THE EFFECT OF INERT BIOMASS SUPPORT MEDIA ON ACTIVATED SLUDGE TREATMENT OF A HIGH-STRENGTH INDUSTRIAL WASTEWATER

by

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(ABSTRACT)

A high strength industrial wastewater was treated in a bench-scale activated sludge reactor modified by the addition of biomass support media to the aeration tank. Two experimental biomass support systems (BSS) and one conventional activated sludge system were operated at different mean cell retention times (mixed liquor MCRTs). Three separate media were tested, NOR-PAC and Linpor used as free-floating supports, and BIONET used as a fixed-bed support. The effect of the media on substrate and oxygen utilization, and solid-liquid separation was investigated.

Substantial attached growth did not occur on the NOR-PAC and BIONET media. The attached biomass concentration in the Linpor systems increased with increased media concentration. The ratio of attached volatile solids to total volatile solids (attached volatile solids + MLVSS) decreased with increased mixed liquor MCRT. The advantages of the BSS would occur at low mixed liquor MCRTs.

Both the BSS and control systems achieved greater than 94% COD removal and substrate utilization rates (mg/h) did not significantly change during the experiments. Therefore, both systems were substrate limited. The substrate limitations caused decreased oxygen uptake rates of the attached biomass with increased mixed liquor MCRT.

The sludge settling of the Linpor systems was a function of mixed liquor MCRT, filamentous upsets, and the presence of the media. Enhanced settling was observed in the Linpor system only at the 3 day mixed liquor MCRT experiment.

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I. INTRODUCTION

Treatment of the cellulose acetate manufacturing wastewater produced by the Hoechst-Celanese plant, at Narrows, VA was investigated in this study. The activated sludge treatment system may, in the near future, be required by its National Pollutant Discharge Elimination System (NPDES) permit to attain significantly lower effluent standards. The proposed monthly effluent averages for the five day biochemical oxygen demand (BOD_5) and total suspended solids (TSS) values are 24 and 40 mg/l, respectively (Hoechst-Celanese, 1991).

Varied organic loading of the wastewater has adversely affected the performance of the operation. These shock loads have frequently resulted in high effluent COD and TSS values. Expansion of the wastewater treatment operation, for improved design, is limited by the available land. In addition, current performance is affected by inconsistent efficiency of solid-liquid separation in the secondary clarifiers (Hoechst-Celanese, 1991).

The performance of an activated sludge system could be enhanced by increasing the total biomass in the system without significant modifications to plant design. This may be accomplished by the use of a Biomass Support System (BSS) in which an inert media is placed in the aeration basin of an activated sludge system. In addition, the use of a BSS may improve activated sludge settling (Wanner, et al. 1987). Therefore, the selection of a BSS for the Hoechst-Celanese wastewater may be a viable option for achieving the proposed effluent standards.

Two types of support media were selected for this study; free floating and fixed-bed. The free floating media consisted of a solid trickling filter packing, NOR-PAC, produced by NSW AG, and a foam polyurethane media, Linpor, produced by Linde AG. BIO-NET modules, also produced by NSW AG, were selected as the submerged fixed media. Both Linpor and BIO-NET media have demonstrated an ability to improve solid-liquid separation during secondary clarification (Reimann, 1984; Schlegel, 1986). In addition, it has been shown that utilization of Linpor can dramatically increase the total biomass in the system by the growth of an attached biomass population (Morper and Wildmoser, 1989). This additional biomass may increase the total substrate removal capability and increase percent nitrification.

Successful bench, pilot and full-scale studies involving the media have been reported by several authors in Germany (Hedgeman, 1984; Heidman et al. 1988; Morper and Wilmoser, 1989; Schlegel, 1986) and in Czechoslovakia (Wanner et al., 1988). However, no studies have been performed in the United States using Linpor or BIO-NET media as a biomass support media in activated sludge operations. NOR-PAC was selected as an additional free floating media.

This media, incorporated in this fashion, had not been previously attempted.

This study was designed to evaluate the effects of the addition of biomass support media within a conventional activated sludge system while treating a high strength industrial wastewater. The objectives of this study were to compare the differences in treatment performance of three medias, NOR-PAC, BIONET, and Linpor, in BSS operation, to that of a conventional activated sludge system with operation at different mean cell residence times (mixed liquor MCRT). The mixed liquor MCRT is the MCRT of the suspended solids fraction of the total biomass (attached volatile solids + MLVSS).

The experiments were performed with twice the COD loading maintained at the Hoechst-Celanese wastewater treatment facility. The loading was increased for two reasons; First, to simulate increased loading conditions that may occur at the wastewater treatment plant, and secondly, to achieve significantly less than 100% soluble COD removal. Consequently, decreases in soluble effluent COD resulting from increases in COD removal should be readily apparent.

The systems in this study were operated at lower mixed liquor MCRT's than the wastewater treatment plant to simulate more stressful conditions, i.e., higher food to microorganism ratios, and to enable the derivation of the total substrate utilization kinetic coefficients from the relationship between effluent substrate and mixed liquor MCRT.

II. LITERATURE REVIEW

The chapter reviews the studies performed on the Hoechst-Celanese wastewater and those studies performed with the selected medias. In addition, a brief description of the most prominent biomass support medias is presented.

2.1 Hoechst-Celanese Wastewater Treatment Studies

Several studies have been performed to improve the operation of the Hoechst-Celanese wastewater treatment plant. These studies have been directed toward pretreatment of the wastewater, and improving sludge settling characteristics.

A study supported by NSW was performed using a pilot-scale activated sludge and trickling filter tower pretreatment (Hoechst-Celanese, 1991). The trickling tower media used, Sessil, was also produced by NSW. The purpose was to determine the buffering capacity of the system to shock loads and observe the system sludge settling. Pramanik (1991) concluded that the tower removed 39% of the total influent COD (TCOD) and showed that the pretreatment performance was not compromised by shock loading. Shah (1990) concluded that filamentous organisms were more prevalent in the control system and that better sludge settling occurred in the experiment system than that of the control system. Lee (1986) observed the relationships of nitrogen addition to extracellular polymers and sludge settling characteristics in a bench-scale activated sludge system. He concluded that the addition of nitrogen promoted the production of high protein content biopolymer, but the correlation to sludge settling was culture specific. In an attempt to improve sludge settling with the addition of divalent cations to a conventional activated sludge system, Segel (1987) found that she could not reproduce the results previously observed at the wastewater treatment plant. Magnesium and calcium did not significantly improve the sludge characteristics.

2.2 Biomass Support Systems

Biomass Support Systems involve the placement of fixed or suspended media in the aeration tank of an activated sludge system. The supporting or carrier media may be of a variety of shapes but all exhibit high surface area/volume ratios.

The performance of foam particles as biomass support structures has been previously observed in several pilot and full-scale studies (Boyle and Wallace, 1986; Heidman et al., 1988; Lessman and Reinmann, 1987). These studies implied several advantages of the BSS over conventional systems;

(1) increased total biomass and hence improved substrate removal when additional removal was possible, (2) lower susceptibility to hydraulic washout due to attached media

biomass, (3) improved solid-liquid separation measured as lower effluent total suspended solids (TSS), total effluent BOD_5, and Sludge Volume Index values (SVI), (4) enhanced nitrification, and (5) reduction in sludge production.
The following is a brief description of the more prominent BSS media and processes in use. The media concentration incorporated into an activated sludge system typically refers to the ratio of the volume of the biomass support media to the volume of the aeration tank.

Captor Process - Simon-Hartley Ltd, Stevenage, U.K.
The Captor media consists of polyurethane cuboidal foam particles 25mm x 25mm x 12.5mm. The porosity is approximately 97% with 30 pores/inch. The free floating pads are periodically removed from the activated sludge basin, cleaned by mechanical squeezing and placed back into the basin. This process serves as wastage from the system and also encourages new growth on the media.(Boyle and Wallace, 1986)

Linpor Process - Linde AG, Hollriegelskreuth, Germany. The Linpor media, similar to the Captor media, consists of cube parallelepiped polyurethane foam particles averaging 12mm x 12mm x 12mm. The porosity is 95% to 97% with 38-50 pores/inch. Wastage from the free floating pads does not occur by mechanical intervention. The biomass is allowed to slough off and regenerate at an unaltered rate. This system was originally designed for the purpose of enhanced nitrification. (Boyle and Wallace, 1986)

BIONET process - NSW AG, Germany. The polyethylene modules, produced with surface areas of 30.5 and 61 ft^2/ft^3, consist of bound bundles of cylindrical open structures. The modules have a specific weight of 1 g/cm^3. These are fixed in suspension in aerobic tanks. (NSW, 1989)

Ringlace process - Japan Engineering & Trading Co. Ltd., Japan. The ringlace media consists of closely bound bundles of small loops of fibers which attach in a spiral fashion to a central strand. The strands are typically suspended vertically within the aeration tank of an activated sludge system. (Wetzel et al.,1986)

NOR-PAC - NSW AG, Germany. This packing is similar in design to BIO-NET but, each piece represents a single open cylinder. The pieces vary in diameter from 1 to 1.5 to 2 inches with surface areas of 54.9, 44.2, and 30.5 ft^2/ft^3, respectively. The packing is utilized primarily in towers and odor scrubbers. (NSW, 1989)

2.3 Pilot Studies Using Biomass Support Media

Numerous pilot studies utilizing Linpor or similar foam particle type media to treat with municipal wastewater, as well as wastewaters from dairy, potato, pulp and paper, brewery, petroleum refinement and vinasse industries, have been reported by Reimann (1984). The reported studies have typically observed SVI, effluent BOD_5 or COD and nitrification as a function of substrate loading measured volumetrically, or as food to microorganism ratio (F/M). These parameters are also a function of mixed liquor MCRT and the ratio of media volume to total aeration tank volume.

Substrate removal and substrate utilization are two completely different phenomena and should be addressed as such. Some authors of the Linpor studies refer to substrate removal using terms such as BOD_5 elimination or effluent COD (Hedgeman, 1984; Morper and Wildmoser, 1989; Reimann, 1984). In these cases, BOD_5 elimination and effluent COD refer to the total effluent BOD_5 and COD respectively, which consists of both soluble effluent substrate and unsettled biomass. An appropriate method to determine substrate removal or utilization should negate the effects of clarifier design by excluding unsettled biomass from the effluent substrate calculations.

Lower sludge volume index was reported by Hegemann (1984) using municipal waste from a wastewater treatment plant and 40% Linpor. The results are presented in Table

2.1. The range of values given represents four series of studies performed. The improvement in the SVI values over the full-scale plant should be noted. The lower effluent BOD_5 concentrations in the pilot systems should be presumed to be the result of lower SVI values, because soluble effluent BOD_5 was not measured.

Similar results were observed with municipal wastes by Reimann (1984). Schlegel (1986), utilizing BIO-NET as the support media, concluded that improvement of the total effluent BOD_5 and COD was primarily the result of improved sludge settling.

The decreased SVI values with the use of foam particle media may be attributed in part to elimination of filaments within the activated sludge. Wanner et al. (1988), have observed a decrease of SVI values from over 2000 ml/g to 200 ml/g following the addition of 30% media in an activated sludge system. The biocenosis of the activated sludge shifted from predominantly filamentous microorganisms to a more normal culture including ciliates and rotifers. It was also demonstrated that as the ratio of attached media biomass to total biomass increased, the SVI values decreased. This phenomenon was suggested to occur because filamentous microorganisms are not able to utilize nitrate or nitrite, the greater fraction of which occur within the media, at the same rate as oxygen (Wartchow, 1988). Therefore, the greater the biomass within the media, the

Table 2.1 Results of Municipal Wastewater Pilot Study Using 40% Linpor

	Volumetric Loading kg/m^3-d	MLSS kg/m^3	Media TS kg/m^3	EMLVS kg/m^3	F/M kg/kg-d	SVI ml/g	Effluent BOD_5 g/m^3
Run 1	1.94	3.42	8.57	5.48	0.35	129	16
Run 2	2.62	3.7	8.1	5.16	0.51	130	16
Run 3	3.86	3.06	9.2	5.51	0.69	128	27
Run 4	1.22	3.26	8.79	5.47	0.22	162	9
full scale plant	1.13	2.58		2.58	0.47	485	48

EMLVS denotes the effective mixed liquor volatile solids in the system.

Source: Hedgeman (1984)

greater the substrate that diffuses across the media and the less substrate available to the suspended biomass. Schlegel (1986) suggested that settling in BIO-NET systems improved because of higher concentrations of ciliates and rotifers. Improved sludge settling and enhanced nitrification may be related to higher media concentrations. Wanner et al. (1988), observed that the effluent TKN was independent of variations in the mixed liquor MCRT, but noted that the effluent TKN significantly decreased with the addition of foam media. However, Wartchow (1988) observed no linear correlation between additional media and increased nitrification.

Wartchow (1988) also compared the nitrogen balance of three types of media including foam media and concluded that simultaneous denitrification occurred within the center of the foam media where oxygen absent. Oxygen uptake rates were reported although sufficient data were not presented for discussion (Morper and Wildmoser, 1989; Reimann, 1984; Wartchow, 1988).

Initial studies on substrate utilization by BSS was performed by Atkinson et al. (1984). Using biomass support media consisting of tightly wound single strands of stainless steel wire within a fluidized bed, the author determined that substrate utilization rates could be described as a half-order equation.

A more comprehensive approach to modeling of substrate and biomass material balances was undertaken by Wetzel et al. (1986). Two models were modified and developed for foam particle media, the Marais-Ekama and the Immobilized Biomass Reactor Models. The Marais-Ekama model was modified to consider both suspended and attached biomass. The model requires the fractions of active and endogenous, heterotrophic, and autotrophic biomass in both suspended and attached forms. However, the model does not include mass transfer and diffusion into the media. Mass transfer and diffusion of the bulk liquid/biofilm interactions are rate limiting factors which are considered in the Immobilized Biomass Reactor Model. Unfortunately, the rate coefficients are not available.

2.4 Full-Scale Operations Using Biomass Support Media

Full-scale systems utilizing Linpor media have been operated for the treatment of municipal wastewater as well as wastewater from paper, dairy and night soil dumping industries (Reimann, 1984; Lessmann and Reimann, 1987). Wastewater treatment systems are usually operated at substrate-limited conditions such that additional biomass, incorporated within or attached to media, would not increase soluble substrate removal. Based on this premise, Wetzel et al. (1986) concluded that the BSS system was not advantageous over conventional activated sludge systems for soluble carbonaceous BOD removal.

Two of three trains of Klarwerk 1, City of Munich wastewater treatment system were converted to Linpor BSS in 1986 (Morper and Wildmoser, 1989). Train 2 was maintained as conventional activated sludge. The reported data are presented in Table 2.2. The Linpor trains were operated at significantly higher MLSS concentrations than train 2, but all trains were operated at similar volumetric loadings. The percent BOD_5 and COD eliminations refer to the differences of total influent substrate and total effluent substrate. Although the Effective Mixed Liquor Suspended Solids (EMLSS) values in trains 1 and 3 were approximately twice than those in train 2, train 2 exhibited similar BOD_5 and COD elimination compared to the other trains. The SVI values were also similar in all three trains.

Another study described the conversion of a cardboard factory wastewater treatment plant to Linpor BSS (Morper and Wildmoser, 1989). The data were presented in a similar fashion and did not include operation parameters or performance prior to the conversion.

The Wyk municipal wastewater treatment system located on the North Sea Island of Fohr, Germany, was converted to a nutrient removal system which included the addition of Linpor media as reported by Morper and Wildmoser, (1989). Although the available information was insufficient for

Table 2.2 Performance Data of Full-Scale Operation of Municipal Wastewater Plant

(After Morper and Wildmoser, 1989)

	Train 1 10% linpor	Train 2 no Linpor	Train 3 30% linpor
MLSS (kg/m^3)	3.8	2.8	3.9
Media TS (kg/m^3)	16.8		12.8
EMLSS (kg/m^3)	5.1	2.8	6.6
SVI (ml/g)	140	150	120
Recycle Ratio (%)	92	84	79
<u>BOD_5</u>			
Influent (mg/l)	205 (67-286)	216 (114-306)	215 (235-491)
Effluent (mg/l)	12 (7-19)	19 (12-26)	10 (4-18)
elimination (%)	94	92	95
<u>COD</u>			
Influent (mg/l)	414 (285-479)	417 (263-507)	410 (235-491)
Effluent (mg/l)	65 (51-77)	81 (58-95)	57 (37-70)
elimination (%)	85	82	86
Volumetric Loading (kg/m^3-d)	1.66 (0.49-2.8)	1.48 (0.5-2.01)	1.55 (0.56-1.94)
F/M (kg/kg-d)	0.35 (0.1-.67)	0.58 (0.14-0.9)	0.24 (0.1-0.29)

EMLSS is denoted as the effective mixed liquor suspended solids in the aeration tank.

analysis, it suggested the system's ability to achieve greater than 50% NH_4 elimination at 10.5 °C. However, the term "ammonia elimination" was not specifically defined.

Rogalla et al. (1989), utilized BIOFIX, a submerged fixed-bed media with a specific surface area of 100 m^2/m^3, in the conversion of one train of a municipal activated sludge plant. The authors concluded that substrate removal efficiencies were consistently higher in the BIOFIX system with increased volumetric loadings and at any given F/M ratio, than those by the control train.

The pilot and full-scale reports did not include significant operating and performance information for both municipal and industrial wastes. For example, soluble effluent BOD_5 or COD were not reported. In addition, enhanced nitrification reports were not supported by detailed nitrogen balances. Based on the studies, improved effluent substrate should be attributed to improved sludge settling in secondary clarification.

Although Wetzel et al. (1986) have used reported data in modeling efforts, studies involving substrate utilization based on soluble substrate removal are needed. In addition, detailed oxygen balances coordinating nitrification and substrate utilization are required.

III. MATERIALS AND METHODS

Two activated sludge biomass support systems (BSS) and one control system were used in the study. The activated sludge seed for the systems was acquired from the Hoechst-Celanese wastewater treatment plant in Narrows, Virginia. This chapter includes a description of the system design and operation, the pertinent parameters measured, and the respective analytical techniques used.

3.1 System Design

All systems were housed in a constant temperature room maintained at 20 °C ± 1 °C. Figure 3.1 illustrates the basic design of the completely mixed tank reactors for both the control and BSS units. The biomass support systems required two additional diffused aerators to ensure complete mixing of the media within the mixed liquor.

The concentration of media in the systems was calculated as the percentage of media volume to aerobic tank volume. The NSW media volume was measured as the volume occupying the total space within a graduated cylinder. The Linpor media volume was derived based on the relative volume calculated from an average dimension of 12mm x 12mm x 12mm. Therefore, an average Linpor particle occupied approximately 1.728 ml.

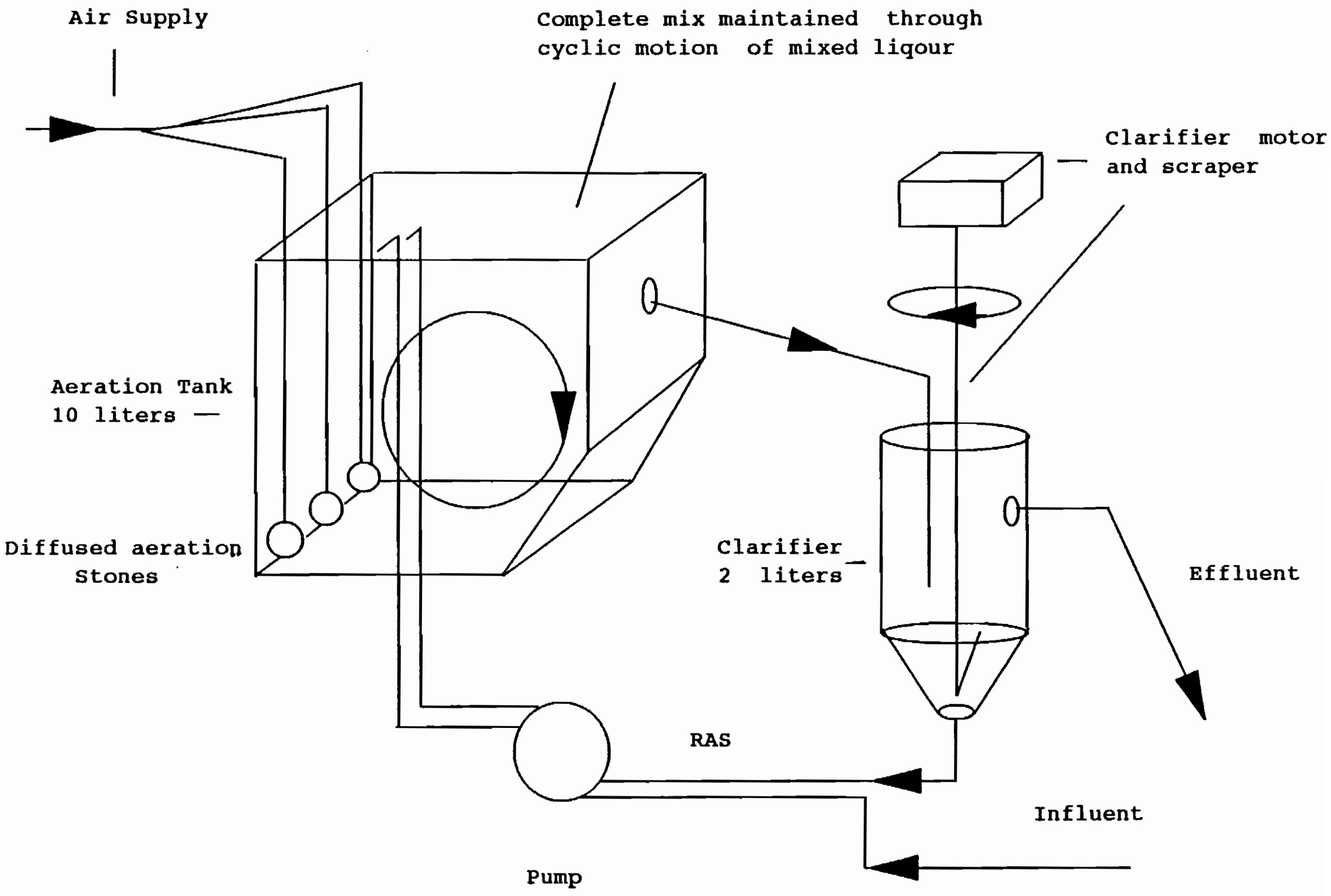

Figure 3.1 Set-up for BSS and Control Systems

3.2 System Operation and Maintenance

The study consisted of two system operational phases, the first utilizing the NSW media and the second phase utilizing the Linpor media. The dissolved oxygen in the mixed liquor was maintained between 3 and 8 mg/l. The mixed liquor MCRT and sludge wastage rate (l/day) were determined from the concentrations of the effluent volatile suspended solids and the mixed liquor volatile suspended solids (MLVSS). Waste sludge was removed daily directly from the aeration tank. Wastage rate and mixed liquor MCRT were calculated as follows;

$$MCRT=\frac{XV}{XQ_w+X_e(Q-Q_w)} \qquad (3-1)$$

where; X = MLVSS in reactor (mg/l)

X_e = effluent VSS (mg/l)

V = volume of reactor (l)

Q_w = sludge wastage rate (l/day)

Q = influent flow rate (l/day)

Steady state conditions were determined from the stabilization of soluble effluent COD, concentration of MLVSS, and media VS. Recycle activated sludge flow rates were maintained identical to the influent flow rates.

3.3 Operational Phases

Initial start-up involved acclimation of the activated sludge to the operating conditions using a single reactor with an aeration basin volume of 19.4 l, and operated at a 12 day mixed liquor MCRT and a 2 day nominal hydraulic residence time (HRT). Phase one was initiated with the addition of 50% NSW media to the aeration basin on day 27. The system parameters were changed on day 60 to a 6 day mixed liquor MCRT and 1 day HRT. On day 81 the aeration basin volume was reduced by 50% and an additional system was created to serve as a control.

After day 80, the volumetric loading to the systems was changed and maintained for the duration of the study at between 2.2 and 2.6 kg COD/day with a subsequent HRT range of 0.8 to 1.3 days. The full scale wastewater treatment plant after which the bench-scale plant was modeled, operates at approximately a 2 day HRT. The loading to the bench systems was essentially doubled compared to the full scale plant, by reducing system volumes, in an effort to induce extreme COD loading conditions. It was hoped that the potential of the biomass support systems could be evaluated using this approach. The control and the BSS were operated at identical mixed liquor MCRTs and HRTs for the remainder of the study. The systems were operated at 6, 3, 2, and 1 day mixed liquor MCRTs.

NOR-PAC was replaced by Linpor media on day 126 of the study. The HRT was calculated based on the aerobic tank volume of 10 l. The actual sterile volume of the media is insignificant, i.e., porosity is a minimum of 95%, and the volume of the liquid displaced is insignificant.

During Phase two, the Linpor and control systems were operated at 12, 6, 3, and 1 day mixed liquor MCRTs and the Linpor system at 10%, 15%, 20% and 30% Linpor media concentrations. An additional Linpor system identical to that of the first Linpor system, was operated only at a 12 day mixed liquor MCRT and 10%, 15%, 20%, and 30% Linpor media concentrations. The steady-state data gathered during the start-up of this latter system served as control data.

BIO-NET failed to develop attached growth at the mixed liquor MCRTs previously mentioned. Therefore, data are not reported for this media.

Periods determined as steady-state and changes in mixed liquor MCRT and media concentration operation are depicted in Appendix A, Figures A.1 through A.6. Steady state operational parameters are listed in Table A.1, Appendix A.

3.4 Wastewater Characterization

The influent feed consisted of wastewater taken from the equalization basin at the Hoechst-Celanese wastewater treatment plant and stored in carboys at 20°C. The wastewater consisted primarily of acetic acid from the production of cellulose acetate. Secondary constituents included Isopropyl Alcohol, Acetone, Methyl Cyanide and, to a lesser extent, sanitary wastes and heavy metals. Table 3.1 describes the results of wastewater characterization of the equalization basin effluent.

3.5 Nutrient Requirements

The quantity of nutrients required were based on the following ratios derived from basic cell composition of E.Coli; Nitrogen:Phosphorus:Potassium, 14:3:1 respectively. The average nitrogen cell mass was assumed to be 12.2% and used as the basis for nutrient calculations (Gaudy and Gaudy, 1988). Nutrients required were based on sludge production as follows;

$$\text{N required (mg/day)} = (.122 \times P_x) - (19\ \text{mg/l})/Q\ \text{indigenous N} \tag{3-2}$$

$$\text{P required (mg/day)} = (.026 \times P_x) - (17\ \text{mg/l})/Q\ \text{indigenous P} \tag{3-3}$$

$$\text{K required (mg/day)} = (.009 \times P_x) \tag{3-4}$$

where P_x = sludge production (mg/day)

Indigenous P and N refers to inherent nutrient concentrations in the wastewater. Sludge production was calculated based on MLVSS concentrations excluding attached media biomass concentrations. Nitrogen was added to the wastewater in the form of urea for required cell maintenance

Table 3.1 Hoechst-Celanese Wastewater Characterization

Characteristic	(mg/l)	Organic Constituents	(mg/l)	Metals	(mg/l)
pH	4.4	Acetic Acid	770	Potassium	1.65
TCOD	2271	Isopropyl Alcohol	127	Copper	0.32
Suspended Solids	88.5	Acetone	47	Nickel	0.23
		Methyl Cyanide	29	Lead	0.16
		Methyl Ethyl Ketone	9	Chromium	0.07
Nutrients	(mg/l)	Ethanol	0.99		
		Isopropyl Acetate	0.51		
Total Phosphorus	18.5	Methyl Acetate	0.51		
Total Nitrogen	13.97	Ethyl Acetate	0.37		
Nitrite	2.1	Methanol	0.26		
Nitrate	3.75	Mesityl Oxide	0.17		
Ammonia	0.94	*Benzene	<0.1		
TKN	7.36				

* detectable concentrations only occur during plant upsets

Note - All numbers denote mean values for the period of study from June 1990 to February 1991.
The concentrations represented were samples taken from the equalization basin effluent.

Source: Hoechst-Celanese (1991).

and growth. In addition, 0.50 g/day urea was added to the influent so that the media biomass would not be nitrogen deficient. During the 1 day mixed liquor MCRT experiments, phosphorus requirements exceeded the indigenous concentrations and potassium phosphate monobasic was added to supplement both phosphorus and potassium requirements. A minimum of 25 mg/l potassium was added primarily as potassium hydroxide. This concentration was derived from the contemporaneous practices at the wastewater plant. Improved settling characteristics had apparently occurred as a result of potassium addition. Sludge production and nutrient requirements during the study are presented in Table A.2, Appendix A.

3.6 Chemical Oxygen Demand (COD)

The COD analysis was performed according to the closed reflux titrimetric method outlined in Standard Methods for the Examination of Water and Wastewater, 5220-C. Influent COD samples were removed directly from the carboys and measured as total chemical oxygen demand (TCOD). Effluent COD samples were filtered according to Standard Methods to exclude unsettled suspended solids and recorded as soluble chemical oxygen demand (SCOD).

3.7 Solids Determination

All suspended solids were determined in accordance with Standard Methods for the Examination of Water and Wastewater, 2540-D and 2540-E. mixed liquor suspended solids (MLSS), MLVSS plus, influent and effluent total suspended solids (TSS) and volatile suspended solids (VSS) were monitored.

Linpor total solids and volatile solids were also determined. An average dried weight (at 105°C) of 0.0498 g/particle was determined from a random sample of 500 particles. The particles were subsequently volatilized at 550°C for 20 minutes to measure inorganic constituents. The particles contained no measurable inorganic constituents and therefore were not considered in further calculations. The sampling technique for Linpor media solids was then determined as follows. Particles were removed from the aerobic tank, allowed to drain for 15 seconds to remove bulk phase and suspended biomass and placed within a 105°C convection oven for 24 hours (Heidman et al., 1988). The particles were subsequently desiccated for 1 hour and weighed. The difference between this measurement and the predetermined sterile weight/particle represented an approximation of the total solids/particle. The particles were subsequently volatilized at 550°C for 20 minutes. A covered crucible, not weighing more than three times that of the sample particles was used. Ten particles were sacrificed for analysis and subsequently replaced with new media. The sum of the MLVSS (g) and attached VS (g) was the total volatile solids.

A consistently reliable technique for the measurement of biofilm growth on the NSW media was not developed. The deviation of mean sterile weight/particle was significantly greater than any potentially measurable attached solids dry weight/particle. Therefore, the methods used for Linpor solids determination could not be used with the NSW media and attached solids on the NSW media were not measured. Solids concentrations for steady state periods are listed in Table A.3, Appendix A.

3.8 Substrate Utilization

The substrate utilization model chosen for this study was the Marais-Ekama equation modified by Wetzel et al. (1986) which describes substrate uptake rate, R_s, as follows:

$$-R_s = \left[\frac{(F_{ac})\,(1-F_{suc}-F_{puc})\,(COD_i)-(COD_i)}{HRT} \right] +$$

$$1.42\,(F_{db})\,(b)\,(X_{sh}+X_{ph}) - \left[\frac{K_m S}{K_s+S} \right] (X_{sh}+X_{ph}) \qquad (3\text{-}5)$$

where;

F_{ac} = fraction of readily assimilable COD

F_{suc} = fraction of soluble undegradable COD

F_{puc} = fraction of particulate undegradable COD

COD_i = total COD (mg/l)

COD_a = readily assimilable COD (mg/l)

F_{db} = fraction of degradable VSS

b = heterotrophic cell endogenous rate (1/days)

X_{sh} = heterotrophic suspended biomass (mg)

X_{ph} = heterotrophic particle bound biomass (mg)

K_m = maximum substrate utilization rate for soluble substrate (1/days)

K_s = half saturation coefficient for soluble substrate (mg/l)

S = readily assimilable substrate (mg/l)

For practical application of the model, the following assumptions were made;

- The wastewater is such that all of the substrate is easily assimilable.
- The endogenous decay rate is negligible compared to substrate removed.
- The specific fractions of heterotrophic biomass to autotrophic biomass within the suspended solids and particle bound solids cannot be precisely determined. Therefore, the total biomass was considered heterotrophic.
- K_m and K_s are identical for both suspended and attached biomass.
- K_m and K_s for suspended solids in both the control and media systems are identical.

The following equation is the modified description for total substrate utilization (mg/h) for the Linpor systems;

$$-R_{s1}=\left[\frac{(K_m)(S)}{(K_s+S)}\right](X_s+X_p) \qquad (3\text{-}6)$$

and for the Control system;

$$-R_{s2}=\left[\frac{(K_m)(S)}{(K_s+S)}\right](X_s) \qquad (3\text{-}7)$$

where;

- R_{s1} = substrate utilization rate of the BSS (mg/hour)
- R_{s2} = substrate utilization rate of control system (mg/hour)

X_s = suspended solids in reactor (g)

X_p = particle bound solids in reactor (g)

The particle bound biomass specific substrate utilization rate, -Rsp, can be theoretically calculated as;

$$-R_{sp}=\frac{R_{s1}-R_{s2}}{X_p} \qquad (3\text{-}8)$$

The total substrate uptake rates for the BSS were determined as follows;

$$-R_{s1} = (COD_a-COD_e)(Q) \qquad (3\text{-}9)$$

and for the control system;

$$-R_{s2} = (COD_a - COD_e)(Q) \qquad (3\text{-}10)$$

where;

COD_e = soluble effluent COD

The specific rates were determined by division of $(X_p + X_s)$ in equation 3-9 and X_s in equation 3-10.

Substrate utilization rates are listed in Table B.1, Appendix B.

3.9 Settling Characteristics

Sludge settling characteristics were analyzed using zone settling velocity (ZSV) and sludge volume index (SVI). One liter of mixed liquor was removed from the aeration tank and placed in a 1 liter graduated cylinder. At 2 to 5 minute time intervals the interface height was observed and the volume of the settled sludge was recorded at the elapsed time of 30 minutes. The ZSV (cm/min) was the slope of the portion of the interface height vs time plot indicated as zone settling. When the change in interface height was insignificant over the period of 30 minutes the entire difference was calculated as the ZSV. The SVI value was determined after 30 minute settling and calculated as described in Standard Methods for the Examination of Water and Wastewater, 2710-D. Results of SVI and ZSV are tabulated in Table A.4, Appendix A.

3.10 Oxygen Uptake

The determination of oxygen uptake rate required several modifications of the techniques described in Standard Methods for the Examination of Water and Wastewater, 2710-B. During Phase One, only the total oxygen uptake rate (TOUR) was observed within both systems. With the incorporation of Linpor media, however, both the mixed liquor oxygen uptake rate and the TOUR in the BSS were observed.

3.10.a NOR-PAC

The dimensions of the NSW media required that uptake rates be observed directly within the aerobic tank. The method used incorporated a mechanical stirrer to provide continuous stirring within the tank. System flow was not interrupted. A submersible D.O. probe was used in place of the BOD bottle probe.

3.10.b Linpor media

mixed liquor oxygen uptake rates and uptake rates during phase two were determined utilizing a 500 ml Erlenmeyer flask with continuous mixing maintained using a magnetic stirrer. The number of particles placed in the flask represented the equivalent concentration in the aerobic tank and therefore represented an equivalent uptake rate. At concentrations of 30%, the equivalent particle concentration could not be maintained as completely mixed. Therefore, the uptake rate per particle was determined from placing half of the desired concentration of particles within the flask. The uptake rates consistently represented a linear relationship with time which suggested that there was no interference by oxygen bubbles trapped within the media.

The specific oxygen uptake rate for the attached biomass, (LSOUR), mg/attached VS g-hour was calculated as follows:

$$LSOUR = \frac{TOUR - MLOUR}{X_p} \qquad (3\text{-}11)$$

where; TOUR = Total oxygen uptake rate (mg/hour)

MLOUR = Mixed liquor oxygen uptake rate (mg/hour)

All oxygen uptake values are presented in Table A.5, Appendix A.

3.11 Nitrogen Determination

All nitrogen determination procedures followed were performed according to Standard Methods for the Examination of Water and Wastewater. Influent and effluent nitrate and nitrite concentrations were determined using the Ion

Chromatograph procedure, 4110-B. Total Kjeldahl nitrogen (TKN) of the influent, effluent, and mixed liquor was determined using the semi-micro-Kjeldahl method, 4500-N_{org} C.

The nitrogen nitrified (mg/day) was calculated from the following material balance;

$$\text{N nitrified} = \text{Available N} - \text{Effluent } NH_3 \qquad (3\text{-}12)$$

$$\text{Available N} = TKN_i - TKN_b - TKN_n \qquad (3\text{-}13)$$

where;

TKN_i = (influent TKN)(Q) (mg/day)

TKN_b = Q_w(MLVSS)(0.1) + ($Q-Q_w$)(eff VSS)(0.1) (mg/day)

TKN_n = 1.5(Q_w) + 1.5($Q-Q_w$) (mg/day)

The nondegradable TKN value of 1.5 mg/l was taken from the full-scale data obtained by Hoechst-Celanese (1991). The biomass TKN content of both effluent and mixed liquor is estimated as 10% of the VSS g. The effluent NH_3 was estimated from the following equation;

$$\text{Effluent } NH_3 = \text{Effluent TKN} - (Q-Q_w)[1.5 + (\text{eff VSS})(0.1)] \quad (\text{mg/day}) \qquad (3\text{-}14)$$

Therefore, the % N nitrified was defined by;

$$\%\text{N nitrified} = \frac{(\text{N nitrified})(100)}{\text{AvailableN}} \qquad (3\text{-}15)$$

The mass (mg/day) of nitrogen denitrified was calculated as follows;

$$\text{N denitrified} = \text{N nitrified} + NO_{Xi} - NO_{Xe} - NO_{Xw} \qquad (3\text{-}16)$$

where;

NO_{xi} = influent nitrate + influent nitrite (mg/day)

NO_{xe} = effluent nitrate + effluent nitrite (mg/day)

NO_{xw} = nitrate wasted + nitrite wasted (mg/day)

NO_{xw} was not measured and was assumed as;

NO_{xw} = (effluent nitrate + effluent nitrite)(mg/l)(Q_w) (3-17)

Therefore, the % N denitrified was calculated as follows;

$$\%N\ \text{denitrified} = \frac{(N\ \text{denitrified})(100)}{N\ \text{nitrified} + NO_x} \qquad (3\text{-}18)$$

Nitrification/denitrification data is listed in Table B.2, Appendix B.

IV. RESULTS

The basic approach of this study was to observe system performance at different mixed liquor MCRTs during steady state periods. System performance data and substrate and oxygen uptake of the biomass support systems were compared to that of the control.

Efforts were made to separate the suspended solids and attached solids components with respect to oxygen uptake rates to elucidate attached biomass substrate consumption.

4.1 Biomass Growth

The NOR-PAC system did not perform as hoped. Attached growth was observed only during the one day mixed liquor MCRT experiment. Growth occurred between individual pieces of the media which had become interconnected during the operation of the system. Attempts to induce growth by reducing the system turbulence throughout operational days 82-125 by reductions in diffused air flow failed. The incomplete aerobic tank mixing resulted in severe short circuiting. Figure A.7, Appendix A, compares the MLVSS of the NOR-PAC and control systems.

The non-degradable soluble COD was determined to be 37 mg/l during Phase One and was verified by the Hoechst-Celanese (1991) performance data. This value was used in later calculations.

The use of the polyurethane foam particles, Linpor, provided two physical conditions unattainable with the other biomass support media; a quiescent environment in which active biomass could become attached, and a substantially greater surface area through which a greater ratio of total biomass per unit volume of reactor would result. Figure 4.1 shows the observed increase in total volatile solids with increased mixed liquor MCRT. Figures 4.2 and 4.3 illustrate the change in the suspended solids and attached solids, respectively. The increase in MLVSS in both control and Linpor systems suggested that the suspended solids biomass growth was not substrate limited. As mixed liquor MCRT increased, attached biomass solids concentrations slightly decreased or stabilized, which indicated that the media environment became growth-limiting as mixed liquor MCRT increased. This may have been caused by restricted or insufficient diffusion of oxygen, substrate or nutrients to the media biomass. Figure 4.4 illustrates the decrease of the ratio of attached volatile solids to total volatile solids with increased mixed liquor MCRT. The relationship of attached biomass concentrations to media concentration in the reactor is shown in Figure 4.5. Clearly, the attached biomass concentrations were primarily a function of media concentration.

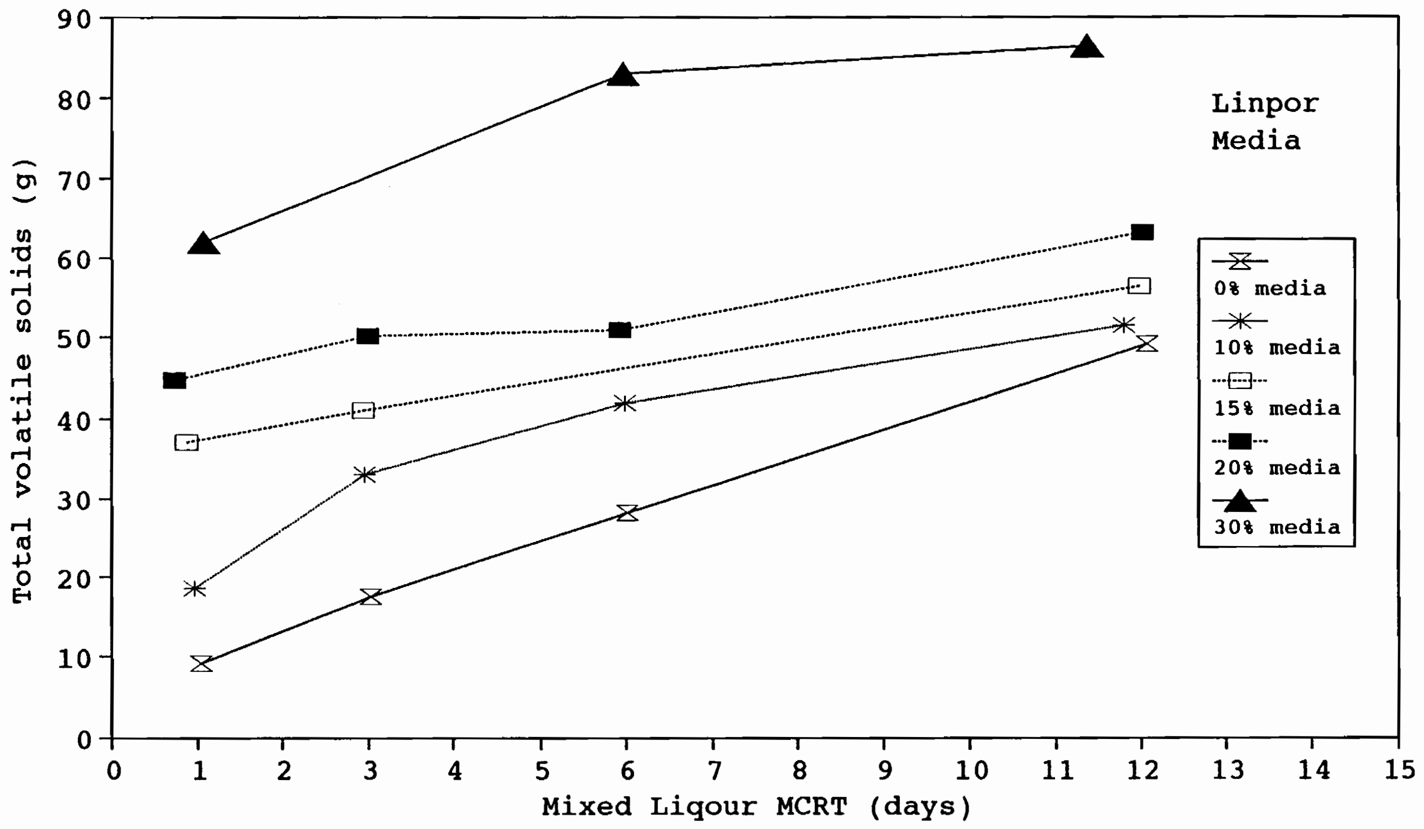

Figure 4.1 Total (Attached VS + MLVSS) Volatile Solids as a Function of Mixed Liquor MCRT

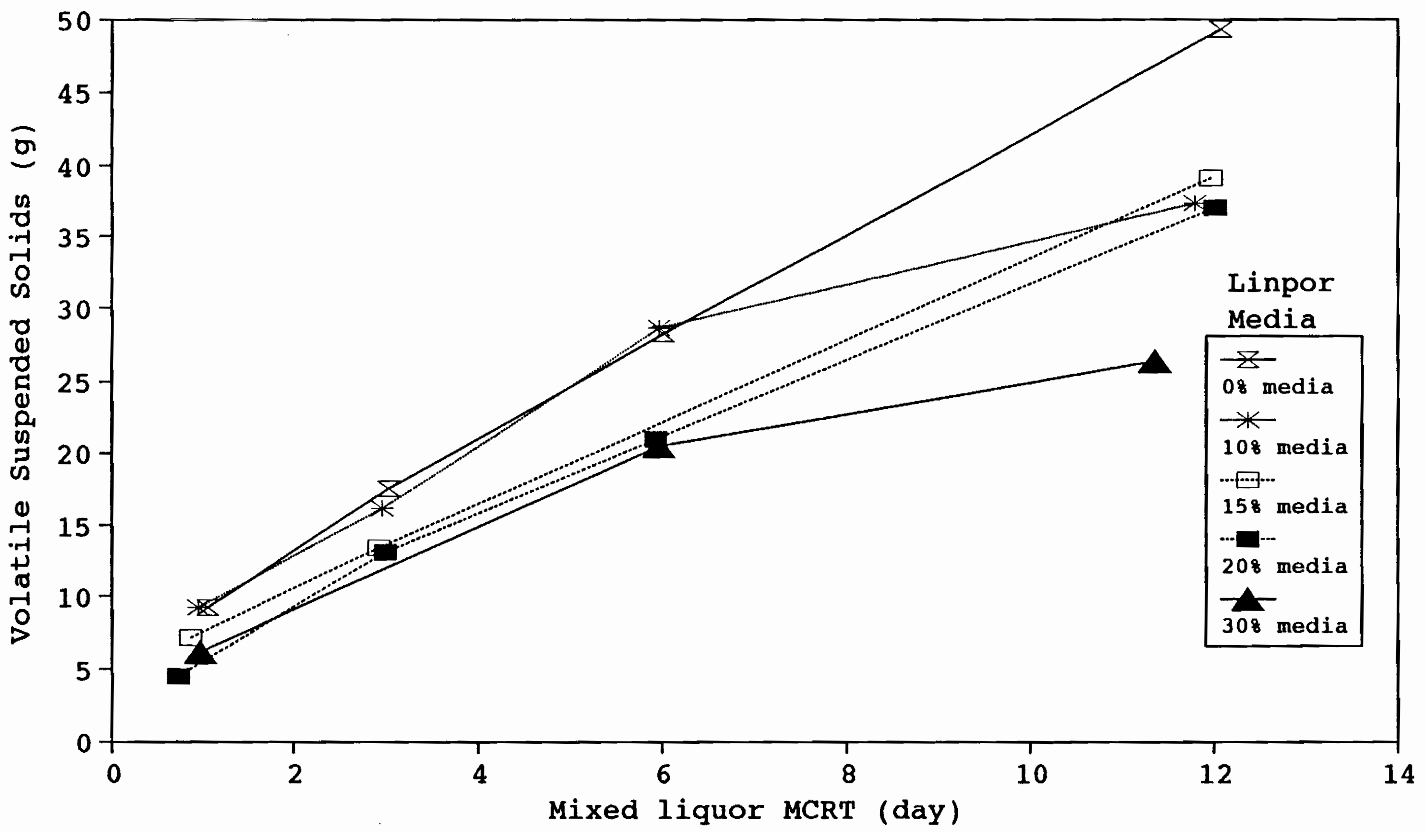

Figure 4.2 Change in Mixed Liquor Volatile Suspended Solids with Mixed Liquor MCRT

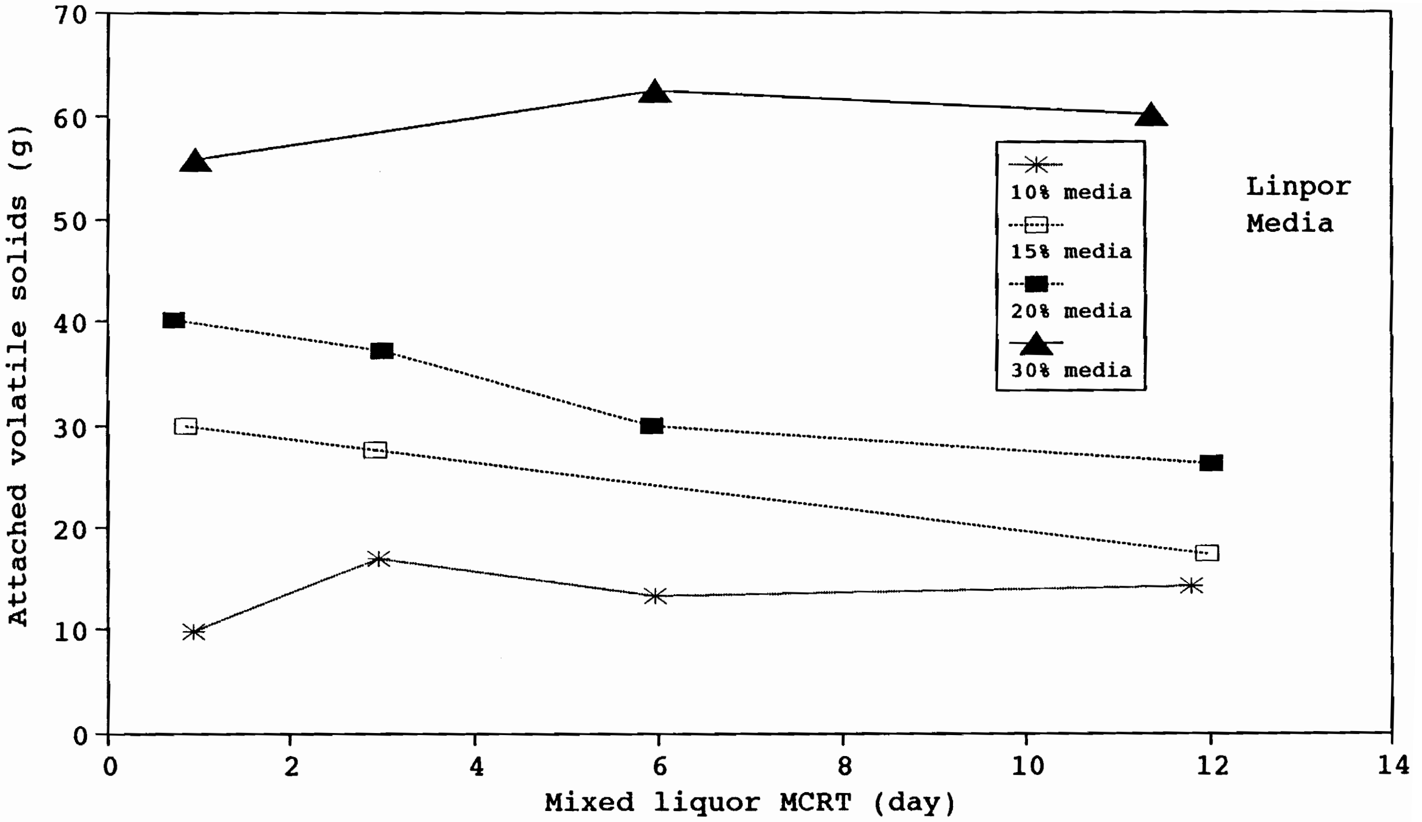

Figure 4.3 Change in Attached Volatile Solids with Mixed Liquor MCRT

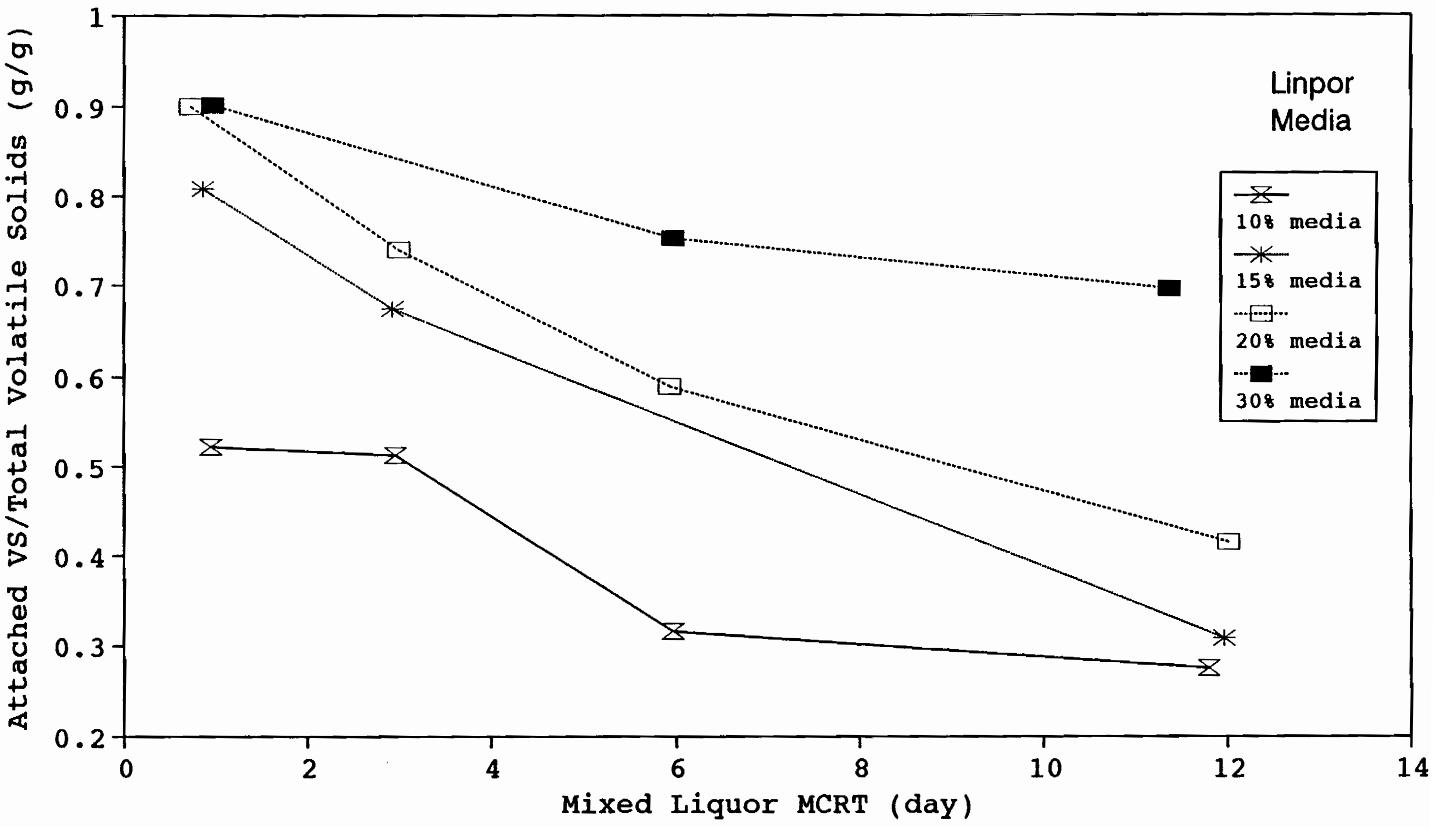

Figure 4.4 Change in Attached VS/Total Volatile Solids Ratio with Mixed Liquor MCRT

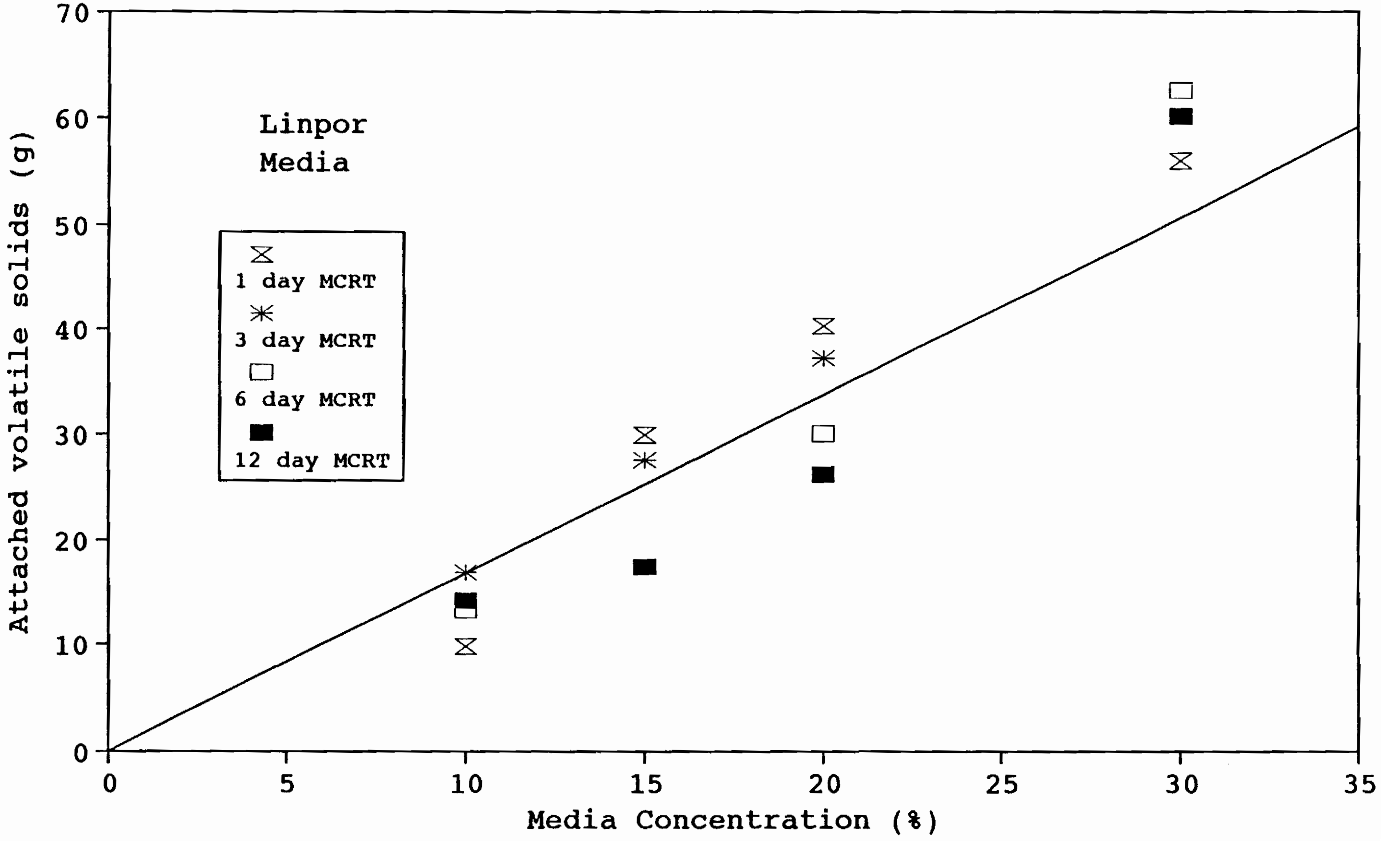

Figure 4.5 Change in Attached Volatile Solids with Media Concentration

4.2 Substrate Utilization

Figure 4.6 illustrates the relationship between soluble effluent COD and effective MCRT. It should be apparent that increased media concentrations did not result in reduced effluent COD. Compared to the 6 and 12 day mixed liquor MCRTs, it is apparent that some soluble COD was not stabilized by either the control system or the Linpor BSS at the 1 and 3 day mixed liquor MCRTs. Also shown in Figure 4.7, increased media concentration did not directly result in decreased effluent COD. Lower effluent COD values were recorded at the 12 and 6 day mixed liquor MCRT experiments. It would appear that soluble effluent COD was primarily a function of mixed liquor MCRT based on the relationships shown in Figure 4.8. Changes in the total effluent COD do not exclusively imply operational performance. The total substrate utilization is a more appropriate parameter to elucidate the effects at different mixed liquor MCRTs and media concentration.

Figure 4.9 illustrates the recorded changes in substrate uptake rate with increased media concentration. Although variations occurred in the substrate uptake rates, the differences from 0 to 30% media was not significant. The total substrate utilization rates of the control and Linpor systems compared with soluble effluent COD were also similar, as shown in Figure 4.10. However, the total specific substrate utilization rates of the control and

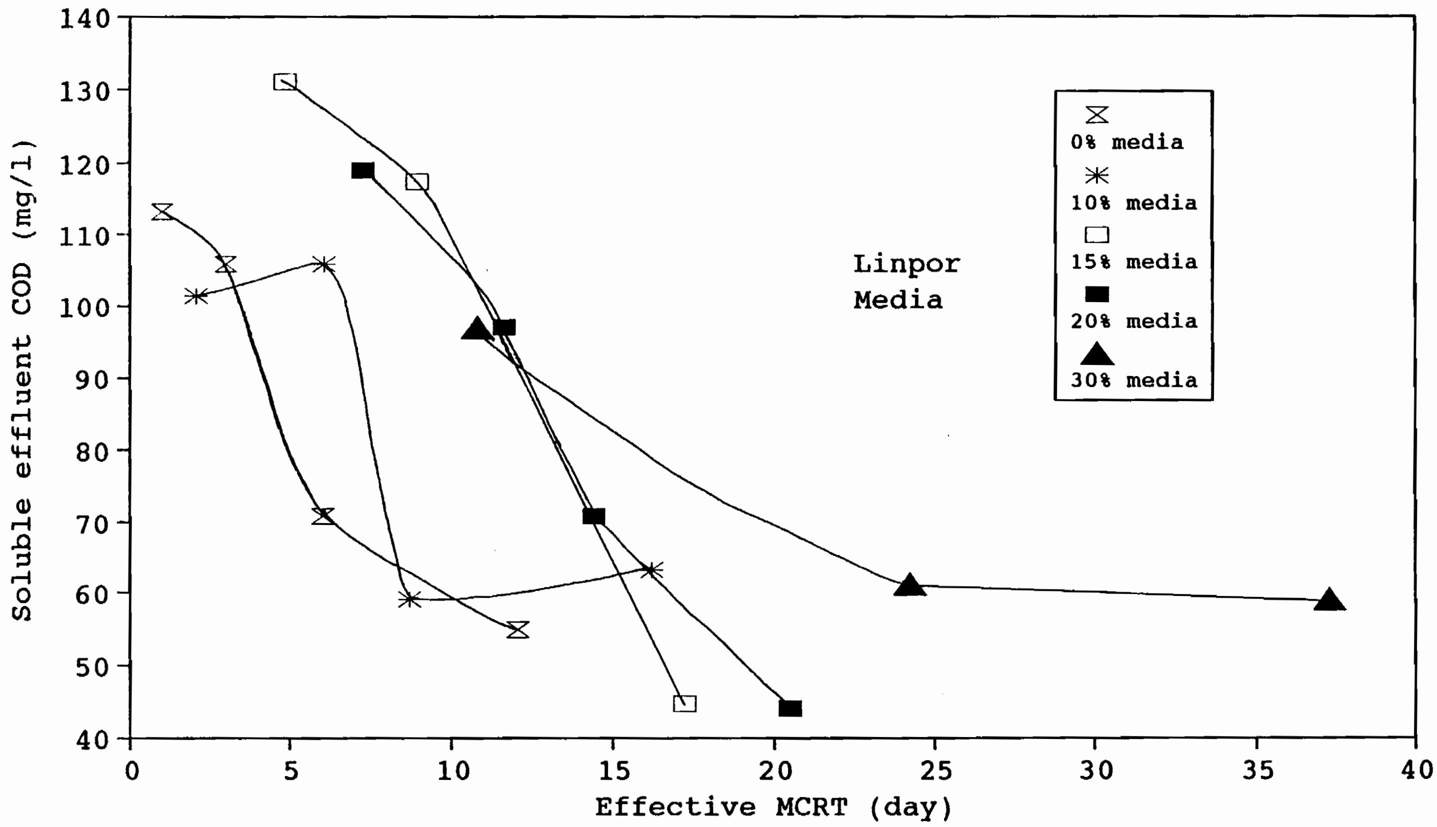

Figure 4.6 Variations in Soluble Effluent COD with Effective MCRT

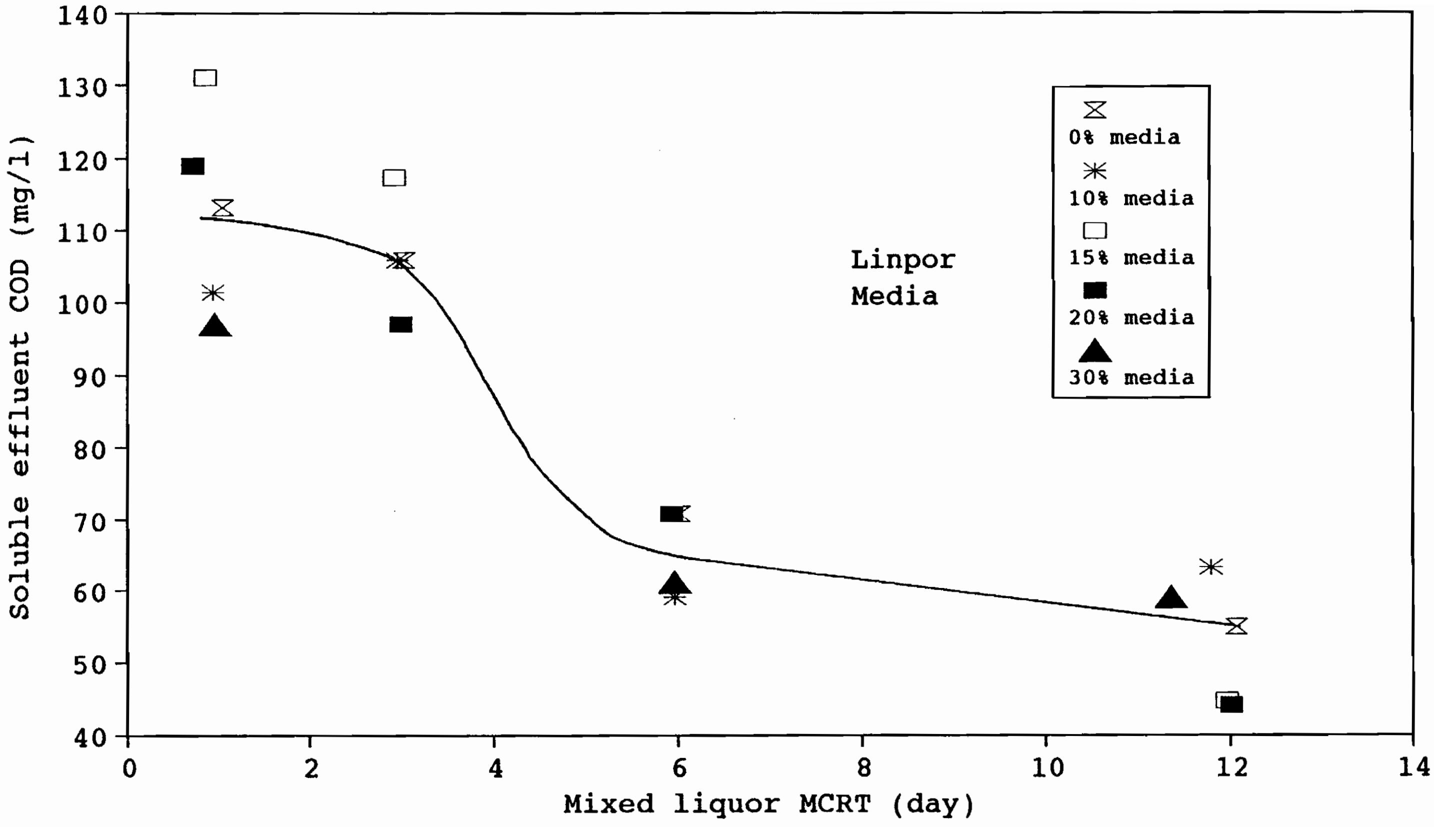

Figure 4.7 Variations in Soluble Effluent COD with Mixed Liquor MCRT

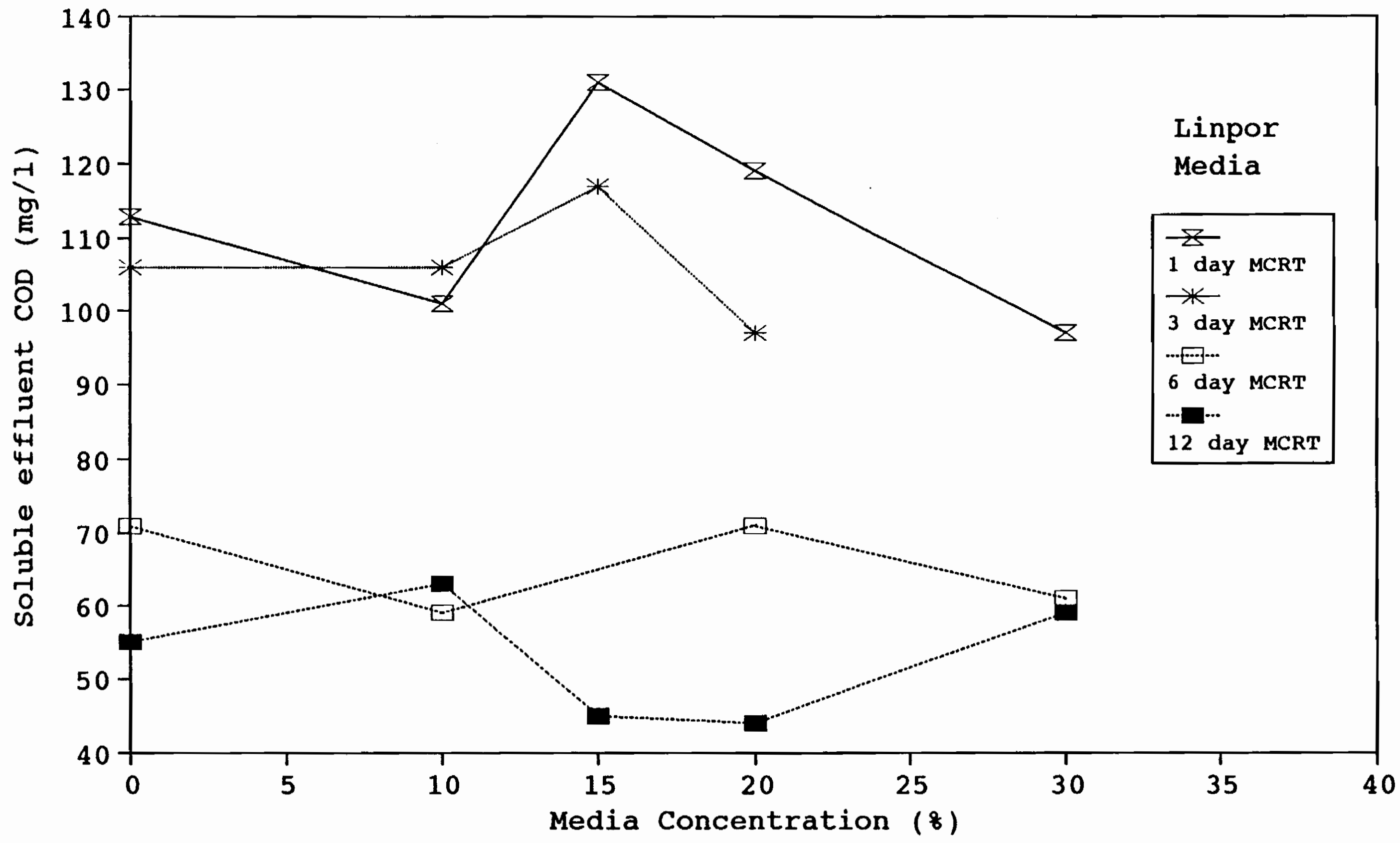

Figure 4.8 Comparison of Soluble Effluent COD with Media Concentration

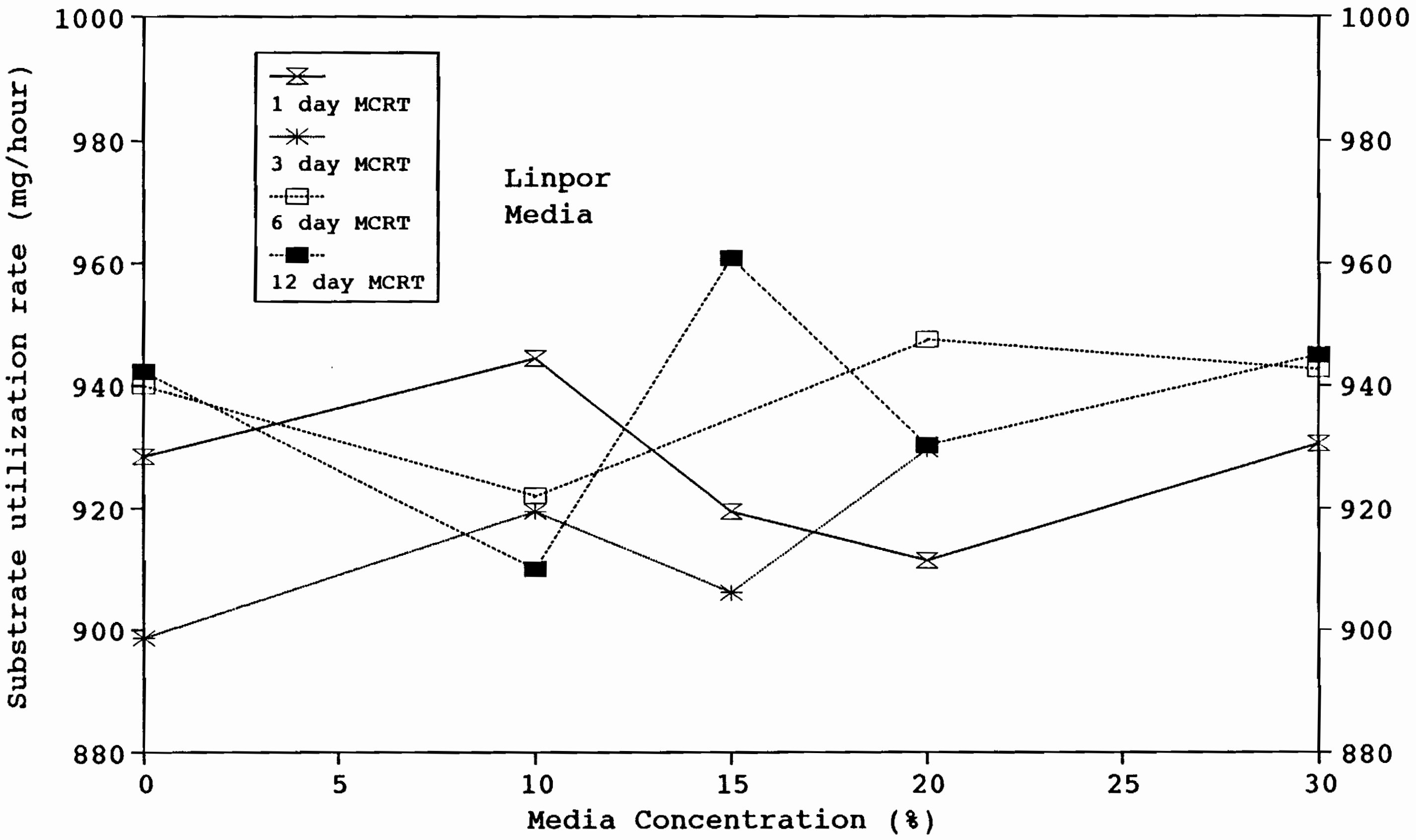

Figure 4.9 Comparison of Total Substrate Utilization Rates with Media Concentration

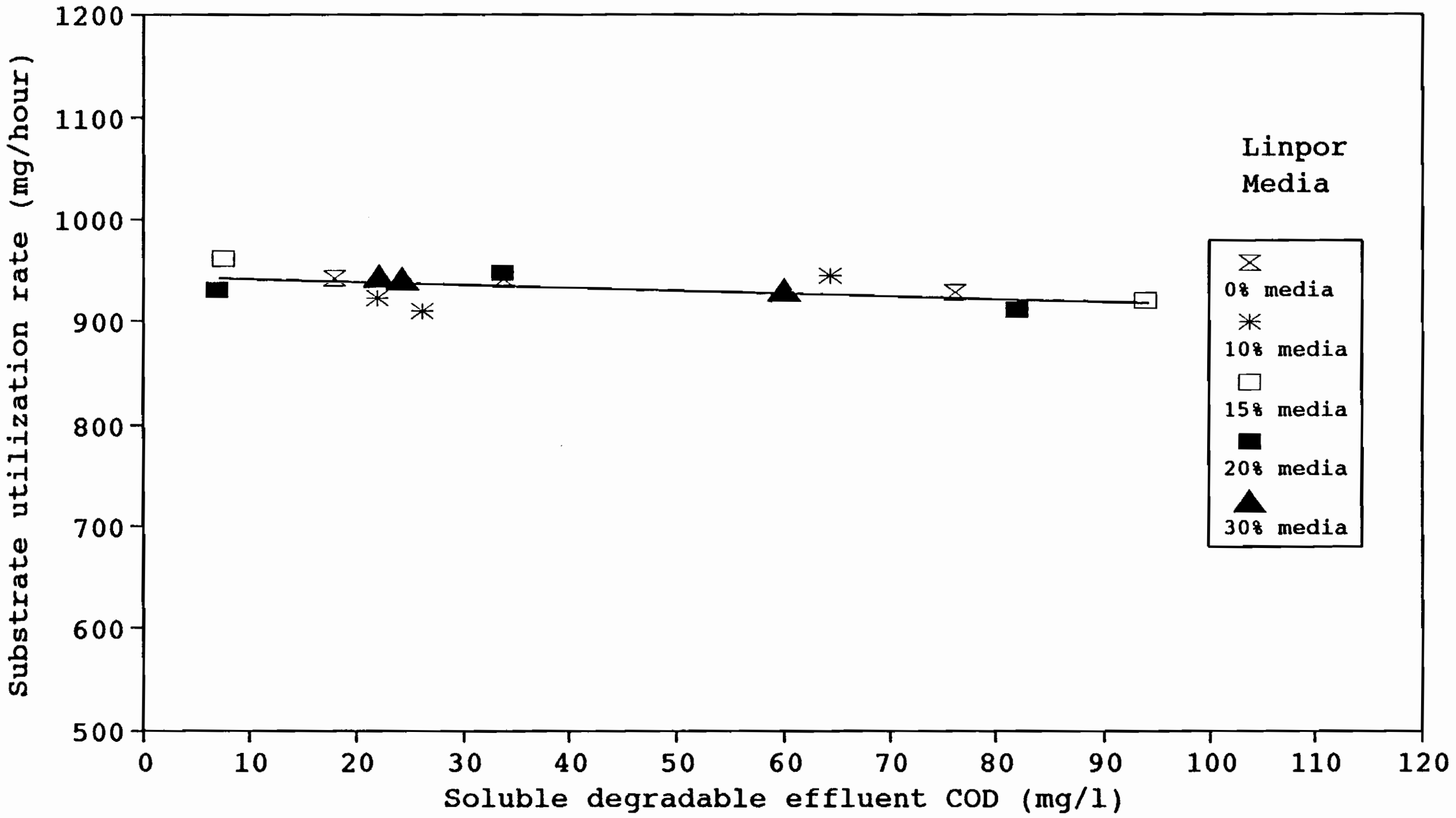

Figure 4.10 Comparison of Total Substrate Utilization Rates of Linpor and Control Systems

Linpor systems decreased with increased media concentration, as shown in Figure 4.11. This implied that the attached biomass specific utilization rates were substantially lower than the suspended biomass rates. It also showed that substrate removal of the 15, 20, and 30% Linpor systems did not significantly change with different mixed liquor MCRTs compared to the control system.

The kinetic constants for the total specific substrate utilization rates and oxygen utilization rates were determined by linear regression as shown in Figures B.1, B.2, and B.3 in Appendix B and are listed in Table 4.1. The values of the total rate constants decreased with increased media concentration from 0 to 10%, i.e., increased total attached biomass. At 15, 20 and 30% media the rate constants were similar. The maximum substrate utilization rates, K_m, and the half reaction constants, K_s, also decreased with increased media concentration.

4.3 Oxygen Utilization

Total oxygen utilization in a BSS is comprised of two separate components, the demand exerted by the suspended solids and that exerted by the attached biomass. Except for 15% media, the total oxygen consumption was greater in the Linpor systems than that of the control system as shown in Figure 4.12. In addition, the total oxygen rates decreased with increased mixed liquor MCRT for 15, 20, and 30% media.

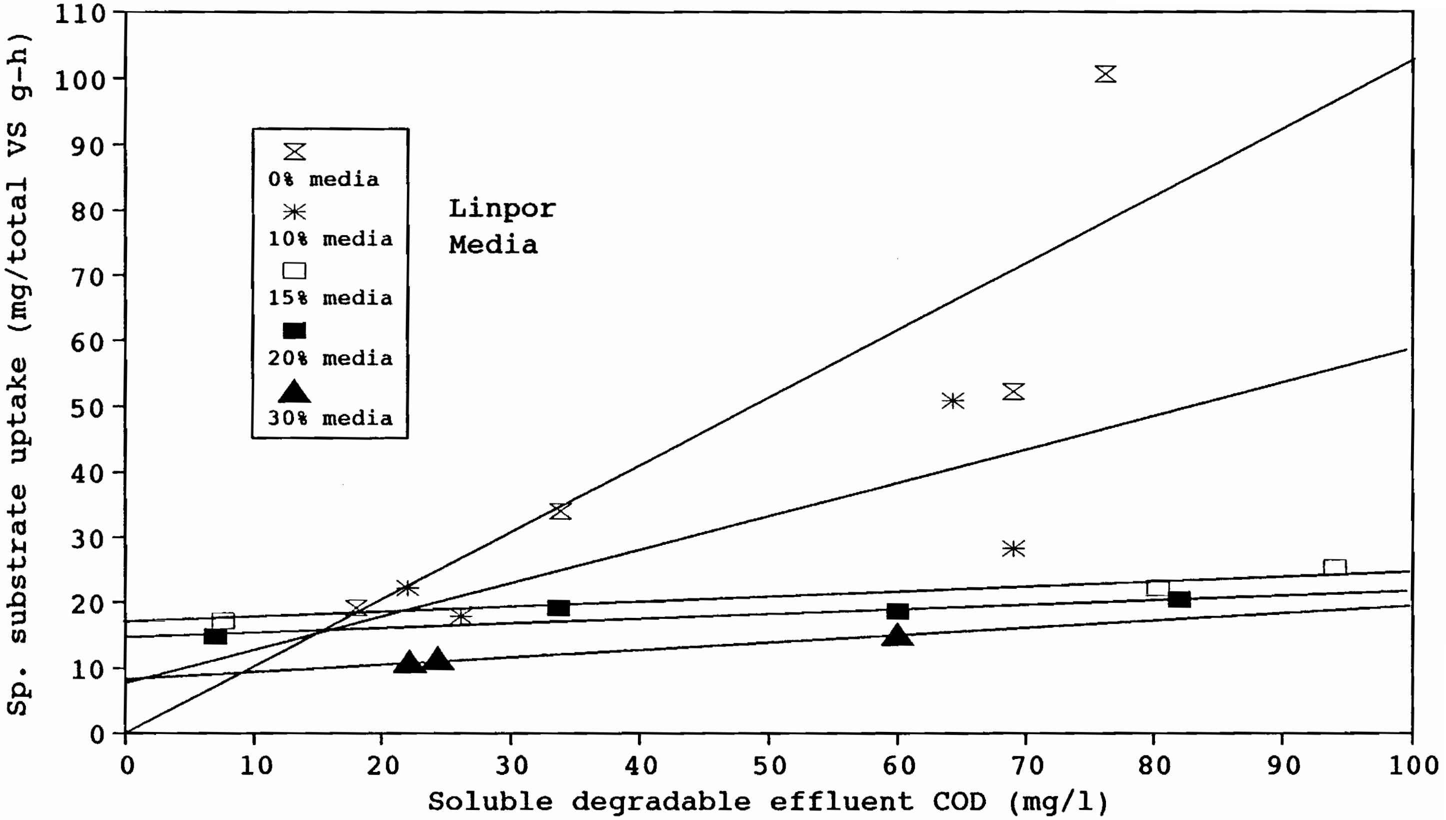

Figure 4.11 Comparison of Specific Substrate Uptake Rates of Linpor and Control Systems

Table 4.1 Steady-State Kinetic Coefficients

	% media	Rate Constant K l/g-h	1/Km h-g/mg	Km mg/g-h	Ks/Km g-h/l	Ks mg/l	Oxygen Uptake Coeff mg/g-h/ mg/g-h
NOR-PAC	0	1.55	0.0038	263.2	0.75	197.4	
	50	1.32	0.0027	370.4	0.46	170.4	
Linpor	0	1.12	0.0022	454.5	0.91	413.6	0.17
	10	0.42	0.0174	57.5	0.77	44.3	0.23
	15	0.09	0.0410	24.4	0.14	3.4	1.4
	20	0.07	0.0490	20.4	0.13	2.7	1.4
	30	0.11	0.0520	19.2	0.87	16.7	1.4

The units in grams (g) represent the total BSS volatile solids.
The values at 0% media represent the control kinetics.

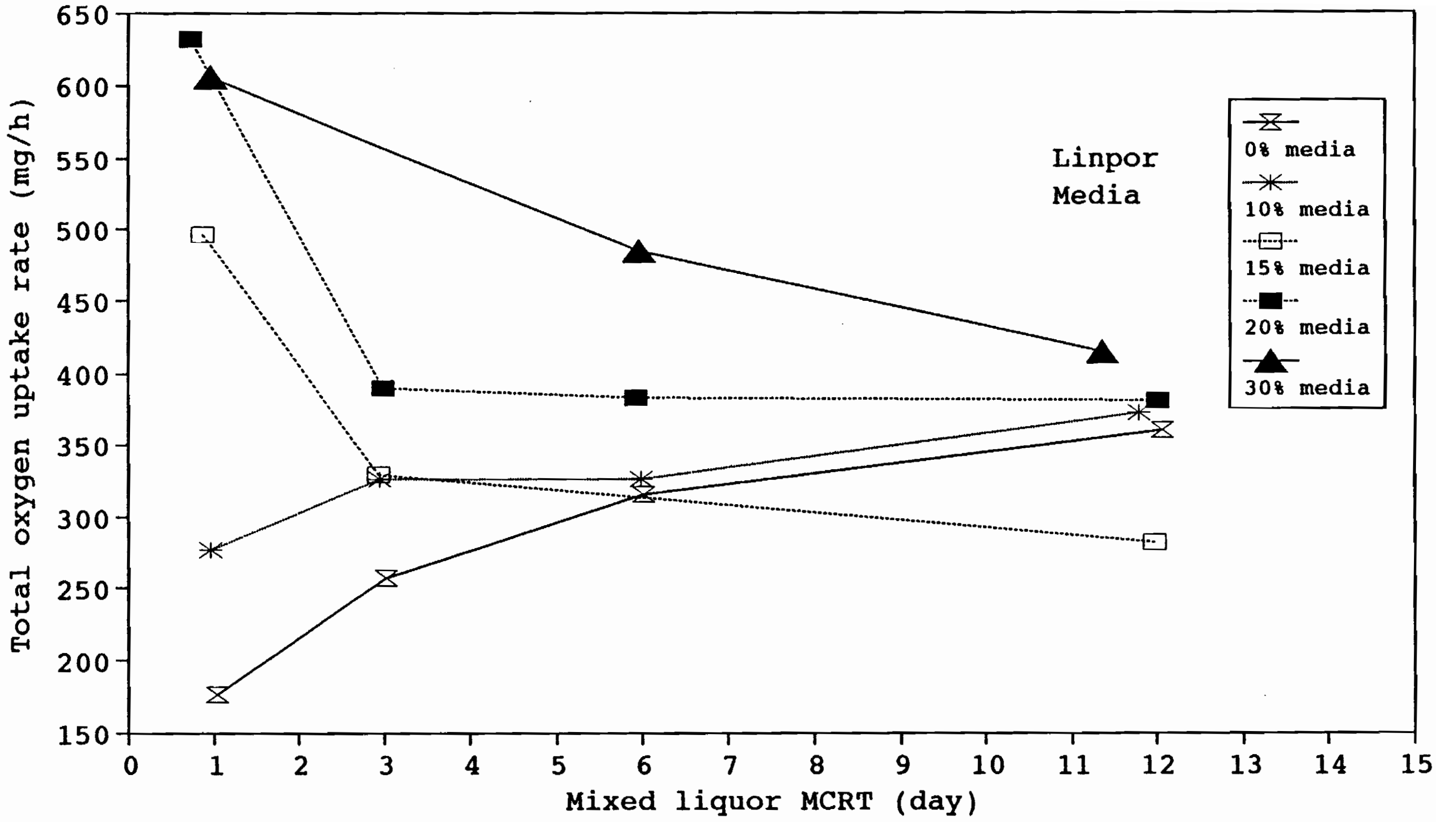

Figure 4.12 Change in Total Oxygen Uptake Rates (Attached VS + MLVSS) with Mixed Liquor MCRT

The total specific oxygen utilization rates are shown in Figure 4.13. It is apparent that the Linpor systems utilized substantially less oxygen/gram of viable biomass than the control system. This decrease is also depicted in Figure 4.14, which illustrates the change of the attached biomass oxygen uptake rates.

The specific oxygen uptake rates of the attached biomass are shown in Figure 4.15. The attached biomass oxygen requirements rapidly decreased from the 1 day mixed liquor MCRT to the 3 day mixed liquor MCRT experiments. In addition, the attached biomass specific uptake rates were presumably lower than the suspended solids uptake rates. Because the attached volatile solids always constituted the larger fraction of the total biomass, the Linpor systems exhibited lower total specific oxygen uptake rates. The oxygen total uptake coefficients, mg of total oxygen required/mg total substrate utilized, are listed in Table 4.1. Increases in media concentration resulted in increased oxygen uptake coefficients.

The determination of kinetic constants and oxygen utilization coefficients are presented in Figures B.4, B.5, and B.6, Appendix B. The total oxygen uptake rates for the NOR-PAC system is shown in Figure A.8, Appendix A.

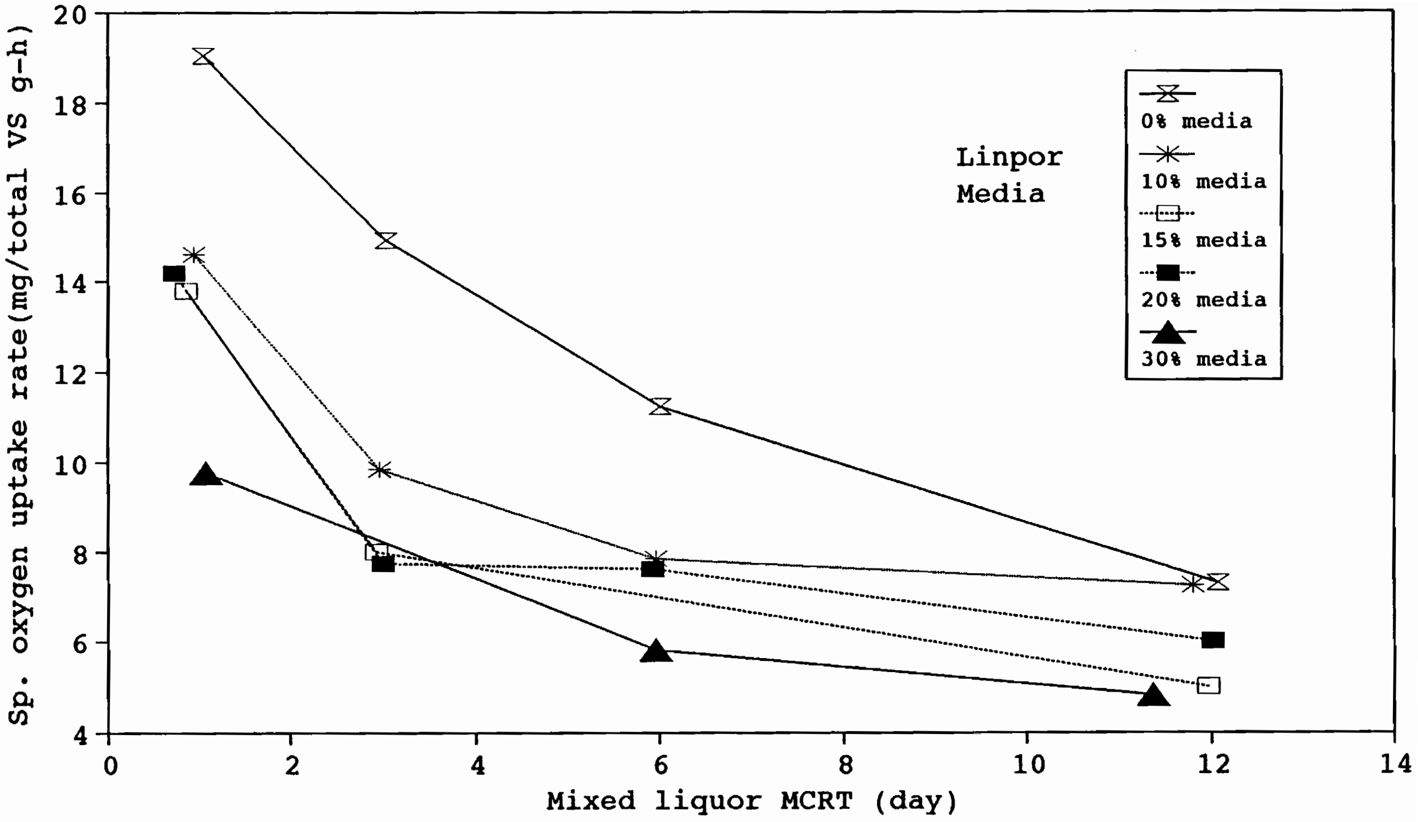

Figure 4.13 Variation in Specific Oxygen Uptake Rates with Mixed Liquor MCRT

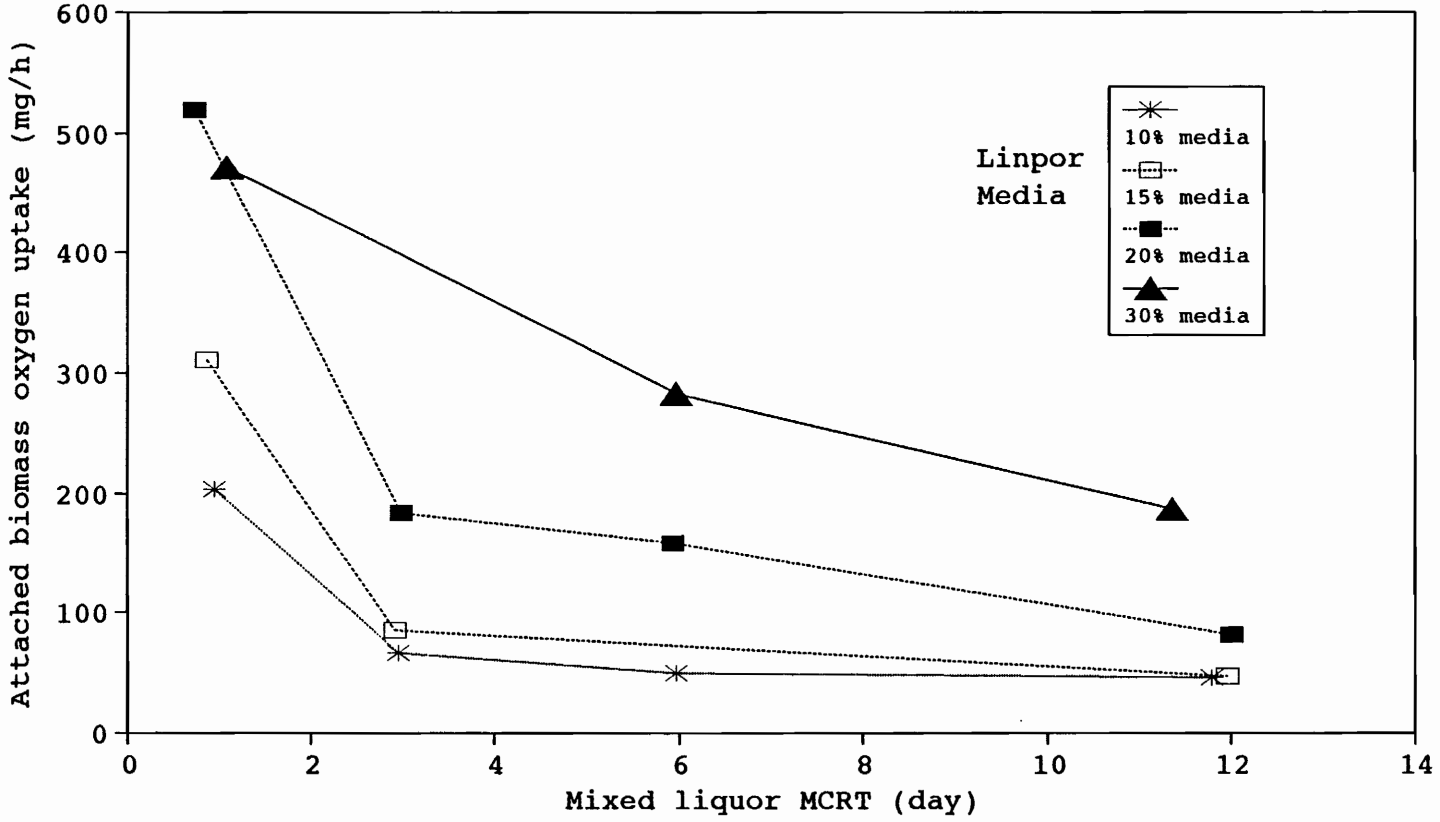

Figure 4.14 Change in Attached Biomass Oxygen Uptake Rates with Mixed Liquor MCRT

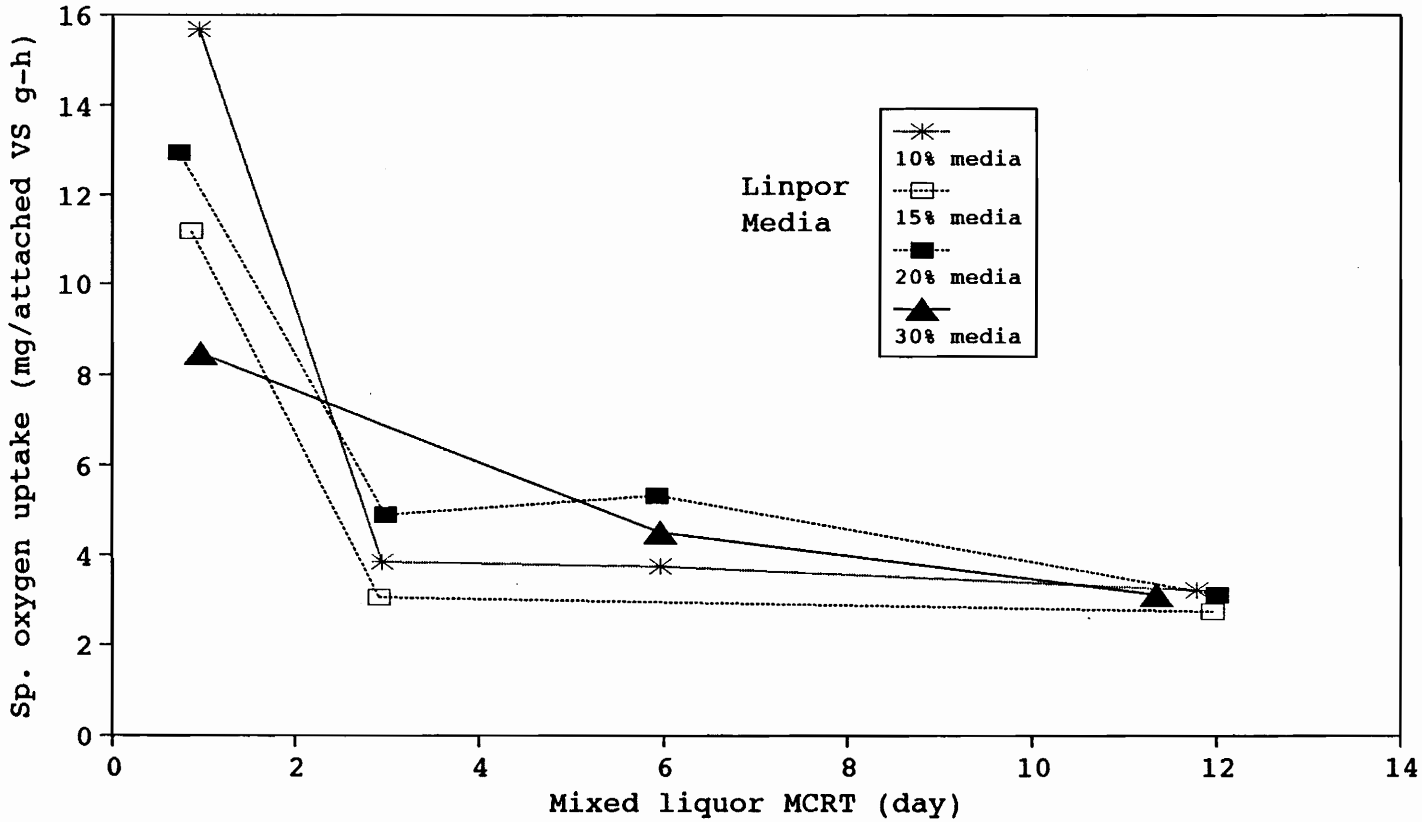

Figure 4.15 Variation in Specific Oxygen Uptake Rates of Attached Biomass with Mixed Liquor MCRT

4.4 Nitrification and Denitrification

Nitrification and denitrification was monitored only during 30% Linpor media experiments. It was hoped that the higher oxygen uptake rates which occurred in the Linpor systems were the result of proportionally greater percent nitrification to that of the control system.

Nitrification and denitrification occurred in both the Linpor and the control systems. Both systems accomplished greater than 80% nitrification as shown in Figure 4.16.

Floating sludge was observed in the secondary clarifiers of all systems during the Phase Two. This phenomenon was probably the result of nitrogen gas trapped within the sludge blanket. Apparently denitrification occurred in the clarifiers. Table 4.2 describes the extent of nitrification and denitrification which occurred in the Linpor and the control systems.

Nitrification and oxygen utilization data are presented in Tables B.2 and B.3, Appendix B.

4.5 Solid-liquid Separation

Previous studies have recorded lower sludge volume index values in biomass support systems than conventional activated sludge systems. Improved settling has been attributed to the reduction in the numbers of filamentous organisms. During the SVI experiment the supernatant was typically turbid. As a result, specific values obtained

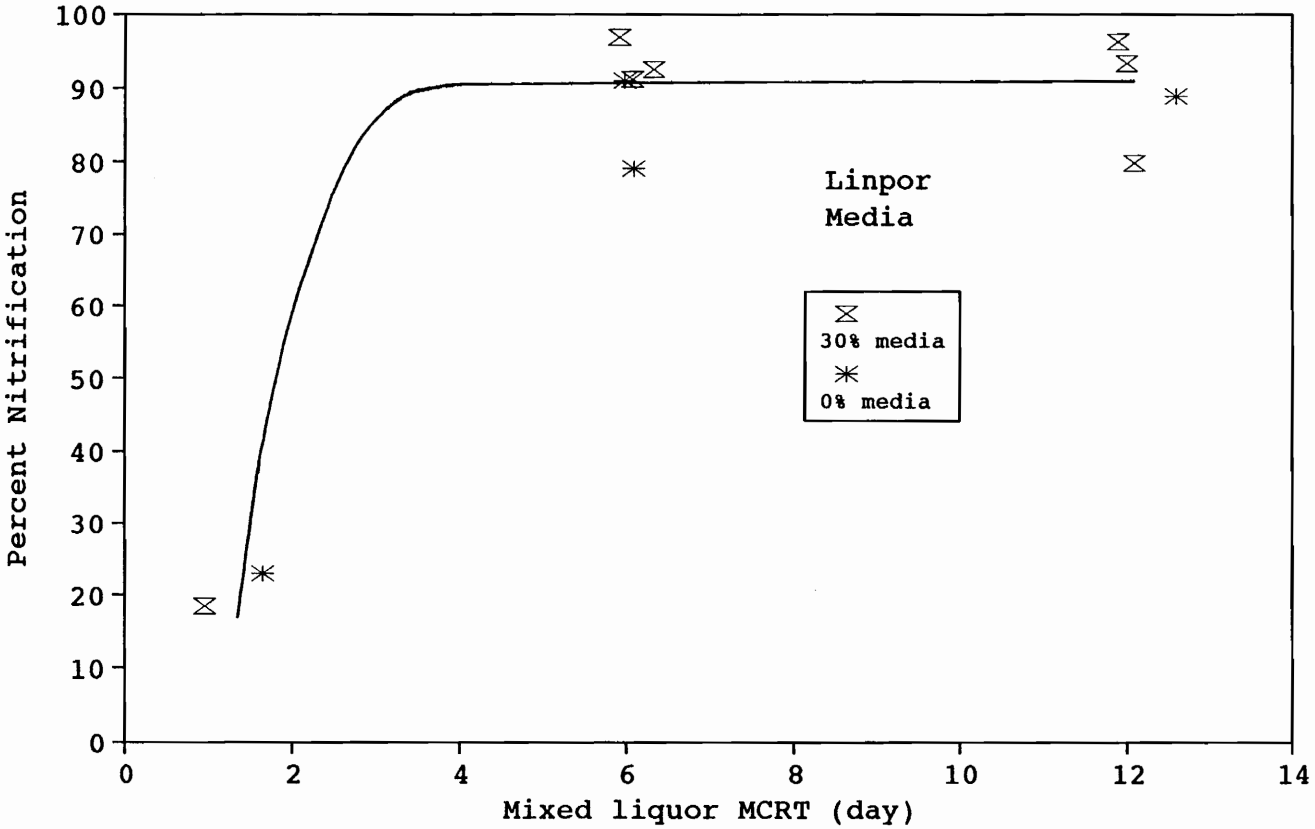

Figure 4.16 Percent Nitrification of 30% Linpor BSS compared to Control System as a Function of Mixed Liquor MCRT

Table 4.2 Comparison of Percent Nitrification and Denitrification of Linpor and Control Systems

Linpor System (30% media)

MCRT day	Percent Nitrified	Percent Denitrified	Effluent Ammonia	Effluent Nitrate	Effluent Nitrite
1.0	18.5	0.0	1502.3	674.9	88.0
6.0	92.4	28.8	9.2	176.0	13.4
6.1	96.8	58.2	38.6	138.5	11.4
6.3	91.2	44.9	52.7	302.6	11.8
11.9	96.1	71.2	19.9	118.3	22.2
12.0	93.2	59.2	23.4	128.2	8.7
12.1	79.7	21.7	61.5	177.5	32.9

Control System

MCRT day	Percent Nitrified	Percent Denitrified	Effluent Ammonia	Effluent Nitrate	Effluent Nitrite
1.7	23.1	69.3	1326.3	103.2	24.6
6.0	79.0	89.1	47.3	44.2	2.3
6.1	90.9	66.7	105.6	102.8	14.8
6.1	100.0	48.5	88.6	56.2	58.0
12.6	88.8	57.2	99.6	291.8	38.1

Note - Units of effluent concentrations are in mg/day during the experiments may not be accurate.

As shown in Figure 4.17, the solid-liquid separation of the NOR-PAC system only improved at the one day mixed liquor MCRT. Attached growth was also observed only at this MCRT.

During the three day mixed liquor MCRT experiment (Figure 4.18) the Linpor system consistently maintained a SVI of less than 50 ml/g, except during days 172-176 when severe filamentous organism growth occurred. This SVI value was considerably less than that for the control system. Clearly, the Linpor system produced a better settling sludge than the control system.

During the initial start of the six day mixed liquor MCRT experiment SVI values for the Linpor system sludge increased rapidly as shown in Figure 4.19. Microscopic examination revealed filamentous organisms in both the suspended solids and within the media of the Linpor system. The control system exhibited severe filamentous growth and bulking during days 202-217. From day 217 to 270, the Linpor system exhibited severe filamentous organism growth. The nature of the floc of the two systems was dramatically different. The Linpor system maintained somewhat of a pinpoint floc with a turbid supernatant during the SVI procedure. The control system exhibited more of an ideal floc as characterized by Jenkins et al. (1986), i.e., the flocs had a filamentous backbone. The mean SVI values for the Linpor system operated at 12 day mixed liquor MCRT, 160

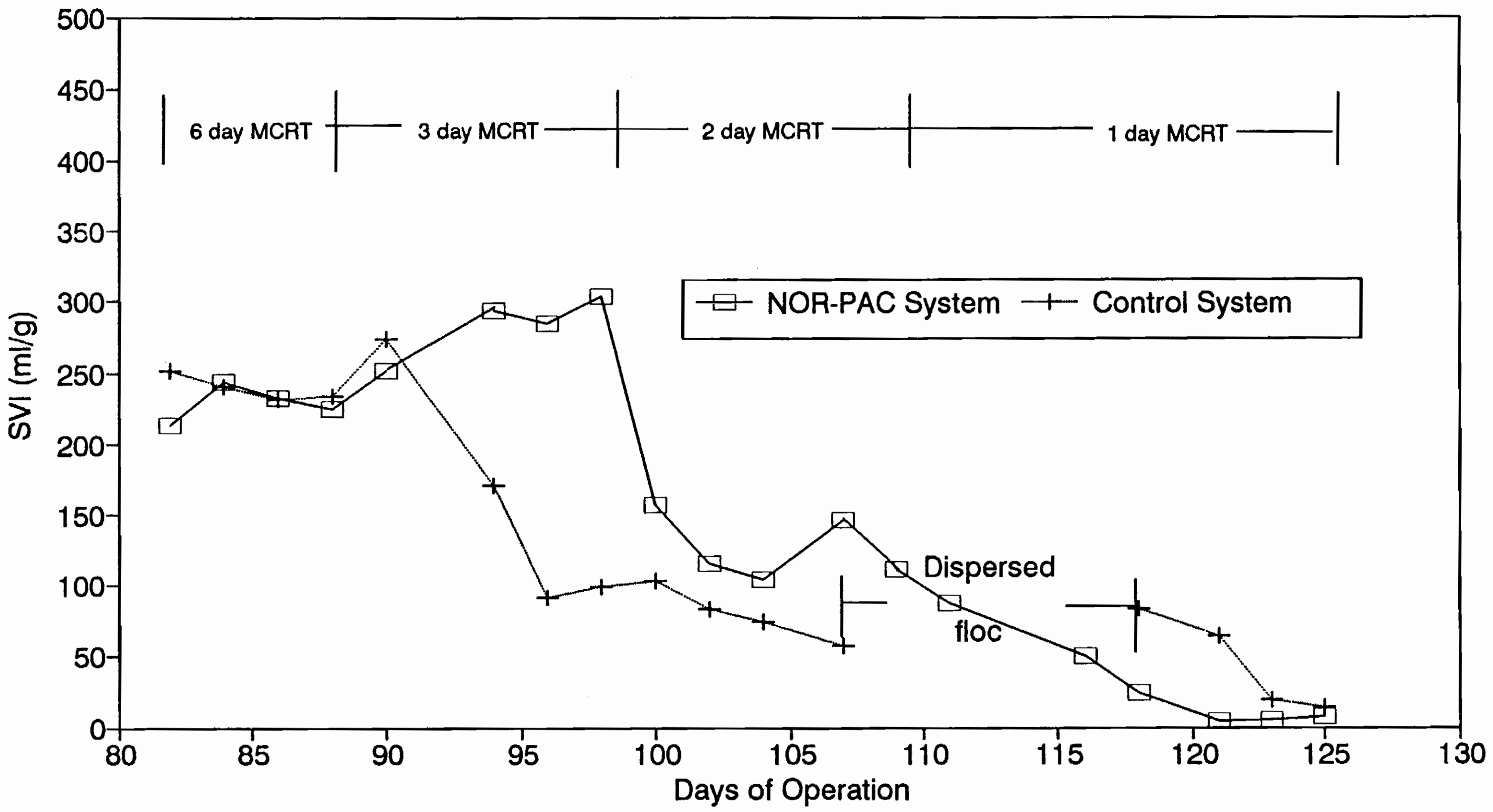

Figure 4.17 Variation in Sludge Volume Index of NOR-PAC System with Time

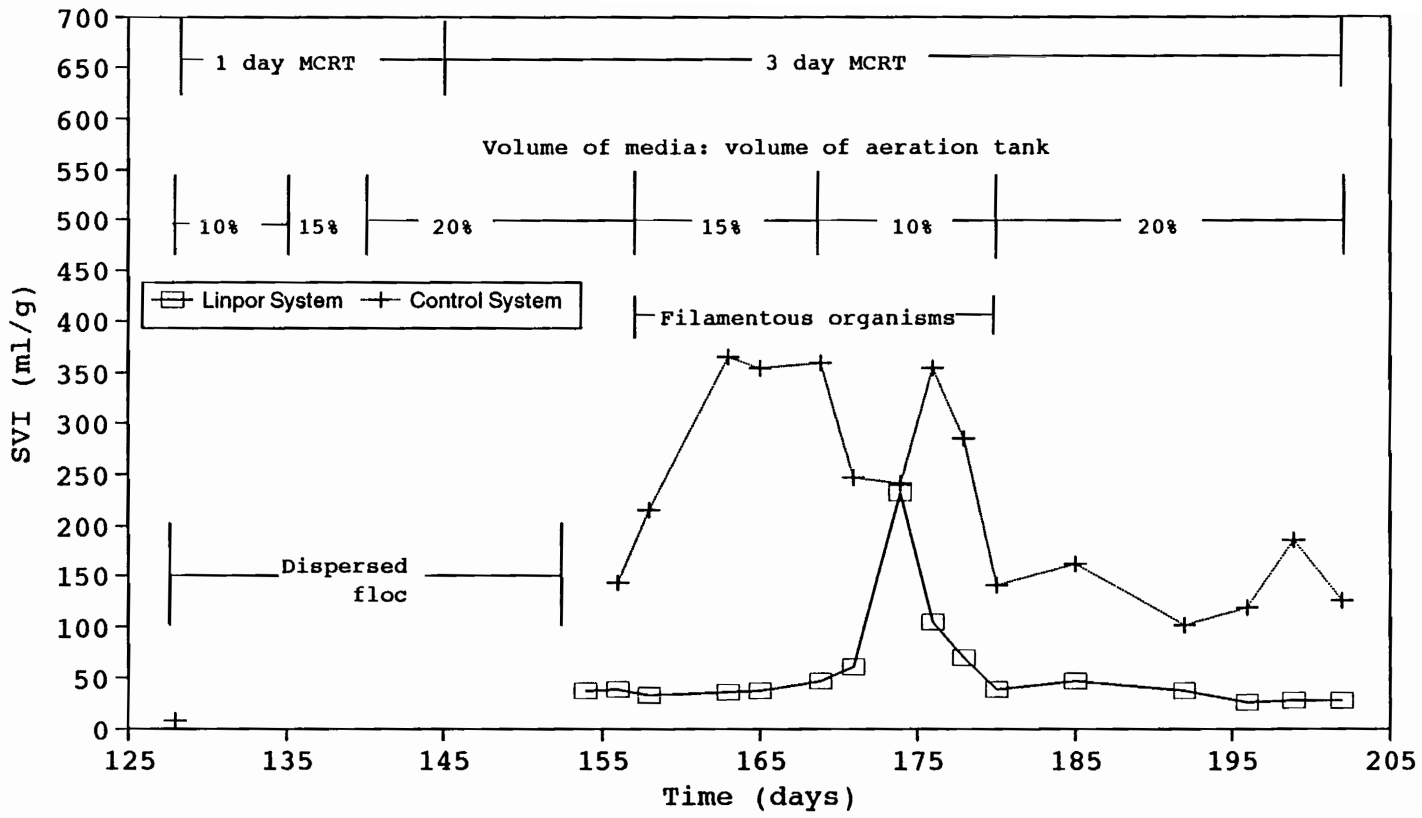

Figure 4.18 Comparison of BSS and Control System Performances during Filamentous Organism Upsets

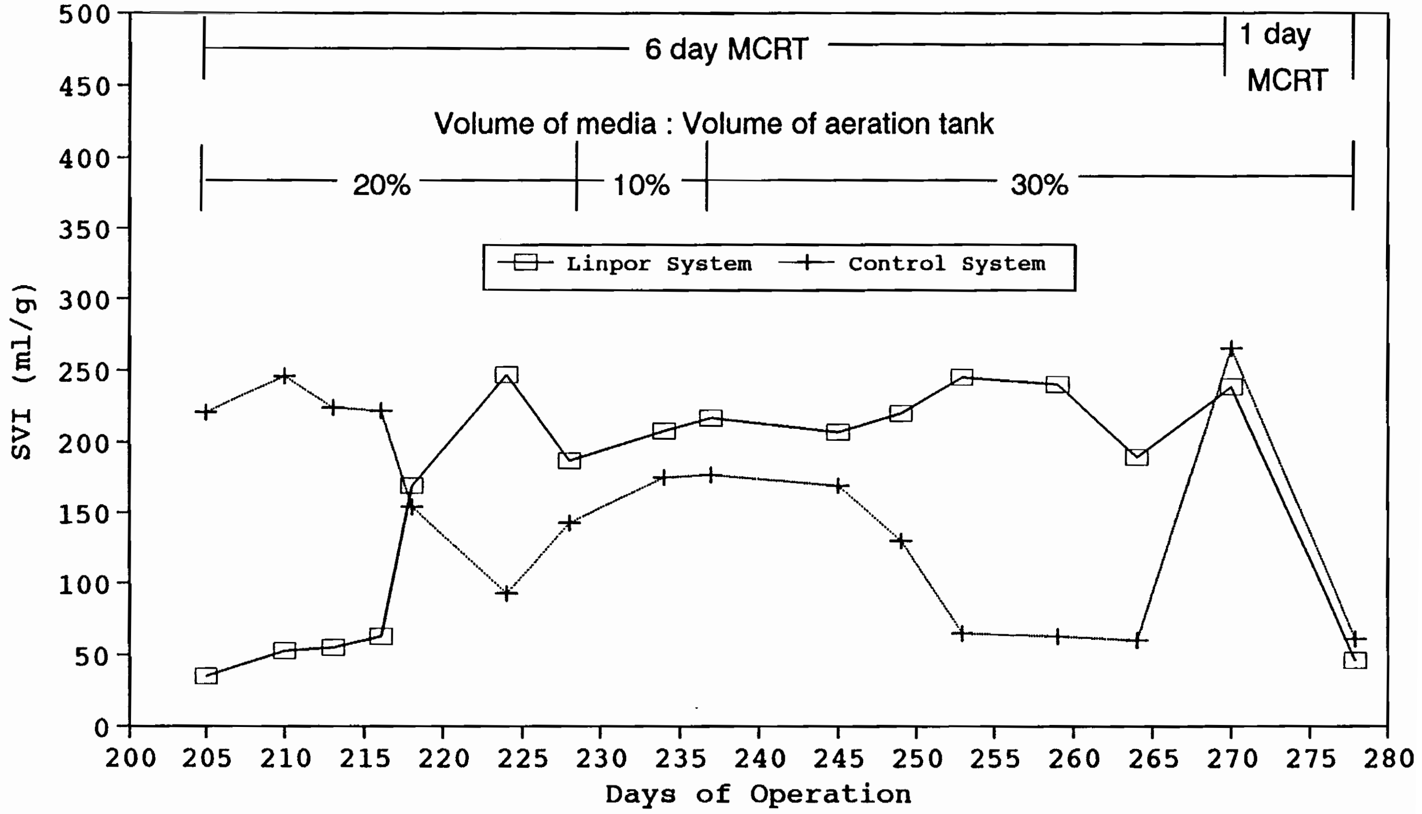

Figure 4.19 Sludge Volume Index Comparison for Operational Days 205-278

ml/g, appeared to have increased with increased media concentration as shown in Figure 4.20. Periods of filamentous bulking occurred between days 40-70 and days 105-129. Filaments were observed in the suspended biomass and within the media. Prior to the addition of the Linpor media, the floc did not exhibit extended filaments and appeared much like an ideal floc. After the periods of bulking, however, extended filaments were present and remained within the floc for the duration of this system's operation.

The relationship between the zone settling velocity and the SVI values for the Linpor system is compared with the control system as shown in figure 4.21. High SVI values were typically associated with low ZSV values.

4.6 Sludge Production

Reduced sludge production has been claimed as an attribute of Linpor systems. The total sludge production is defined as the sum of the total solids wastage rate from the reactor and the total solids in the effluent. Figure 4.22 describes sludge production as a function of mixed liquor MCRT and Linpor media. The sludge production, in terms of total suspended solids, was similar in the Linpor and control system. However, at the 1 day mixed liquor MCRT experiment sludge production was significantly reduced for 20 and 30% media concentrations (Figure 4.23).

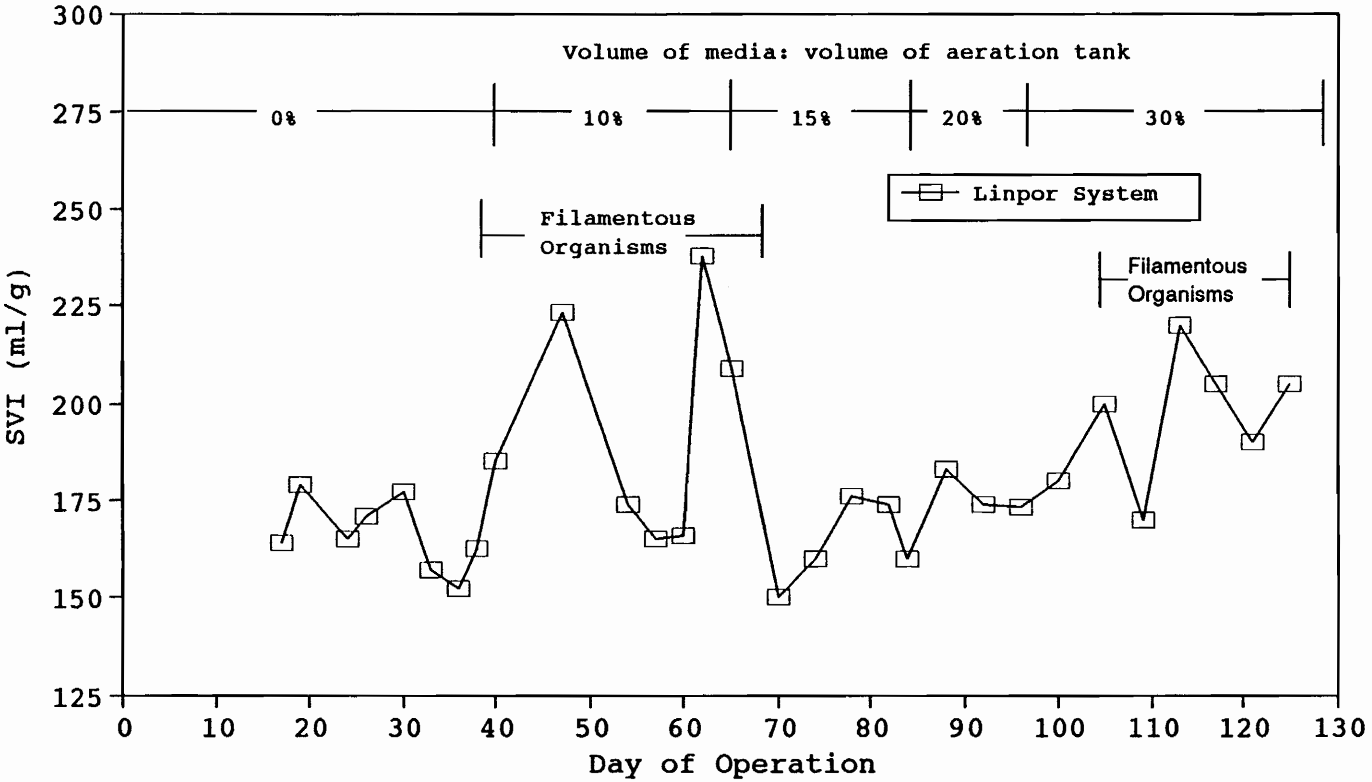

Figure 4.20 12 Day Mixed Liquor MCRT Linpor System Sludge Volume Index Values for Operational Days 0-130

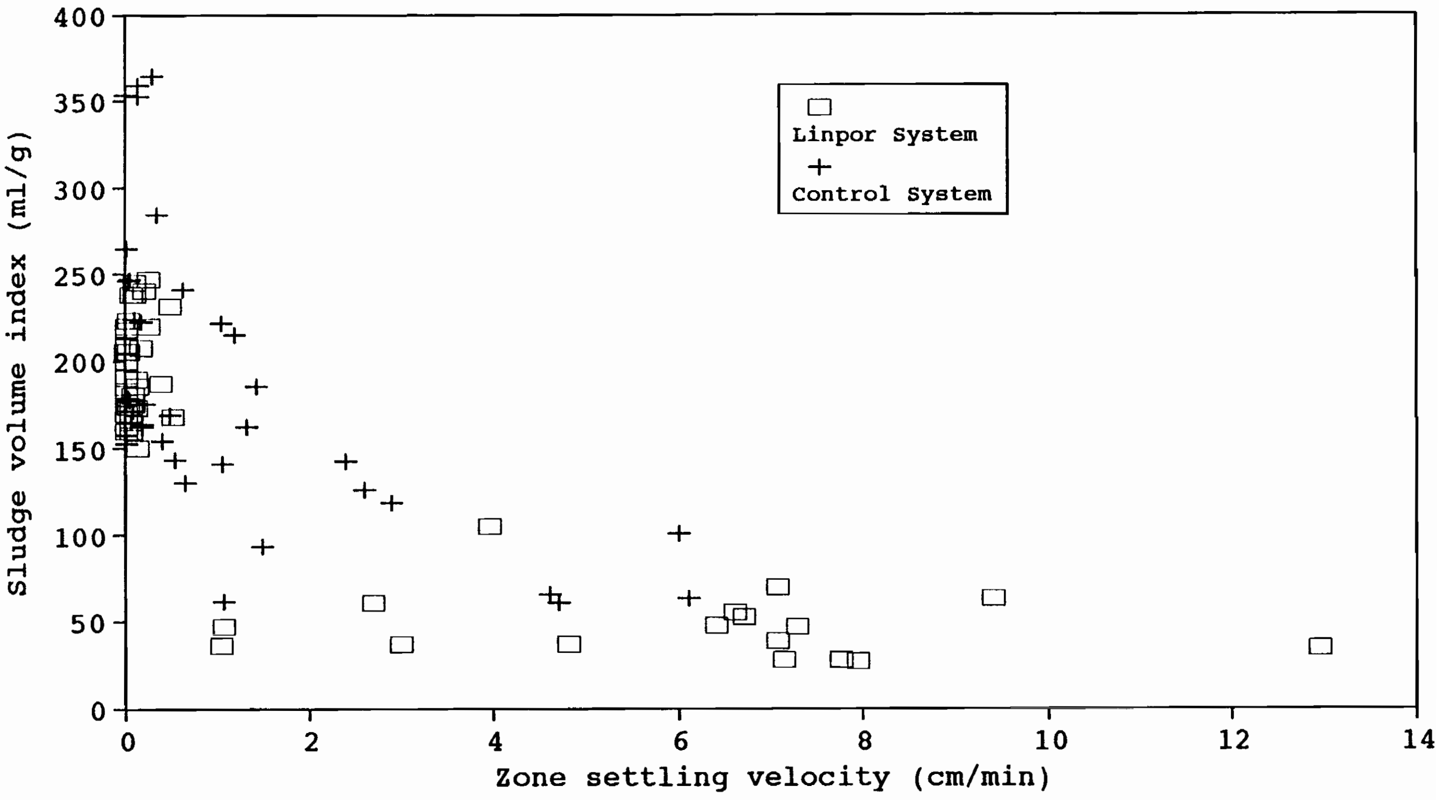

Figure 4.21 Relationship of Sludge Volume Index with Zone Settling Velocity

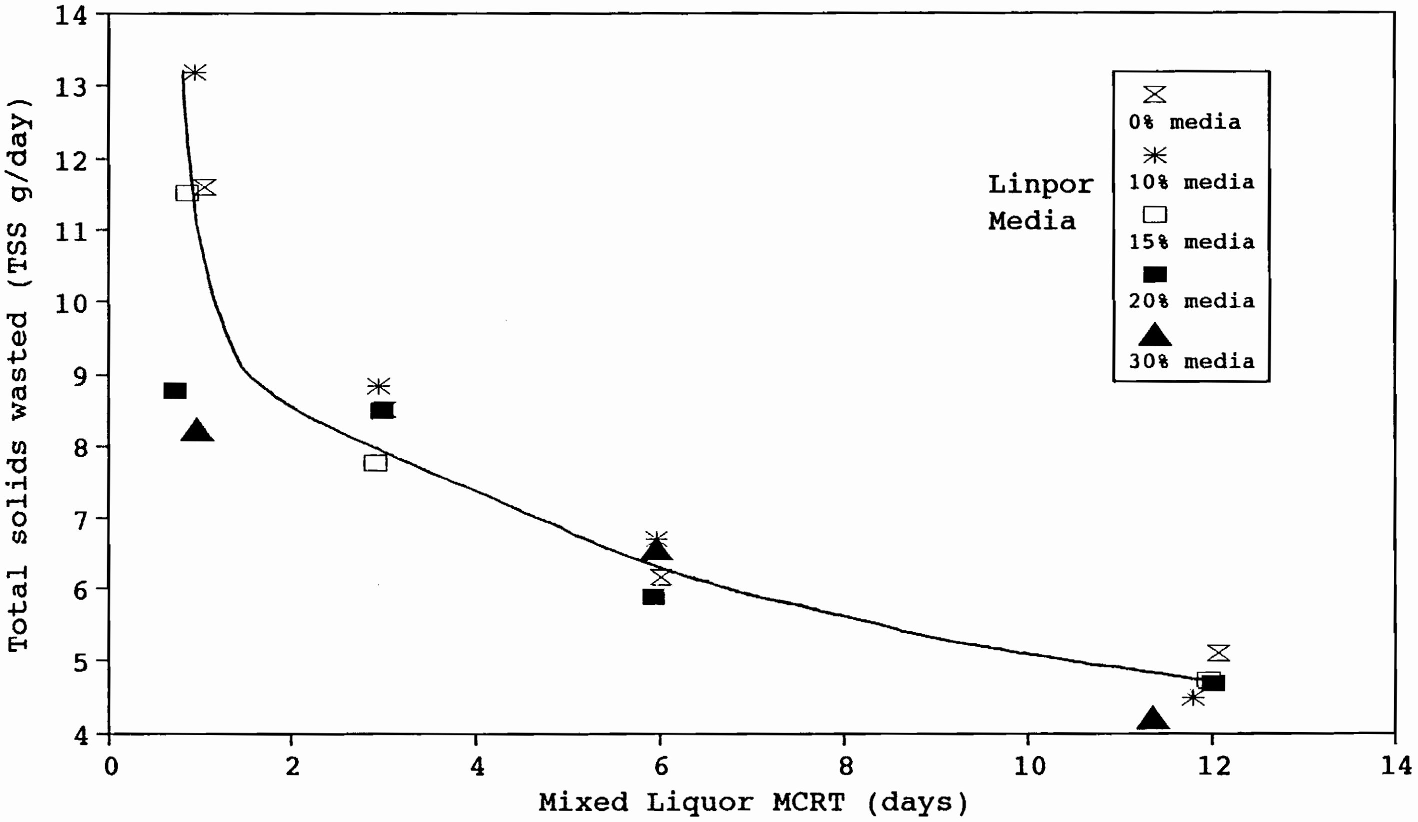

Figure 4.22 Change in Total Solids Wasted with Mixed Liquor MCRT

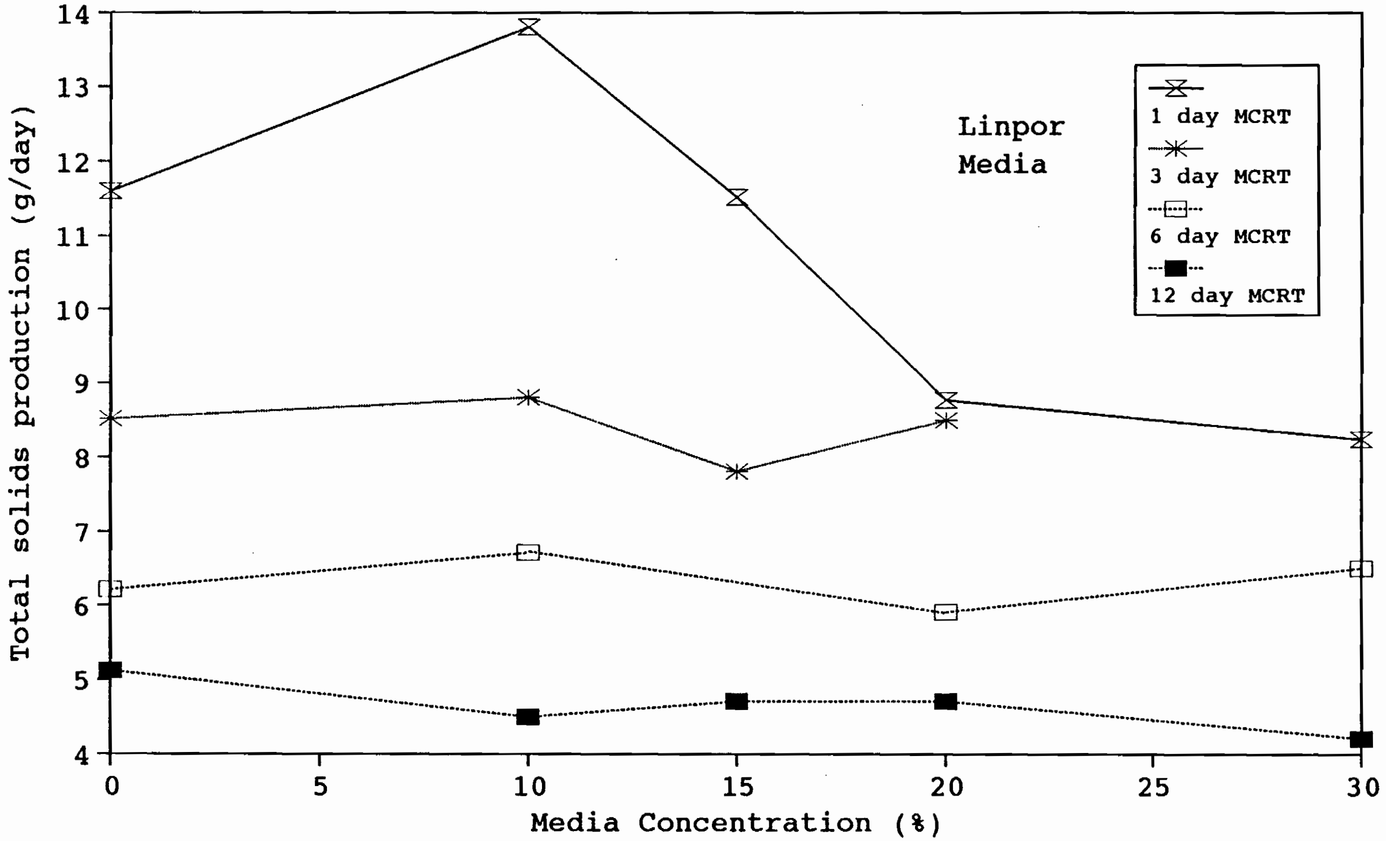

Figure 4.23 Comparison of Total Suspended Solids Production with Media Concentration

V. DISCUSSION

Results of the treatment of municipal wastes using BSS were presented in Chapter 2. Detailed results of the treatment of industrial wastewater using biomass support media are not available in the literature. This study was the first to present detailed observations and analysis of the use of Linpor, BIONET, and NOR-PAC media as biomass supports for the treatment of a high-strength industrial wastewater.

5.1 Sludge Age

The MCRTs in the Linpor systems were calculated using the MLVSS fractions of the total biomass for the purpose of comparisons with the control system. The effective MCRTs can be calculated by substitution of X in equation 3-1 with $(X_s + X_p)$. Effective MCRTs are listed in Table A.4, Appendix A. The relationship of effective and mixed liquor MCRTs is shown in Figure 5.1.

The growth rate of the attached biomass could not be determined. The attached biomass MCRT is theoretically equal to 1/specific detachment rate but, the rate could not be measured. The attached biomass concentrations slightly decreased or stabilized with increased mixed liquor MCRT. The attached biomass concentrations appear to have been a function of mixed liquor MCRT i.e., substrate and oxygen

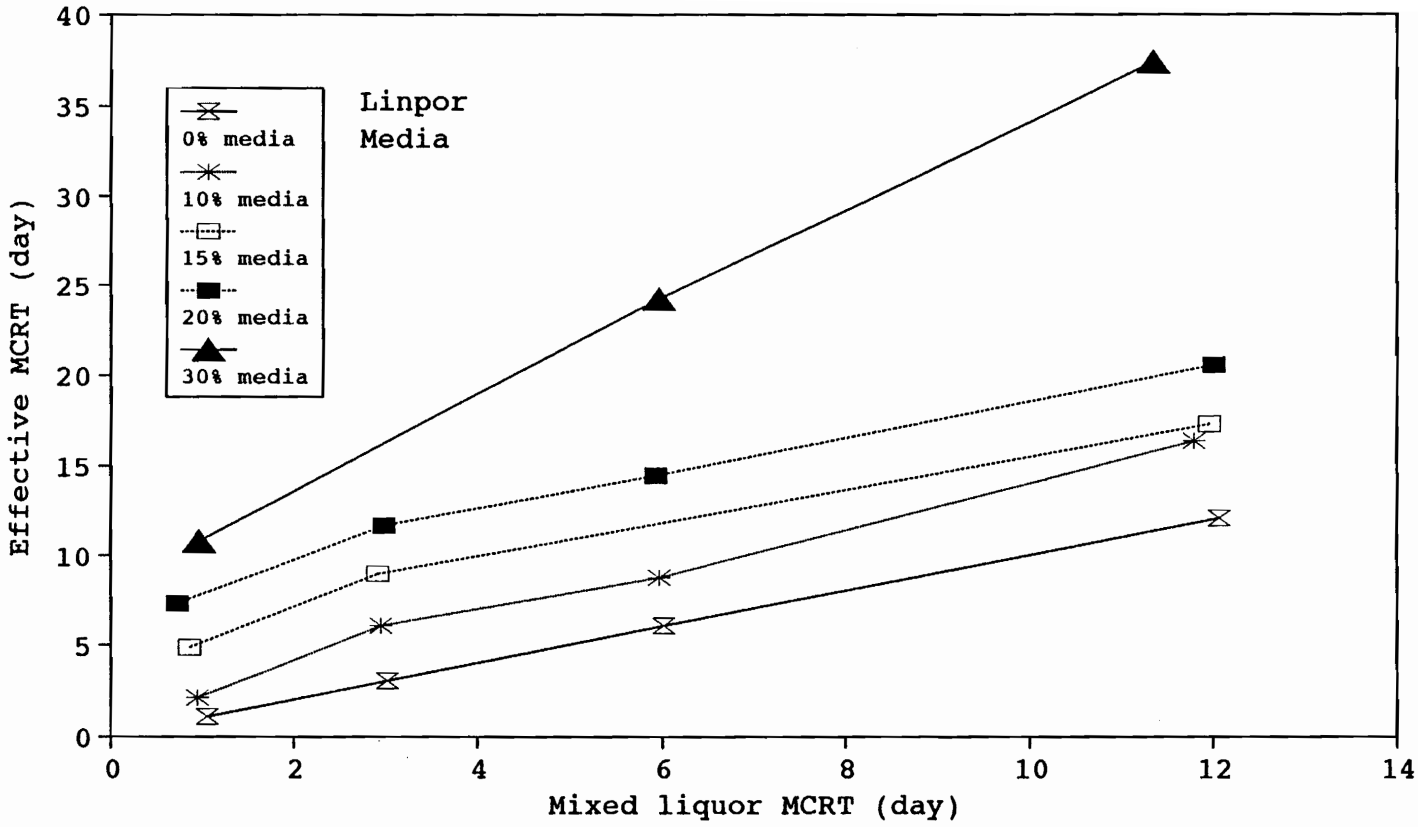

Figure 5.1 Variations of Effective MCRT with Media Concentration

availability to the attached biomass.

5.2 Biomass Support Media Attached Growth

The NOR-PAC and BIONET media failed to produce significant attached biomass. Comparisons of the physical characteristics of these media to the Linpor media may provide insight into the reasons why the NOR-PAC and BIONET media did not support biomass. The physical environment and operational parameters should also be considered.

The same aeration tanks and clarifiers were used for all three media. The same activated sludge seed was used for the entire study. The COD loading, manipulated by slightly varying the flow rate, remained relatively constant for the period of the study. The HRT varied between 0.8 and 1.3 days. The diffused aeration set-up remained similar. The air flow and subsequent agitation remained somewhat constant. However, the size and shape of the aeration tank relative to that of the NOR-PAC media might have influenced the turbulence required for complete mixing. It appeared that the high turbulence prevented attached growth on the surfaces. Larger dimension tanks may require less turbulence for complete mixing and may permit attached growth.

The physical characteristics of the three media varied significantly. The exact surface area of the Linpor media was not known, but could be assumed to be significantly greater than that of the NSW media. The Linpor media, by design, provides a quiescent environment inside the particles for the growth of attached biomass. The surfaces of the other media are all external, and attached growth occurred on the NOR-PAC media only in the sheltered spaces between 2 and 3 interlocked pieces. No growth occurred on the BIO-NET media, which did not provide any sheltered areas. It seemed apparent that a quiescent environment is a requirement for attached growth on medias in activated sludge mixed liquor. The D.O. values were always greater that 3.0 mg/l and was not a limiting factor.

The primary constituent of the wastewater, acetic acid, is readily biodegradable. Attached growth occurred on the NOR-PAC only at the 1 day mixed liquor MCRT experiment. If the attached biomass was substrate limited, then it is apparent that the suspended solids fraction of the BSS could have stabilized a large portion of the substrate and consequently deprived the attached biomass of sufficient substrate for substantial growth. The decrease in the Linpor system's attached biomass concentration with increased mixed liquor MCRT has not been previously reported. Again, this could have been the result of substrate deprivation. It is suggested that the growth of attached biomass in a BSS is also a function of substrate composition.

If the substrate utilization of the attached biomass was exclusively a factor of substrate limitations caused by insufficient organic loading, the volatile attached fraction of the biomass should have stabilized some of the undegraded substrate. This effect should have been observed as lower soluble effluent COD and observed at the 1 day mixed liquor MCRT experiment, i.e., highest F/M ratio. However, this does not appear to have occurred in the Linpor system. No significant increase of COD removal resulted from increased media concentration.

The relationship of soluble effluent COD to mixed liquor MCRT may be misleading. The characterization of the Hoescht-Celanese wastewater varies. It is possible that the nondegradable COD varied during the study. The COD removal for the study including all systems ranged from 94.6 and 98.2%. The substrate utilization rate ranged from 879 to 979 mg/h. If the nondegradable COD varied during the study then it is possible that both the Linpor and control systems achieved maximum substrate uptake throughout the experiments. A relationship between mixed liquor MCRT, substrate utilization, and media concentration could not be developed from this study.

Some other factors may also have effected the degradation of the COD. The design of the media, i.e., the pore size and density, may have limited the diffusion of oxygen and substrate thereby inhibiting substrate utilization. The production of extracellular polymers by the attached biomass may have increased the nondegradable soluble COD which would have increased the effluent soluble COD.

5.3 Linpor BSS Oxygen Utilization and Substrate Uptake Rate Coefficients

Decreased oxygen utilization in the Linpor systems during this study should be attributed to the substrate limited attached biomass.

The K, K_s, and K_m values decreased with increased media concentrations and the total substrate utilization rates remained relatively constant (see Table 4.1). This indicates that the kinetic coefficients were not identical to those of the suspended solids fraction. The total system biomass at any mixed liquor MCRT increased with increased media concentration (see Figure 4.1). Therefore, if the attached biomass had little effect on the total substrate utilization rate, increasing the attached biomass should result in decreased K_m and K values. The effect of the media concentration on K can be determined by plotting the specific substrate uptake of the MLVSS with the soluble effluent COD. As shown in Figure 5.2, the K values of all of the media percentages except 30% are similar. This implies that the attached biomass had little effect on the total substrate utilization because it was substrate

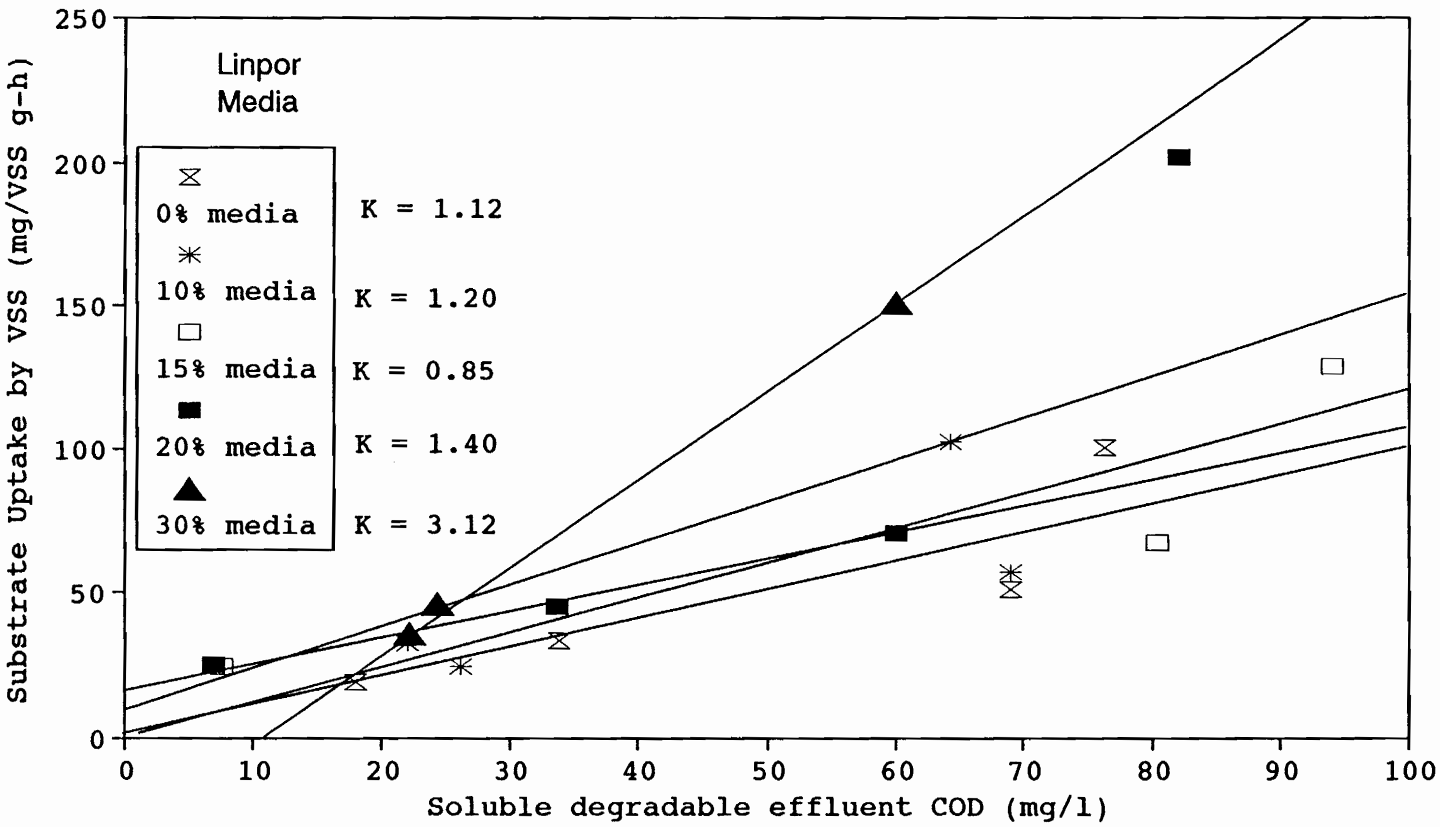

Figure 5.2 Comparison of Substrate Uptake by Volatile Suspended Solids at Different Media Concentrations

limited.

5.4 Nitrification and Denitrification

At 30% Linpor media, the percent nitrification did not improve significantly compared to that of the control. For the 6 and 12 day mixed liquor MCRT experiments the extent of nitrification was similar and also nearly complete. Therefore, comparisons of the Linpor and control systems at these mixed liquor MCRTs were not possible. For the 1 day mixed liquor MCRT experiment the percent nitrification was incomplete and the values of both systems were also similar. There is no evidence to suggest that enhanced nitrification occurred in the Linpor systems. However, a lack of data for the range between the 1 and 3 day mixed liquor MCRTs precludes any conclusions pertaining to nitrification and media concentration. Floating sludge was observed in the secondary clarifiers. Because the interior of the media was characterized by a black colored biomass it can be implied that the media interior was in a reduced oxidation state. Therefore, denitrification may have occurred in both the aeration tank and secondary clarifier of the Linpor BSS.

5.5 Sludge Settling

The SVI experiments were typified by cloudy supernatant and therefore the values obtained do not accurately reflect the true settling properties. However, the relative differences in SVI values should be considered to reflect relative changes of sludge settling during the study.

Filamentous organisms became significantly more abundant in the attached biomass at the 6 and 12 day mixed liquor MCRT experiments than the 1 and 3 day mixed liquor MCRTs. Concurrently, the Linpor System SVI values increased and the ZSV values decreased. Sludge settling appeared to be a function of both mixed liquor MCRT and the presence of filamentous growth in the attached biomass. As shown in Figure 5.3, SVI values may have also been a function of the attached biomass/total biomass ratio. Enhanced settling occurred in the media system during periods of no filamentous growth compared to the control system.

5.6 Attached Biomass in the Linpor Systems

The nature of the attached biomass can be characterized from the results and observations of this study. Several key points are highlighted. The Linpor media biomass, throughout the entire study, exhibited a dark gray appearance and emitted a slight H_2S odor when squeezed. The attached biomass may not have been accountable for the nitrification and denitrification which occurred in the Linpor Systems, but probably contributed to both. Increased media concentration, i.e., increased attached biomass, did not significantly affect the substrate utilization of the

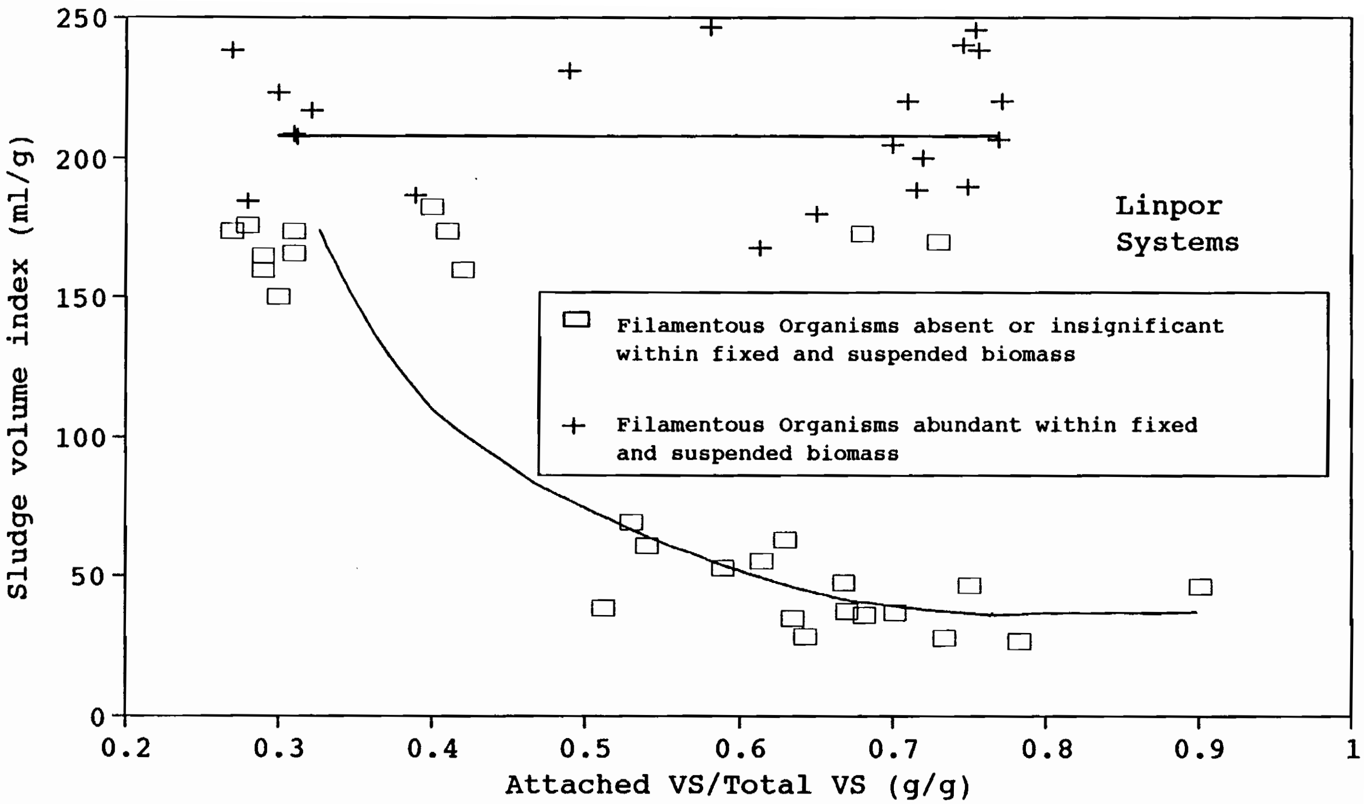

Figure 5.3 Relationship of Sludge Volume Index with the Ratio of Attached Volatile Solids to Total Volatile Solids

Linpor systems compared to the control system. This indicates that the systems were substrate limited for both the control and BSS.

VI. CONCLUSIONS

Based on an extensive study of the use of Biomass Support Systems (BSS) to treat the Hoechst-Celanese wastewater, several conclusions were reached. Substrate and ammonia oxidation was virtually complete in all control experiments indicating the systems were substrate limited. This made it impossible to demonstrate marked improvements. The following conclusions are based on the performance of the experimental systems compared to the control system using the Hoechst-Celanese wastewater.

1) The NOR-PAC and BIONET media did not support attached biomass growth on the media. It was concluded that turbulence prevented attached growth on the two medias.

2) Increased Linpor media concentrations resulted in increased attached volatile biomass concentrations. However, the highest attached volatile solids to total volatile solids ratio occurred during the one day MCRT experiment and decreased with increased mixed liqour MCRT. It was concluded that the probable advantages of biomass support media are greatest at low mixed liqour MCRTs.

3) The attached biomass population in the Linpor systems did not increase the substrate utilization rates or reduce

effluent COD concentrations. It is probable that all systems, both control and experiment, were substrate limited and it was not possible to show significant differences in the experiments performed.

4) The specific oxygen uptake rates were lower in the BSS than in the control systems. The decreased oxygen uptake rates (mg/h) of the Linpor BSS with increased mixed liqour MCRT could have been the result of greater substrate limitation of the attached biomass.

5) Sludge settling was a function of the operating mixed liquor MCRT, filamentous upsets, and percent Linpor media. The Linpor system exhibited lower SVI values than the control during periods of high filamentous upsets at the 3 day mixed liquor MCRT experiment.

6) Changes in total suspended solids production in the Linpor system were primarily a function of mixed liquor MCRT. Decreased total suspended solids production was observed only at the 1 day mixed liquor MCRT experiment using 20 and 30% Linpor media concentrations.

VII. RECOMMENDATIONS FOR FUTURE STUDY

Based on the study with an industrial wastewater several recommendations for future studies with BSS can be made.

7.1 Substrate Composition

The wastewater used for this study consisted of acetic acid and easily biodegradable solvents. If the Linpor media attached biomass was substrate limited, then increasing COD loading to the Linpor system may have induced substantial substrate utilization by the attached biomass. However, the hydraulic loading for this study had been doubled and the mixed liquor MCRTs reduced compared to that of the full-scale operation at the Hoechst-Celanese wastewater treatment plant. The Linpor system operated at low mixed liquor MCRTs exhibited soluble effluent CODs which were comparable to those of the control system.

The Linpor system may be better suited for a wastewater which consists of two distinctly different components, one which is easily degraded and is subsequently stabilized by the suspended solids fraction, and another which is more slowly metabolized and could be stabilized by the attached biomass.

7.2 Future Modeling Efforts

The dissolved oxygen or the redox potential of both the attached and suspended biomass should be measured. The soluble COD of the mixed liquor in the aeration tank and that in the media interior should also be measured. The purpose is to determine the diffusional gradients across the media. It is suggested from this study that both the attached and suspended fractions of the total biomass exhibit dramatically different oxygen and substrate uptake rates and this difference could have been the result of different rates of material diffusion into the Linpor media. Future studies should be performed to determine rates of diffusion across the porous support media. Future modeling efforts should include the attached biomass substrate uptake as a function of the rates of substrate diffusion into the media.

7.3 Experiment Reactor Size to Media Size

The relationship between the size and shape of the batch-scale aeration basin and the size and shape of the free-floating media might have influenced the turbulence required to maintain complete mixing. Aeration tanks of larger dimensions such as full-scale operations may not encounter this effect. Biomass would be more likely to attach and remain attached in a quiescent environment.

7.4 Other Considerations

Extracellular polymers should be monitored in relationship to attached biomass concentrations. The production of nondegradable biopolymer may result in increased COD values.

The Captor process includes wastage of the attached biomass. This technique is thought to maintain a continuous new growth on the media and subsequently encourage greater substrate utilization.

Future pilot studies should include a separate BSS in which all operating parameters i.e., HRT, mixed liquor MCRT, organic loading, media concentration, are maintained at constant values. Changes in nitrification, denitrification, substrate and oxygen uptake, and settling characteristics could be recorded and analyzed in relationship to changes in the attached biomass concentrations with time. Reimann (1984) reported results from a pilot-scale Linpor BSS which indicated that the attached biomass concentrations increased 2.5 times during the period of 1 year.

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APPENDIX A: PERFORMANCE RESULTS

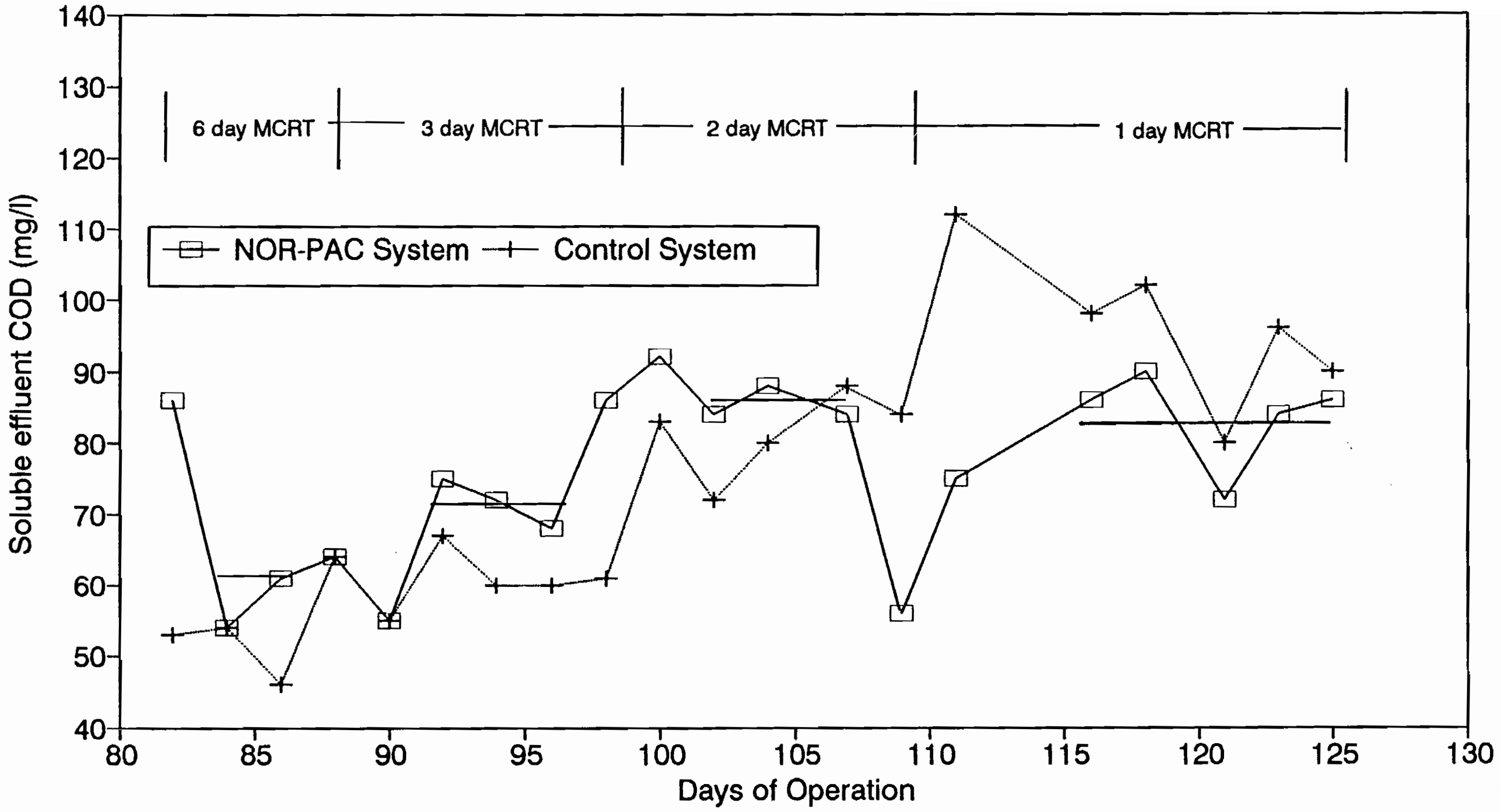

Figure A.1 Periods Determined as Steady-State for Operational Days 82-125 using NOR-PAC Media

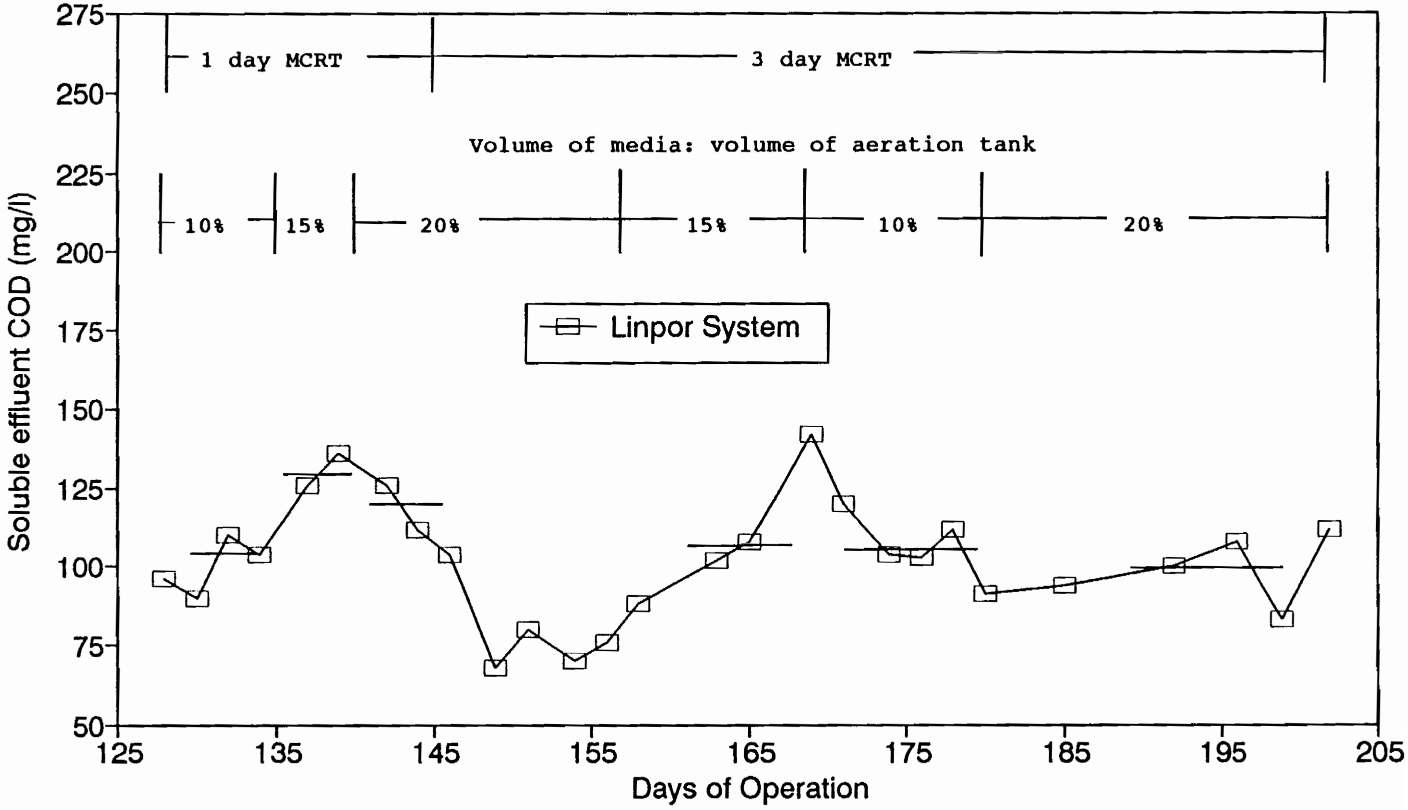

Figure A.2 Periods Determined as Steady-State for Operational Days 127-202. for Linpor System

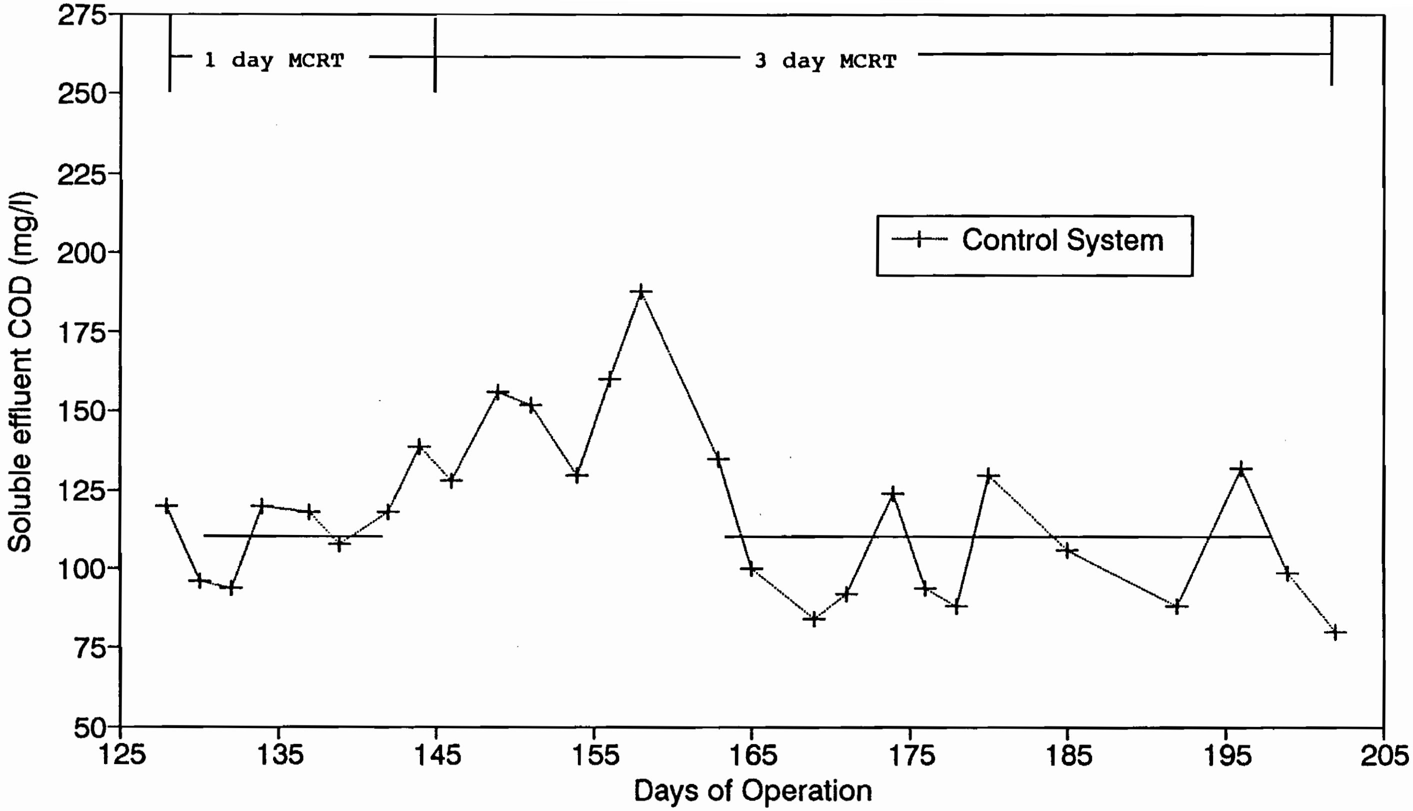

Figure A.3 Periods Determined as Steady-state for Operational Days 127-202 for Control System

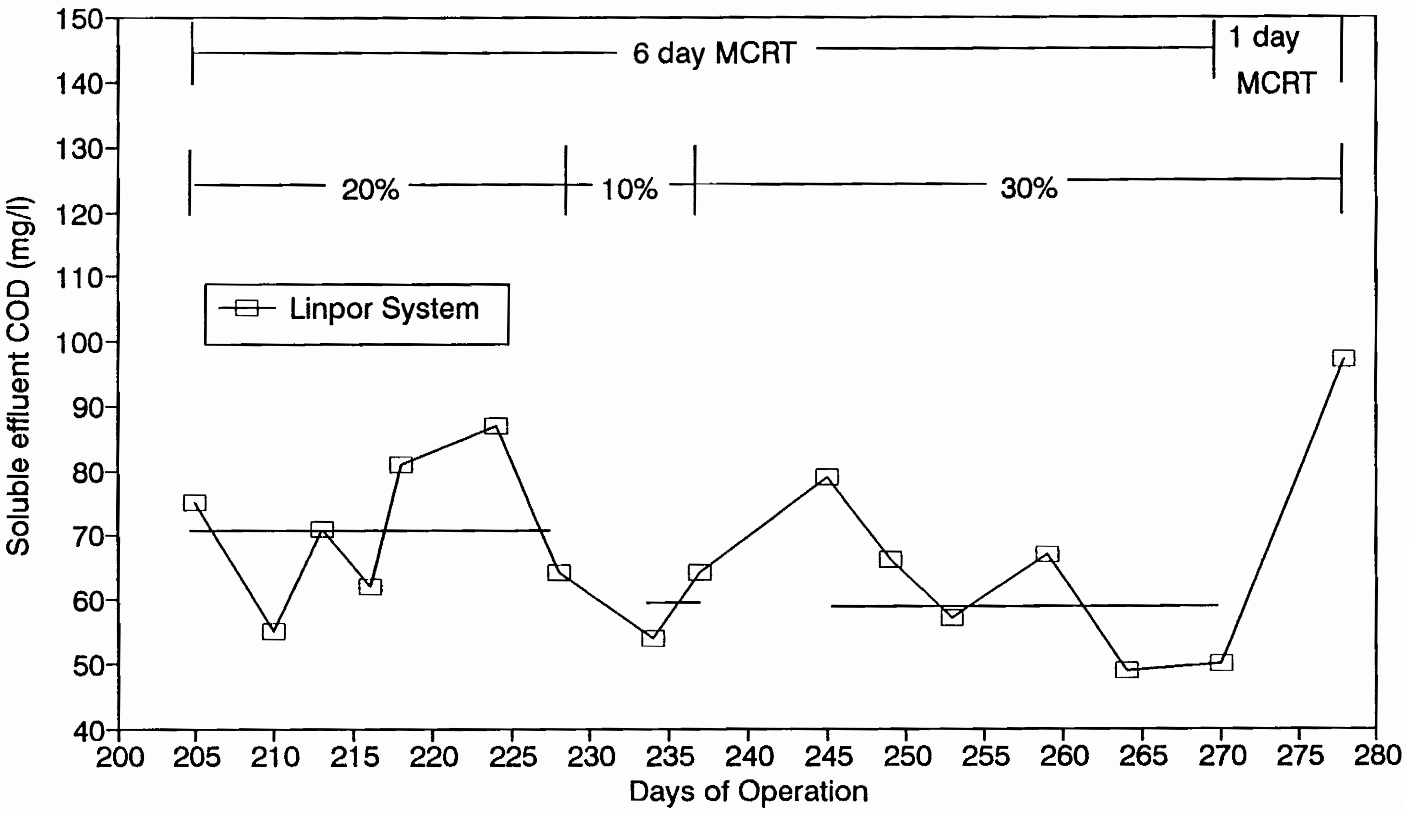

Figure A.4 Periods Determined as Steady-State for Operational Days 205-278

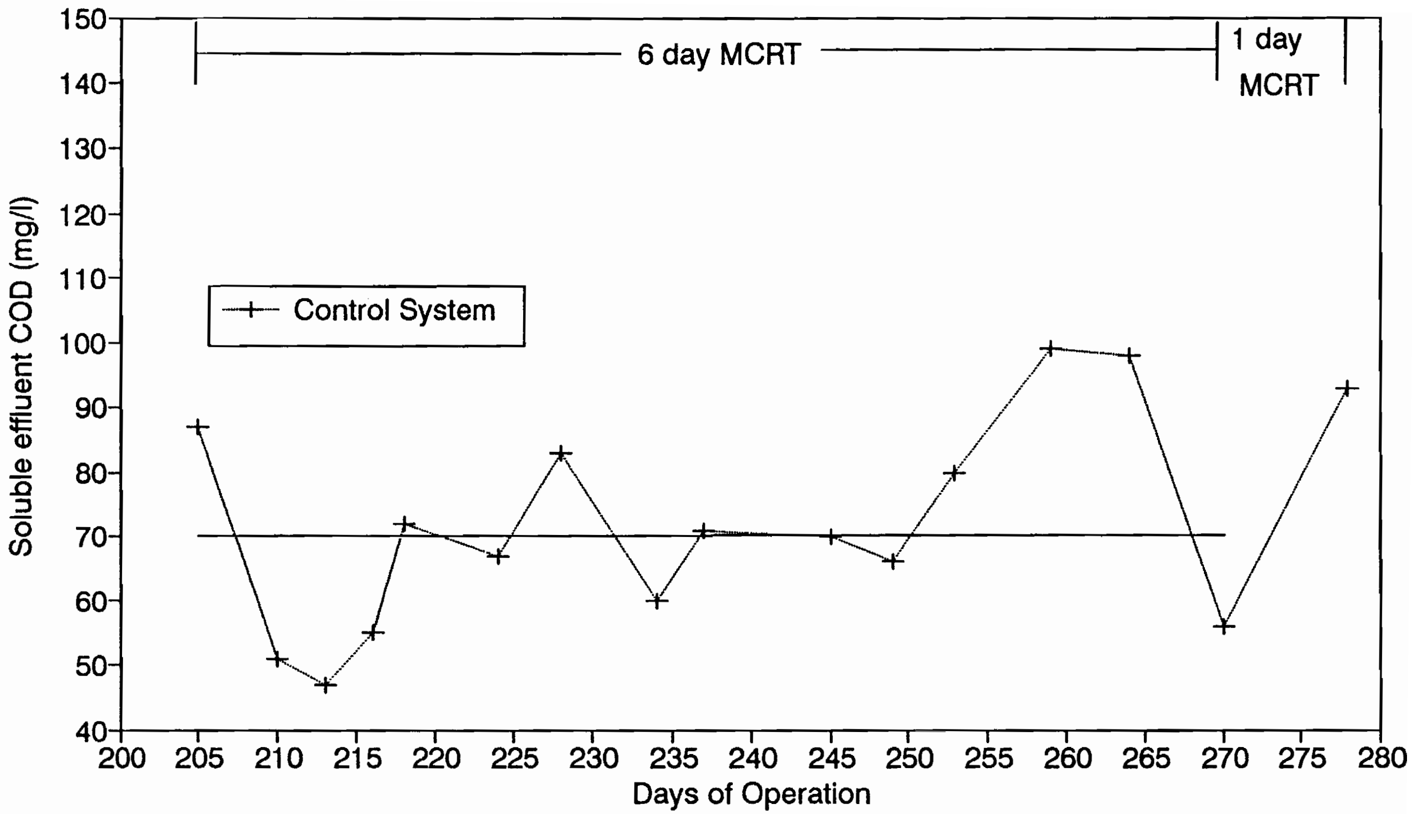

Figure A.5   Periods Determined as Steady-State for Operational Days 205-278

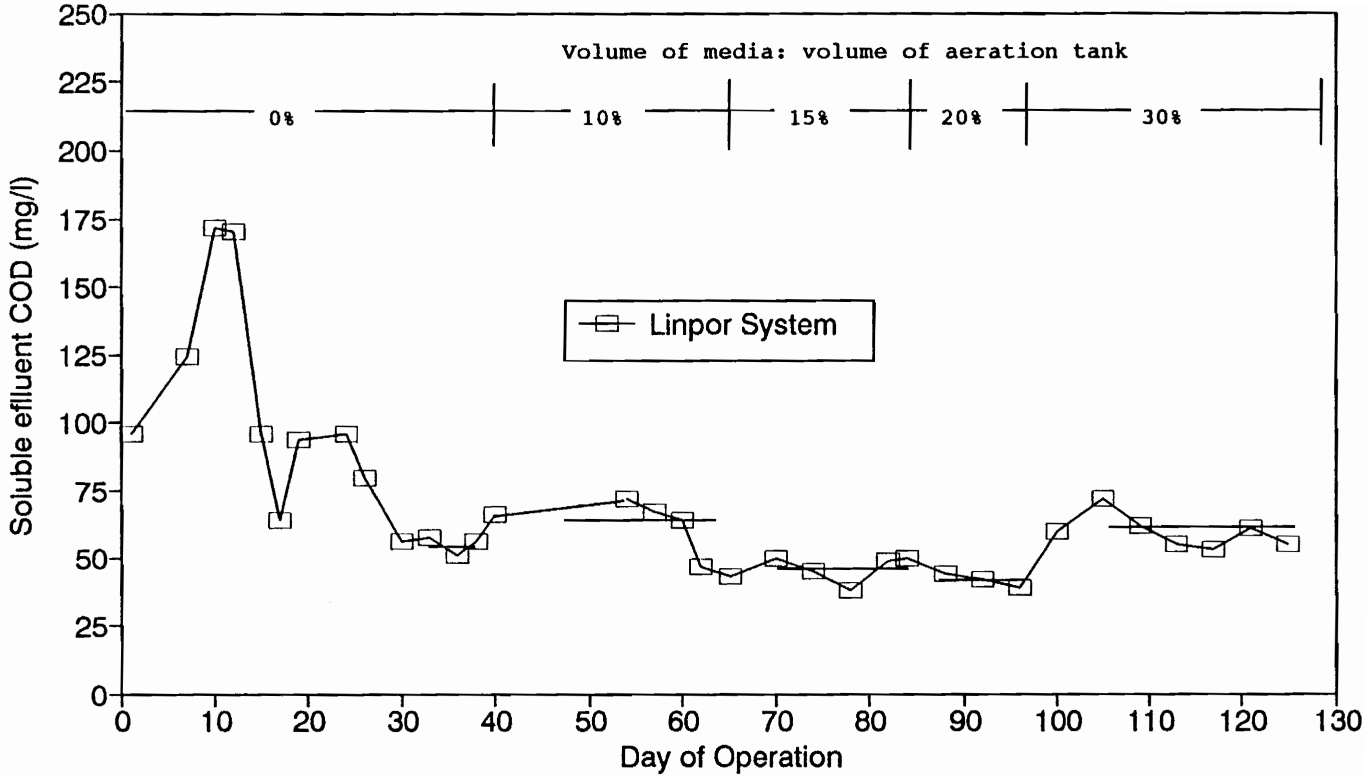

Figure A.6 Periods Determined as Steady-State for Operational Days 0 to 129 for the 12 Day MCRT Linpor System

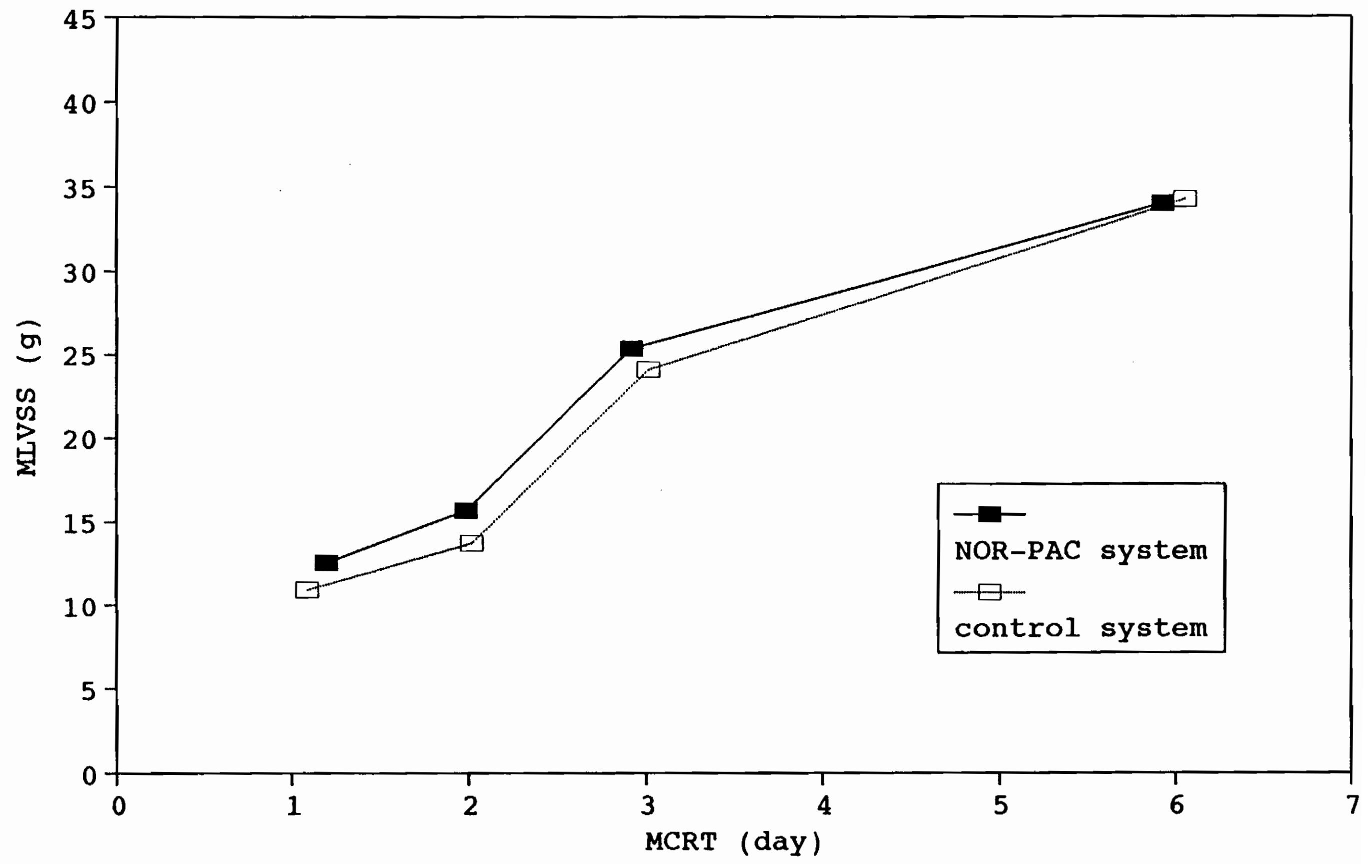

Figure A.7 MLVSS (g) of the NOR-PAC and control systems for operational days 82-125.

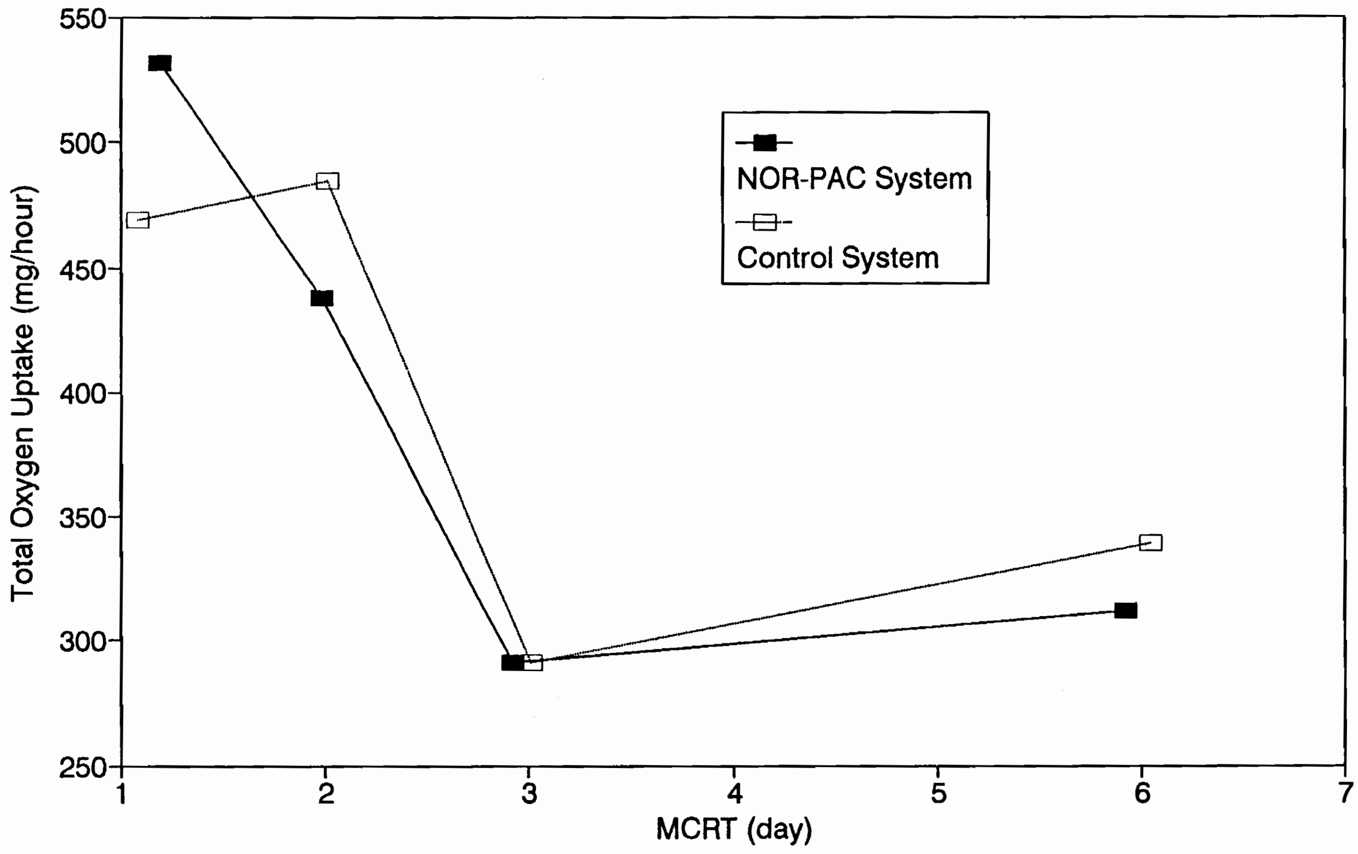

Figure A.8. Comparison of Total Oxygen Uptake of Control and NSW Systems

Table A.1 OPERATIONAL PARAMETERS

Linpor System

day	media	MCRT day	Effluent VSS mg/l	MLVSS mg/l	D.O. mg/l	HRT day	Sludge Production g/day	COD load kg/m3-day
84-86		5.93	85	3550	7.4	0.88	5.46	2.32
92-96		2.92	120	2650	8.2	1.02	8.27	2.45
102-108		1.98	77	1636	7.2	0.93	7.77	2.51
116-125		1.19	1142	1310	7.3	1.04	11.59	2.60
130-134	0.1	0.96	1025	1022	6.00	1.07	9.59	2.40
171-180	0.1	2.96	136	1790	5.32	0.94	5.82	2.36
234-237	0.1	5.97	29	3184	6.35	1.07	5.32	2.30
137-139	0.15	0.87	863	840	5.75	1.03	8.38	2.37
163-169	0.15	2.92	211	1577	5.27	1.26	5.09	2.30
142-144	0.2	0.74	610	565	6.15	0.99	6.15	2.34
192-199	0.2	2.99	55	1637	6.83	0.93	5.39	2.38
205-228	0.2	5.93	25	2624	6.10	1.02	4.36	2.38
278	0.3	0.97	680	880	6.00	1.07	6.36	2.36
245-270	0.3	5.97	31	2927	6.30	1.13	4.81	2.35
Control System								
84-86	0	6.05	84	3420	5.3	0.93	5.65	2.21
92-96	0	3.02	249	2407	6.9	1.07	7.98	2.44
102-108	0	2.01	165	1370	7.2	0.97	7.06	2.40
116-125	0	1.09	1016	1086	5.5	1.09	10.05	2.49
130-144	0	1.04	911	924	4.69	1.04	8.93	2.37
205-270	0	6.02	70	2825	4.63	1.07	4.65	2.36
278	0	1.66	638	990	5.5	1.07	9.49	2.36
12 Day MCRT Linpor System								
36-40	0	12.07	49	4927	4.87	0.95	4.08	2.35
47-65	0.1	11.80	48	4147	6.50	1.00	3.46	2.26
70-84	0.15	11.97	24	4602	6.12	1.04	3.81	2.38
88-97	0.2	12.02	19	4626	6.03	1.04	3.81	2.31
105-129	0.3	11.36	45	3757	6.30	1.13	3.15	2.35

Table A.2 NUTRIENT REQUIREMENTS

Linpor System

day	media	MCRT day	Sludge Production g/day	N req'd g/day	Urea req'd g/l	K req'd g/day	KOH req'd mg/l	P req'd g/day	KH2PO4 req'd g/l
84-86	0.5	5.93	5.46	0.46	0.14	0.05		-0.04	-0.18
92-96	0.5	2.92	8.27	0.83	0.25	0.07		0.06	0.25
102-10	0.5	1.98	7.77	0.75	0.21	0.07		0.03	0.12
116-12	0.5	1.19	11.59	1.24	0.35	0.10		0.14	0.64
130-13	0.1	0.96	8.54	0.86	0.25	0.08	0.10	0.06	0.03
171-18	0.1	2.96	5.45	0.46	0.14	0.05	0.06	-0.04	-0.02
234-23	0.1	5.97	4.81	0.41	0.15	0.04	0.06	-0.03	-0.02
137-13	0.15	0.87	6.97	0.67	0.20	0.06	0.08	0.02	0.01
163-16	0.15	2.92	4.59	0.41	0.18	0.04	0.06	-0.02	-0.01
142-14	0.2	0.74	4.56	0.37	0.13	0.04	0.05	-0.05	-0.02
192-19	0.2	2.99	4.38	0.33	0.11	0.04	0.05	-0.07	-0.03
205-22	0.2	5.93	3.54	0.25	0.11	0.03	0.04	-0.07	-0.03
278	0.3	0.97	5.72	0.52	0.17	0.05	0.07	-0.01	-0.00
245-27	0.3	5.97	3.44	0.25	0.12	0.03	0.04	-0.06	-0.03
Control System									
84-86	0	6.05	5.65	0.48	0.14	0.05		-0.04	-0.16
92-96	0	3.02	7.98	0.80	0.24	0.07		0.05	0.21
102-10	0	2.01	7.06	0.67	0.19	0.06		0.01	0.04
116-12	0	1.09	10.05	1.05	0.30	0.09		0.10	0.46
130-14	0	1.04	8.93	0.91	0.20	0.08	0.10	0.07	0.03
163-19	0	3.01	5.81	0.52	0.12	0.05	0.07	-0.02	-0.01
205-27	0	6.02	4.70	0.40	0.09	0.04	0.06	-0.04	-0.02
278	0	1.66	9.49	0.98	0.21	0.09	0.11	0.09	0.04
12 Day MCRT Linpor System									
36-40	0	12.1	4.08	0.30	0.11	0.04	0.04	-0.07	-0.03
47-65	0.1	11.8	3.16	0.19	0.09	0.03	0.04	-0.09	-0.04
70-84	0.15	12.0	3.27	0.22	0.10	0.03	0.04	-0.08	-0.04
88-97	0.2	12.0	3.08	0.19	0.10	0.03	0.04	-0.08	-0.04
105-12	0.3	11.4	2.31	0.11	0.08	0.02	0.03	-0.09	-0.04

Table A.3 SOLIDS

Linpor System		Effluent		Aeration basin		Attached Solids		Total Solids	
		TSS mg/l	VSS mg/l	MLSS g	MLVSS g	TS g	VS g	EMLSS g	EMLVSS g
day	media								
84-86	0.5	120	85	39.87	33.90				
92-96	0.5	160	120	32.06	25.31				
102-108	0.5	102	77	18.90	15.63				
116-125	0.5	1620	1142	18.10	12.51				
130-134	0.1	1408	1025	13.46	9.20	13.93	9.72	27.07	18.65
171-180	0.1	197	136	24.71	16.11	19.16	16.88	43.87	32.99
234-237	0.1	39	29	36.00	28.66	14.75	13.28	50.75	41.93
137-139	0.15	1185	863	10.43	7.14	34.48	29.92	44.91	37.06
163-169	0.15	250	211	21.79	13.40	32.17	27.62	53.96	41.02
142-144	0.2	870	610	6.48	4.52	46.23	40.20	52.71	44.71
192-199	0.2	78	55	20.80	13.09	43.33	37.15	64.13	50.24
205-228	0.2	37	25	28.15	20.99	33.27	29.98	61.41	50.97
278	0.3	880	680	9.17	6.16	62.00	55.80	71.17	61.96
245-270	0.3	45	31	27.81	20.49	69.25	62.45	97.07	82.94
Control System									
84-86	0	114	84	41.25	34.20				
92-96	0	331	249	30.50	24.07				
102-108	0	204	165	17.18	13.70				
116-125	0	1349	1016	15.02	10.86				
130-144	0	1199	911	12.34	9.24				
163-199	0	178	114	25.33	17.49				
205-270	0	110	70	36.56	28.25				
278	0	956	638	14.7	9.9				
12 Day MCRT Linpor System									
36-40	0	70	49	6.05	49.27				49.27
47-65	0.1	74	48	47.00	37.32	15.76	14.18	62.76	51.50
70-84	0.15	38	24	47.69	39.12	19.32	17.39	67.01	56.51
88-97	0.2	26	19	45.33	37.01	29.09	26.18	74.43	63.19
105-129	0.3	71	45	34.35	26.30	66.77	60.09	101.12	86.39

Table A.4 SETTLING CHARACTERISTICS

Linpor System

day	media	MCRT day	Actual MCRT day	MLSS g	ZSV cm/min	SVI l/g
84-86	0.5	5.93		39.87	0.02	238
92-96	0.5	2.92		32.06	0.06	289
102-108	0.5	1.98		18.90	5.43	122
116-125	0.5	1.19		18.10	2.42	18
130-134	0.1	0.96	2.07	13.46		
171-180	0.1	2.96	6.07	24.71	4.26	101
234-237	0.1	5.97	8.74	36.00	0.03	213
137-139	0.15	0.87	4.88	10.43		
163-169	0.15	2.92	8.95	21.79	3.48	40
142-144	0.2	0.74	7.29	6.48		
192-199	0.2	2.99	11.64	20.80	6.83	30
205-228	0.2	5.93	14.46	28.15	5.26	115
278	0.3	0.97	10.82	9.17	1.08	46
245-270	0.3	5.97	24.24	27.81	0.17	223
Control System						
84-86	0	6.05		41.25	0.03	236
92-96	0	3.02		30.50	4.12	131
102-108	0	2.01		17.18	7.33	72
116-125	0	1.09		15.02		45
130-144	0	1.04		12.34		
163-199	0	3.01		25.33	1.19	243
205-270	0	6.02		36.56	1.38	160
278	0	1.66		14.7	1.08	61
12 Day MCRT Linpor System						
36-40	0	12.07	12.07	6.05	1.38	160
47-65	0.1	11.80	16.29	47.00	0.08	183
70-84	0.15	11.97	17.29	47.69	0.03	176
88-97	0.2	12.02	20.53	45.33	0.02	174
105-129	0.3	11.36	37.34	34.35	0.02	204

Table A.5 OXYGEN UPTAKE

day	media	MLOUR mg/l-mi	MLOUR mg/h	MLSOUR mg/g-h	TOUR mg/l-mi	TOUR mg/h	TSOUR mg/g-h	LOUR mg/h	LSOUR mg/g-h
Linpor System									
84-86	0.5				0.52	312	8.8		
92-96	0.5				0.49	291	11.0		
102-108	0.5				0.73	438	26.8		
116-125	0.5				0.89	469	40.6		
130-134	0.1	0.41	221	20.2	0.46	277	14.6	203.0	15.7
171-180	0.1	0.48	260	16.2	0.54	326	9.8	66.0	3.8
234-237	0.1	0.52	278	9.7	0.54	327	7.8	48.7	3.7
137-139	0.15	0.37	186	26.9	0.83	496	13.8	310.2	11.2
163-169	0.15	0.48	245	18.2	0.55	329	8.0	84.4	3.1
142-144	0.2	0.24	113	25.1	1.05	631	14.2	518.6	13.0
192-199	0.2	0.43	206	16.0	0.65	390	7.8	183.4	4.9
205-228	0.2	0.47	224	10.6	0.64	383	7.6	158.4	5.3
278	0.3	0.32	134	21.8	1.01	606	9.8	471.6	8.5
245-270	0.3	0.48	201	9.9	0.81	484	5.8	283.3	4.5
Control System									
84-86	0				0.57	339	9.9		
92-96	0				0.49	291	12.1		
102-108	0				0.81	485	35.7		
116-125	0				0.78	469	44.3		
130-144	0	0.29	176	19.0	0.29	176	19.0		
163-199	0	0.43	258	14.9	0.43	258	14.9		
205-270	0	0.53	315	11.2	0.53	315	11.2		
278	0	0.34			0.34		20.06		
12 Day MCRT Linpor System									
36-40	0	0.60	360	7.3	0.60	360	7.3		
47-65	0.1	0.61	327	8.8	0.62	372	7.2	45.6	3.2
70-84	0.15	0.46	235	6.0	0.47	282	5.0	47.4	2.7
88-97	0.2	0.62	299	8.1	0.63	380	6.0	81.3	3.1
105-129	0.3	0.54	227	8.6	0.69	414	4.8	187.2	3.1

MLOUR and MLSOUR refer to the oxygen uptake rate of the suspended solids frac
TOUR and TSOUR refer to the total oxygen uptake rate.
LOUR and LSOUR refer to the oxygen uptake rate of the fixed biomass.

Table A.6 SYSTEM PERFORMANCE

Linpor System				Effluent			
		Inf COD	MCRT	COD	TSS	VSS	pH
day	media	mg/l	day	mg/l	mg/l	mg/l	
84-86	0.5	2049	5.93	58	120	85	8.35
92-96	0.5	2496	2.92	72	160	120	8.30
102-108	0.5	2310	1.98	85	102	77	8.25
116-125	0.5	2704	1.19	84	1620	1142	8.14
130-134	0.1	2560	0.96	101	1408	1025	8.39
171-180	0.1	2220	2.96	106	197	136	8.05
234-237	0.1	2460	5.97	59	39	29	8.05
137-139	0.15	2443	0.87	131	1185	863	8.51
163-169	0.15	2900	2.92	117	250	211	8.19
142-144	0.2	2326	0.74	119	870	610	8.45
192-199	0.2	2200	2.99	97	78	55	8.21
205-228	0.2	2437	5.93	71	37	25	8.05
278	0.3	2520	0.97	97	880	680	8.42
245-270	0.3	2650	5.97	61	45	31	8.17
Control System							
84-86	0	2049	6.05	50	114	84	8.10
92-96	0	2609	3.02	62	331	249	8.07
102-108	0	2310	2.01	80	204	165	7.98
116-125	0	2707	1.09	93	1349	1016	7.83
130-144	0	2460	1.04	113	1199	911	7.95
205-270	0	2383	6.02	71	110	70	7.99
278	0	2525	1.66	93	956	638	8.39
12 Day MCRT Linpor System							
36-40	0	2233	12.07	55	70	49	7.89
47-65	0.1	2267	11.80	63	74	48	7.88
70-84	0.15	2472	11.97	45	38	24	8.15
88-97	0.2	2407	12.02	44	26	19	8.05
105-129	0.3	2650	11.36	59	71	45	8.13

APPENDIX B: SUBSTRATE UTILIZATION AND NITROGEN BALANCE

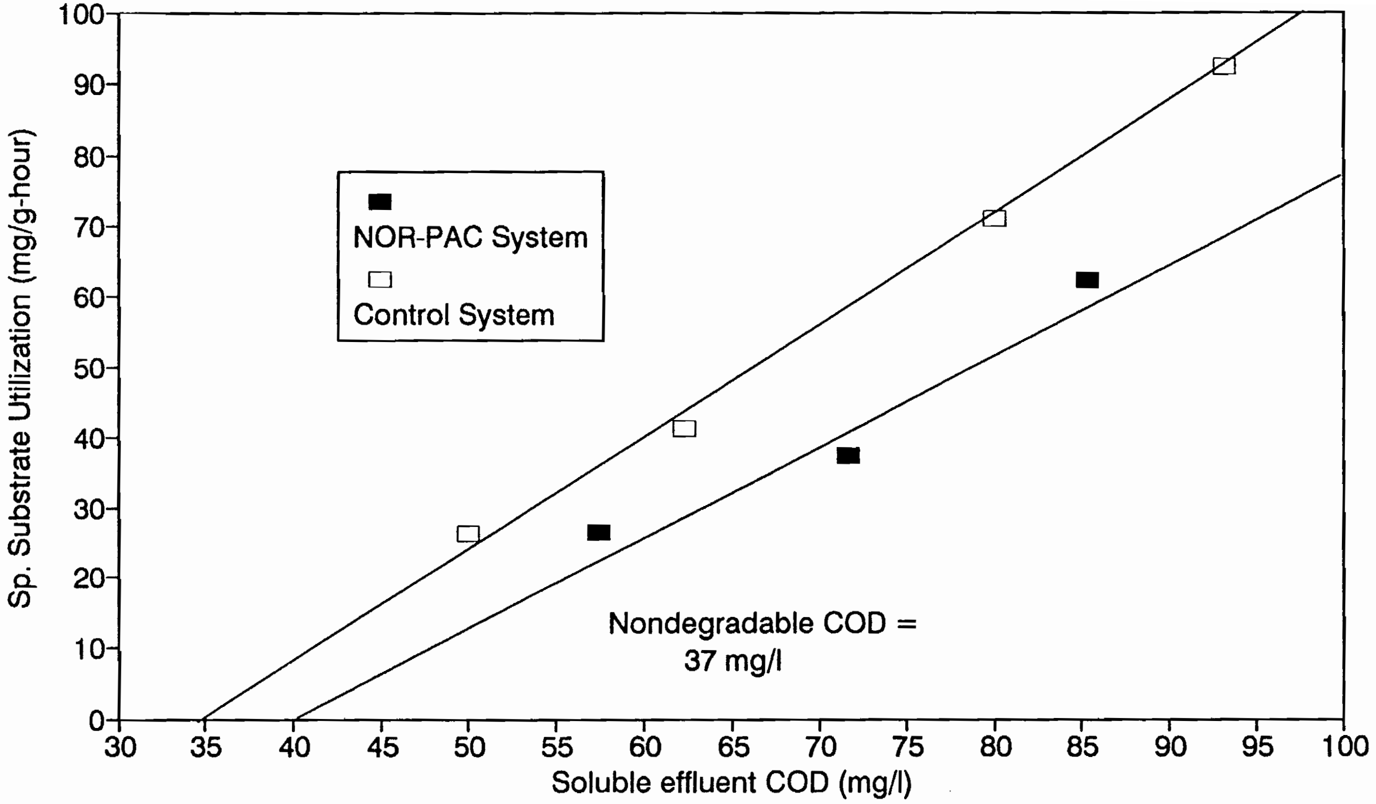

Figure B.1 Determination of Soluble Nondegradable COD

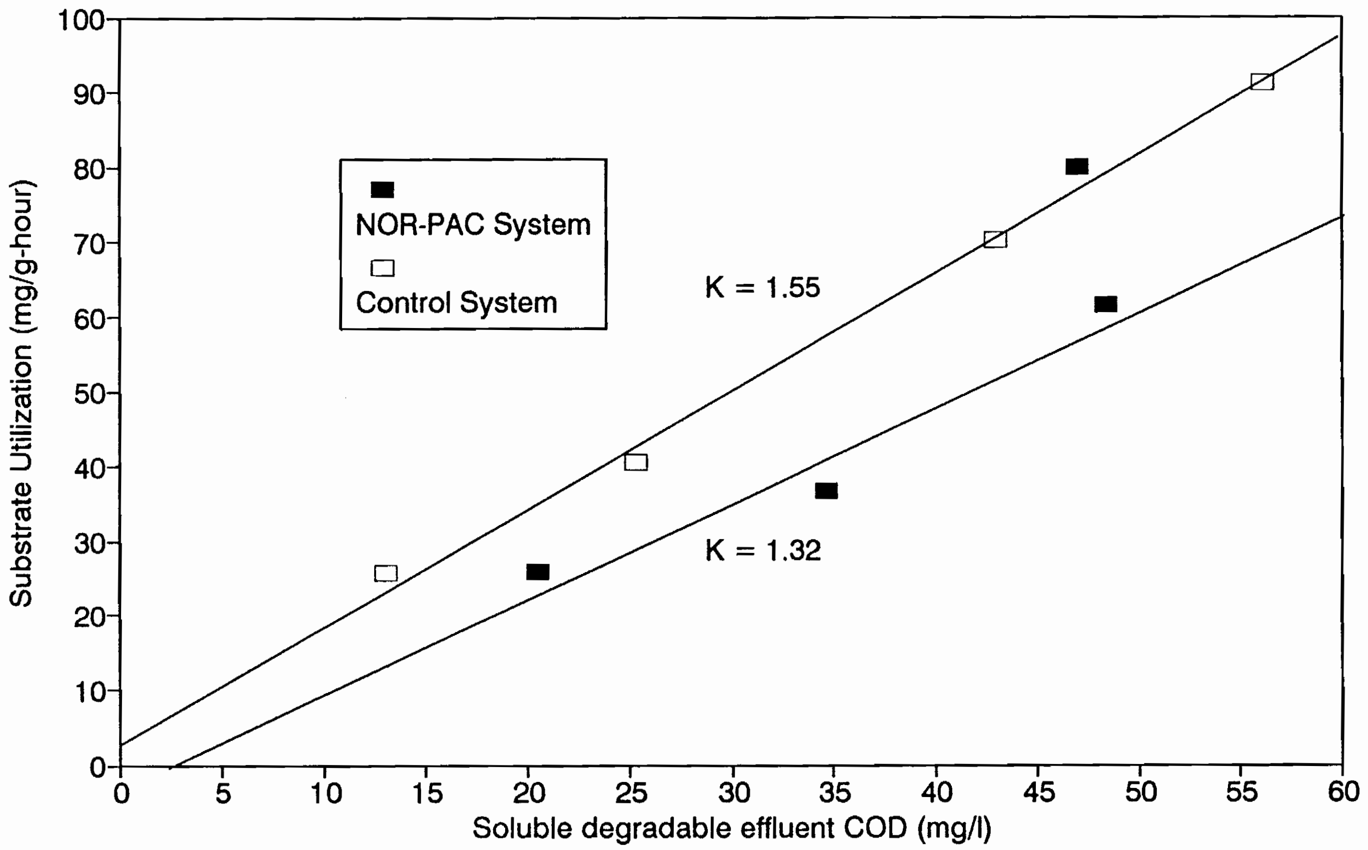

Figure B.2 Reaction Rate Constants of NOR-PAC System (excluding the Nondegradable Soluble Effluent COD of 37 mg/l)

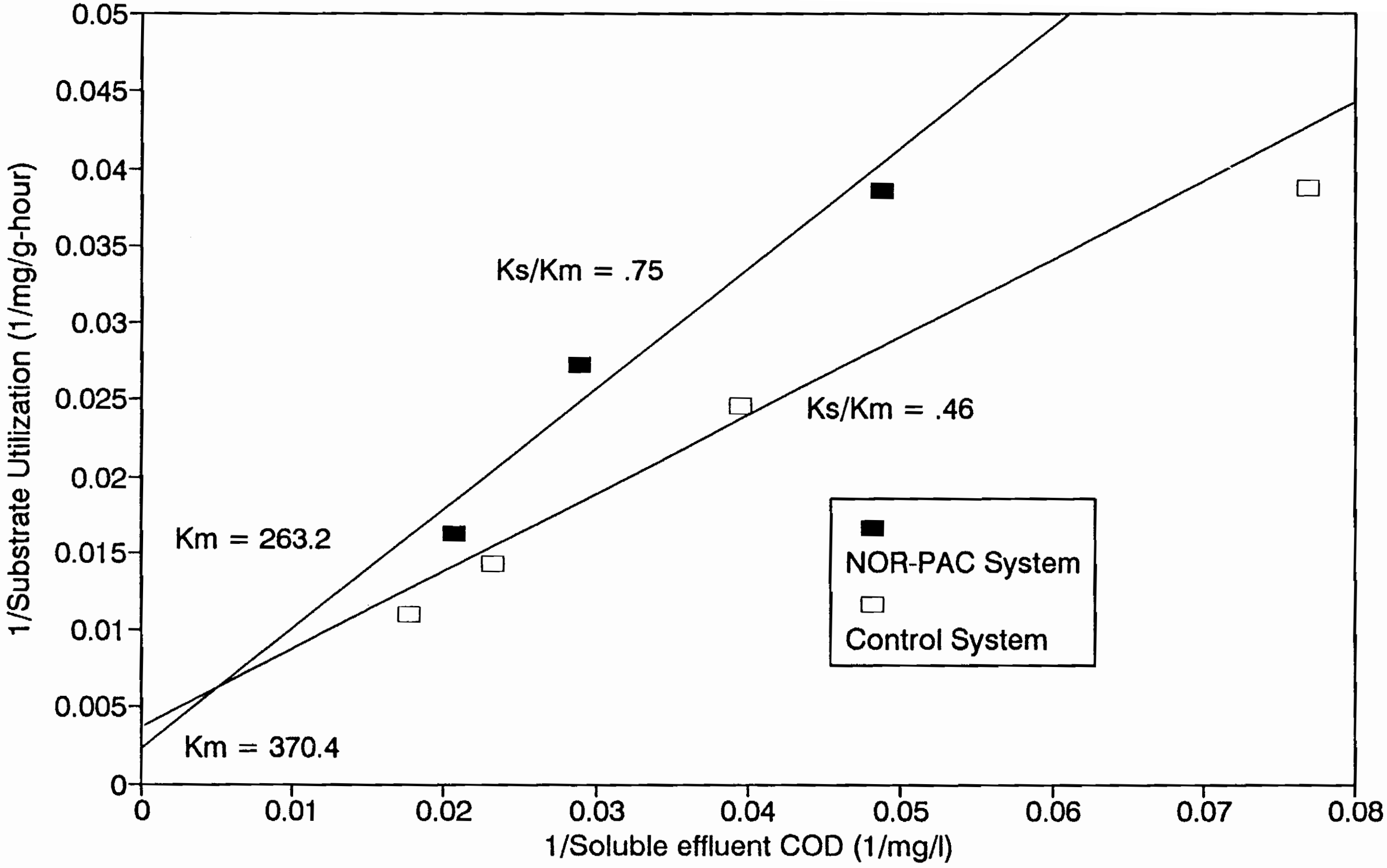

Figure B.3 Half Saturation and Maximum Utilization Constants based on Monod Kinetics for Operational Days 82-125

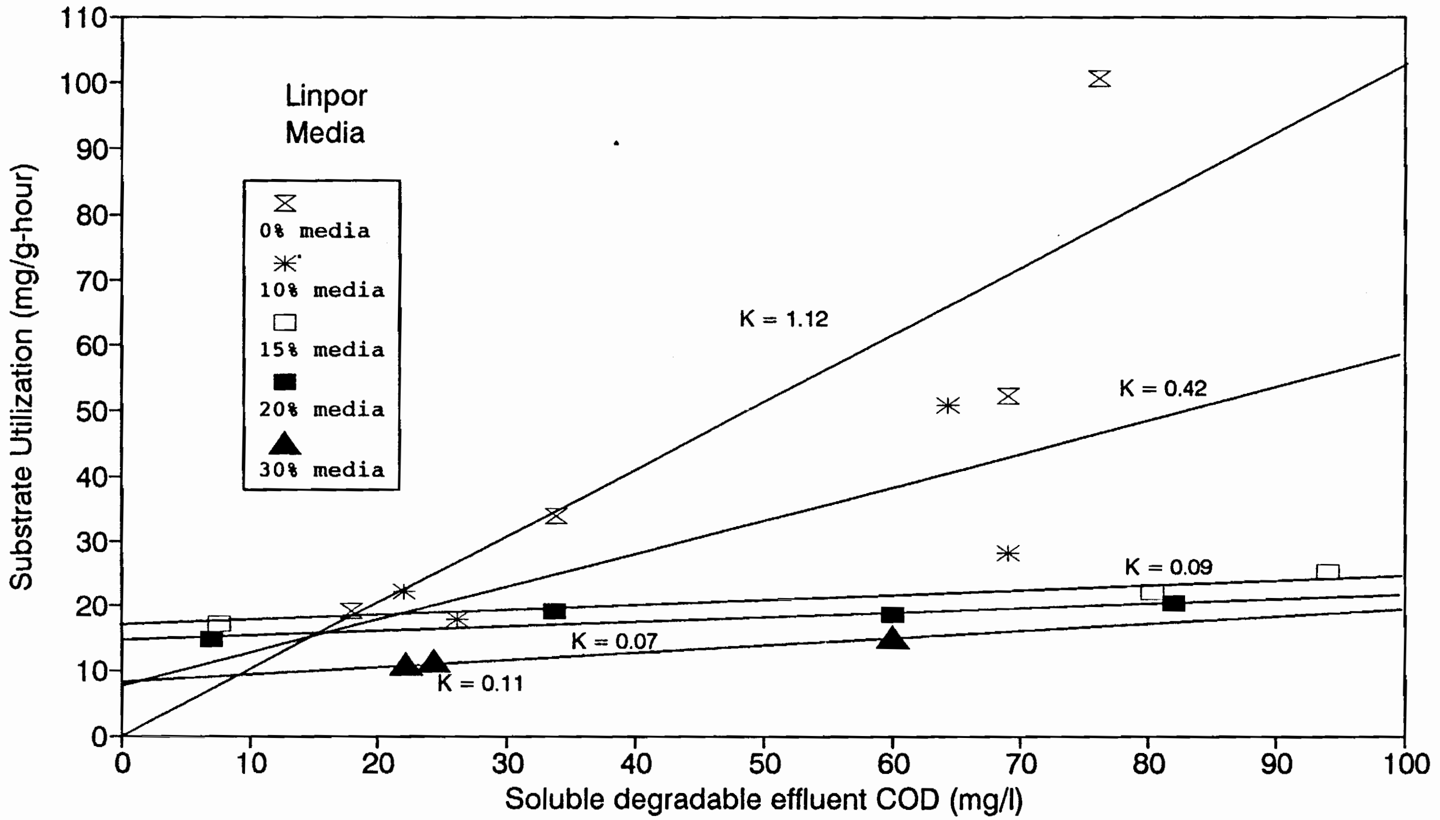

Figure B.4 Decreased Reaction Rate Constants with Changes in Percent Media

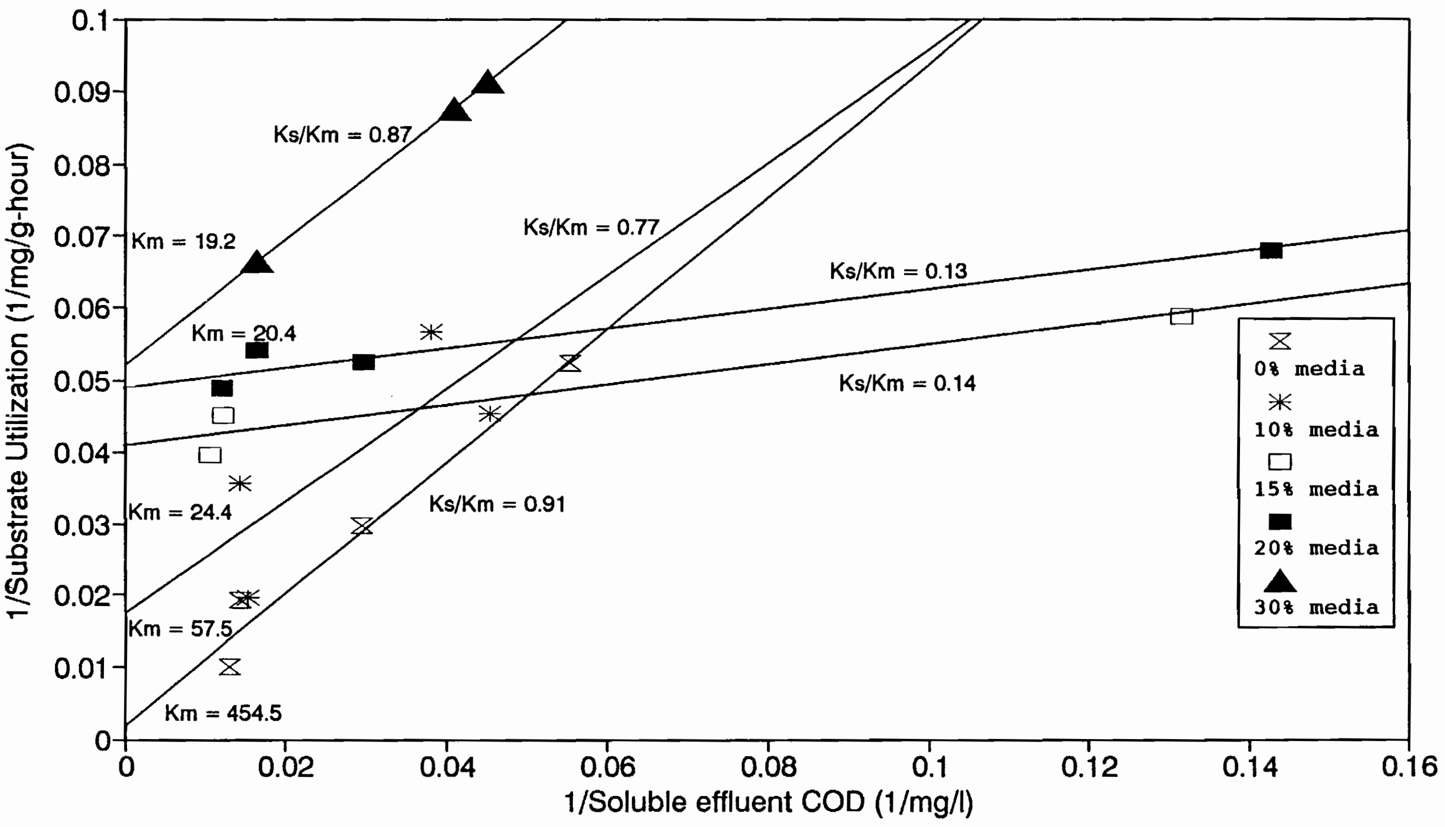

Figure B.5 Half Saturation and Maximum Utilization Constants for Operational Days 127-278

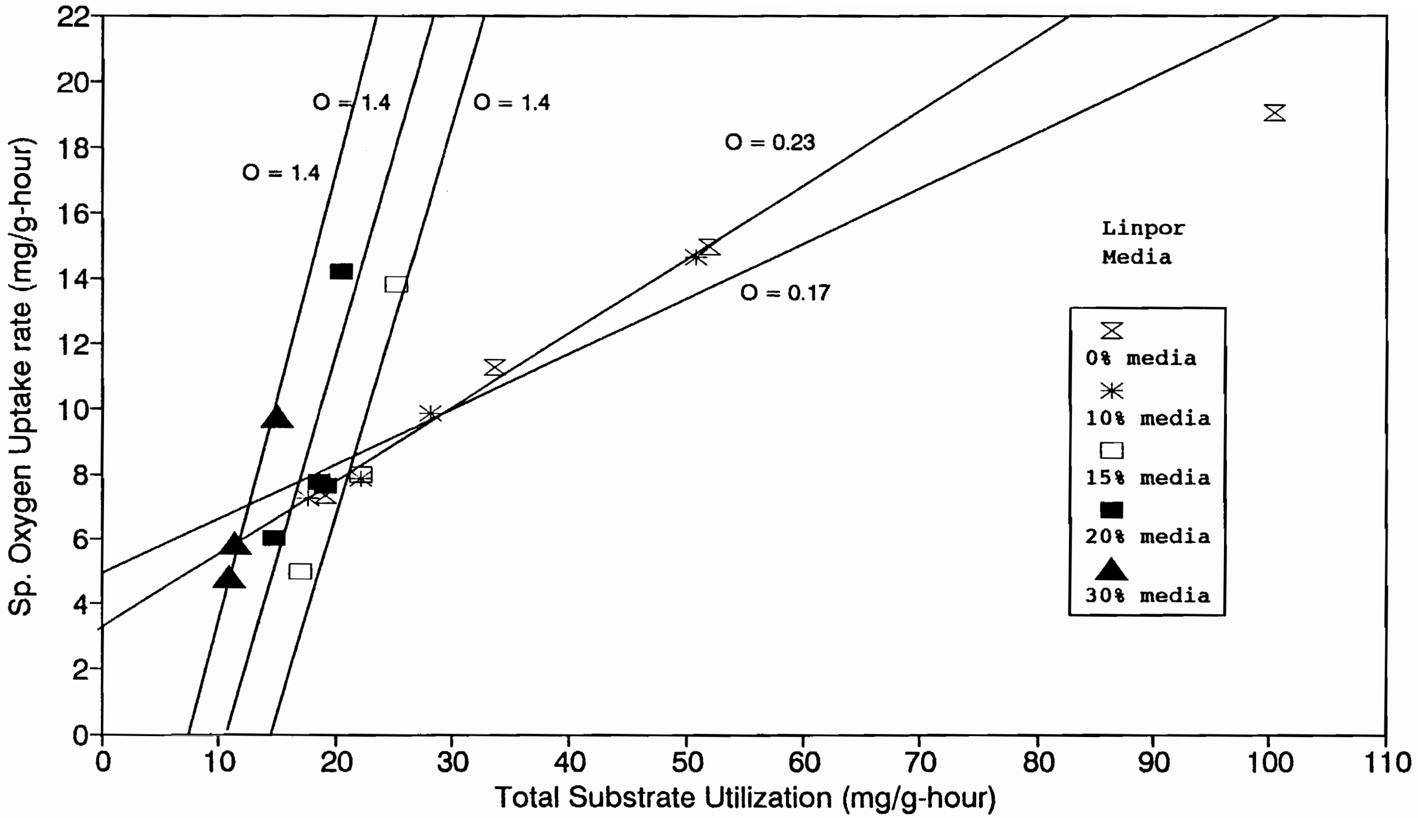

Figure B.6 Changes of Oxygen Utilization Coefficients with Changes in Percent Media

Table B.1 SUBSTRATE UTILIZATION

Linpor System

day	media	COD-37 mg/l	total q mg/h	total q mg/g-h	ml q mg/h	ml q mg/g-h	LIN q mg/h	LIN q mg/g-h
84-86	0.5	21	879	26				
92-96	0.5	35	931	37				
102-10	0.5	48	955	62				
116-12	0.5	47	989	80				
130-13	0.1	64	944	51	913	99	276	25
171-18	0.1	69	919	28	842	52	130	8
234-23	0.1	22	922	22	931	33	42	3
137-13	0.15	94	920	25	701	98	219	7
163-16	0.15	80	906	22	684	51	222	8
142-14	0.2	82	911	20	474	105	437	11
192-19	0.2	60	930	19	749	56	355	9
205-22	0.2	34	947	19	670	32	277	10
278	0.3	60	931	15	580	94	351	6
245-27	0.3	24	942	11	730	36	212	3
Control System								
84-86	0	13	883	26				
92-96	0	25	979	41				
102-10	0	43	956	70				
116-12	0	56	987	92				
130-14	0	76	929	101	929			
163-19	0	69	898	52	898			
205-27	0	34	940	34	940			
278	0	56	932	94	932			
12 Day MCRT Linpor System								
36-40	0	18	942	19	942	19		19
47-65	0.1	26	910	18	714	19	196	14
70-84	0.15	8	961	17	748	19	213	12
88-97	0.2	7	930	15	708	19	223	8
105-12	0.3	22	945	11	503	19	442	7

Table B.2 NITROGEN BALANCE

Influent

day	media	MCRT	nitrite mg/l	nitrate mg/l	TKN mg/l	TKN mg/day	nitrate mg/day
259	0.3	6.1	0.0	4.2	105.0	907.2	36.3
270	0.3	6.3	0.0	4.5	120.0	1123.2	42.1
278	0.3	1.0	0.0	4.9	356.0	3332.2	45.9
119	0.3	11.9	0.0	4.2	92.7	801.2	36.3
124	0.3	12.1	0.0	5.2	67.0	627.1	48.7
130	0.3	12.0	0.0	4.5	71.0	664.6	42.1
259	0.0	6.1	0.0	4.2	109.0	941.8	36.3
264	0.0	6.1	0.0	5.2	100.0	864.0	44.9
270	0.0	6.0	0.0	4.5	105.0	982.8	42.1
278	0.0	1.7	0.0	4.9	350.0	3276.0	45.9
134	0.0	12.6	0.0	4.9	112.0	1048.3	45.9

Effluent

day	media	mcrt	nitrite mg/l	nitrite mg/day	nitrate mg/l	nitrate mg/day	TKN mg/day
259	0.3	6.1	1.6	11.4	19.4	138.5	78.5
264	0.3	5.9	1.9	13.4	25.0	176.0	39.4
270	0.3	6.3	1.5	11.8	38.5	302.6	78.6
278	0.3	1.0	9.4	88.0	72.1	674.9	2152.8
119	0.3	11.9	2.8	22.2	14.9	118.3	59.6
124	0.3	12.1	3.8	32.9	20.5	177.5	121.2
130	0.3	12.0	1.0	8.7	14.8	128.2	59.8
259	0.0	6.1	2.1	14.8	14.6	102.8	126.7
264	0.0	6.1	3.1	24.6	13.0	103.2	117.5
270	0.0	6.0	0.3	2.3	5.7	44.2	77.6
278	0.0	1.7	6.2	58.0	6.0	56.2	1937.5
134	0.0	12.6	4.4	38.1	33.7	291.8	259.8

Table B.2 NITROGEN BALANCE (continued)

day	media	MCRT	TKN mixed liqour mg/l	Soluble TKN mixed liqour mg/l	Soluble TKN wasted mg/day	Available N mg/day
259	0.3	6.1	340.0	306	459.0	436.0
264	0.3	5.9	297.0	267.3	427.7	290.5
270	0.3	6.3	297.0	267.3	401.0	690.0
278	0.3	1.0	165.0	148.5	1390.0	1843.9
119	0.3	11.9	350.0	315	220.5	515.5
124	0.3	12.1	332.0	298.8	209.2	303.3
130	0.3	12.0	303.0	272.7	190.9	343.6
259	0.0	6.1	225.0	202.5	324.0	502.2
264	0.0	6.1	256.0	230.4	161.3	395.8
270	0.0	6.0	300.0	270	432.0	521.3
278	0.0	1.7	207.0	186.3	1743.8	1724.1
134	0.0	12.6	403.0	362.7	253.9	887.1

day	media	MCRT day	N nitrified mg/day	percent nitrified	N denitrified mg/day	Percent Denitrified
259	0.3	6.1	397.4	91.2	252.3	58.2
264	0.3	5.9	281.3	96.8	93.9	28.8
270	0.3	6.3	637.3	92.4	305.1	44.9
278	0.3	1.0	341.6	18.5	0.0	0.0
119	0.3	11.9	495.6	96.1	379.0	71.2
124	0.3	12.1	241.8	79.7	63.1	21.7
130	0.3	12.0	320.3	93.2	214.5	59.2
259	0.0	6.1	396.6	79.0	288.6	66.7
264	0.0	6.1	307.2	103.0	213.1	69.3
270	0.0	6.0	474.0	90.9	460.0	89.1
278	0.0	1.7	397.8	23.1	215.3	48.5
134	0.0	12.6	787.5	88.8	476.7	57.2

Table B.3 OXYGEN UTILIZED FOR NITRIFICATION

day	media	MCRT day	Oxygen req'd nitrification mg/hour	Total Oxygen Uptake mg/hour	Oxygen req'd substrate mg/hour
259	0.3	6.1	75.7	420	344.3
264	0.3	5.9	53.6	342	288.4
270	0.3	6.3	121.4	438	316.6
278	0.3	1.0	65.1	606	540.9
119	0.3	11.9	94.4	400	305.6
124	0.3	12.1	46.1	414	367.9
130	0.3	12.0	61.0	420	359.0
259	0.0	6.1	75.5	342	266.5
264	0.0	6.1	58.5	228	169.5
270	0.0	6.0	90.3	240	149.7
278	0.0	1.7	75.7	204	128.3
134	0.0	12.6	149.9	360	210.1

VITA

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