	1800	37.1	4947.0	25.8	1000.0	40.0	570.0	6.0	452.1		351.6	116.7
Reactor 1		4	1450	37.4	3951.0	25.9	1000.0	43 i	519.0	4.9	416.1			
Reactor 1		5	1450				1000.0	43 i	468.0	7.9	380.1			
Reactor 1		6	1700	41.9	4555.0	29.1	1000.0	43 i	417.0	5.8	344.0			
Reactor 1		7							391.5 i					
Reactor 1		8	1650						366.0		308.0		411.3	
Reactor 1		9	1550	47.3	3500.0	32.9	0.0	43 i	389.0	17.8	334.1	758.2	659.3	
Reactor 1	Ends	10	1650	38.2	4716.0	26.5	1000.0	66.0	412.0	4.7	360.1		659.3	153.0
Reactor 1		Mean		39.9		27.7			478.1	7.6	407.7		494.0	151.7
Reactor 5		1	1600		8340.0		90.0	76.4	1078.0		904.5		530.7	244.1
Reactor 5		2	1650	24.5	4528.0	39.0	90.0	106.0	998.0	13.1	800.3		351.6	228.2
Reactor 5		3	1800	25.5	5025.0	36.5	90.0	92.0	848.0	12.2	676.1		351.6	188.4

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 5		4	1450	20.5										
Reactor 5		5	1450	24.0	5080.0	34.0								
Reactor 5		6	1700	26.5										
Reactor 5		7												
Reactor 5		8	1650	23.5					968.0		812.2		411.3	
Reactor 5		9	1550	23.0	4750.0	34.9	0.0					758.2	659.3	
Reactor 5	Begins	10	1650	25.0	5615.0	32.1	330.0	40.0	1272.0	15.1	1054.0			137.1
Reactor 5		11	1300	20.5	4706.0	31.4	10.0							
Reactor 5		12	1900	30.0	5596.0	38.6	130.0	91.0	1162.0	16.1	951.5	560.4	520.9	153.0
Reactor 5		13	1500	20.0	3470.0	41.5	130.0	56.0	992.0	18.8	787.2		560.0	
Reactor 5		14	1600	25.0	4240.0	42.5	50.0	73.0	1002.0	21.1		481.3	432.0	137.1
Reactor 5		15	1600	24.0	11960	14.4	0.0	32.0						
Reactor 5		16	1750	25.5	6150.0	29.9	50.0	25.0	1170.0	42.4		813.3	733.3	101.3
Reactor 5		17	2050	27.0	4635.0	41.9	480.0	32.0	1224.0	13.8				
Reactor 5		18	1400	17.5	3600.0	35.0	260.0	22.0	1278.0	16.5		493.3	453.3	165.3
Reactor 5		19	1800	28.0	5650.0	35.7	280.0	32.0	1173.0	19.7				
Reactor 5		20					0.0		1067.0					
Reactor 5		21	1050		4090.0		460.0	83.0	962.0		830.1			
Reactor 5		22	1600	29.5	6130.0	34.6	50.0	113.0	1146.0	13.6	1131.6	523.3	493.3	149.3
Reactor 5		23	1550	23.5	4680.0	36.2	50.0	54.0	994.0	23.4	712.0	543.3	433.3	149.3
Reactor 5		24	1500	23.5	4670.0	36.2	0.0	73.1	1440.0	29.7	1326.0			
Reactor 5		25	1650	25.5	5260.0	34.9	50.0	78.0	1240.0	20.3	1326.0	983.3	773.3	53.3
Reactor 5	Ends	26	1550	23.0	4900.0	33.8	0.0	73.1	1440.0	27.7	1326.0			

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 5		Mean				34.6			1170.8	21.4	1049.4		549.9	130.7
Reactor 6	Begins	1	1600		5725.0		330.0	220.5	11140.0		10370.2		530.7	53.1
Reactor 6		2	1650	24.5	3417.0	51.6	330.0	45.0	15126.0	21.7	14048.2		351.6	69.0
Reactor 6		3	1800	25.5	3658.0	50.2	330.0	41.0	15804.0	22.6	14731.9		351.6	45.1
Reactor 6		4	1450	20.5			333.0							
Reactor 6		5	1450	24.0	3637.0	47.5	333.0							
Reactor 6		6	1700	26.5	4213.0	45.3	333.0							
Reactor 6		7												
Reactor 6		8	1650	23.5	3370.0	50.2			13180.0		12342.0		411.3	37.1
Reactor 6		9	1550	23.0	4460.0	37.1	330.0					758.2	659.3	
Reactor 6		10	1650	25.0	8740.0	20.6	330.0	416.0	6262.0	8.4	5815.9			105.5
Reactor 6		11	1300	20.5	4680.0	31.5	330.0							
Reactor 6		12	1900	30.0	5783.0	37.4	330.0	144.0	20350.0	24.4	18984.0	560.4	520.9	73.8
Reactor 6		13	1500	20.0	3850.0	37.4	320.0	255.0	20368.0	16.5	18936.7		560.0	
Reactor 6		14	1600	25.0	4920.0	36.6	270.0	300 i	17000.0	21.3		481.3	432.0	42.2
Reactor 6		15	1600	24.0	4510.0	38.3	270.0	300 i	14000.0	20.0				
Reactor 6		16	1750	25.5	4820.0	38.1	270.0	27.0	11814.0	27.3		813.3	733.3	37.3
Reactor 6		17	2050	27.0	5350.0	36.3	270.0	300 i	14000.0	21.4				
Reactor 6		18					500.0	300 i	15458.0			493.3	453.3	77.3
Reactor 6		19	1800		5860.0		320.0	300 i	14700.0					
Reactor 6		20					0.0	300 i	13600.0					
Reactor 6		21	1050		3950.0		490.0	589.0	12700.0		11699.8			
Reactor 6		22	1600	29.5	6480.0	32.8	220.0	631.0	6362.0	10.5	6516.1	523.3	493.3	61.3

Table A-1: Daily Data for Feed Batch # 1 Runs

												Feed	Feed	Effluent
				Time Elapsed	Flow	HRT	ML	EffTSS	MLTSS	SRT	MLVSS	TCOD	SCOD	SCOD
	Steady-State	Day	Time	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Reactor 6		23	1550	23.5	5950.0	28.4	260.0	198.0	10770.0	19.3	9983.8	543.3	433.3	101.3
Reactor 6		24	1500	23.5	4930.0	34.3	0.0	882.7	11840.0	19.2	11157.5			
Reactor 6		25	1650	25.5	5360.0	34.3	50.0	1178.0	11634.0	13.0		983.3	773.3	341.3
Reactor 6		26	1550	23.0	5280.0	31.4	100.0	882.7	11840.0	14.2	11157.5			
Reactor 6		27	1400	22.5	4980.0	32.5	100.0	882.7	11840.0	14.6	11157.5			
Reactor 6		28	1600	26.0	5750.0	32.6	50.0	141.0	13994.0	72.6	13007.6	1020.7	834.8	177.4
Reactor 6		29	1600	24.0	5150.0	33.6	50.0	140.0	15366.0	74.6	14090.0			138.3
Reactor 6		30	1442	22.4	4880.0	33.1	50.0	140.0	15366.0	71.5	14090.0			138.3
Reactor 6		31	1750	27.1	4170.0	46.8	300.0	514.0	15672.0	19.0	14392.1	678.3	560.9	130.4
Reactor 6		32	1558	22.1	14870	10.7	300.0	514.0	15672.0	8.5	14392.1	678.3	560.9	130.4
Reactor 6		33	2030	28.7	5406.0	38.3	170.0							
Reactor 6		34	2047	24.2	4967.0	35.0	143.0							
Reactor 6		35	2100	24.5	5298.0	33.3	143.0							
Reactor 6		36	2200	25.0	6117.0	29.4	143.0	244.0	15782.0	31.9	14960.3			
Reactor 6		37	2215	24.2	5038.4	34.5	250.4	244.0	15782.0	22.3	14960.3			
Reactor 6		38	2145	23.3	4873.0	34.4	250.4							
Reactor 6		39	2350	26.1	5408.0	34.7	250.4	208.0	15844.0	24.6				
Reactor 6		40	2215	22.7	4692.4	34.8	250.4	208.0	15844.0	22.0				
Reactor 6		41	2093	22.8	4940.6 i	33.2	177.0							
Reactor 6		42	1972	22.8	5188.8 i	31.6	177.0							
Reactor 6		43	1850	22.8	5437.0	30.2	271.0	348.0	16436.0	18.0			547.2	73.6
Reactor 6	Ends	44	1837	23.9	4983 i	34.5	297.0	348.0	16436.0	18.1			547.2	73.6
Reactor 6		Mean			5277.3	35.5			14124.4	25.3			541.9	100.3

Table A-1: Daily Data for Feed Batch # 1 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 4		1		14440		25	197.1	1409.3		1197.3		198.4
Reactor 4		2		12910		25	197.1	1409.3		1197.3		198.4
Reactor 4		3		13860		25	197.1	1409.3		1197.3		198.4
Reactor 4		4		14780		25	51.4	2054.7		1782.7		211.2
Reactor 4		5		15750		25	51.4	2054.7		1782.7		
Reactor 4		6	24.3	15680	11.2	25	51.4	2054.7	17.5	1782.7		
Reactor 4		7	27.0	17090	11.4	75.0	37.6	3092.0	28.7	2681.3		201.6
Reactor 4		8	24.8	16260	11.0	75.0	37.6	3092.0	27.3	2681.3		201.6
Reactor 4		9	21.2	13580	11.2	75.0	37.6	3092.0	26.6	2681.3		201.6
Reactor 4		10	22.2	14430	11.1	330.0	31.4	4054.7	15.2	3525.3		182.4
Reactor 4		11	28.8	18735	11.1	330.0	31.4	4054.7	18.3	3525.3		182.4
Reactor 4		12	20.7	13430	11.1	330.0	31.4	4054.7	14.4	3525.3		182.4
Reactor 4		13	28.7	15110	13.7	390.0	26.7	4162.7	17.8	3624.0		227.2
Reactor 4		14	21.8	12880	12.2	390.0	26.7	4162.7	13.9	3624.0		227.2
Reactor 4		15	22.0	14380	11.0	390.0	26.7	4162.7	13.8	3624.0		227.2
Reactor 4		16	26.8	17680	10.9	410.0	31.9	4175.0	14.9	3912.5		
Reactor 4		17	22.8	14930	11.0	410.0	31.9	4175.0	13.2	3912.5		
Reactor 4		18	24.3	14440	12.1	410.0	31.9	4175.0	14.1	3912.5		
Reactor 4		19	21.7	13530	11.5	410.0	28.1	3900.0	12.9	3394.7		
Reactor 4		20	27.3	16160	12.2	255.0	28.1	3900.0	22.2	3394.7		

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 4		21	23.4	14880.0	11.3	255.0	28.1	3900.0	19.5	3394.7		
Reactor 4		22	24.2	14830.0	11.7	410.0	120.0	3808.0	8.4	3240.0		
Reactor 4		23	23.2	13750.0	12.1	410.0	120.0	3808.0	8.4	3240.0		
Reactor 4		24	23.5	15920.0	10.6	410.0	120.0	3808.0	7.8	3240.0		
Reactor 4		25	23.3	15600.0	10.8	300.0	26.2	3701.3	17.1	3252.0		
Reactor 4		26	24.9	15590.0	11.5	300.0	26.2	3701.3	18.3	3252.0		
Reactor 4		27	24.5	15760.0	11.2	300.0	26.2	3701.3	18.0	3252.0		
Reactor 4		28	23.5	14800.0	11.4	400.0	68.1	3530.7	10.4	3128.0		
Reactor 4		29	23.0	14840.0	11.2	400.0	68.1	3530.7	10.2	3128.0		
Reactor 4		30	25.8	16210.0	11.4	400.0	68.1	3530.7	11.0	3128.0	289.7	
Reactor 4	Begins	31	25.5	16010.0	11.5	220.0	118.6	3032.0	9.1	5677.3	258.2	88.2
Reactor 4		32	19.9	12370.0	11.6	220.0	118.6	3032.0	8.6	5677.3	258.2	88.2
Reactor 4		33	26.6	16270.0	11.8	220.0	118.6	3032.0	9.4	5677.3	258.2	88.2
Reactor 4		34	23.3	14900.0	11.3	25.0	117.6	2569.3	9.9	2292.0	270.8	97.6
Reactor 4		35	24.5	15700.0	11.2	25.0	117.6	2569.3	9.9	2292.0	270.8	97.6
Reactor 4		36	24.0	15870.0	10.9	25.0	117.6	2569.3	9.6	2292.0	270.8	97.6
Reactor 4		37	24.3	16090.0	10.9	25.0	23.8	3112.0	49.2	2770.7	498.8	141.7
Reactor 4		38	22.8	14780.0	11.1	25.0	23.8	3112.0	49.7	2770.7	498.8	141.7
Reactor 4		39	26.3	17020.0	11.1	25.0	23.8	3112.0	51.0	2770.7	498.8	141.7
Reactor 4		40	25.3	16340.0	11.1	400.0	24.8	3290.7	14.6	2976.0	327.5	92.9

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 4		41	21.1	13430.0	11.3	400.0	24.8	3290.7	12.7	2976.0	327.5	92.9
Reactor 4		42	29.3	18246.0	11.6	400.0	24.8	3290.7	16.5	2976.0	327.5	92.9
Reactor 4		43	26.3	16550.0	11.4	400.0	42.9	3020.0	12.5	2740.0	417.2	137.8
Reactor 4		44	22.5	14410.0	11.2	400.0	41.0	2938.7	11.3	2625.3	417.2	124.4
Reactor 4		45	22.4	14370.0	11.2	400.0	41.0	2938.7	11.3	2625.3	417.2	124.4
Reactor 4	Ends	46	21.8	13740.0	11.4	400.0	41.0	2938.7	11.1	2625.3		124.4
Reactor 4		Mean		15381.0	11.3			2990.5	18.5		354.5	110.8
Reactor 2		1	20.7	17245.0				9683.0		8798.0		
Reactor 2		2	28.8	11345.0	18.3	1400.0		10184.0	6.2	9141.3		198.4
Reactor 2		3	21.7	10679.0	14.6	450.0	10.0	10184.0	14.1	9141.3		198.4
Reactor 2		4	22.3	14545.0	11.1	450.0	10.0	10184.0	14.4	9141.3		198.4
Reactor 2		5	26.7	17305.0	11.1	3300.0	17.9	4770.7	2.4	4277.3		
Reactor 2		6	22.7	14335.0	11.4	950.0	17.9	4770.7	6.8	4277.3		
Reactor 2		7	24.4	14555.0	12.1	950.0	17.9	4770.7	7.3	4277.3		
Reactor 2		8	21.6	16115.0	9.6	950.0	15.7	4341.3	6.4	3942.7		
Reactor 2		9	26.6	15605.0	12.3	950.0	15.7	4341.3	7.9	3942.7		
Reactor 2		10	24.2	14405.0	12.1	950.0	15.7	4341.3	7.3	3942.7		
Reactor 2		11	23.4	12115.0	13.9	950.0	31.0	4274.7	6.8	3866.7		
Reactor 2		12	23.3	12065.0	13.9	950.0	31.0	4274.7	6.8	3866.7		
Reactor 2		13	22.8	19895.0	8.3	950.0	31.0	4274.7	6.3	3866.7		

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 2		14	24.0	15885.0	10.9	900.0	31.4	4292.0	7.1	3878.7		
Reactor 2		15	24.3	17825.0	9.8	900.0	31.4	4292.0	7.1	3878.7		
Reactor 2		16	25.6	14065.0	13.1	900.0	31.4	4292.0	7.7	3878.7	332.8	
Reactor 2	Begins	17	24.5	15555.0	11.3	900.0	43.8	3772.0	6.9	3430.7	289.7	116.5
Reactor 2		18	23.1	15065.0	11.0	900.0	43.8	3772.0	6.5	3430.7	289.7	116.5
Reactor 2		19	26.0	15885.0	11.8	900.0	43.8	3772.0	7.3	3430.7	289.7	116.5
Reactor 2		20	25.2	10645.0	17.0	850.0	31.9	3213.3	8.0	5904.0	258.2	132.2
Reactor 2		21	19.9	9595.0	14.9	850.0	31.9	3213.3	6.4	5904.0	258.2	132.2
Reactor 2		22	27.0	11305.0	17.2	850.0	31.9	3213.3	8.5	5904.0	258.2	132.2
Reactor 2		23	23.2	26245.0	6.4	870.0	13.3	4349.3	7.3	3976.0	270.8	110.2
Reactor 2		24	24.5	21725.0	8.1	870.0	13.3	4349.3	7.9	3976.0	270.8	110.2
Reactor 2		25	23.8	19375.0	8.9	870.0	13.3	4349.3	7.7	3976.0	270.8	110.2
Reactor 2		26	24.6	15735.0	11.2	960.0	12.4	4062.7	7.3	3705.3	498.8	129.1
Reactor 2		27	22.5	14455.0	11.2	960.0	12.4	4062.7	6.7	3705.3	498.8	129.1
Reactor 2		28	26.3	16945.0	11.2	960.0	12.4	4062.7	7.8	3705.3	498.8	129.1
Reactor 2		29	25.1	16215.0	11.1	960.0	16.7	3774.7	7.3	3413.3	327.5	74.0
Reactor 2		30	21.2	12615.0	12.1	960.0	16.7	3774.7	6.3	3413.3	327.5	74.0
Reactor 2		31	29.5	17869.0	11.9	960.0	16.7	3774.7	8.6	3413.3	327.5	74.0
Reactor 2		32	26.3	15965.0	11.8	960.0	12.9	3960.0	7.8	3660.0	417.2	141.7
Reactor 2		33	22.4	14785.0	10.9	940.0	10.0	3504.0	6.9	3194.7	417.2	86.6

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 2		34	22.4	12695.0	12.7	940.0	10.0	3504.0	6.9	3194.7	417.2	86.6
Reactor 2	Ends	35	22.1	15275.0	10.4	940.0	10.0	3504.0	6.8	3194.7		86.6
Reactor 2		Mean		15681.5	11.6			3788.8	7.3		343.7	109.9
Reactor 3		1	20.7	11955.0	12.4	800.0	37.9	4612.0	7.0	4156.0		182.4
Reactor 3		2	23.3	6735.0	25.0	800.0	37.9	4612.0	8.3	4156.0		182.4
Reactor 3		3	26.7	18185.0	10.6	880.0	25.7	3941.3	8.1	3554.7		
Reactor 3		4	22.7	6385.0	25.6	880.0	25.7	3941.3	7.4	3554.7		
Reactor 3		5	24.4	20835.0	8.4	880.0	25.7	3941.3	7.3	3554.7		
Reactor 3		6	21.7	9375.0	16.6	800.0	105.6	4409.3	6.5	3984.0		
Reactor 3		7	26.4	11215.0	17.0	800.0	105.6	4409.3	7.6	3984.0		
Reactor 3		8	24.2	18845.0	9.2	800.0	105.6	4409.3	5.9	3984.0		
Reactor 3		9	23.4	18535.0	9.1	660.0	47.6	5146.7	8.5	4565.3		
Reactor 3		10	23.4	11585.0	14.6	660.0	47.6	5146.7	9.2	4565.3		
Reactor 3		11	23.2	14685.0	11.4	660.0	47.6	5146.7	8.8	4565.3	422.4	
Reactor 3	Begins	12	23.6	18205.0	9.3	880.0	26.2	5954.7	7.4	5437.3	332.8	128.0
Reactor 3		13	24.4	15605.0	11.3	880.0	26.2	5954.7	7.8	5437.3	332.8	128.0
Reactor 3		14	24.5	15255.0	11.6	880.0	26.2	5954.7	7.8	5437.3	332.8	128.0
Reactor 3		15	23.6	14335.0	11.8	940.0	48.1	5484.0	6.7	5058.7	289.7	141.7
Reactor 3		16	23.1	15895.0	10.5	940.0	48.1	5484.0	6.5	5058.7	289.7	141.7
Reactor 3		17	26.0	15915.0	11.8	940.0	48.1	5484.0	7.3	5058.7	289.7	141.7

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 3		18	25.2	16335.0	11.1	880.0	47.1	5376.0	7.4	7998.7	258.2	78.7
Reactor 3		19	20.0	9715.0	14.8	880.0	47.1	5376.0	6.3	7998.7	258.2	78.7
Reactor 3		20	27.0	20325.0	9.6	880.0	47.1	5376.0	7.7	7998.7	258.2	78.7
Reactor 3		21	23.2	12865.0	13.0	880.0	41.9	5449.3	7.1	5029.3	270.8	62.2
Reactor 3		22	24.4	17565.0	10.0	880.0	41.9	5449.3	7.3	5029.3	270.8	62.2
Reactor 3		23	24.0	14305.0	12.1	880.0	41.9	5449.3	7.3	5029.3	270.8	62.2
Reactor 3		24	24.5	16255.0	10.9	900.0	41.4	5376.0	7.2	4945.3	498.8	
Reactor 3		25	22.5	12975.0	12.5	900.0	41.4	5376.0	6.8	4945.3	498.8	
Reactor 3		26	26.3	18895.0	10.0	900.0	41.4	5376.0	7.6	4945.3	498.8	
Reactor 3		27	25.0	14605.0	12.3	900.0	37.1	4976.0	7.5	4574.7	327.5	88.2
Reactor 3		28	21.3	14615.0	10.5	900.0	37.1	4976.0	6.4	4574.7	327.5	88.2
Reactor 3		29	29.6			900.0	37.1	4976.0	9.9	4574.7	327.5	88.2
Reactor 3		30	26.3	16105.0	11.7	900.0	47.1	5176.0	7.6	4792.0	417.2	135.8
Reactor 3		31	22.5	13775.0	11.8	900.0	42.9	5352.0	6.7	4920.0	417.2	88.2
Reactor 3		32	22.5	14865.0	10.9	900.0	42.9	5352.0	6.7	4920.0	417.2	88.2
Reactor 3	Ends	33	22.1	14935.0	10.6	900.0	42.9	5352.0	6.5	4920.0		88.2
Reactor 3		Mean		15397.4	11.3			5412.7	7.2		342.1	99.8
Reactor 1		1	24.5	13502.0	13.1		31.0	1784.0	31.4	1564.0		
Reactor 1		2	27.0	14872.0	13.1	760.0	28.1	2264.0	8.7	1988.0		224.0
Reactor 1		3	24.7	18012.0	9.9	760.0	28.1	2264.0	7.6	1988.0		224.0

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 1		4	21.2	10972.0	13.9	760.0	28.1	2264.0	7.2	1988.0		224.0
Reactor 1		5	22.3	15282.0	10.5	820.0	37.1	2600.0	6.5	2290.7		220.8
Reactor 1		6	28.7	18782.0	11.0	820.0	37.1	2600.0	8.0	2290.7		220.8
Reactor 1		7.0	21.3	14082.0	10.9	820.0	37.1	2600.0	6.3	2290.7		220.8
Reactor 1		8	28.2	13062.0	15.5	800.0	37.6	2258.7	8.4	1982.7		246.4
Reactor 1		9	22.0	11872.0	13.3	800.0	37.6	2258.7	6.7	1982.7		246.4
Reactor 1		10	22.2	14952.0	10.7	800.0	37.6	2258.7	6.4	1982.7		246.4
Reactor 1		11	26.7	16322.0	11.8	760.0	17.1	1690.7	8.7	1481.3		
Reactor 1		12	22.7	13342.0	12.2	760.0	17.1	1690.7	7.7	1481.3		
Reactor 1		13	24.3	17792.0	9.8	760.0	17.1	1690.7	7.8	1481.3		
Reactor 1		14	21.8	14192.0	11.0	780.0	51.9	2188.0	5.9	1918.7		
Reactor 1		15	26.4	16802.0	11.3	860.0	51.9	2188.0	6.4	1918.7		
Reactor 1		16	24.2	13822.0	12.6	860.0	51.9	2188.0	6.2	1918.7		
Reactor 1		17	23.5	12122.0	14.0	660.0	42.4	2260.0	8.1	1949.3		
Reactor 1		18	23.5	12332.0	13.7	660.0	42.4	2260.0	8.0	1949.3		
Reactor 1		19	24.2	18732.0	9.3	660.0	42.4	2260.0	7.3	1949.3		
Reactor 1		20	22.5	14832.0	10.9	750.0	34.8	2485.3	7.1	2196.0		
Reactor 1		21	24.5	16512.0	10.7	750.0	34.8	2485.3	7.6	2196.0		
Reactor 1		22	24.4	13952.0	12.6	750.0	34.8	2485.3	7.8	2196.0	332.8	
Reactor 1	Begins	23	23.7	14422.0	11.8	810.0	37.1	2032.0	6.7	1801.3	289.7	141.7

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 1		24	23.0	15362.0	10.8	810.0	37.1	2032.0	6.4	1801.3	289.7	141.7
Reactor 1		25	26.0	16080.0	11.6	810.0	37.1	2032.0	7.2	1801.3	289.7	141.7
Reactor 1		26	25.3	12712.0	14.3	750.0	46.7	1805.3	7.2	4461.3	258.2	97.6
Reactor 1		27	19.8	11452.0	12.5	750.0	46.7	1805.3	5.8	4461.3	258.2	97.6
Reactor 1		28	27.0	16460.0	11.8	750.0	46.7	1805.3	7.0	4461.3	258.2	97.6
Reactor 1		29	23.3	23030.0	7.3	650.0	18.1	2054.7	8.2	1842.7	270.8	102.3
Reactor 1		30	24.4	17530.0	10.0	650.0	18.1	2054.7	9.2	1842.7	270.8	102.3
Reactor 1		31	24.0	15400.0	11.2	650.0	18.1	2054.7	9.2	1842.7	270.8	102.3
Reactor 1		32	24.7	16570.0	10.7	880.0	34.8	1824.0	6.3	1637.3	498.8	107.1
Reactor 1		33	22.3	13540.0	11.9	880.0	34.8	1824.0	6.0	1637.3	498.8	107.1
Reactor 1		34	26.3	19170.0	9.9	880.0	34.8	1824.0	6.4	1637.3	498.8	107.1
Reactor 1		35	25.0	15980.0	11.3	750.0	27.6	1665.3	7.5	1497.3	327.5	119.7
Reactor 1		36	21.3	13710.0	11.2	750.0	27.6	1665.3	6.6	1497.3	327.5	119.7
Reactor 1		37	29.9	17770.0	12.1	750.0	27.6	1665.3	8.7	1497.3	327.5	119.7
Reactor 1		38	26.7	16240.0	11.8	750.0	24.3	1588.0	8.1	1456.0	417.2	171.2
Reactor 1		39	22.6	14320.0	11.4	780.0	16.7	1778.7	7.5	1596.0	417.2	113.4
Reactor 1		40	22.4	14510.0	11.1	780.0	16.7	1778.7	7.4	1596.0	417.2	113.4
Reactor 1	Ends	41	22.3	13740.0	11.7	780.0	16.7	1778.7	7.4	1596.0		113.4
Reactor 1		Mean		15684.1	11.3			1845.7	7.3	1628.9	343.7	116.7
Reactor 6		1		16162.0		127.0	81.0	3808.0		3486.0	539.0	

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 6		2		14925.0		262.0	81.0	3808.0		3486.0	539.0	
Reactor 6		3		14570.0		262.0						
Reactor 6		4		16289.0		262.0	209.0	4736.0		4308.0	539.0	
Reactor 6		5		14026.0		262.0	209.0	4736.0		4308.0	539.0	
Reactor 6		6		14803.0		0.0						
Reactor 6		7		15580.5		0.0						
Reactor 6		8		16358.0		57.0	104.0	5752.0		5130.0		
Reactor 6		9		14939.0		62.0	104.0	5752.0		5130.0		
Reactor 6		10		13520.0		0.0						
Reactor 6		11		13365.5		200.0						
Reactor 6		12		13211.0		200.0						
Reactor 6		13		15417.0		200.0						
Reactor 6		14		17623.0		165.0	77.5	5136.0				
Reactor 6		15		16078.0		165.0						
Reactor 6		16		14533.0		165.0	77.5	5136.0				
Reactor 6		17		13499.0		165.0						
Reactor 6		18		15152.5								
Reactor 6		19		9320		63	36.0	6554.0				217.6
Reactor 6		20		1920		0.0	36.0	6554.0				217.6
Reactor 6		21		16450		244	40.0					204.8

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 6		22		note			na	4900.0		4224.0		
Reactor 6		23		14620		1400	91.4	1933.3		1660.0		204.8
Reactor 6		24		12260		150	91.4	1933.3		1660.0		204.8
Reactor 6		25		13130		150	91.4	1933.3		1660.0		204.8
Reactor 6		26		13500		25	50.0	3789.3		2600.0		201.6
Reactor 6		27		15300		25	50.0	3789.3		2600.0		
Reactor 6		28	24.2	15050	11.6	25.0	50.0	3789.3	32.5	2600.0		
Reactor 6		29	26.8	16680.0	11.6	115.0	38.6	4242.7	30.3	3641.3		204.8
Reactor 6		30	24.8	15350.0	11.6	115.0	38.6	4242.7	29.3	3641.3		204.8
Reactor 6		31	21.2	13170.0	11.6	115.0	38.6	4242.7	27.2	3641.3		204.8
Reactor 6		32	22.2	13840.0	11.5	200.0	56.2	4958.7	18.8	4264.0		211.2
Reactor 6		33	28.8	17850.0	11.6	200.0	56.2	4958.7	21.6	4264.0		211.2
Reactor 6		34	20.3	13120.0	11.1	200.0	56.2	4958.7	17.5	4264.0		211.2
Reactor 6		35	28.7	10450.0	19.8	165.0	72.1	4500.0	26.1	3808.0		275.2
Reactor 6		36	22.0	0.0		0.0						275.2
Reactor 6		37	22.0	11920.0	13.3	165 0	72.1	4500.0	18.7	3808.0		275.2
Reactor 6		38	26.5	17190.0	11.1	95.0	30.5	4569.3	38.0	3892.0		
Reactor 6		39	22.8	14510.0	11.3	95.0	30.5	4569.3	35.7	3892.0		
Reactor 6		40	24.4	15570.0	11.3	95.0	30.5	4569.3	37.0	3892.0		
Reactor 6		41	21.6	13330.0	11.7	150.0	43.3	4718.7	23.9	4052.0		

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 6		42	26.8	16440.0	11.7	240.0	43.3	4718.7	20.7	4052.0		
Reactor 6		43	23.4	14170.0	11.9	240.0	43.3	4718.7	19.1	4052.0		
Reactor 6		44	24.2	15070.0	11.5	200.0	60.5	4588.0	18.3	3933.3		
Reactor 6		45	23.2	13870.0	12.0	200.0	60.5	4588.0	18.3	3933.3		
Reactor 6		46	22.9	14930.0	11.1	200.0	60.5	4588.0	17.4	3933.3		
Reactor 6		47	24.0	15290.0	11.3	180.0	75.7	4488.0	16.6	3890.7		
Reactor 6		48	24.5	15990.0	11.0	180.0	75.7	4488.0	16.5	3890.7		
Reactor 6		49	24.5	14520.0	12.1	180.0	75.7	4488.0	17.4	3890.7	332.8	
Reactor 6	Begins	50	23.5	14730.0	11.5	80.0	76.7	3441.3	17.3	3018.7	289.7	154.3
Reactor 6		51	23.0	14460.0	11.5	80.0	76.7	3441.3	17.2	3018.7	289.7	154.3
Reactor 6		52	26.0	16350.0	11.4	80.0	76.7	3441.3	17.6	3018.7	289.7	154.3
Reactor 6		53	25.3	16080.0	11.3	25.0	47.6	3074.7	27.7	5754.7	258.2	85.0
Reactor 6		54	20.0	12360.0	11.7	25.0	47.6	3074.7	27.8	5754.7	258.2	85.0
Reactor 6		55	26.5	16310.0	11.7	25.0	47.6	3074.7	28.7	5754.7	258.2	85.0
Reactor 6		56	23.4	14940.0	11.3	100.0	23.8	3552.0	35.2	3130.7	270.8	103.9
Reactor 6		57	24.5	15290.0	11.5	100.0	23.8	3552.0	36.4	3130.7	270.8	103.9
Reactor 6		58	247.0	15600.0	114.0	100.0	23.8	3552.0		3130.7	270.8	103.9
Reactor 6		59	24.3	15160.0	11.5	240.0	17.1	3541.3	23.3	3078.7	498.8	144.8
Reactor 6		60	22.8	14950.0	11.0	240.0	17.1	3541.3	21.9	3078.7	498.8	144.8
Reactor 6		61	26.4	16710.0	11.4	240.0	17.1	3541.3	24.8	3078.7	498.8	144.8

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 6		62	25.2	15980.0	11.3	270.0	21.9	3397.3	20.3	2974.7	327.5	119.7
Reactor 6		63	20.9	13300.0	11.3	270.0	21.9	3397.3	17.7	2974.7	327.5	119.7
Reactor 6		64	29.3	18373.0	11.5	270.0	21.9	3397.3	22.7	2974.7	327.5	119.7
Reactor 6		65	26.3	16630.0	11.4	270.0	11.4	3572.0	24.4	3176.0	417.2	147.6
Reactor 6		66	22.2	14380.0	11.1	240.0	17.1	3765.3	21.9	3308.0	417.2	91.3
Reactor 6		67	22.4	14320.0	11.3	240.0	17.1	3765.3	22.1	3308.0	417.2	91.3
Reactor 6	Ends	68	22.0	13750.0	11.5	240.0	17.1	3765.3	21.9	3308.0		91.3
Reactor 6		Mean		15245.9	11.3			3467.8	23.8		343.7	118.1
Reactor 5		1		6117.0		143.0	244.0	15782.0		14984.0	539.0	
Reactor 5		2		5038.4		250.4	244.0	15782.0		14984.0	539.0	
Reactor 5		3		4873.0		250.4						
Reactor 5		4		5408.0		250.4	208.0	15844.0		15146.0	539.0	
Reactor 5		5		4692.4		250.4	208.0	15844.0		15146.0	539.0	
Reactor 5		6		4940.6		177.0						
Reactor 5		7		5188.8		177.0						
Reactor 5		8		5437.0		271.0	348.0	16372.0		15246.0	547.2	73.6
Reactor 5		9		4983.0		297.0	348.0	16372.0		15246.0	547.2	73.6
Reactor 5		10		4529.0		248.0						
Reactor 5		11		4657.0							588.8	105.6
Reactor 5		12		4785.0							588.8	

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 5		13		5563.0								
Reactor 5		14		6341.0		284.0	18.0	658.0				
Reactor 5		15		5546.0		284.0						
Reactor 5		16		4751.0		284.0	18.0	658.0				
Reactor 5		17		4342.0		284.0						
Reactor 5		18		4129.0								
Reactor 5		19		7760		37	98.7	2018.0			531.2	201.6
Reactor 5		20		5420		40	98.7	2018.0			531.2	201.6
Reactor 5		21		12220		25	248.5	3034.0		6994.0	544.0	211.2
Reactor 5		22		13230		25	248.5	3034.0		2542.0		
Reactor 5		23		16380		25	43.3	3765.3		3334.7	608.0	185.6
Reactor 5		24		13370		25	43.3	3765.3		3334.7	608.0	185.6
Reactor 5		25		13690		25	43.3	3765.3		3334.7	608.0	185.6
Reactor 5		26		13930		340	34.3	5426.7		4838.7	544.0	224.0
Reactor 5		27		14720		340	34.3	5426.7		4838.7	544.0	
Reactor 5		28	24.5	14670	12.0	340.0	34.3	5426.7	17.0	4838.7	544.0	
Reactor 5		29	26.8	17370.0	11.1	395.0	41.4	5937.3	15.7	5260.0	585.6	195.2
Reactor 5		30	24.8	15800.0	11.3	395.0	41.4	5937.3	14.8	5260.0	585.6	195.2
Reactor 5		31	21.0	13780.0	11.0	395.0	41.4	5937.3	12.9	5260.0	585.6	195.2
Reactor 5		32	22.5	13560.0	11.9	400.0	28.6	6774.7	14.8	6036.0	582.4	192.0

Table A-2: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 5		33	28.6	16910.0	12.2	400.0	28.6	6774.7	18.3	6036.0	582.4	192.0
Reactor 5		34	20.8	12580.0	11.9	400.0	28.6	6774.7	13.8	6036.0	582.4	192.0
Reactor 5		35	28.9	14750.0	14.1	440.0	22.4	7669.3	18.0	6761.3	588.8	220.8
Reactor 5		36	21.7	12880.0	12.1	440.0	22.4	7669.3	13.6	6761.3	588.8	220.8
Reactor 5		37	22.3	14140.0	11.4	440.0	22.4	7669.3	14.0	6761.3	588.8	220.8
Reactor 5		38	26.7	16650.0	11.5	460.0	16.2	7652.0	16.2	6825.3		
Reactor 5		39	22.7	13700.0	11.9	460.0	16.2	7652.0	13.9	6825.3		
Reactor 5		40	24.5	14780.0	11.9	460.0	16.2	7652.0	15.0	6825.3		
Reactor 5		41	21.5	14220.0	10.9	450.0	17.6	7364.0	13.4	6576.0		
Reactor 5		42	26.7	16740.0	11.5	450.0	17.6	7364.0	16.4	6576.0		
Reactor 5		43	23.5	11880.0	14.2	450.0	17.6	7364.0	14.7	6576.0		
Reactor 5		44	24.1	13490.0	12.9	465.0	80.0	7065.3	11.8	6325.3		
Reactor 5		45	23.3	12360.0	13.6	465.0	80.0	7065.3	11.7	6325.3		
Reactor 5		46	22.8	17230.0	9.5	465.0	80.0	7065.3	10.5	6325.3		
Reactor 5		47	24.0	15730.0	11.0	340.0	57.1	7200.0	15.6	6488.0		
Reactor 5		48	24.4	16560.0	10.6	340.0	57.1	7200.0	15.6	6488.0		
Reactor 5		49	24.6	14860.0	11.9	340.0	57.1	7200.0	16.2	6488.0		
Reactor 5		50	23.4	14060.0	12.0	390.0	102.4	6881.3	11.8	6308.0		
Reactor 5		51	23.2	14320.0	11.6	390.0	102.4	6881.3	11.6	6308.0		
Reactor 5		52	25.8	16160.0	11.5	390.0	102.4	6881.3	12.4	6308.0	289.7	

<u>Table A-2</u>: Daily Data for Feed Batch # 2 Runs

											Feed	Effluent
	Steady-state	Day	Time Elapsed	Flow	HRT	ML Wasting	EffTSS	MLTSS	SRT	MLVSS	SCOD	SCOD
			(Hours)	(ml)	(Hours)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)	(mg/L)
Reactor 5	Begins	53	25.3	12850.0	14.1	290.0	121.4	5898.7	13.8	8570.7	258.2	81.9
Reactor 5		54	20.0	11245.0	12.8	290.0	121.4	5898.7	11.6	8570.7	258.2	81.9
Reactor 5		55	26.5	14300.0	13.3	290.0	121.4	5898.7	13.7	8570.7	258.2	81.9
Reactor 5		56	23.5	20560.0	8.2	200.0	100.5	5661.3	12.6	5236.0	270.8	110.2
Reactor 5		57	24.5	16540.0	10.7	200.0	100.5	5661.3	15.0	5236.0	270.8	110.2
Reactor 5		58	24.0	15770.0	11.0	200.0	100.5	5661.3	15.1	5236.0	270.8	110.2
Reactor 5		59	24.3	16040.0	10.9	240.0	94.3	4974.7	13.5	4589.3	498.8	132.2
Reactor 5		60	22.8	14600.0	11.2	240.0	94.3	4974.7	13.3	4589.3	498.8	132.2
Reactor 5		61	26.3	16860.0	11.2	240.0	94.3	4974.7	14.2	4589.3	498.8	132.2
Reactor 5		62	25.2	16350.0	11.1	220.0	76.7	4974.7	16.1	4606.7	327.5	129.1
Reactor 5		63	21.2	13510.0	11.3	220.0	76.7	4974.7	14.9	4606.7	327.5	129.1
Reactor 5		64	29.4	18358.0	11.5	220.0	76.7	4974.7	17.7	4606.7	327.5	129.1
Reactor 5		65	26.3	15900.0	11.9	220.0	74.3	5208.0	17.8	4892.0	417.2	149.6
Reactor 5		66	22.4	14300.0	11.3	220.0	70.0	5422.7	16.7	5020.0	417.2	129.1
Reactor 5		67	22.4	14060.0	11.5	220.0	70.0	5422.7	16.9	5020.0	417.2	129.1
Reactor 5	Ends	68	22.1	13250.0	12.0	220.0	70.0	5422.7	17.1	5020.0		129.1
Reactor 5		Mean		15280.8	11.5			5375.3	15.0			118.6

Table A-2: Daily Data for Feed Batch # 2 Runs

										Feed	Effluent
			Time Elapsed	FLOW	HRT	ML Wasting	EffTSS	MLTSS	SRT	SCOD	SCOD
	Steady-State	Day	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)		(days)	(mg/L)	(mg/L)
Reactor 1		1	26.8	15440.0	12.5	816.0	28.0	2155.0	8.0		
Reactor 1		2	21.8	18068.0	8.7	630.0	28.0	2155.0	7.6		
Reactor 1		3	23.5	18373.0	9.2	630.0	28.0	2155.0	8.2		
Reactor 1		4	23.4	17772.0	9.5	601.0	108.0	2668.0	5.4		
Reactor 1		5	17.6	11082.0	11.4	601.0	108.0	2668.0	5.2		
Reactor 1		6	26.6	16691.0	11.5	401.0	85.0	2572.0	8.5		
Reactor 1		7	23.3	14542.0	11.5	409.0	85.0	2572.0	8.0	1285.3	
Reactor 1	Begins	8	25.5	15644.0	11.7	522.0	114.0	3164.0	7.2	714.7	229.3
Reactor 1		9	21.7	13375.0	11.7	522.0	114.0	3164.0	6.6		229.3
Reactor 1		10	27.6	16980.0	11.7	477.0	26.0	3260.0	13.6		
Reactor 1		11	25.4	15620.0	11.7	477.0	26.0	3260.0	12.7	789.3	
Reactor 1		12	22.8	14005.0	11.7	477.0	17.0	3562.0	12.6	800.0	157.3
Reactor 1		13	23.8	14623.0	11.7	887.0	17.0	3562.0	7.5	981.3	157.3
Reactor 1		14	25.6	15522.0	11.9	887.0	17.0	3552.0	8.0	981.3	232.0
Reactor 1		15	20.5	12456.0	11.8	933.0	17.0	3552.0	6.2	426.7	232.0
Reactor 1		16	25.6	16533.0	11.1	933.0	22.0	3084.0	7.3	426.7	141.3
Reactor 1		17	25.6	16490.0	11.2	933.0	22.0	3084.0	7.3	597.3	141.3
Reactor 1		18	22.8	14088.0	11.6	933.0	22.0	3084.0	6.7	597.3	141.3
Reactor 1		19	25.8	16903.0	11.0	933.0	33.3	2822.0	6.9	528.0	160.0
Reactor 1	Ends	20	21.7	14133.0	11.1	899.0	33.3	2822.0	6.2	528.0	160.0
		Mean			11.5			3228.6	8.4	670.1	180.1

Table A-3: Daily Data for Feed Batch # 3 Runs

										Feed	Effluent
			Time Elapsed	FLOW	HRT	ML Wasting	EffTSS	MLTSS	SRT	SCOD	SCOD
	Steady-State	Day	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)		(days)	(mg/L)	(mg/L)
Reactor 2		1	26.8	5656.0	34.1	920.0	41.3	11761.0	8.6		
Reactor 2		2	21.9	15155.0	10.4	920.0	41.3	11761.0	6.8		
Reactor 2		3	23.5	13047.0	13.0	961.0	41.3	11761.0	7.0		
Reactor 2		4	23.3	14359.0	11.7	961.0	34.0	11834.0	7.0		
Reactor 2		5	17.6	10605.0	11.9	961.0	34.0	11834.0	5.3		
Reactor 2		6	26.9	16312.0	11.9	960.0	34.0	10780.0	8.0		
Reactor 2		7	23.1	13805.0	12.1	960.0	34.0	10780.0	6.9	1285.3	
Reactor 2	Begins	8	25.5	16266.0	11.3	956.0	76.0	12024.0	7.3	714.7	146.7
Reactor 2		9	21.7	13020.0	12.0	956.0	76.0	12024.0	6.3		146.7
Reactor 2		10	27.6	16069.0	12.3	911.0	27.0	12416.0	8.8		
Reactor 2		11	25.5	15053.0	12.2	911.0	27.0	12416.0	8.1	789.3	
Reactor 2		12	22.7			911.0	30.0	10884.0	7.5	800.0	120.0
Reactor 2		13	23.9	15523.0	11.1	969.0	30.0	10884.0	7.1	981.3	120.0
Reactor 2		14	25.5	15935.0	11.5	969.0	40.0	10306.0	7.4	981.3	192.0
Reactor 2		15	20.6	12909.0	11.5	961.0	40.0	10306.0	6.1	426.7	192.0
Reactor 2		16	25.4	16645.0	11.0	961.0	46.0	11140.0	7.4	426.7	106.7
Reactor 2		17	25.5	15288.0	12.0	945.0	46.0	11140.0	7.6	597.3	106.7
Reactor 2		18	22.8	14084.0	11.7	945.0	46.0	11140.0	6.8	597.3	106.7
Reactor 2		19	25.6	16711.0	11.0	945.0	55.6	10655.0	7.5	528.0	106.7
Reactor 2	Ends	20	21.6	14140.0	11.0	942.0	55.6	10655.0	6.4	528.0	106.7
		Mean			11.5			11230.0	7.3	670.1	131.9

Table A-3: Daily Data for Feed Batch # 3 Runs

										Feed	Effluent
			Time Elapsed	FLOW	HRT	ML Wasting	EffTSS	MLTSS	SRT	SCOD	SCOD
	Steady-State	Day	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)		(days)	(mg/L)	(mg/L)
Reactor 3		1	27.0	9243.0	21.0	940.0	53.3	18279.0	8.4		
Reactor 3		2	21.7	11611.0	13.4	940.0	53.3	18279.0	6.7		
Reactor 3		3	23.6	12374.0	13.7	953.0	53.3	18279.0	7.2		
Reactor 3		4	20.3	12166.0	12.0	953.0	60.0	18990.0	6.2		
Reactor 3		5	17.5	10900.0	11.6	953.0	60.0	18990.0	5.3		
Reactor 3		6	26.9	17324.0	11.2	956.0	96.0	18120.0	7.7		
Reactor 3		7	23.1	14655.0	11.3	956.0	96.0	18120.0	6.7	1285.3	
Reactor 3	Begins	8	25.5	16344.0	11.2	925.0	244.0	18942.0	6.8	714.7	53.3
Reactor 3		9	21.7	13574.0	11.5	925.0	244.0	18942.0	6.0		53.3
Reactor 3		10	27.5	17025.0	11.6	817.0	107.0	18996.0	9.1		
Reactor 3		11	25.5	15594.0	11.8	817.0	107.0	18996.0	8.5	789.3	
Reactor 3		12	22.7	14251.0	11.4	817.0	78.0	14928.0	7.7	800.0	74.7
Reactor 3		13	23.8	15264.0	11.2	920.0	78.0	14928.0	7.2	981.3	74.7
Reactor 3		14	25.5	15974.0	11.5	920.0	92.0	20880.0	7.7	981.3	122.7
Reactor 3		15	20.7	13382.0	11.1	933.0	92.0	20880.0	6.3	426.7	122.7
Reactor 3		16	24.7	16071.0	11.1	933.0	134.0	18459.0	7.1	426.7	53.3
Reactor 3		17	25.3	14285.0	12.8	876.0	134.0	18459.0	7.8	597.3	53.3
Reactor 3		18	22.8	12402.0	13.2	876.0	134.0	18459.0	7.1	597.3	53.3
Reactor 3		19	25.7	16572.0	11.2	876.0	113.3	18678.0	7.9	528.0	53.3
Reactor 3	Ends	20	21.5	14174.0	10.9	898.0	113.3	18678.0	6.6	528.0	53.3
		Mean			11.6			18478.8	7.4	670.1	69.8

<u>Table A-3</u>: Daily Data for Feed Batch # 3 Runs

										Feed	Effluent
			Time Elapsed	FLOW	HRT	ML Wasting	EffTSS	MLTSS	SRT	SCOD	SCOD
	Steady-State	Day	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)		(days)	(mg/L)	(mg/L)
Reactor 4		1	26.8	12751.0	15.1	430.0	70.0	22029.0	17.2		
Reactor 4		2	21.8			430.0	70.0	22029.0	15.2		
Reactor 4		3	23.5	12885.0	13.1	445.0	70.0	22029.0	14.5		
Reactor 4		4	23.4	15437.0	10.9	445.0	50.0	23936.0	14.7		
Reactor 4		5	17.6	10750.0	11.8	445.0	50.0	23936.0	11.3		
Reactor 4		6	26.6	15992.0	12.0	470.0	36.0	23518.0	16.2		
Reactor 4		7	23.3	12940.0	13.0	470.0	36.0	23518.0	14.3	1285.3	
Reactor 4	Begins	8	25.5	17198.0	10.7	478.0	136.0	22016.0	13.2	714.7	125.3
Reactor 4		9	21.8	14383.0	10.9	478.0	136.0	22016.0	11.6		125.3
Reactor 4		10	27.5	16860.0	11.8	410.0	91.0	24258.0	17.5		
Reactor 4		11	25.5	15342.0	12.0	410.0	91.0	24258.0	16.4	789.3	
Reactor 4		12	22.7	14050.0	11.6	410.0	82.0	22148.0	14.8	800.0	93.3
Reactor 4		13	23.8	14876.0	11.5	445.0	82.0	22148.0	14.3	981.3	93.3
Reactor 4		14	25.5	15220.0	12.1	445.0	63.0	21242.0	15.6	981.3	173.3
Reactor 4		15	20.9	12058.0	12.5	446.0	63.0	21242.0	13.0	426.7	173.3
Reactor 4		16	25.4	17093.0	10.7	446.0	120.0	21697.0	14.2	426.7	98.7
Reactor 4		17	25.5	16110.0	11.4	457.0	120.0	21697.0	14.1	597.3	98.7
Reactor 4		18	22.8	14260.0	11.5	457.0	120.0	21697.0	12.8	597.3	98.7
Reactor 4		19	25.7	16253.0	11.4	457.0	123.3	21290.0	14.0	528.0	106.7
Reactor 4	Ends	20	21.7	14284.0	10.9	419.0	123.3	21290.0	13.1	528.0	106.7
		Mean			11.5			22076.8	14.2	721.3	117.6

Table A-3: Daily Data for Feed Batch # 3 Runs

										Feed	Effluent
			Time Elapsed	FLOW	HRT	ML Wasting	EffTSS	MLTSS	SRT	SCOD	SCOD
	Steady-State	Day	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)
Reactor 1	Begins SRT/HRT	1	22.1	27330.0	5.8	780.0	47.0	6033.0	6.7		225.0
Reactor 1		2	24.0	26430.0	6.5	780.0	47.0	6033.0	7.3	300.0	225.0
Reactor 1		3	29.0	35540.0	5.9	780.0	75.0	5583.0	7.0		225.0
Reactor 1		4	23.8	29450.0	5.8	780.0	75.0	5583.0	6.1		225.0
Reactor 1		5	23.6	29720.0	5.7	620.0	93.0	4920.0	6.0	675.0	240.0
Reactor 1		6	25.0	31820.0	5.7	620.0	93.0	4920.0	6.2	675.0	240.0
Reactor 1		7	26.5	31860.0	6.0	450.0	38.0	5188.0	11.7	422.0	379.0
Reactor 1		8	20.4	27710.0	5.3	450.0	38.0	5188.0	9.4	422.0	379.0
Reactor 1		9	23.8	29640.0	5.8	790.0				769.0	550.0
Reactor 1		10	22.6	25950.0	6.3	790.0				769.0	550.0
Reactor 1		11	19.9	33780.0	4.2	730.0	25.0	5034.0	6.7	492.0	217.0
Reactor 1		12	22.6	26000.0	6.3	730.0	25.0	5034.0	7.9	492.0	217.0
Reactor 1		13	23.2	27780.0	6.0	860.0	33.0	4892.0	6.7	900.0	322.5
Reactor 1		14	20.8	25200.0	6.0	860.0	33.0	4892.0	6.1	900.0	322.5
Reactor 1		15	31.9	40200.0	5.7	810.0	57.0	5362.0	7.8	938.0	375.0
Reactor 1		16	23.3	25190.0	6.7	810.0	57.0	5362.0	6.5	938.0	375.0
Reactor 1		17	19.9	3883.0	36.8	660.0	76.0	4768.0	8.4	1040.0	425.0
Reactor 1	Begins Efficiency	18	22.4	11130.0	14.5	220.0	240.0	4240.0	8.0	975.0	360.0
Reactor 1		19	23.7	29270.0	5.8	700.0	45.0	4676.0	7.3	947.0	300.0
Reactor 1		20	23.8	29550.0	5.8	260.0	115.0	4620.0	7.2	956.0	300.0
Reactor 1	Ends	21	25.7	29400.0	6.3		60.0	4640.0			311.0
		Mean			7.8			4544.0	7.4	979.5	303.7

Table A-4: Daily Data for Feed Batch # 4 Runs

										Feed	Effluent
			Time Elapsed	FLOW	HRT	ML Wasting	EffTSS	MLTSS	SRT	SCOD	SCOD
	Steady-State	Day	(Hrs)	(ml)	(Hrs)	(ml)	(mg/L)	(mg/L)	(days)	(mg/L)	(mg/L)
Reactor 2	Begins SRT/HRT	1	21.7	27090.0	5.8	810.0	122.0	25817.0	7.0		150.0
Reactor 2		2	24.0	26730.0	6.5	810.0	122.0	25817.0	7.7	300.0	150.0
Reactor 2		3	29.0	35780.0	5.8	870.0	117.0	25263.0	8.4		120.0
Reactor 2		4	23.8	29850.0	5.7	870.0	117.0	25263.0	7.1		120.0
Reactor 2		5	23.3	29110.0	5.8	870.0	120.0	25230.0	6.9	675.0	157.5
Reactor 2		6	25.3	32250.0	5.7	870.0	120.0	25230.0	7.5	675.0	157.5
Reactor 2		7	24.5	30990.0	5.7	870.0	79.0	24920.0	7.6	422.0	135.0
Reactor 2		8	22.4	27650.0	5.8	870.0	79.0	24920.0	7.0	422.0	135.0
Reactor 2		9	23.9	28610.0	6.0	910.0				769.0	187.5
Reactor 2		10	22.6	30640.0	5.3	910.0				769.0	187.5
Reactor 2		11	27.8	37920.0	5.3	920.0	79.0	23516.0	8.0	492.0	97.5
Reactor 2		12	22.8	30740.0	5.3	920.0	79.0	23516.0	6.7	492.0	97.5
Reactor 2		13	23.0	31270.0	5.3	905.0	49.0	22318.0	7.1	900.0	120.0
Reactor 2		14	21.0	28100.0	5.4	925.0	49.0	22318.0	6.4	900.0	120.0
Reactor 2		15	32.2	43847.0	5.3	940.0	96.0			938.0	195.0
Reactor 2		16	23.8	29000.0	5.9	940.0	96.0	20844.0	6.7	938.0	195.0
Reactor 2		17	21.0	28070.0	5.4	870.0	181.0	21072.0	5.7	1040.0	202.0
Reactor 2	Begins Efficiency	18	22.4	28930.0	5.6	870.0	134.0	20014.0	6.4	975.0	225.0
Reactor 2		19	23.7	27990.0	6.1	800.0	129.0	20012.0	7.3	947.0	210.0
Reactor 2		20	23.8	26910.0	6.4	840.0	108.0	20420.0	7.3	956.0	225.0
Reactor 2	Ends	21	25.8	33380.0	5.6		105.0	18734.0			247.0
		Mean			5.7			19795.0	7.1	979.5	226.8

Table A-4: Daily Data for Feed Batch # 4 Runs

Appendix B

Sample	SAOX (mg Cl/L)	% Removal
R4 Feed	10.9	-
R4 Effluent	2.5	77
R6 Feed	11.4	-
R6 Effluent	3.2	72
R3 Effluent	5 and 6.4	N.A.
R5 Effluent	0.1 and 5.4	N.A.

Table B-1: SAOX for Feed Batch 1 Runs

N.B. : The two R3 and R5 effluent values shown were from two different sample dates, 3 weeks apart