ACID FERMENTATION OF PRIMARY SLUDGE AT 20·C

by

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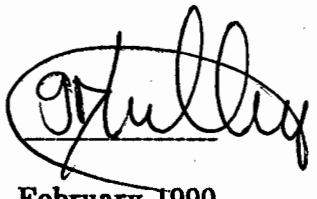
DECLARATION BY CANDIDATE

I, IAN DAVID LILLEY, hereby declare that this thesis is my own work and that it has not been submitted for a degree at another University.



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SYNOPSIS

Full scale studies on biological excess phosphrous removal plants have demonstrated the biological excess phosphorous removal can be increased by acid fermenting the settled sludge in the primary settling tank, and adding either the fermented sludge, or the acids elutriated from the sludge, to the influent of the biological phosphorous removal plant. Considerable uncertainty still exists, however, as to the mass of short chain fatty acids that can be generated and the degree of improvement in phosphorous removal that can be expected. This study was undertaken to (1) evaluate short chain fatty acid production in laboratory scale batch, single and in-series completely mixed reactor systems, (2) development of a model for acid fermentation, and (3) theoretically estimate the effect of acid addition on biological excess phosphorous removal.

The laboratory investigation comprised studies of, (1) batch systems with batch retention times up to about 10 days for influent volatile solids concentrations ranging from 11 to 42 g/ℓ, (2) 3 in-series completely mixed reactor systems with each reactor having 1 day flow through retention time for influent volatile solids concentrations ranging from 37 to 60 g/ℓ and, (3) single completely mixed reactor systems with flow through retention times of 1, 2, 3, 5, 6 and 9 days for influent volatile solids influent concentrations ranging from 36 to 50 g/ℓ. All the studies were made at 20° C.

From the fermentation studies the following conclusions were formed.

- The raw sludge appears to have an acid fermentation potential for the production of SCFA, of about 17 percent of the influent sludge COD i.e. a specific potential yield of 0,17 mgSCFA as COD/mg influent sludge COD.

- The potential does not appear to be influenced by the concentration of the influent primary sludge.

- The production of SCFA appears to conform to a first order reaction with a reaction rate constant of about 0,16 day^{-1} at 20° C.

- Besides generating SCFA, acid fermentation also generates soluble complex molecules approximately equal in concentration to the concentration of SCFA,

i.e. of the total soluble (<0,45μm) COD concentration generated, approximately half is SCFA (as COD) and half is non-SCFA soluble COD. The production rate of the total soluble COD, (and therefore also that of the non-SCFA soluble COD) also approximates a first order rate not influenced by sludge concentration.

- Hydraulic retention time in an acid fermentation system should not exceed about 6 days at 20°C; at longer retention time work (elsewhere) indicates that methane fermentation can take place thereby reducing the net SCFA yield.

- The COD yield of SCFA at 6 days at 20°C is approximately 38 percent of the potential yield, and can be estimated from the specific potential yield (0,17 mgSCFA as COD/mg influent sludge COD by:

$$\text{COD SCFA at 6 days} = 0{,}17(1-e^{0{,}16\cdot 6})\ \text{COD of influent sludge}$$

giving a yield of 0,065 mgSCFA as COD/mg influent sludge COD. Thus only a minor fraction of the SCFA potential can be generated at these short retention times.

Knowing the potential acid production and the reaction order a model for acid fermentation was constructed and equations developed for SCFA yield at any retention time, for single, in-series and accumulating batch reactor systems. No solutions were developed for acid fermentation in primary settling tanks with underflow recycle to the influent. Applying the model to evaluate the effect of the fermentation systems on the biological excess phosphorus removal (BEPR) systems, it was found that:

- For total retention times up to about 6 days the differences in the SCFA yield between a single reactor, 3 in-series reactors and accumulating batch reactor are small. In consequence the selection of a specific system for acid fermentation will be governed by the cost of construction and the ease of operation.

- From a practical and economic point of view the most appropriate retention time in fermentation systems appears to be about 3 days: With 3 days acid fermentation retention time biological excess phosphorus removal in the BEPR plant will increase by about 15 per cent. Increasing the acid fermentation time

to 6 days will improve the phosphorus removal in the BEPR plant only by a further 3 percent. These values apply to BEPR systems treating settled or unsettled influents.

The study reported here did not investigate experimentally, the effects of the addition of the fermented products on BEPR, denitrification and aerobic processes in the nitrification denitrification (ND) BEPR system. Such a study is important because it would give an indication what proportion of the non-SCFA soluble (<0,45μm) COD generated is RBCOD which can be converted to SCFA in the anaerobic rector. The increases in BEPR cited above are those due only to SCFA generation and ignore the possible additional BEPR due to a RBCOD component in the non-SCFA soluble COD fraction. Earlier investigations at laboratory scale (Bagg *et al.*, 1985) and full scale (Osborn *et al.*, 1986, 1989) indicate that the non-SCFA soluble COD does contain RBCOD because the increases in BEPR achieved by acid fermentation are greater than can be accounted for by SCFA generation only. The RBCOD and SCFA generated by acid fermentation also may be important for improving denitrification when a nitrate standard is imposed: Some of the RBCOD/SCFA generated can be passed by the anaerobic reactor (with a concomitant reduction in BEPR) and discharged to anoxic reactors to improve the denitrification. It is most desirable that the combined acid fermentation/NDBEPR system be investigated further. This cannot be done very effectively at laboratory scale and is best investigated at pilot or full scale.

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LIST OF SYMBOLS

Symbol	Description
BEPR	Biological excess phosphorus removal
COD	Chemical oxygen demand
DSVI	Diluted sludge volume index (mℓ/g)
HAc	Acetate concentration in the acetic acid form (mg/ℓ)
k	First order acid generation constant (d^{-1})
n	Number of reactors
NH_3-N	Free and saline ammonia as nitrogen
P	Potential for acid generation in the effluent sludge from a reactor (mgCOD/ℓ)
P_o	Potential for acid generation in the influent sludge (mgCOD/ℓ)
pH_2	Hydrogen partial pressure (atm)
PHB	*Polyhydroxybutyrate*
PST	Primary settling tank
Q	Influent and effluent flows (ℓ/d)
R	Hydraulic retention time (d)
R_n	Retention time in the n^{th} reactor (d)
RBCOD	Readily biodegradable COD (mgCOD/ℓ)
SCFA	Short chain fatty acids (mgCOD/ℓ)
$SCFA'_n$	Effluent mgSCFA (as COD)/mg initial VSS (as COD) at the end of n days
$SCFA'_{neff}$	mgSCFA (as COD)/ℓ in the effluent of n^{th} reactor
$SCFA'_{nvo}$	Effluent mgSCFA (as COD)/mg initial VSS (as COD) from the n^{th} reactor

regulatory limits.

In order to increase the RBCOD fraction research workers at the Johannesburg City Council proposed acid fermentation of the settled sludge in the primary settling tank (PST). The settled sludge is retained in the bottom of the tank for a period of about 3 days. Acid fermentation takes place and the generated SCFA is added to the BEPR influent waste water flow as follows: In BEPR systems treating settled sewage, the SCFA is separated from the fermented sludge by recycling the PST underflow to the influent of the PST, thereby elutriating the SCFA to the supernatent. In BEPR systems treating raw sewage, both the underflow and elutriated material is discharged to the BEPR system.

Full scale experimentation has demonstrated that the SCFA generated from the primary sludge significantly improves the phosphorous removal . However there is still uncertainty as to the quantity of SCFA and other solubilized fractions that are generated when acid ferments the primary sludge.

In order to bring about a greater understanding of acid fermentation and its effects, this study was undertaken with the following objectives:

(1) Evaluation of short chain fatty acid production in laboratory scale batch, single and in-series completely mixed reactor systems,

(2) development of a model for acid fermentation, and

(3) theoretical assessment of the effects of the addition of the SCFA on biological excess phospherous removal.

Chapter 2 gives a review of the state of the art of acid fermentation. Chapters 3, 4 and 5 describe the experimental fermentation study, and the development of a model describing the acid fermentation process; Chapter 6 extends and consolidates the model and developes practical criteria for design of acid fermentation systems; in Chapter 7, using the latest BEPR model, a study is undertaken to estimate the influence of acid fermented products on biological phosphorous removal.

CHAPTER 2

LITERATURE REVIEW

Pitman (1983) appears to have been the first to formally propose addition of acid rich supernatant liquor from a high rate (acid) digester to the influent of a biological excess phosphorus (BEPR) plant, to increase biological phosphorus removal. In 1984 Barnard proposed conceptually that one way of accomplishing acid fermentation is to discharge the underflow of the primary sedimentation tank (PST) to a gravity thickener and recycle some of the thickener underflow to the influent to the PST, in this manner maintaining a sludge blanket in the PST. Fermentation should take place in the thickener and sludge blanket and the recycle from the thickener would elutriate the acids to the supernatant of the PST.

In a pilot scale study Rabinowitz and Oldham (1985a) coupled a fermenter to a pilot BEPR plant (operated as a simplified UCT process). The raw influent sewage to the system passed through a PST. The clarified supernatant from the PST formed the influent to the BEPR plant, discharging to the anaerobic reactor. The underflow from the PST was pumped at rate one tenth of the raw sewage flow to a 2 in-series fermenter reactor system discharging to a settler, called the fermenter settler. The supernatant of the fermenter settler was fed to the anaerobic reactor of the BEPR system and the underflow was recycled to the first reactor of the fermentation system. The system was operated with a nominal retention time of 2,5 days and a sludge age of 10 days. The sludge age was maintained at 10 days by hydraulic control, by wasting one tenth of the total volume of the fermenter reactor system from the second fermenter reactor each day.

The influent raw sewage COD to the PST was about 330 mg/ℓ. The PST removed about 44 percent of the COD. At an underflow withdrawal rate of 1/10 of the raw sewage flow this gave an underflow COD of $0{,}44 \cdot 330 \cdot 10 \approx 1450$ mg/ℓ which roughly corresponds to a VSS of $1620/1{,}42 \approx 1000$ mgVSS/ℓ. These concentrations are extremely low compared with the concentrations in the underflows from PSTs in South African plants, 10 to 30 times lower. The low concentrations would be the principal reason why it was possible to operate the fermenter system with a sludge age of 10 days – the VSS in the reactors would not have exceeded 10 000 mg/ℓ and liquid solid separation in the fermenter settler would be feasible.

The concentration of short chain fatty acids (SCFA) in the supernatant from the fermenter system was 148 mg/ℓ as acetate (HAc), that is 148·1,07 = 158 mgHAc (as COD). Relative to the raw sewage influent flow the increase in SCFA would be approximately 158/10 = 15,8 mgSCFA (as COD). Assume that the raw sewage had a readily biodegradable COD (RBCOD) approximately the same as in the average raw sewage of a municipality in South Africa, viz. 20 percent of the influent COD, the RBCOD $\approx$ 330·0,2 = 66. Hence the percentage increase in RBCOD due to fermentation of the underflow would be 23 percent. This implies an increase in P removal potential of approximately 20 percent. In their BEPR plant, (UCT system, 20 day sludge age, anaerobic mass fraction of 0,1) when treating the *raw sewage directly* the experimental P removal per influent COD (ΔP/COD) was 0,009. This value is very low, the expected value, using the BEPR model of Wentzel *et al.* (1989), should be nearer 0,015. When the raw sewage was settled and the underflow (44 percent of the influent COD) was fermented, and recombined with the supernatant of the PST before discharge to the BEPR, the ΔP/COD increased to 0,013 (based on the raw sewage influent COD). Again this removal was low compared to that expectated from BEPR plants in South Africa. Unfortunately the data given in the paper is not sufficient to evaluate the process performance more thoroughly.

With the aim of optimizing SCFA production from the underflow, Rabinowitz and Oldham (1985b) carried out the same type of experimental investigation described above on a 2 in-series primary sludge fermenter. The sludge fermenter received the underflow from the raw sewage PST of the pilot plant. The fermenter was operated over four time periods during which the sludge ages in the fermenter were maintained at 2,5; 3,5; 5 and 10 days respectively.

For the sludge ages 2,5; 3,5 and 5 days the system was operated as a flow through system and the fermenter sludge age maintained at 2,5; 3,5 or 5 days by controlling the underflow flow rate from the PST to the fermenter. The flow from the fermenter was recombined with the supernatant flow from the PST and discharged to the anaerobic reactor of the BEPR system. For the 10 days sludge age the fermenter was operated as in the first series of tests, i.e. a fermenter settler was added to the fermenter system and the underflow recycled back to the first fermenter; the sludge age was maintained by hydraulic control. The wasted sludge was combined with the supernatant from the fermenter settler and discharged to the BEPR system as before. The fermenter was operated at ambient temperatures, except during winter

when heating maintained the temperature around 20° C. The pH in the fermenter was uncontrolled. The primary sludge influent COD in the 4 separate test periods was very low, 1160, 1790, 1720 and 1857 respectively. The following significant observations were made:

(1) The SCFA's produced, in decreasing order, were acetic, propionic and butyric. Acetic and propionic acids made up more than 95 percent of the total SCFA's. The ratio of acetic:propionic acids (as mgHAc/ℓ) was approximately 55:45 and appeared to be independent of the fermenter sludge age.

(2) Optimum SCFA yields were achieved at 3,5 and 5 days sludge ages, 0,093 mgHAc/mg influent COD to the fermenter system, with slightly lower values of 0,078 and 0,082 at the 2,5 and 10 day sludge ages respectively.

Rabinowitz and Oldham (1985b) considered the optimum yield to be low and proposed two ways to increase the yield: (1) increase the operating temperature of the fermenter to within the mesophilic temperature range (around 37° C) and (2) control the fermenter pH. During these experiments the pH ranged from 5,1 to 6,1 and this range, they state, is not the optimal one for SCFA production, according to "evidence in the literature".

Gupta, Oldham and Coleman (1985) investigated the effects of temperature, pH and retention time on SCFA production. The following conditions were investigated: Temperatures of 10, 20 and 30° C, retention times of 3, 6 and 9 days, pH either uncontrolled or controlled at 7. The COD of the sludge from the PST underflow which served as influent to the fermenter was maintained at about 2 000 mgCOD/ℓ. The raw sewage COD was in the region of 300 mg/ℓ implying that the underflow was in the range of 10 to 15 percent of the raw sewage flow. After conducting 18 tests on various combinations of temperature, retention time and pH, the following conclusions are listed:

(1) Control of pH at 7 did not seem to affect the net total SCFA production significantly, but did affect the relative concentrations of acetic and propionic acids.

(2) Maximum net total SCFA production was obtained at 6 days retention time

at 30° C. The lower SCFA yield obtained at 9 days at 30° C they ascribed to methane fermentation.

(3) In the system run with the pH uncontrolled, the lowest average pH was 5,63. Lower pH's were not observed probably due to the natural buffering capacity of the sludge.

(4) From a statistical analysis of variance they concluded that the parameters investigated tend to be interactive so that it was not possible to isolate the influent of each independent of the others.

The yields obtained in this study were all very low. For example at 20° C, at 9 days sludge age, the yield was 0,064 mgSCFA (as COD) per mg fermenter influent COD, whereas from the previous study by Rabinowitz and Oldham (1985b), the estimated yield would have been roughly 0,105 mgSCFA (as COD)/mg influent COD. The whole set of data exhibits relatively low yields for which no explanation is forthcoming.

Lötter and Murphy (1986) found that acid fermentation is improved by raising the temperature and concluded that in the winter, acid production may be expected to decline if the fermenter is not heated. They found further that only the total amount of generated SCFA's is affected by temperature; the ratio of generated acetic to propionic acids at 14° C and 20° C appeared to be similar.

In a comparative study Pitman and Lötter (1986) investigated the generation of SCFA's in two anaerobic digesters (for acid fermentation) and in a primary settling tank. The two digesters were operated alternately, on a fill-and-draw cycle, being fed with a daily batch of primary sludge, the batches accumulated over a period of 3 to 4 days. After the daily feeding the tanks' contents were mixed for 4 to 6 hours. At the end of the 3 to 4 day feeding part of the cycle, the fermenters' contents were allowed to settle and the acid supernatant liquor fed to the anaerobic zone of the BEPR plant in daily batches (pumped over approximately 8 hours) for the next 2 to 3 days. The digesters were then emptied via the underflow and the cycle repeated.

Acid fermentation in a PST was as follows: The settled solids from the raw sewage was allowed to accumulate on the bottom of the PST for 3 to 4 days. The SCFAs generated in the sludge were released to the PST supernatant by 'recycling, about

half of the fermented primary sludge withdrawn back to the inlet of the primary tanks and thus the fermentation products were elutriated into the bulk liquid." After the feed cycle, the sludge on the bottom of the settling tank was drained completely – this was necessary otherwise the sludge went black due to sulphide generation and SCFAs were lost due to methane fermentation.

Comparing the two systems, when the acid rich supernatant from the accumulating batch acid digestion system was added to the anaerobic zone of the BEPR plant, good P removal was observed, from an influent value of 15 mgPℓ to an effluent value of 1,3 mgP/ℓ. When the PST fermentation system was put into operation an even lower effluent P concentration was achieved, less than 1 mgP/ℓ. Pitman and Lötter concluded that SCFA generation in PST's provided considerably higher levels of acids than the acid digester. They noted however that elutriation of the sludge in the PST added non-SCFA COD to the PST overflow.

In a separate set of batch experiments Pitman and Lötter found that by elutriating a sludge sample from the underflow sludge with different quantities of settled sewage the SCFA recovery increased when the volume of elutriating liquid flow rate was increased.

Eastman and Ferguson (1981) did an extensive investigation into the acidogenic phase of anaerobic digestion at 35°C. They were particularly interested in the solubilization of particulate COD and the generation of soluble COD and SCFAs. They used one batch of underflow sludge with a total COD of 52 000 mgCOD/ℓ and a VSS of 26 600 mgVSS/ℓ. Assuming the COD/VSS ratio equal to 1,42, then the particulate COD fraction was $26600 \cdot 1{,}42/52000 = 0{,}73$, that is about 27 percent was soluble COD. The SCFA (as COD) content of the sludge influent was 1900 mg/ℓ, giving an initial SCFA (as COD)/total influent COD ratio equal to 0,037 or $1900/(0{,}73 \times 52000) = 0{,}05$ mgSCFA (as COD)/mgVSS (as COD). They performed two series of studies, on completely mixed flow through reactor and batch reactor systems. The flow through experiment was run at sludge ages of 9, 18, 36 and 72 hours to give the yields of SCFA (as COD)/total influent COD and –0,45μm COD/total influent COD as listed in Table 2.1. To determine the maximum yield, some of the flow through experiments, when completed, were operated as a batch system for a further period of about 14 days, giving maximum yields of 0,223 mgSCFA (as COD)/mg total influent COD and 0,240 mg –0,45μm COD/mg total influent COD.

In the flow through tests the pH was not controlled. The influent pH was 5,2 and rather unexpectedly the pH in the reactors remained constant at this value or declined slightly to 5,13.

Batch tests were performed at initial solids concentration of 12,9, 26,6 and 55,1 gVSS/ℓ. The batch tests were done with the pH controlled at 6. The data obtained by the 14th day of the test showed that the SCFA and soluble COD productions were proportional to the influent VSS concentration, that is, the specific solubilization rate did not appear to be affected by the initial VSS between 12 and 60 gVSS/ℓ. However, the propionic and acetic acid concentration decreased, but the butyric and valeric acids increased with sludge concentration. From tests in which the pH was controlled between 5,1 and 6,8 both the SCFA (as COD) and soluble COD production was higher at the higher pH's. They also found that the lipids in the influent were not degraded to SCFA. Very likely the lipids were degraded only to long chain fatty acids, (LCFA). This is not unexpected because in the acidogenic phase the hydrogen partial pressure ($\bar{p}H_2$) can be expected to be high for carbohydrate and nitrogenous wastes; LCFAs however are broken down to SCFA only under low $\bar{p}H_2$ via β oxidation. In their tests the presence of high $\bar{p}H_2$ is confirmed in that propionate and acetate were generated; if the $\bar{p}H_2$ had been low, acetate only would have been generated and any propionate generated would have been converted to acetate by acetogenesis.

A finding of great interest in the investigation of Eastman and Ferguson is the relatively low yield of SCFA. The maximum estimated yield was about 0,223 mgSCFA (as COD)/mg influent total COD. The yields obtained from the flow through systems, at 3 days sludge age, were only 0,161 mgSCFA (as COD)/mg influent total COD. Three day sludge age systems are probably a practical full scale proposition but if the fermentation temperature is lower than 35° C, at ambient temperature, say 20° C, the yield is likely to be nearer 0,1 then the 0,16 observed at 35° C. This estimated yield (of 0,1) is not significantly different from that obtained by Rabinowitz and Oldham (1985b) and forces the conclusion that SCFA generation from raw sludge is limited.

An interesting contribution of Eastman and Ferguson is that they could model the generation of SCFA as a first order type reaction with respect to the biodegradable COD remaining. An alternative approach would be to replace the biodegradable COD in the influent by a maximum SCFA production potential and assume that

the SCFA generation is first order with respect to the potential remaining. This approach would require only to determine the potential with regard to the sludge COD and the kinetic rate constant. These values could be estimated by curve fitting to SCFA production values assuming a first order type reaction.

CONCLUSIONS

The review of the findings on acid fermentation would indicate the following:

(1) Acid fermentation of the underflow from a primary settling tank produces principally acetic and propionic acids.

(2) Low pH in the fermenter does not appear to influence the total production of SCFA, only the proportion of propionic and acetic acids.

(3) The SCFA yield from fermentation of the underflow depends on the fermentation retention time.

(4) The potential or maximum yield is relatively low. At 35° C the maximum yield is about 0,22 of the underflow COD, at about 10 day retention time. At 20° C the maximum yield again is low, probably not more than 0,18 to 0,2 of the influent underflow COD.

(5) The rate of acid production appears to be of a first order type in which the reaction constant is dependent on the temperature; at 20° C a fermentation retention time of 6 to 20 days seems to be needed to develop the full SCFA production potential.

(6) At retention times in excess of 6 days and 20° C there is the possibility that methane fermentation can commence and reduce the yield of SCFA.

Table 2.1: Yield values of the SCFA (as COD) and –0,45μm COD/mg influent total COD raw underflow sludge at 35° C obtained by Eastman and Ferguson (1981).

Retention time (h)	mgSCFA (as COD)/ mg influent COD	mg –0,45μm COD/ mg influent COD	–0,45μm COD/ SCFA (COD)
Influent	0,037	0,092	–
9	0,103	0,119	1,15
18	0,125	0,136	1,09
36	0,147	0,158	1,14
72	0,161	0,178	1,10
			Mean 1,12

CHAPTER 3

BATCH EXPERIMENTS

3.1 INTRODUCTION

Investigation into anaerobic fermentation of primary sludge, under batch conditions, had the following objectives:

(1) To measure the rate of short chain fatty acid (SCFA) production.

(2) To determine the unit potential for acid production, i.e. acid production (as COD) per mg initial VSS (as COD).

(3) To determine the onset of methanogenesis.

3.2 EXPERIMENTAL SET-UP

The anaerobic reactor consisted of a perspex 3ℓ reactor. The reactor's contents were kept in a completely mixed state by electric motor driven paddles rotating at 100 to 120 r.p.m. (see Fig 3.1). To prevent oxygen entry to the mixed liquor, a polystyrene disc was floated on the liquid surface. The system was operated in a temperature controlled room at 20° C.

3.3 OPERATION

Twenty five litres of raw sludge were collected from the underflow primary sedimentation tank at the Mitchell's Plain Treatment Works just prior to the morning desludging at 10h00. At the laboratory the sludge was well mixed and used either undiluted, or when the effect of raw sludge concentration was being investigated, appropriate volumes of raw sludge were diluted to the selected concentration with distilled water. In order to test the effect of concentration, a range of influent sludge VSS was tested, from 11 000 to 42 000 mgVSS/ℓ. The reactors were filled to the 3ℓ mark and the test commenced. During the test period the following monitoring program was put into operation: At test time zero, and every day thereafter, for a period of 9 to 19 days at approximately 08h00, two 50 mℓ samples were taken and tested. The following tests were done:

(1) pH.

(2) Volatile and total suspended solids (VSS and TSS) concentrations of the sludge pellet obtained after centrifugation.

(3) COD concentration of the sludge pellet [termed VSS (as COD)].

(4) COD concentration of the supernatant from (2) and (3) above after filtration through a 0,45μm filter.

(5) Total kjeldahl nitrogen (TKN) and free and saline ammonia (NH_3-N) concentrations of the –0,45μm filtrate.

(6) Short chain fatty acids (SCFA) concentration of the –0,45μm filtrate.

The sampling techniques and measurement procedures are set out in Appendix A.

3.4 RESULTS

A total of 14 batch tests were completed. The results for each batch test are listed in Tables B.1 to B.14 in Appendix B. In these tables the COD of each SCFA was calculated using the conversion factors of Eastman and Ferguson (1981) listed in Table 3.1, and summed to give the total equivalent COD of the SCFA's, listed as SCFA (as COD).

For each batch, plots were made of the following parameters versus time:

(1) pH.
(2) TSS and VSS concentrations.
(3) COD of the VSS concentrations.
(4) TKN and NH_3-N concentrations.
(5) –0,45μm COD and the total SCFA (as COD) concentrations.
(6) Acetic, propionic, butyric and valeric acid concentrations.

The plots also are included in Appendix B. Figures 3.2 to 3.7 show the plots of typical results obtained in a batch. Figures 3.8 to 3.13 show results obtained on a batch in which a lag period is exhibited. From an examination of all the plots, the following general observations can be made:

(1) pH – The pH decreased with increasing retention time. The minimum pH in

a batch test was 5,0.

(2) VSS – The VSS concentration decreased with increasing retention time.

(3) VSS (as COD) – The COD of the VSS concentration decreased with increasing retention time.

(4) TKN and NH_3-N – TKN and NH_3-N concentrations increased with increasing retention time.

(5) SCFA's –

(i) In most tests SCFA generation commenced immediately at a relatively high rate, but the rate continually decreased with time to a very low value after 10 days i.e. after 10 days the SCFA generation appeared to be virtually complete.

(ii) Five of the fourteen batches exhibited lag periods of up to 6 days before acid generation commenced (see Figs B.6, B.18, B.24, B.30 and B.36). However, the lag period did not appear to affect the maximum possible SCFA concentration attainable. Neither did the lag period appear to be linked to solids concentration.

(iii) In Fig 3.14, a correlation plot of SCFA (as COD) versus –0,45μm COD concentrations is shown, for all batch tests. From this plot it appears that the SCFA (as COD) constitute approximately 77 percent of the –0,45μm COD. From the tables in the appendix the ratio of acetic:propionic:butyric:valeric acids (as COD) was approximately 1:1,6:0,1:0,1. Acetic plus propionic acids contributed approximately 90 percent of the total SCFA (as COD), the balance being made up of butyric and valeric acids.

(iv) In not one of the batch tests did the SCFA concentration show any decline with time - there did not appear to be any significant methane fermentation, possibly because of inhibition of the growth of methanogenes by the low pH's, or insufficient time for the development of these slow growing organisms.

For convenience, for each batch the measured values of the following parameters are listed in Table 3.2; (1) Maximum SCFA concentration, (2) maximum total SCFA (as COD) concentration, (3) influent –0,45μm COD concentration, (4) influent VSS concentration, (5) influent VSS (as COD) concentration, (6) day maximum acid concentration attained and (7) lag or delay period.

3.5 MODELLING OF SCFA GENERATION

The batch data reported above are not in a form suitable for determining quantitative kinetic information – each batch had a different VSS (as COD) concentration. In order to reduce the data to a common basis, the data was divided by the influent (initial) VSS (as COD) concentration to give values per mg initial VSS (as COD). Accordingly the parameters mg–0,45μm COD/mg initial VSS (as COD) and mgSCFA (as COD)/mg initial VSS (as COD) were calculated for all batch tests.

Figure 3.15 shows a plot of the parameter mg–0,45μm COD/mg initial VSS (as COD) versus batch time. There appear to be two distinct groups, batches 1 to 4 and batches 5 to 14. In batches 1–4 the –0,45μm generation per VSS is very high; up to 0,7, whereas in batches 5–14 a maximum of 0,2 is obtained. In all the sewage batches subsequently utilized in the investigation (a further 10 batches of sewage tested under different operating conditions) the indications are that the behavioural pattern conforms to that of batches 5 to 14. Consequently it was accepted that batches 5 to 14 were more representative than batches 1 – 4; in the analysis of the SCFA generation (discussed later), only batches 5 to 14 were considered.

In Fig 3.16 the parameter mgSCFA (as COD)/mg initial VSS (as COD) has been plotted for batches 5–14.

The plots in Figs 3.15 and 3.16 appear to conform to a first order type of reaction with maximum potentials of approximately 0,17mg –0,45μmCOD per mg initial VSS (as COD), and 0,14 mg SCFA (as COD) per mg initial VSS (as COD) respectively. These maxima were attained after approximately 9 days fermentation.

3.5.1 Theory

Taking the responses of batches 5 to 14 as typical and accepting that the SCFA fermentation process conforms to a first order type reaction, formulation of SCFA generation was developed as follows: Referring to Fig 3.17

Let X_{vt} = mgVSS concentration at any time t

X'_{vt} = mgVSS (as COD) concentration at any time t

X'_{vo} = mg initial VSS (as COD) concentration

$SCFA_t$ = mgSCFA concentration at any time t

$SCFA'_t$ = mgSCFA (as COD) concentration at any time t

$SCFA'_o$ = mg initial SCFA (as COD) concentration

$SCFA'_{tvo}$ = mgSCFA (as COD) concentration per mg initial VSS (as COD) concentration at any time t, i.e. $SCFA'_{tvo} = SCFA'_t/X'_{vo}$

$SCFA'_{ovo}$ = mg initial SCFA (as COD) concentration per mg initial VSS (as COD) concentration, i.e. $SCFA'_{ovo} = SCFA'_o/X'_{vo}$

$SCFA'_p$ = potential mgSCFA (as COD) concentration

$SCFA'_{pvo}$ = potential mgSCFA (as COD) concentration per mg initial VSS (as COD) concentration, i.e. $SCFA'_{pvo} = SCFA'_p/X'_{vo}$

The first order reaction for SCFA (as COD) generation per mg initial VSS (as COD) can be expressed as

$$d(SCFA'_{tvo}) = -k\, SCFA'_{pvo}\, dt$$

At the time the batch experiment commences, at t = 0, already a concentration of $SCFA'_{ovo}$ has been generated, that is, the potential now is $(SCFA'_{pvo} - SCFA'_{ovo})$. Hence the solution is

$$SCFA'_{tvo} = (SCFA'_{pvo} - SCFA'_{ovo})(1 - e^{-kt}) + SCFA'_{ovo} \qquad (3.1)$$

Multiplying out:

$$SCFA'_{tvo} = SCFA'_{pvo} - SCFA'_{ovo} - e^{-kt}(SCFA'_{pvo} - SCFA'_{ovo}) + SCFA'_{ovo}$$

$$\text{i.e. } (SCFA'_{pvo} - SCFA'_{tvo}) = (SCFA'_{pvo} - SCFA'_{ovo})e^{-kt} \qquad (3.2)$$

Taking logs of both sides of Eq (3.2)

$$\log(SCFA'_{pvo} - SCFA'_{tvo}) = \log(SCFA'_{pvo} - SCFA'_{ovo}) - (k \log_{10}e)t \quad (3.3)$$

Equation (3.3) describes a straight line i.e. $y = m\,x + c$

where $y = \log (SCFA'_{pvo} - SCFA'_{tvo})$ (3.4)

$x = t$

$m = -k \log_{10}e$ (3.5)

$c = \log (SCFA'_{pvo} - SCFA'_{ovo})$ (3.6)

In Eq (3.3), $SCFA'_{pvo}$ and k are unknowns and must be determined from experimental results. These values are obtained by trial as follows: Select a value for $SCFA'_{pvo}$, calculate log ($SCFA'_{pvo}$–$SCFA'_{tvo}$) for all values of $SCFA'_{tvo}$ and plot log ($SCFA'_{pvo}$–$SCFA'_{tvo}$) versus time or equivalently plot ($SCFA'_{pvo}$–$SCFA'_{tvo}$) versus time on semi-log paper. The best value of $SCFA'_{pvo}$ is the one that gives a straight line plot. The slope of the log ($SCFA'_{pvo}$–$SCFA'_{tvo}$) versus time plot defines m in Eq (3.5), to the base 10; to solve for k to the base e, the slope m is multiplied by 2,303

i.e. $k = -m \times 2{,}303$.

The $SCFA'_{pvo}$ and k values obtained by the above procedure, are substituted into Eq (3.1) giving a prediction equation for the mgSCFA (as COD) concentration per mg initial VSS (as COD) at any time t, where t is in days.

3.5.2 Calibration

To obtain a mean value for k from the theory above, the following procedure was used:

(1) From batches 5 to 14 an envelope of the maximum and minimum values of $SCFA'_{tvo}$ were plotted against time in Fig 3.18. The mean values between the maximum and minimum $SCFA'_{tvo}$ values were calculated and plotted in Fig 3.18. This gave preliminary estimates of the mean $SCFA'_{pvo}$ value equal to 0,14, and the mean $SCFA'_{ovo}$ value equal to 0,042.

(2) Select a number of values for the mean potential $SCFA'_{pvo}$ around the maximum mean value in Fig 3.18, select 0,13, 0,14, 0,15.

(3) Calculate the mean potential $SCFA'_{pvo}$ selected in (2) above less the mean values calculated in (1) above. As an example, in Table 3.3, this was done for the selected maximum mean potential, $SCFA'_{pvo}$ = 0,14 mgSCFA (as COD) per mg initial VSS (as COD).

(4) Plot the results of (3) above on semi-log paper (see Fig 3.19). Check if the plotted data approximates a straight line. If the plotted points show an upward/downward curvature, choose a lower/higher value in (2) above, recalculate as in (3), and plot again on semi-log paper until visually a linear plot is approximated. Visually the best linear plot was obtained with a mean potential yield $SCFA'_{pvo}$ = 0,14 mgSCFA (as COD) per mg initial VSS (as COD).

(5) To determine k (for $SCFA'_{pvo}$ = 0,14), the slope of the straight line through the linear plot in (4) above was calculated using a linear regression; the pairs of log ($SCFA'_{pvo} - SCFA'_{tvo}$) values and time for the selected mean $SCFA'_{pvo}$ value of 0,14 were used. The slope, m, was –0,0688. Therefore

$$k = -2{,}303 \times -0{,}0688$$
$$= 0{,}1584.$$

The correlation coefficient obtained from the linear regression analysis was 0,9934. Selecting k = 0,16/day, Eq (3.1) can be written as

$$SCFA'_{tvo} = (0{,}14 - SCFA'_{ovo})(1 - e^{-0{,}16t}) + SCFA'_{ovo} \qquad (3.7)$$

where t is in days,
and $SCFA'_{ovo}$ is obtained from the measured initial SCFA (as COD) and VSS (as COD) concentrations for each batch of sludge.

In Fig 3.20, a correlation plot of theoretical versus experimentally observed $SCFA'_{tvo}$ values is shown [theoretical values from Eq (3.7)]. The plot shows that the data correlate reasonably well.

The theoretical SCFA (as COD) concentrations (i.e. $SCFA'_t$) can easily be determined by converting the $SCFA'_{tvo}$ values obtained from Eq (3.7) via Eq (3.8) to SCFA (as COD) concentrations

$$SCFA'_t = SCFA'_{tvo} \cdot X'_{vo} \qquad (3.8)$$

In Fig 3.21, a correlation plot of theoretical versus experimentally observed $SCFA'_t$ values is shown; once again a reasonably good correlation is observed.

3.6. CONCLUSIONS

In batch fermentation tests using underflow primary sludge, for the batches 5 to 14, with VSS concentrations ranging from 1100 to 42 000 mgVSS/ℓ:

1. The minimum pH attained in a batch reactor was 5,0, with an average minima of about 5,2.

2. In general as the batch retention time increased, the

   (i) VSS concentration decreased
   (ii) VSS (as COD) concentration decreased
   (iii) Filtered TKN and NH_3-N concentrations increased.

3. The SCFA's (as COD) correlated reasonably well with the –0,45μm COD; the SCFA's (as COD) constituted approximately 77 percent of the –0,45μm COD (see Fig 3.14).

4. The lag or delay period observed in the generation of SCFA's in 5 batches did not appear to affect the maximum SCFA concentrations attainable by the sludge.

5. The lag period showed no consistency and ranged from 0 to 6 days.

6. The major SCFA's produced were acetic and propionic acids. Other SCFA's produced were butyric and valeric acids; the ratios of acetic:propionic:butyric:valeric acids (as COD) were 1:1,6:0,1:0,1.

7. From the mgSCFA (as COD)/mg initial VSS (as COD) plot, Fig 3.16, the generation of SCFA's appear to be a first order type reaction with a maximum potential yield of approximately 0,14 mgSCFA (as COD)/mg initial VSS (as COD). The equation

$$SCFA'_{tvo} = (0{,}14 - SCFA'_{ovo})(1 - e^{(0{,}16t)}) + SCFA'_{ovo}$$

developed from batches 5 to 14, gives theoretical values for mgSCFA (as COD) generated per mg initial VSS (as COD), that correlates reasonably well with the observed values (Fig 3.20). For all batch tests, a mean (initial) $SCFA'_{ovo}$ value was estimated as 0,042 mgSCFA (as COD) per mg initial VSS (as COD).

8. Within the range of influent sludge concentrations (11 000 to 42 000 mgVSS/ℓ) no concentration effect could be detected. If such an effect was present the correlation between the theoretical predicted $SCFA'_t$ would have shown a regular deviatory effect with increasing initial sludge concentration. Thus it would appear that between the concentrations 11 000 to 42 000 mgVSS/ℓ the fermentation kinetics per unit initial VSS is independent of VSS concentration.

Table 3.1: COD equivalents of Short Chain Fatty Acids (Eastman and Ferguson, 1981).

Acid	$\frac{\text{mgCOD}}{\text{mgSCFA}}$
Acetic	1,066
Propionic	1,512
Butyric	1,816
Valeric	2,037

Table 3.2: Table giving the concentrations of maximum SCFA, maximum total SCFA (as COD), influent -0,45μm COD, influent VSS, influent VSS (as COD), day maximum acid concentration attained and the lag or delay period, for all Batch Tests.

BATCH NO'S / PARAMETER	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Acetic acid mgHAC/ℓ	2967	1544	1078	400	2200	800	2222	666	733	1611	1333	1611	1100	844
Propionic acid mgHPr/ℓ	2278	744	1367	590	3000	1060	2489	733	589	1744	1500	1467	1200	778
Butyric acid mgHBu/ℓ	167	144	100	20	350	-	133.	10	-	-	-	156	156	-
Valeric acid mgHVr/ℓ	422	78	33	30	260	-	44	-	-	-	-	211	178	-
SCFA's (as COD) mgCOD/ℓ	7770	3191	3465	1416	8046	2456	6463	1836	1672	4355	3689	4649	3633	2076
Influent -0,45μm COD mgCOD/ℓ	3022	1100	1915	652	2458	367	2744	410	1024	2191	1884	1724	1129	759
Influent VSS mgVSS/ℓ	12534	4042	9958	3414	42086	11500	37044	11094	16458	34898	26252	21514	17372	13008
Influent VSS (as COD) mgCOD/ℓ	19738	4934	15000	5470	60000	16000	47923	13926	18022	38502	30310	31601	22572	15595
Day of maximum SCFA	19	19	6	11	11	8	9	9	7	8	10	11	11	11
Lag or delay period	2	0	2	5	3	6	0	0	0	0	0	0	0	0

Table 3.3: Maximum, minimum and mean mgSCFA (as COD)/mg initial VSS (as COD) values at time (t) and the selected mean potential of 0,14 mgSCFA (as COD)/mg initial VSS (as COD) less the mean mgSCFA (as COD)/mg initial VSS (as COD) at time t for the batch tests i.e. max $SCFA'_{tvo}$, min $SCFA'_{tvo}$, mean $SCFA'_{tvo}$, ($SCFA'_{pvo}$ – mean $SCFA'_{tvo}$).

Time (t)	Maximum $SCFA'_{tvo}$	Minimum $SCFA'_{tvo}$	Mean $SCFA'_{tvo}$	Mean $SCFA'_{pvo} = 0,14$ ($SCFA'_{pvo}$–$SCFA'_{tvo}$)
0	0,054	0,030	0,042	0,098
1	0,062	0,044	0,053	0,087
2	0,086	0,064	0,075	0,065
3	0,091	0,068	0,080	0,060
4	0,105	0,073	0,089	0,051
5	0,113	0,078	0,096	0,044
6	0,124	0,086	0,105	0,035
7	0,128	0,093	0,111	0,029
8	0,132	0,098	0,115	0,025
9	0,141	0,088	0,115	0,025
10	0,145	0,090	0,118	0,022
11	0,161	0,086	0,124	0,016
12	0,147			
13	0,154	0,127	0,141	
14	0,135	0,130	0,133	0,007
15	0,167	0,109	0,138	0,002
16	0,141	0,130	0,136	0,004

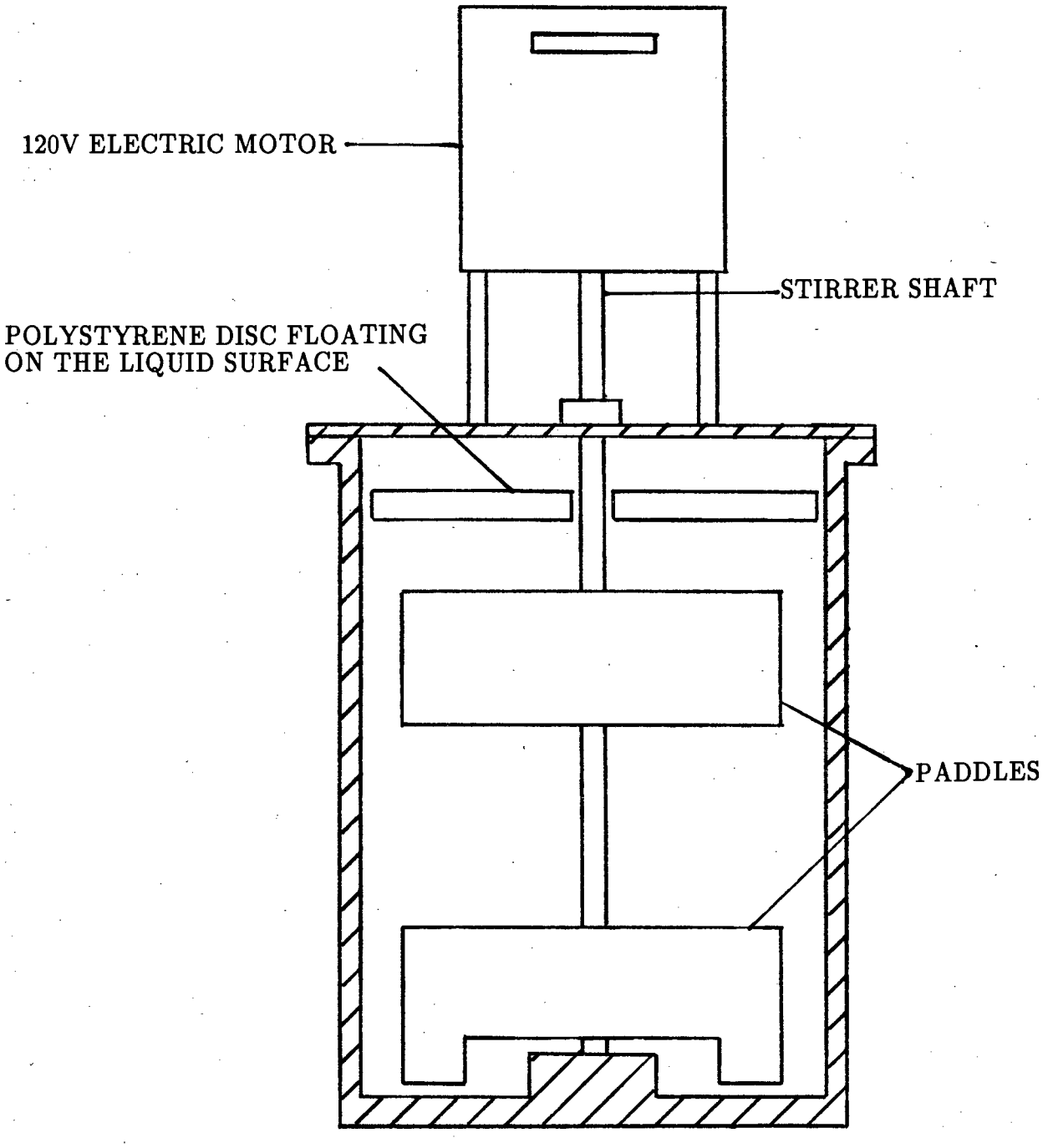

Fig 3.1: Schematic drawing of a three litre anaerobic batch reactor.

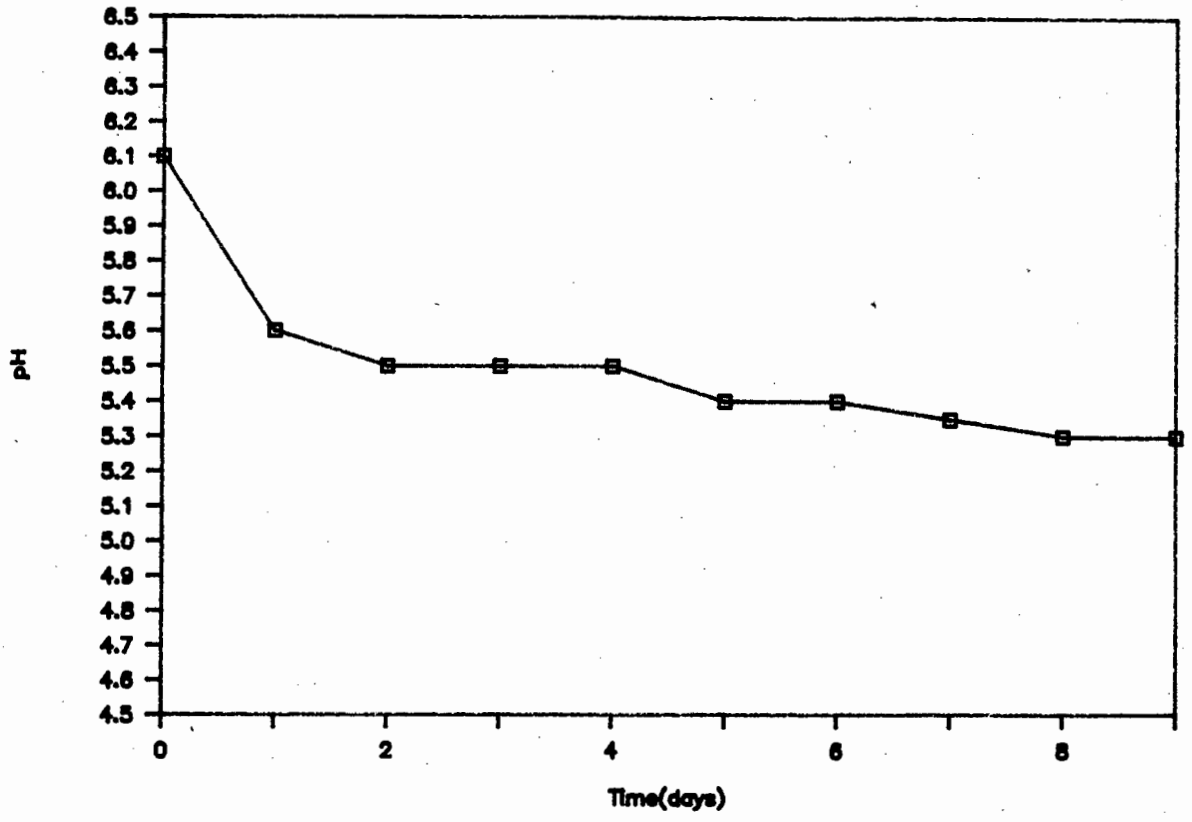

Fig 3.2: pH of a batch reactor versus time – batch test 7.

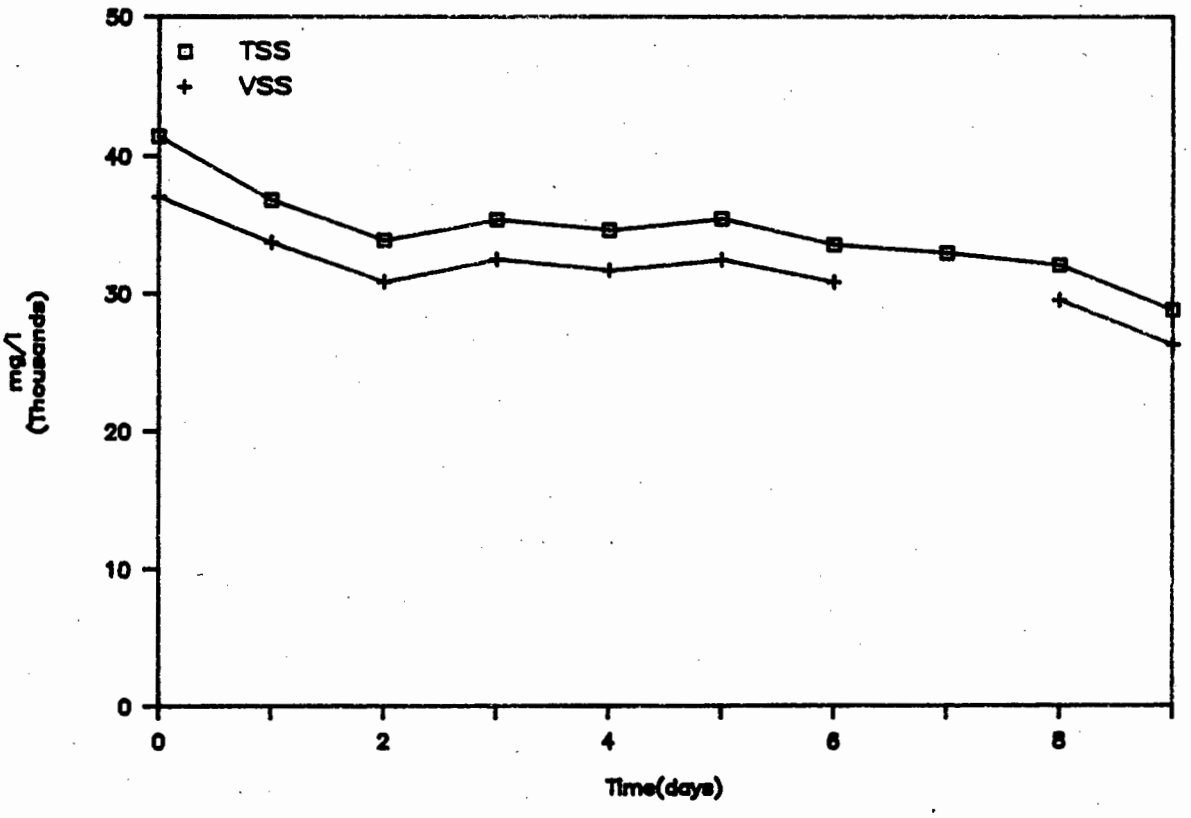

Fig 3.3: TSS and VSS concentrations of a batch reactor versus time – batch test 7.

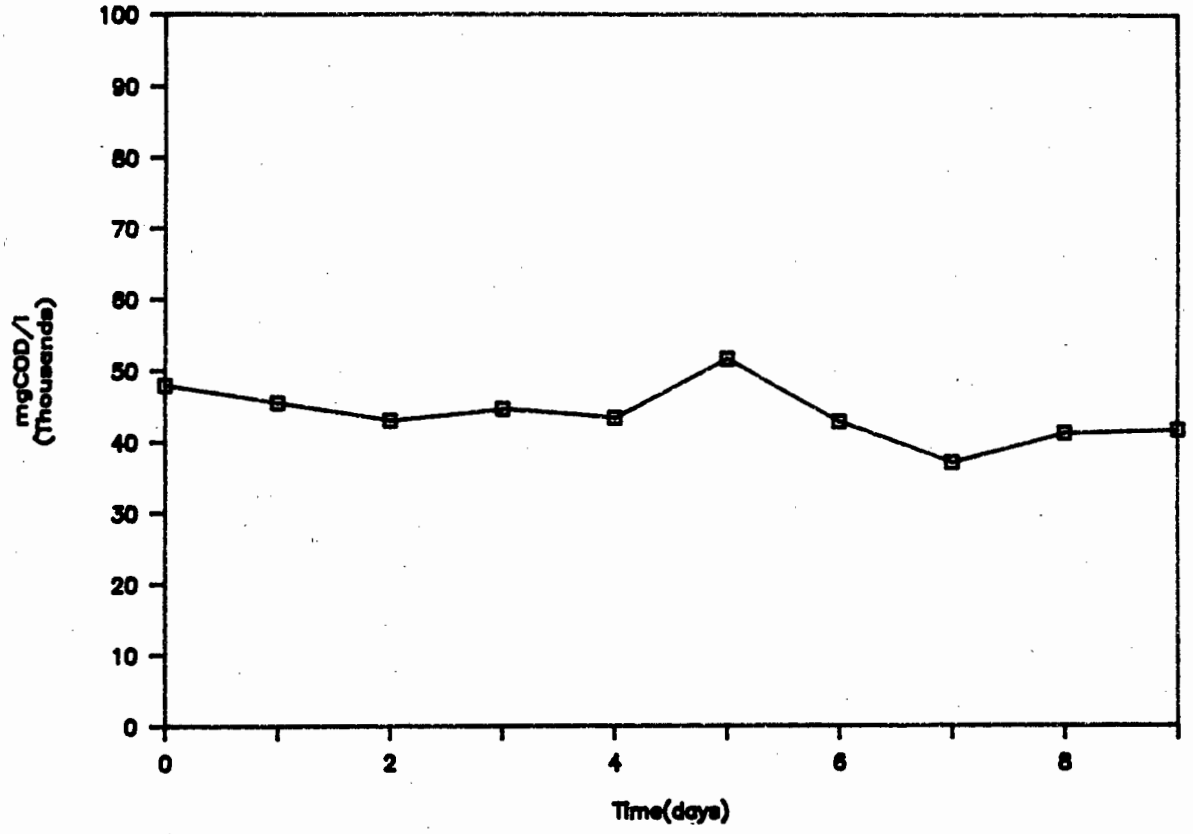

Fig 3.4: COD of the VSS concentrations of a batch reactor versus time – batch test 7.

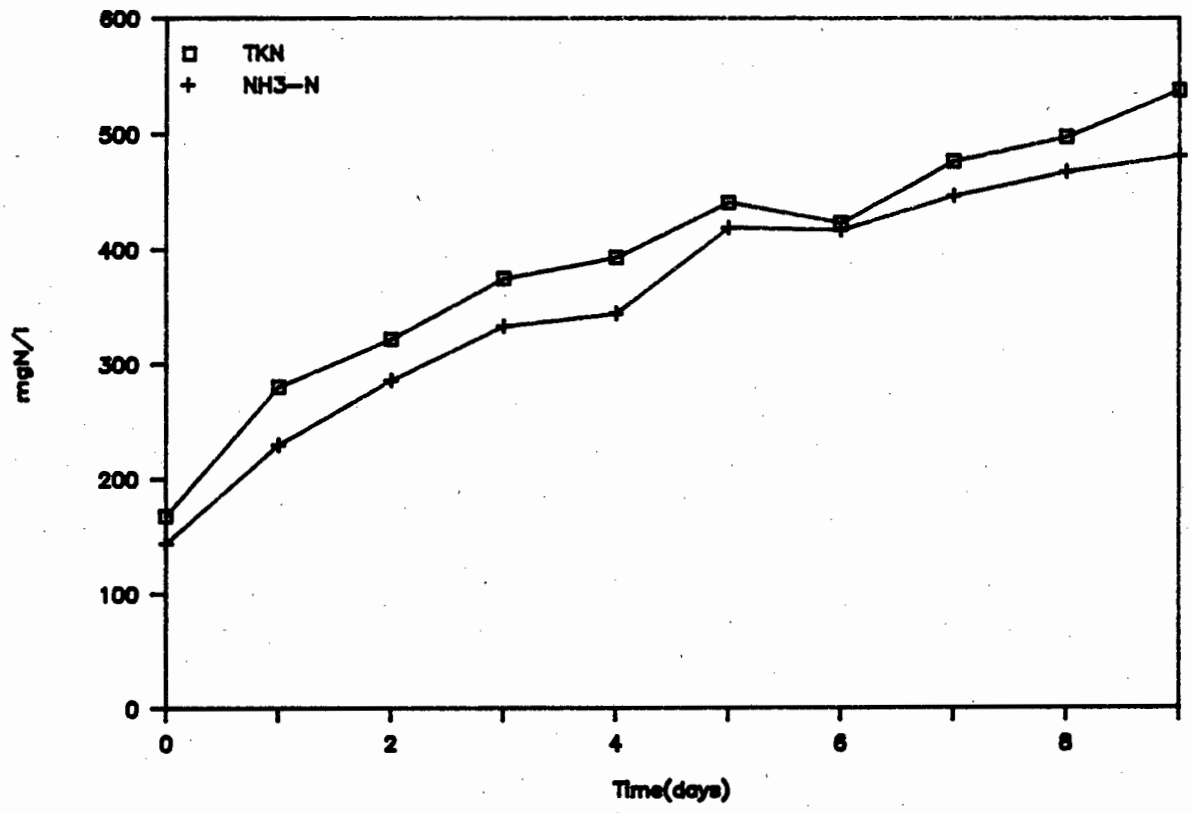

Fig 3.5: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 7.

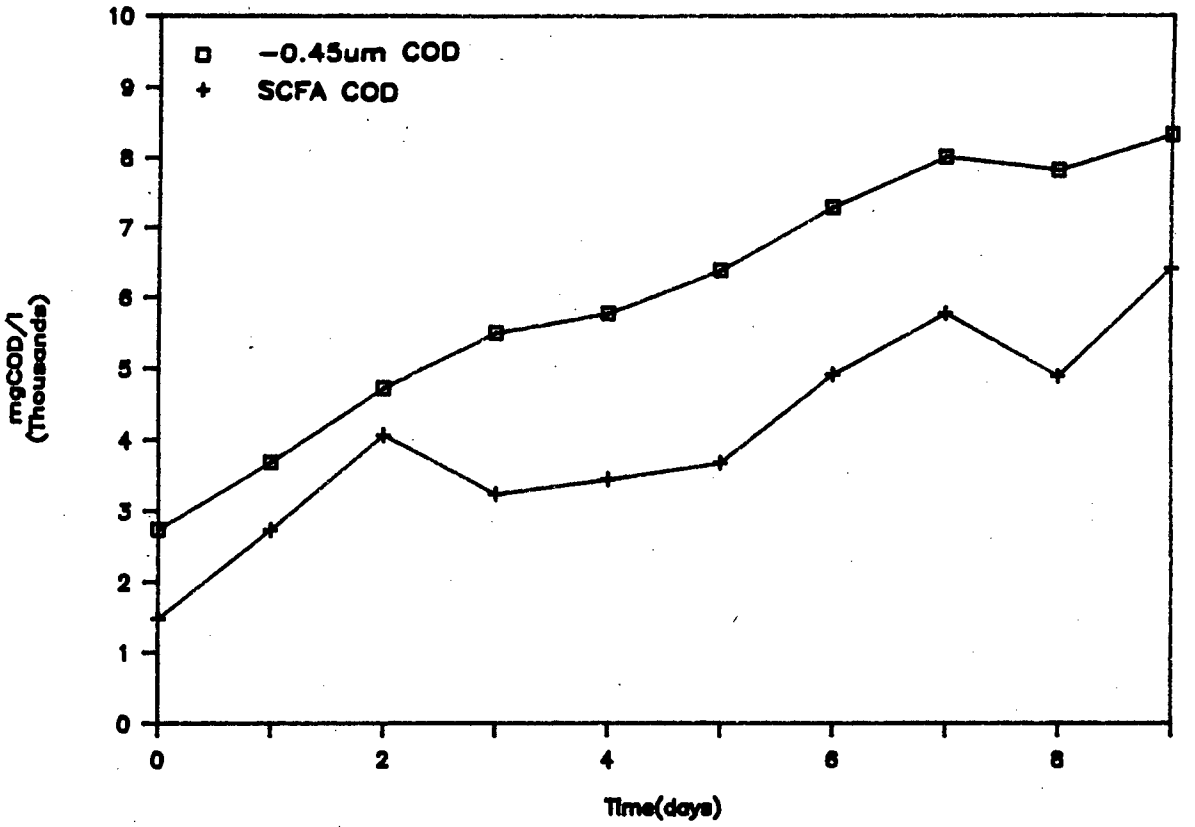

Fig 3.6: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 7.

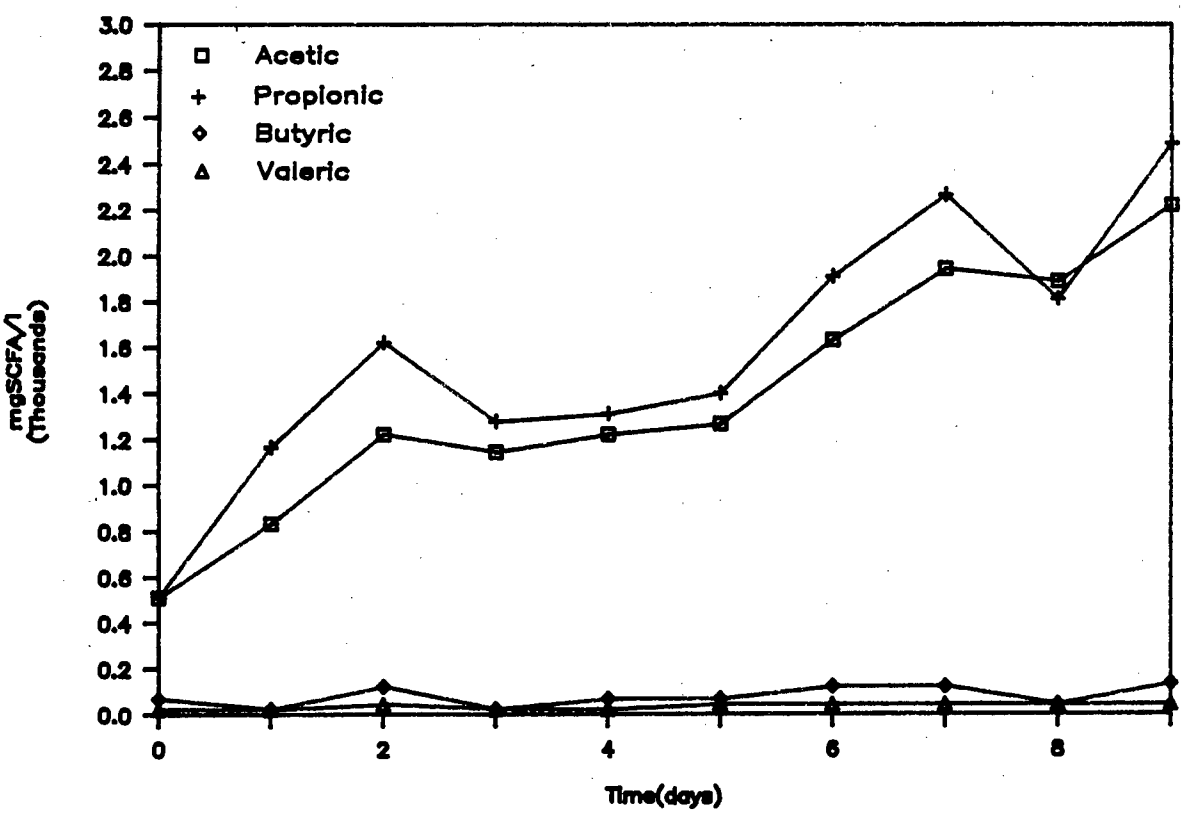

Fig 3.7: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 7.

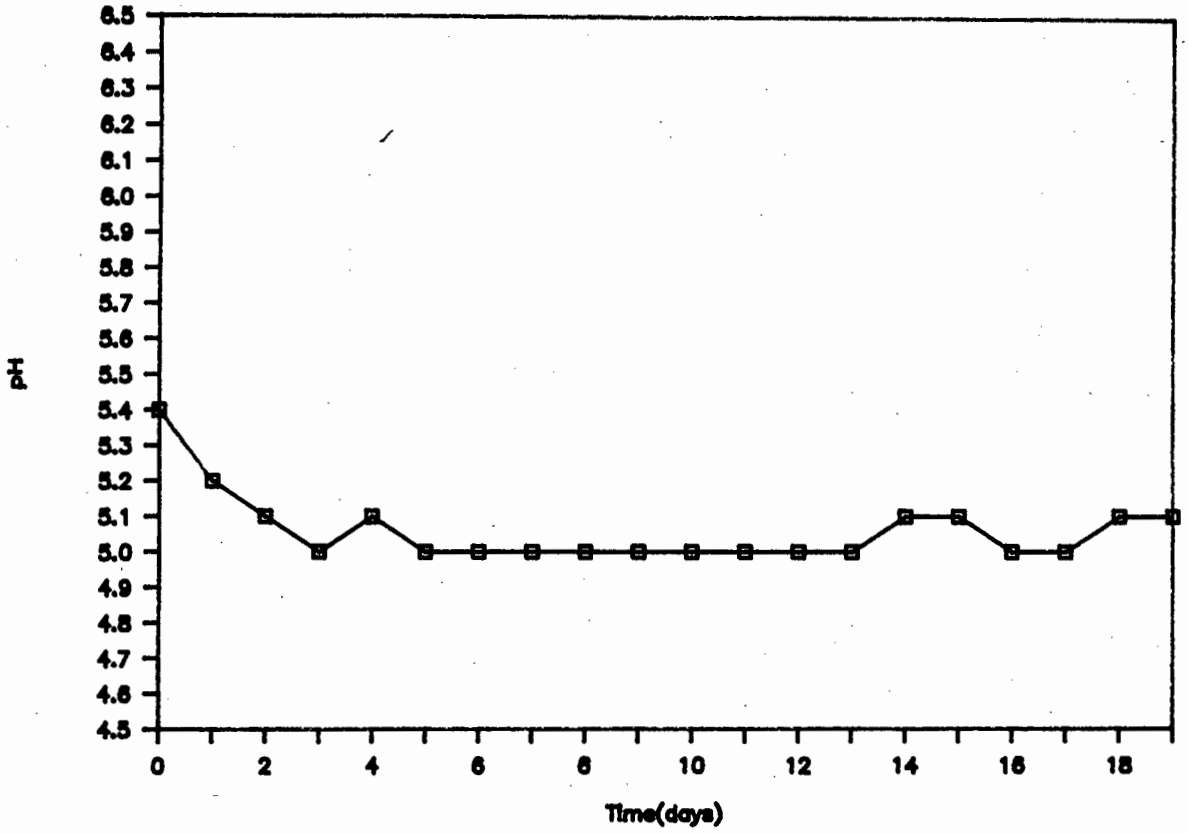

Fig 3.8: pH of a batch reactor versus time – batch test 1.

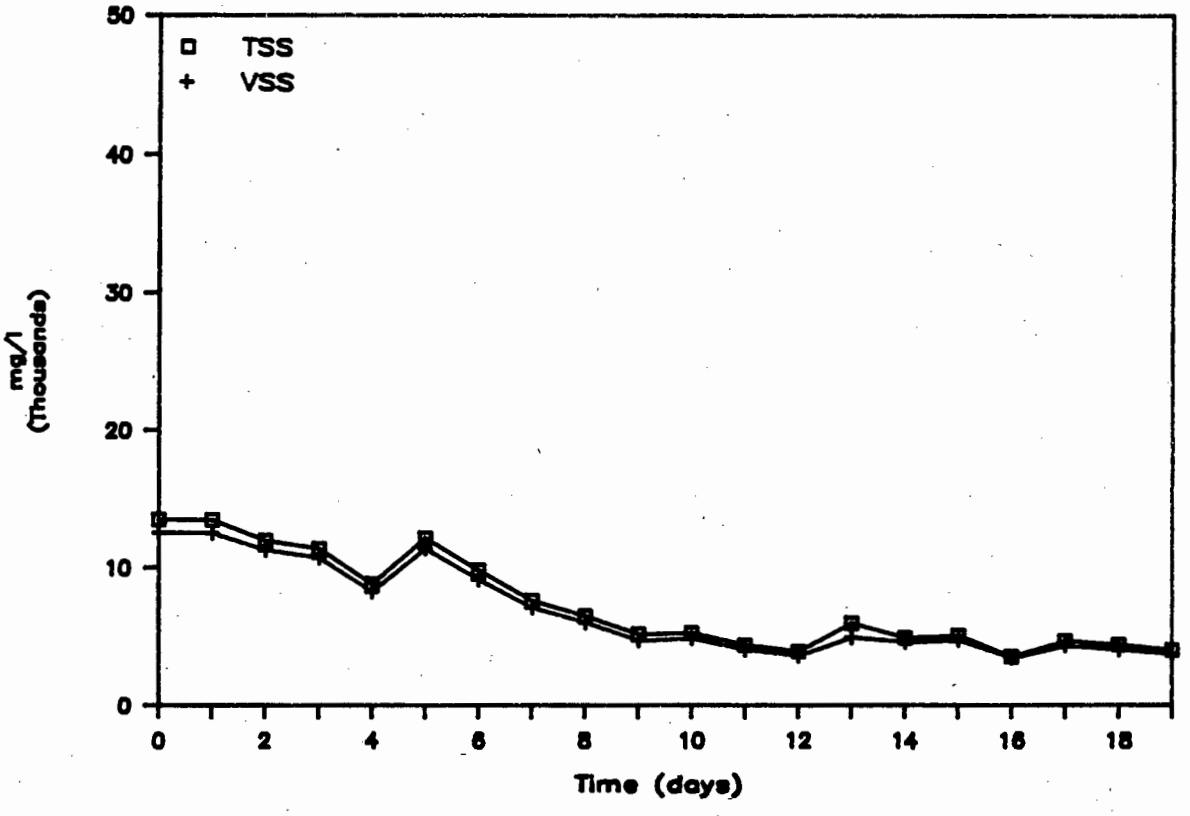

Fig 3.9: TSS and VSS concentrations of a batch reactor versus time – batch test 1.

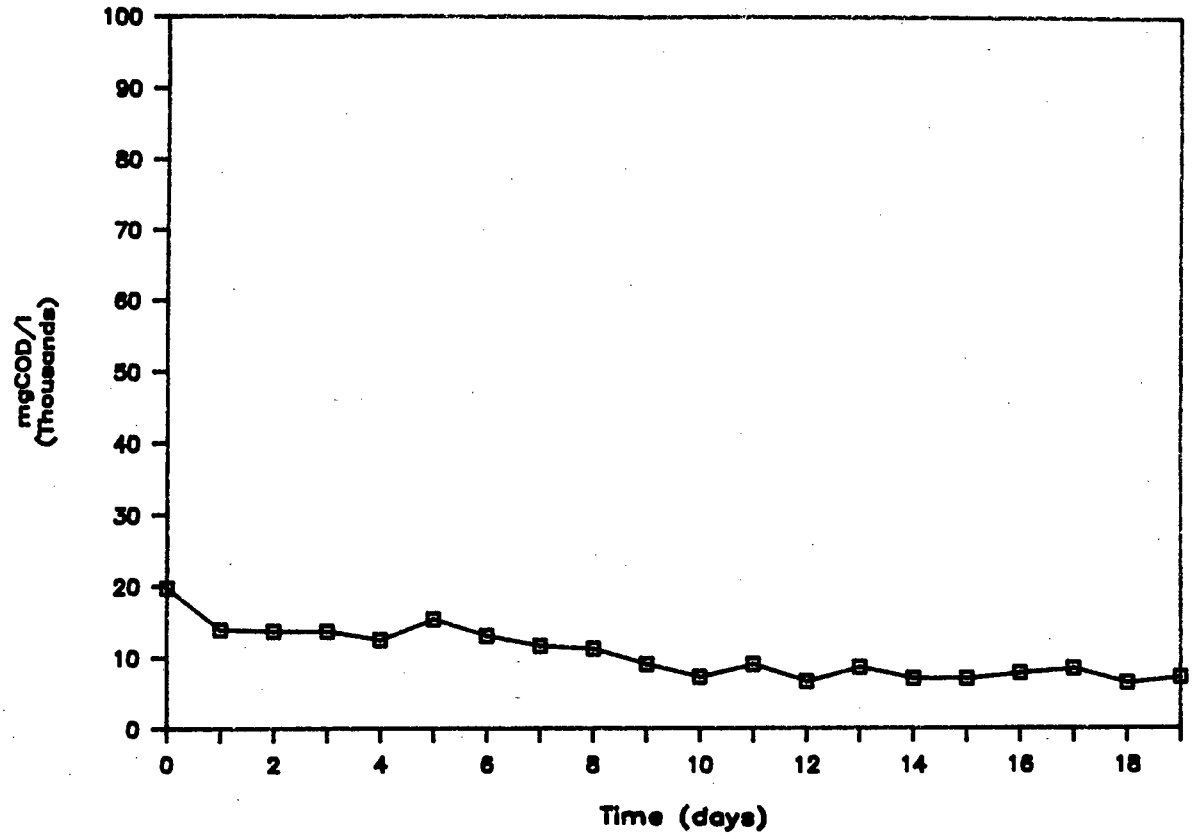

Fig 3.10: COD of the VSS concentrations of a batch reactor versus time – batch test 1.

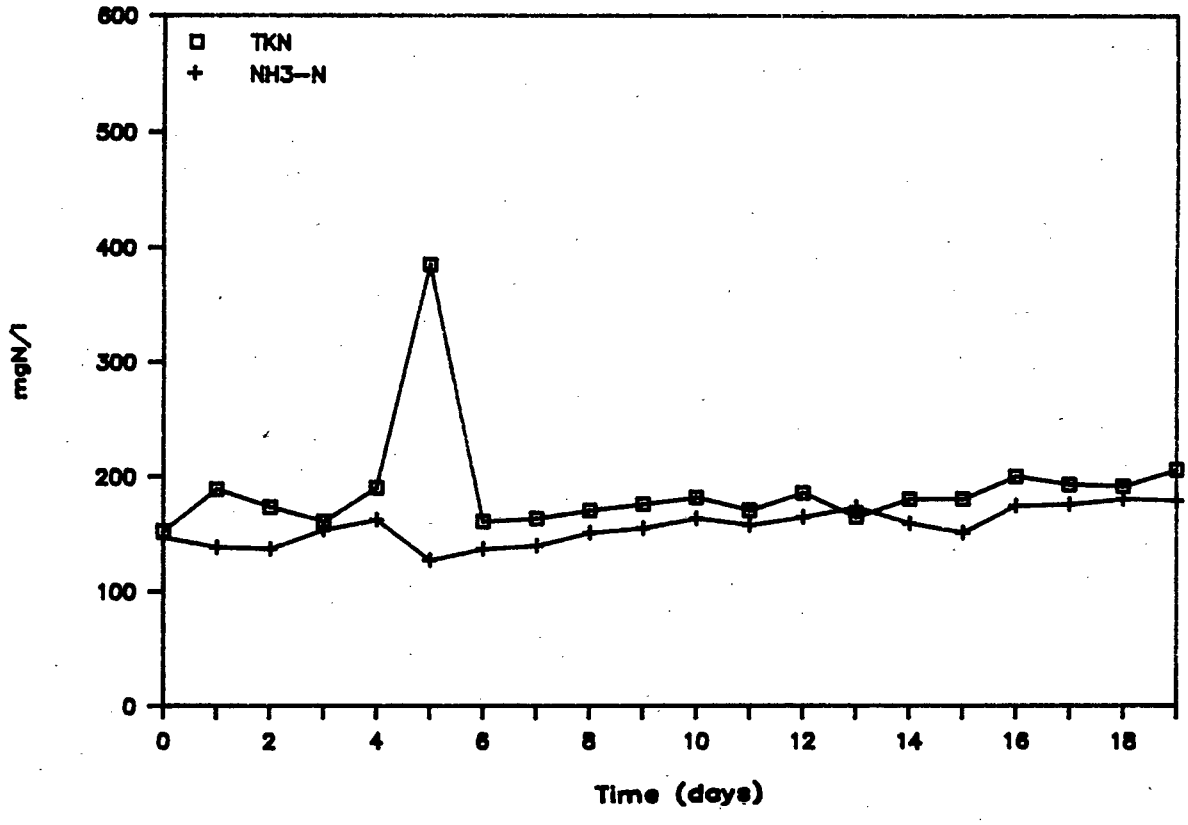

Fig 3.11: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 1.

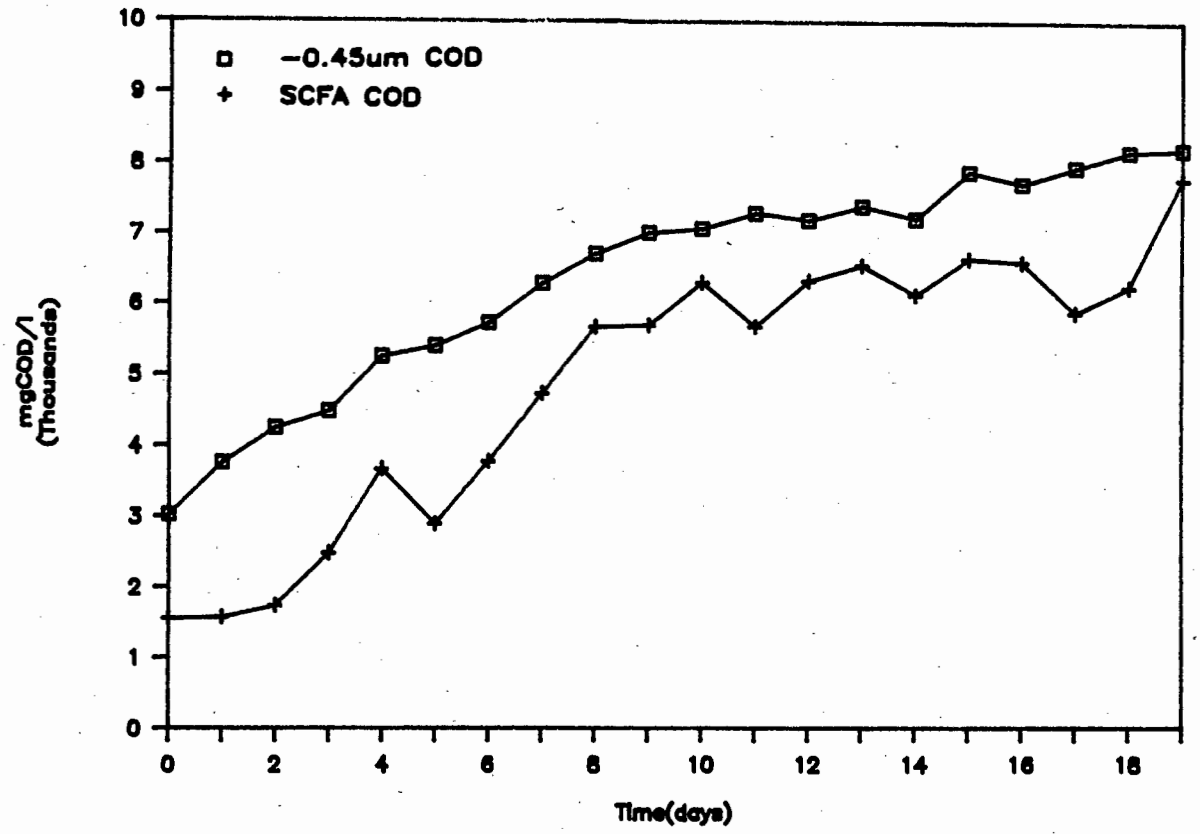

Fig 3.12: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 1.

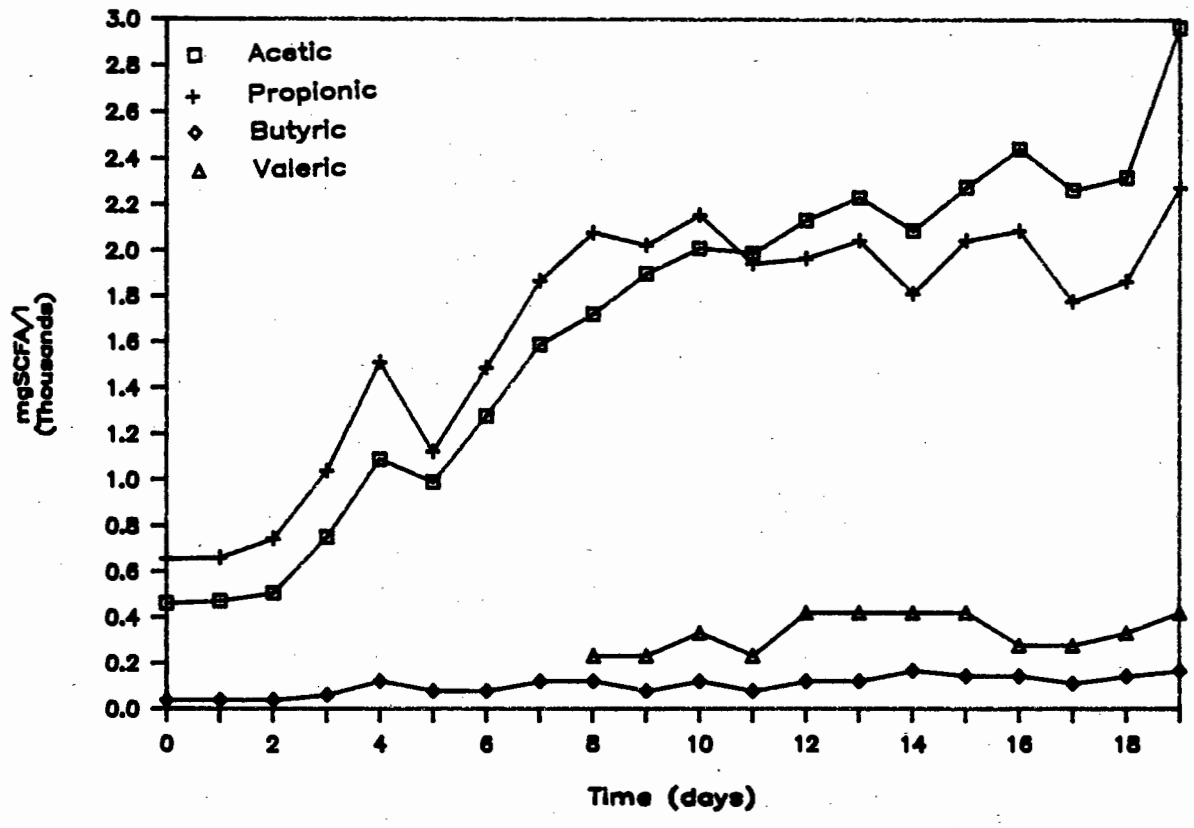

Fig 3.13: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 1.

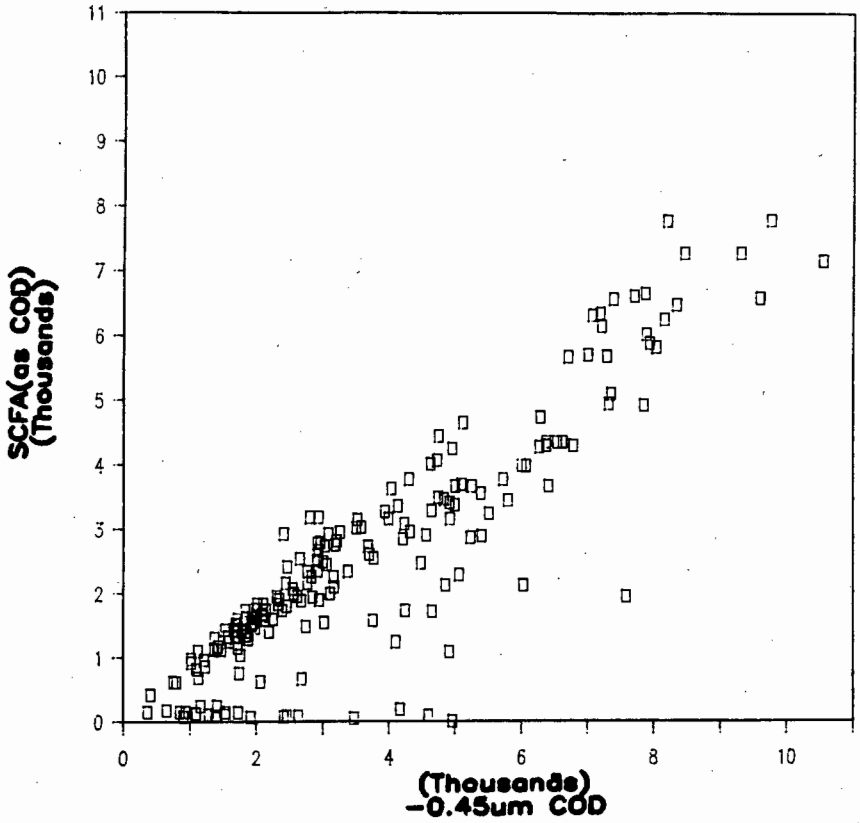

Fig 3.14: Correlation plot of SCFA (as COD) concentration of the –0,45μm filtrate versus the COD concentration of the –0,45μm filtrate for the batch reactor in tests 1 to 14.

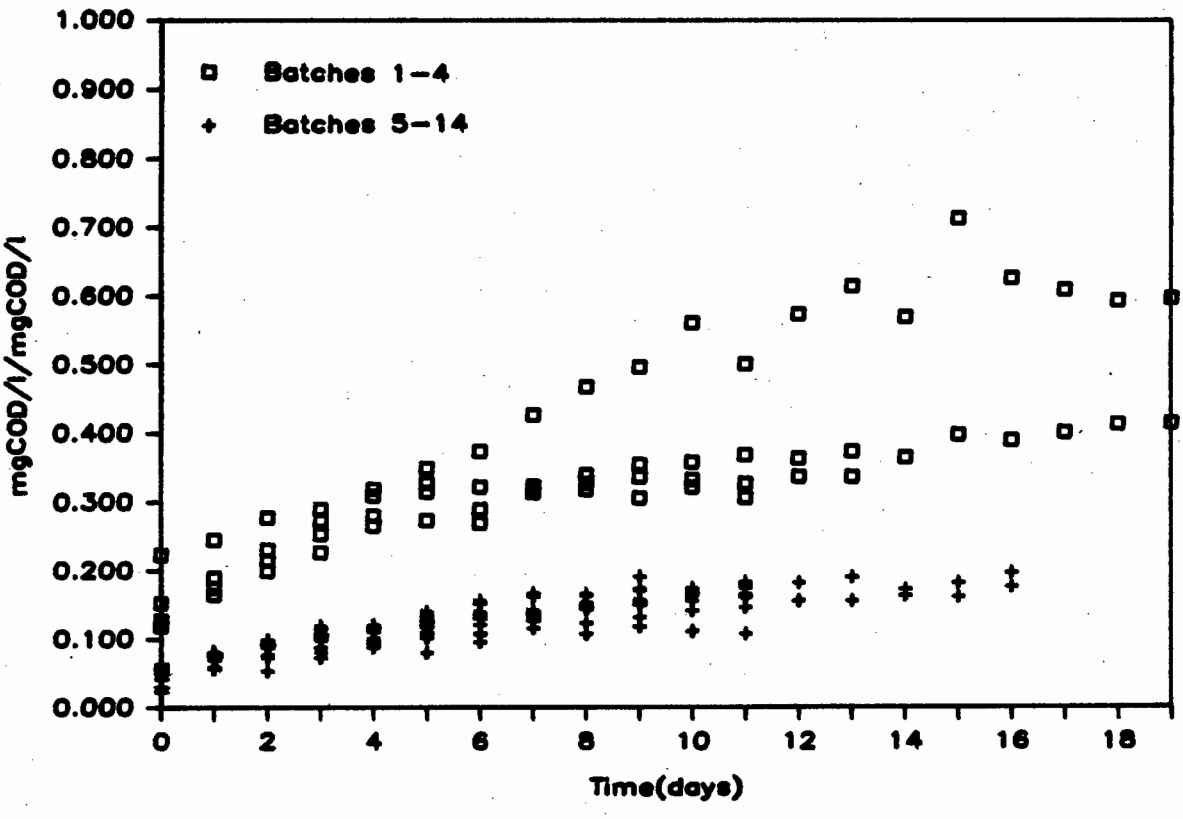

Fig 3.15: mg –0,45μm COD/mg initial VSS (as COD) ratios of a batch reactor versus time for batch tests 1 to 14.

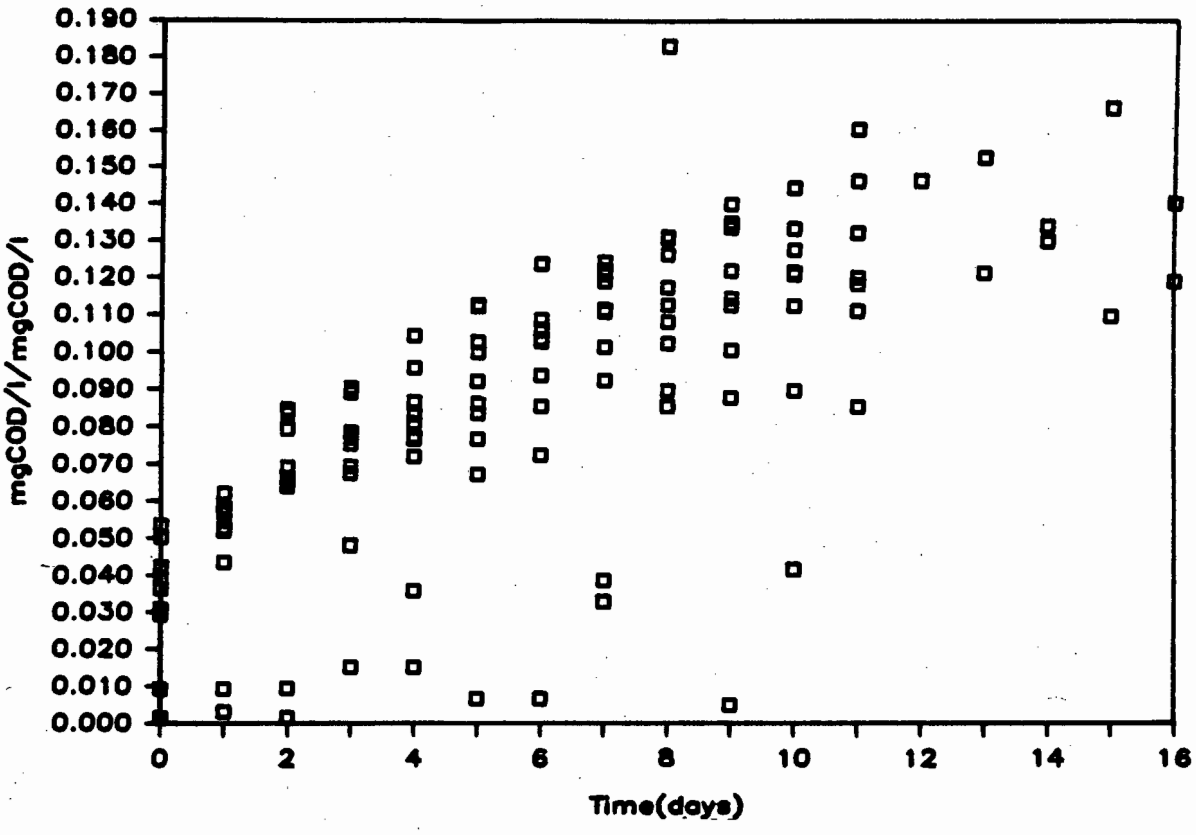

Fig 3.16: mgSCFA (as COD)/mg initial VSS (as COD) ratios of a batch reactor versus time for batch tests 5 to 14.

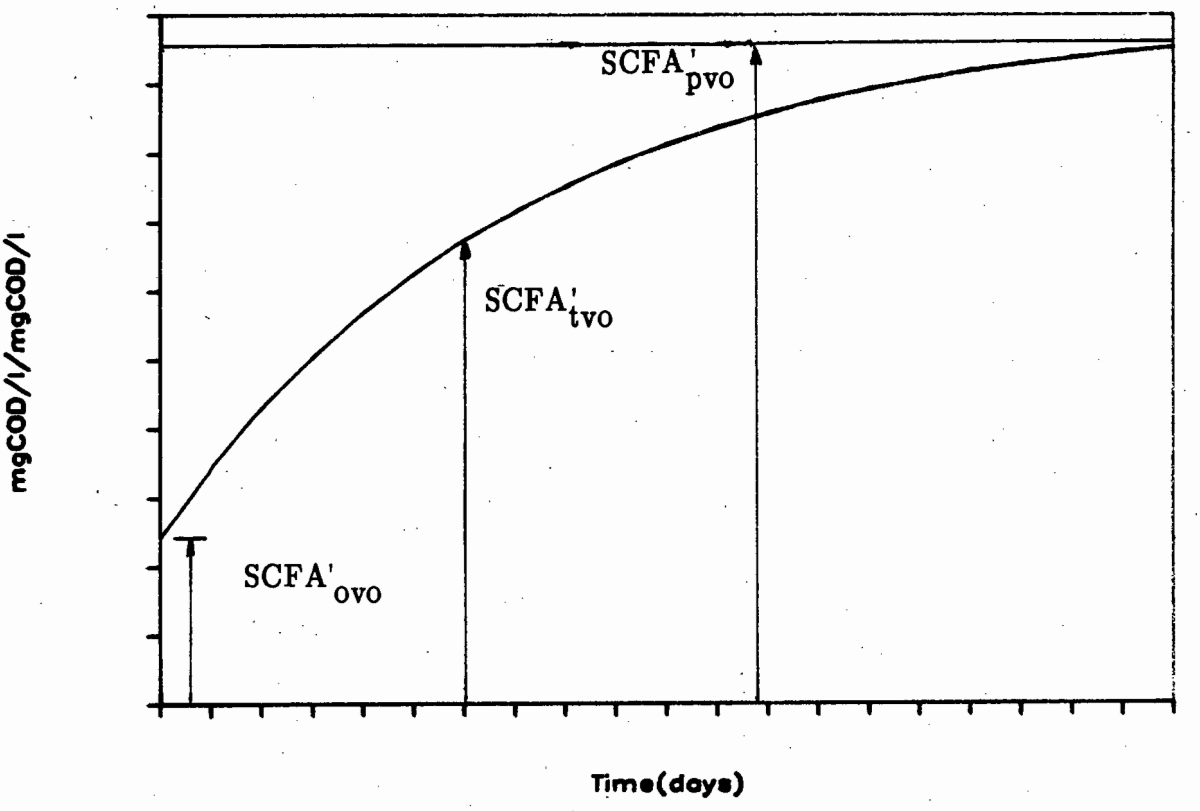

Fig 3.17: Hypothesized first order type reaction for mgSCFA (as COD) per mg initial VSS (as COD) generation for a batch reactor versus time.

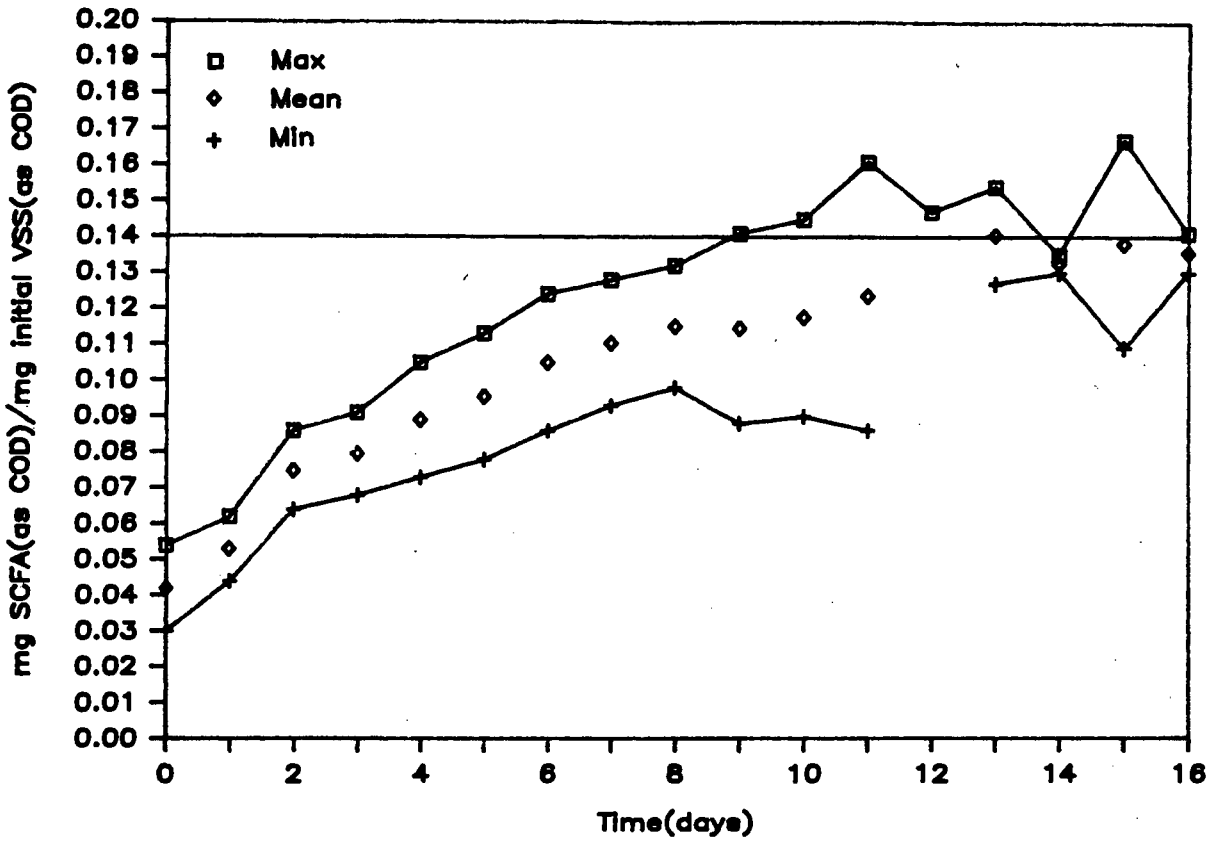

Fig 3.18: Envelope of observed maximum and minimum ratios of mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{tvo}$) and the calculated mean mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{tvo}$) ratio versus time for the batch system. Also shown is the estimated mean potential mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{pvo}$) ratio for the batch system.

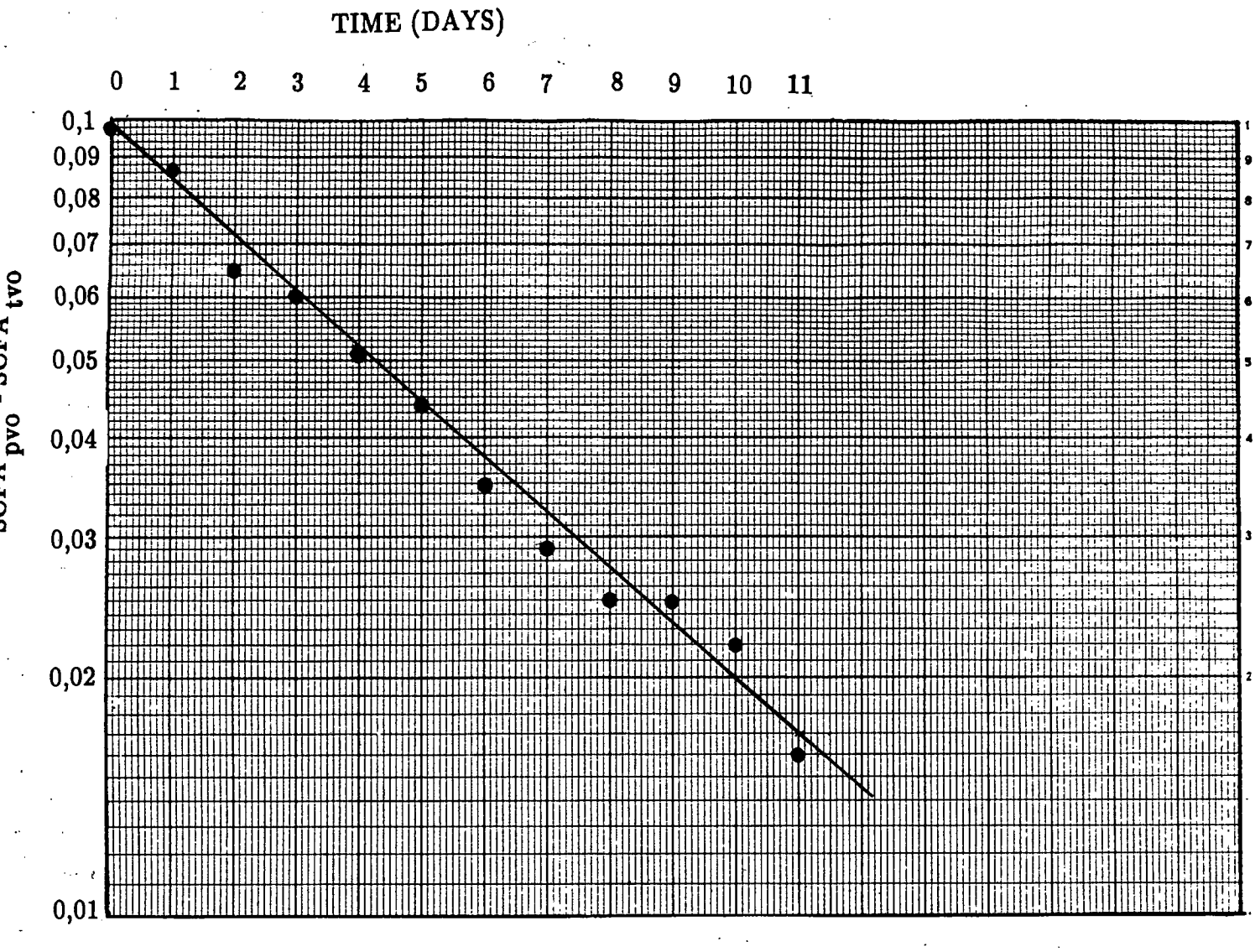

Fig 3.19: Semi-log plot of the estimated mean potential mgSCFA (as COD)/mg initial VSS (as COD) less the mean mgSCFA (as COD)/mg initial VSS (as COD) ratios (i.e. $SCFA'_{pvo} - SCFA'_{tvo}$) versus time for a batch reactor.

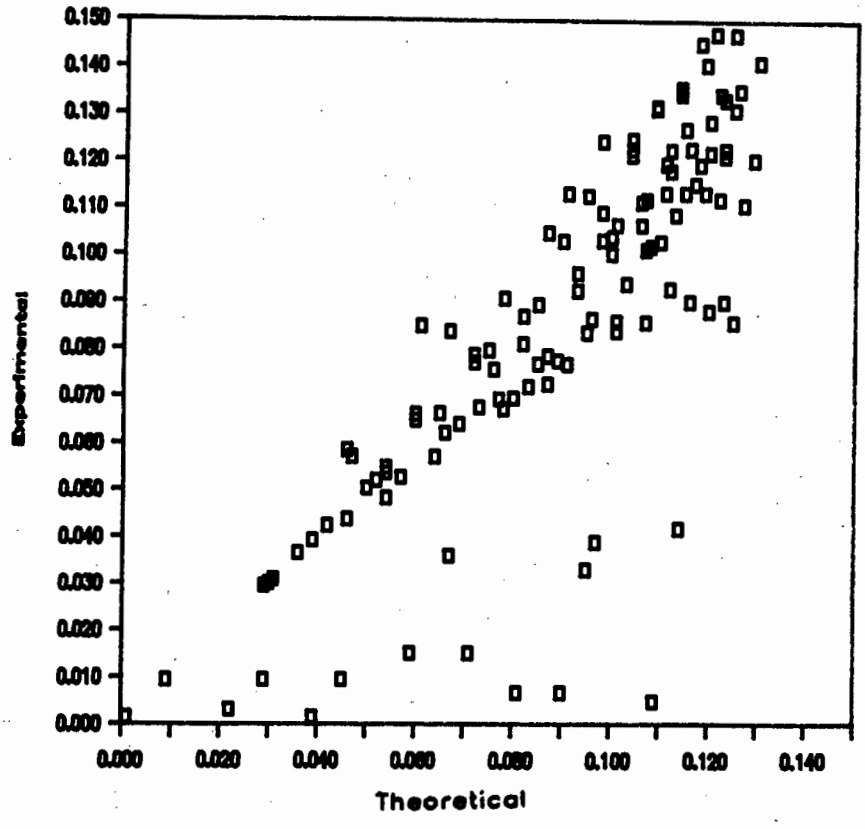

Fig 3.20: Correlation plot of the theoretical mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{tvo}$) values obtained from Eq (3.7) versus experimental mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{tvo}$) data obtained from the batch tests.

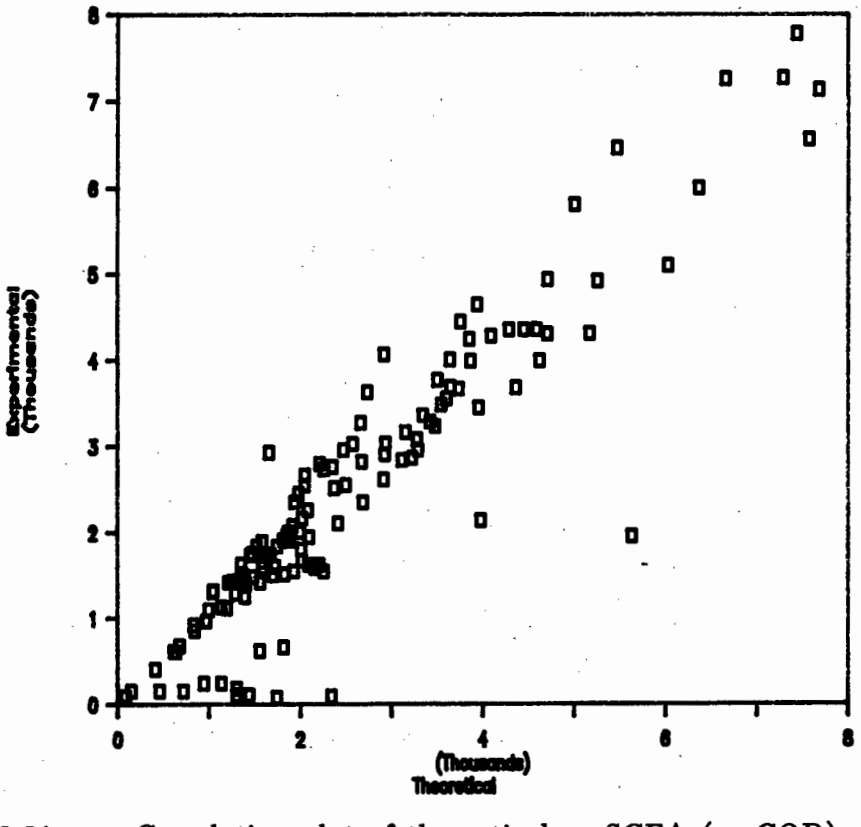

Fig 3.21: Correlation plot of theoretical mgSCFA (as COD) concentrations (i.e. $SCFA'_t$) values versus experimental mgSCFA (as COD) (i.e. $SCFA'_t$) concentrations obtained from the batch tests. ($SCFA'_t = SCFA'_{tvo} \cdot X'_{vo}$)

CHAPTER 4

SEMI–CONTINUOUS IN–SERIES SYSTEM

4.1 INTRODUCTION

In Chapter 3 the behaviour of anaerobic fermenters operated under batch conditions was reported. In some of the batch tests it was noted that a significant lag period was present before fermentation commenced. Very likely these lag periods would be eliminated, and perhaps the rate of fermentation increased, if a batch was inoculated with some partially fermented sludge from a previous batch.

Controlled inoculation requires a 'standard' sludge inoculum which would require a separate continuously fed system to be operated at some fixed sludge age – an inoculum from a previous batch test may vary in organism constitution because the constitution will depend on the time state of the batch test from which it is taken. To overcome this effect it was decided to operate an in-series reactor system, each reactor of the series operating at a selected flow through time. Because the response in the batch tests (a first order time reaction) is most pronounced in the early stage of the test, it was decided to limit the total retention time in the system to about 3 days. To bring out the first order type behaviour, 3 in-series reactors each with 1 day retention, were selected. For ease of operation a semi-continuous feeding pattern was selected (batch feeding twice a day – see later for detailed operational procedures). With this set up, the system could be run over any period of time so that the response behaviour could be monitored over several batches of raw sludge.

The detailed objectives of the in-series reactor investigation were as follows:

(1) To obtain information on acid generation in a 3 in-series reactor system, operated under a constant daily sludge load, each reactor having 1 day retention time, fed semi-continuously.

(2) Compare the response of in-series systems with that in the batch system and extend, if possible, the batch model for SCFA generation to the in-series system.

4.2 EXPERIMENTAL SET UP

The experimental set up consisted of three 3 litre batch reactors placed in-series (see Fig 4.1). Polystyrene discs were floated on the liquid surface to ensure an anaerobic environment in the liquid medium. The apparatus was operated in a temperature controlled room at 20° C.

4.3 OPERATION

Each reactor was operated as a flow through system having a nominal retention time of 1 day (and thus a sludge age of 1 day). The overall sludge age therefore was 3 days for 3 reactors in-series.

Seventy five litres of raw sludge was collected from the underflow primary sedimentation tank at the Mitchell's Plain Treatment Works (just prior to desludging at 10h00). In the early stages of the investigation, the raw sludge was stored at 4° C under anaerobic conditions, but it was found that even at this low temperature, acid generation commenced virtually immediately and the effects became noticeable after about 3 to 4 days storage. To overcome this disturbing influence, on arrival of the sludge from the full scale works, the sludge was divided in approximate daily feed volumes and stored at –14° C. The daily feed was defrosted in the cold room, at 4° C, for 3 days prior to being fed into the first reactor.

To start up the system, reactor 1 was filled to the 2,5 litre mark, reactor 2 to the 2,3 litre mark and reactor 3 to the 2,1 litre mark with the raw sludge collected from the full scale works. These volumes were chosen to maintain the sludge age in each reactor at one day after allowance for the volumes of sludge taken for testing, see below. Feeding procedure was twice a day as follows:

With the high volatile solids concentration, the reactor contents were viscous and there was a measure of uncertainty, as to the efficiency of mixing. Prior to feeding (and sampling for testing), to ensure a well mixed medium, half the contents of each reactor were drained (from the bottom) and poured back at the top of the reactor.

Sampling and sludge age control (one day in each reactor) was done as follows: The last reactor was drained (from the bottom) of half its contents. Two 50 mℓ samples were taken for testing and the remainder discarded. Half the contents of the second last reactor was drained (from the bottom), two 50 mℓ samples taken for testing and the remainder poured into the top of the last reactor. Half the contents of the first

reactor were drained (from the bottom), two 50 mℓ samples taken for testing and the remainder poured into the top of the second last reactor. The first reactor was then filled to the 2,5 litre mark with raw sludge.

The system rapidly attained steady state, within about one week after start up.

Four batches of raw sludge were tested in the experiment. Each batch of raw sludge had a different VSS concentration, ranging from 37 000 to 60 000 mgVSS/ℓ, see Table 4.1. Each batch was tested over a period of approximately 15 days, that is, the system was operated for a total of 67 days.

The same parameters as for the batch tests were measured every second day i.e.

(1) pH of the influent and reactor contents.
(2) TSS and VSS concentrations of the sludge pellet after centrifugation.
(3) COD concentration of the sludge pellet [termed, VSS (as COD)].
(4) COD concentration of the supernatant from (2) and (3) above after filtration through a –0,45μm filter.
(5) TKN and NH_3-N concentrations of the –0,45μm filtrate.
(6) SCFA concentrations of the –0,45μm filtrate.

The sampling techniques and measurement procedures are set out in Appendix A.

4.4 RESULTS

The results for each of the batches are listed in Tables C.1 to C.4 in Appendix C. The COD's of the total SCFA's listed in Tables C.1 to C.4 were calculated using the conversion factors of Eastman and Ferguson (1981) listed in Table 3.1. Plots of the following parameters versus time were made for all batches of raw sludge and all reactors, see Appendix C:

(1) pH,
(2) TSS and VSS concentrations,
(3) COD of the VSS concentrations,
(4) TKN and NH_3-N concentrations,
(5) –0,45μm COD and total SCFA (as COD) concentrations, and
(6) Acetic, propionic, butyric and valeric acid concentrations.

For each batch of raw sludge, average values for the above parameters were calculated. These averages are listed in Table 4.1. Plots of the data listed in Table 4.1 versus retention time are shown in Figs 4.2 to 4.8. From the plots the following general observations can be made:

(1) pH – the pH decreased with increasing retention time (see Fig 4.2). The minimum pH observed was 5,4.

(2) TSS and VSS – The TSS and VSS concentrations decreased with increasing retention time [see Fig 4.3(a) and (b)].

(3) VSS (as COD) – The COD of the VSS concentrations decreased with increasing retention time (see Fig 4.4).

(4) TKN and NH_3-N – The TKN and NH_3-N increased with increasing retention time, [see Figs 4.5(a) and (b)].

(5) –0,45μm COD – The –0,45μm COD concentration increased with increasing retention time (see Fig 4.6). Note that the data in batch No.1 is not typical: the *influent* –0,45μm COD concentration showed an increase from 2052 mgCOD/ℓ to 3708 mgCOD/ℓ in the initial 7 days after the system was started up (see Fig C.5). This increase was due to acid generation occurring in storage at 4°C. With subsequent batches the raw sludge was then stored at –14°C whereupon the influent –0,45μm COD concentration remained relatively constant throughout the time the batch was used.

(6) SCFA (as COD) and –0,45μm COD – From correlation plots of SCFA (as COD) versus –0,45μm COD [see Figs 4.7(a) and (b)], the following is evident; For the raw sludge the SCFA (as COD) constituted approximately 58 percent of the –0,45μm COD [see Fig 4.7(a)]. For all the reactor contents, this percentage was closely 67 percent [see Fig 4.7(b)].

(7) SCFA (as COD) – The SCFA (as COD) concentration increased with increasing retention time (see Fig 4.8):

The following observations also are of interest:

(1) A slight lag period in SCFA generation, of 2 days, was observed in the first reactor upon starting up of the system (see Fig C.12), but a steady state value was achieved after a further 2 to 3 days. Thereafter, the only deviations noted were the transitions associated with a new batch of raw sludge being fed into the system. This transition period extended over about one system sludge age, i.e. 3 days.

(2) The major acids produced were acetic and propionic. Other acids generated were butyric and valeric. The ratios of acetic:propionic:butyric;valeric acids (as COD) were 1:1,4:0,5:0,2.

(3) No significant loss of SCFA's due to methanogenesis was observed during the investigation. Once again this possibly could be due to inhibition of the growth of methanogens caused by the low pH's. A white fungus grew on top of the polystyrene discs in the reactors, but did not appear to have any marked effect on the SCFA concentration and was cleaned off approximately once a week.

4.5 MODELLING OF SCFA GENERATION

Each batch of raw sludge had different VSS (as COD) concentrations; to bring the data to a common basis the SCFA (as COD) concentrations were divided by the influent (initial) VSS (as COD) concentrations. The mgSCFA (as COD)/mg initial VSS (as COD) ratios for each batch of raw sludge, for each reactor, were calculated and plotted in Fig 4.9. Examination of Fig 4.9 would indicate that SCFA generation in the series systems approximates a first order type reaction, similar to that in the batch systems.

4.5.1 Theory

In Chapter 3, Section 5.1, a basic model for SCFA generation under batch conditions was developed, i.e.

$$SCFA'_{tvo} = (SCFA'_{pvo} - SCFA'_{ovo})(1 - e^{-0,16t}) + SCFA'_{ovo} \qquad (3.7)$$

where $SCFA'_{tvo}$ = mgSCFA (as COD)/mg initial VSS (as COD) at time t
$SCFA'_{pvo}$ = potential mgSCFA (as COD)/mg initial VSS (as COD)
$SCFA'_{ovo}$ = mg initial SCFA (as COD)/mg initial VSS (as COD)

t = time in days.

As the SCFA generation in an in-series reactor system also appears to be a first order type reaction, Eq (3.7) was modified to apply to completely mixed, in-series reactors.

In a single completely mixed reactor (see Fig 4.10), let V = volume of the reactor in litres; Q = influent and effluent flows, in ℓ/d; k = first order acid generation constant in day^{-1} units; P_o,P = potential acid generation in the influent and effluent flows respectively in mgCOD/ℓ.

It is assumed that mixing in the reactor is instantaneous and complete. This implies that the concentrations in the reactor and the effluent are identical.

A mass balance over time dt gives: Change in mass of acid potential in the reactor VdP is due to (1) an increase in potential from the influent, P_oQ_o dt; (2) a decrease in potential due to acid generation in the reactor, – kPV dt; and (3) a decrease in potential from loss in the outflow, – PQ dt i.e.

$$V\,dp = P_oQ\,dt - kPV\,dt - PQ\,dt \tag{4.1}$$

$$\text{i.e. } \frac{dP}{dt} = \frac{P_oQ}{V} - kP - \frac{PQ}{V} \tag{4.2}$$

At steady state $\frac{dP}{dt} = 0$

Equation (4.2) reduces to

$$\frac{P_oQ}{V} - kP - \frac{PQ}{V} = 0$$

but $\frac{Q}{V} = \frac{1}{R}$

where R is the retention time in days,

therefore $$\frac{P_o}{R} - kP - \frac{P}{R} = 0$$

$$P_o - kPR - P = 0$$

$$P_o = P(1 + kR)$$

i.e. $$P = \frac{P_o}{(1 + kR)} \qquad (4.3)$$

For reactors in-series, let R_1, R_2 .... Rn be the influent retention times in a series of n reactors. From Eq (4.3) the potential acid production in reactors 1 to n is given by

$$P_1 = P_o/(1 + kR_1)$$

$$P_2 = P_1/(1 + kR_2) = P_o/(1 + kR_1)(1 + kR_2)$$

$$P_n = P_o / \prod_{i=1}^{n} (1 + kR_i) \qquad (4.4)$$

when $R_1 = R_2 = ... = R_n = R$

$$P_n = \frac{P_o}{(1 + kR)^n} \qquad (4.5)$$

Following the same development as for Eq (3.7)

$$SCFA'_{nvo} = (SCFA'_{pvo} - SCFA'_{ovo})\left(1 - \frac{1}{(1+kR)^n}\right) + SCFA'_{ovo} \qquad (4.6)$$

where $SCFA'_{nvo}$ = mgSCFA (as COD)/mg initial VSS (as COD) in the effluent from the n^{th} reactor

$SCFA'_{pvo}$ = potential mgSCFA (as COD)/mg initial VSS (as COD).

$SCFA'_{ovo}$ = mg influent SCFA (as COD)/mg initial VSS (as COD)

k = first order constant in day^{-1}.

4.5.2 Calibration

From Fig 4.9, an average mean value for the initial SCFA (as COD)/mg initial VSS (as COD) was calculated as $SCFA'_{ovo} = 0,035$. From the batch experiments $SCFA'_{pvo} = 0,14$ SCFA (as COD)/mg initial VSS as COD. When this value of $SCFA'_{pvo}$ was substituted in Eq (4.6), it under predicted the SCFA generation (see Fig 4.11). By trial $SCFA'_{pvo}$ was estimated at 0,17 mgSCFA (as COD)/mg initial VSS (as COD) to give the highest correlation. Thus, the theoretical equation for the in-series system becomes

$$SCFA'_{nvo} = (0,17 - SCFA'_{ovo})\left(1 - \frac{1}{(1+0,16R)^n}\right) + SCFA'_{ovo} \qquad (4.7)$$

In Fig 4.12 is shown a correlation plot of the theoretical $SCFA'_{nvo}$ [from Eq (4.7)] versus experimentally observed $SCFA'_{nvo}$ values for each of the reactors in the 3 in-series reactor system (of 1 day retention time per reactor); a reasonable correlation is observed.

Having the $SCFA'_{pvo}$ values (from Eq 4.7) the SCFA in the effluent from the n^{th} reactor now can be found:

Let $SCFA_{neff}$ = mgSCFA (as COD)/ℓ in the effluent of reactor n

X_{vo} = mg initial VSS (as COD)/ℓ

then,

$$SCFA_{neff} = SCFA'_{nvo} \cdot X'_{vo} \qquad (4.8)$$

In Fig 4.13, a correlation plot of theoretical versus observed $SCFA_{neff}$ concentrations is shown; a good correlation once again is evident.

4.6 CONCLUSIONS

From investigation into the production of SCFA's in an anaerobic 3 in-series reactor system the following conclusions are pertinent:

(1) In the semi-continuous in-series reactor operation, no lag period in SCFA

generation was evident in the first reactor. With different batches of raw sludge the transient response from an old batch to a new batch of sludge was completed in one system's sludge age, i.e. within 3 days.

(2) The response down the series was much more consistent than the response over the same period of time in a batch reactor.

(3) Throughout the period of operation of the system, the pH in the system never declined below 5,4, for raw sludge VSS concentrations ranging from 37 000 to 60 000 mgVSS/ℓ.

(4) As the sludge passed through the reactor system:
- (i) The VSS concentration decreased.
- (ii) The VSS (as COD) concentration decreased.
- (iii) The TKN and NH_3-N concentrations increased.

(5) In the in-series system the SCFA (as COD) correlate quite closely with the –0,45μm COD, as also found in the batch experiments (Chapter 3); the SCFA constituted approximately 58 percent of the influent –0,45μm COD and 67 percent of the –0,45μm COD in the reactors.

(6) The major SCFA's produced were acetic and propionic, with butyric and valeric acids also present. The ratios of acetic:propionic:butyric:valeric acids (as COD) were 1:1,4:0,5:0,2.

(7) No loss of SCFA due to methanogenesis was observed over the 67 day time period that the system was operational.

(8) The SCFA (as COD) generation rate appears to be a first order type reaction with a potential yield of 0,17 mgSCFA (as COD)/mg initial VSS (as COD). This yield is higher than the yield of 0,14 mgSCFA (as COD) per mg initial VSS (as COD) obtained in the batch experiment.

(9) The effluent mgSCFA (as COD)/mg initial VSS (as COD) from the reactors, in an in-series reactor system, can be predicted satisfactorily by Eq 4.7.

Table 4.1: Average, pH, TSS, VSS and VSS (as COD) concentrations, TKN, NH_3-N, COD, SCFA (as COD), acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate for the 3 in-series, completely mixed, semi-continuously fed reactor system, each reactor having a flow through retention time of 1 day, for all batches of sludge.

Reactor and Batch number	pH	TSS mgTSS/l	VSS mgVSS/l	VSS (as COD) mgCOD/l	TKN mgN/l	NH3-N mgN/l	-0.45um COD mgCOD/l	SCFA (as COD) mgCOD/l	Acetic acid mgHAc/l	Propionic acid mgHPr/l	Butyric acid mgHBu/l	Valeric acid mgHVa/l
INFLUENT												
1	6.0	44200	37300	63800	321	217	3383	1860	522	611	211	
3	5.7	68500	59700	83800	522	375	6285	4200	997	1075	483	323
4	5.8	53600	46200	59300	435	286	4110	1900	618	591	163	33
5	6.1	50000	45500	56800	325	252	3521	1550	522	478	128	
REACTOR 1	R=1 DAY											
1	5.9	42700	35900	59000	486	329	4950	3070	948	911	259	104
3	5.5	62700	54400	80900	710	570	8700	5350	1635	1517	524	178
4	5.5	49500	42700	58100	541	422	5500	3630	1097	1125	295	111
5	5.9	49700	43600	59100	443	378	4500	3090	933	900	289	100
REACTOR 2	R=2 DAYS											
1	5.8	41500	35000	60800	521	476	5820	3740	1131	1104	296	145
3	5.5	57500	49600	74800	768	666	9300	6980	1870	1937	678	404
4	5.5	47100	41000	58900	578	493	6400	4200	1258	1280	354	111
5	5.8	46800	40500	58200	445	410	5230	3550	1044	1096	311	104
REACTOR 3	R=3 DAYS											
1	5.7	40500	34600	59900	547	500	6371	4100	1310	1075	356	211
3	5.5	55200	47800	72400	784	673	10200	7400	2056	2141	774	296
4	5.4	46300	39700	57700	605	523	7000	4500	1457	1360	380	111
5	5.7	45900	40200	58900	507	464	5800	3800	1178	1167	338	95

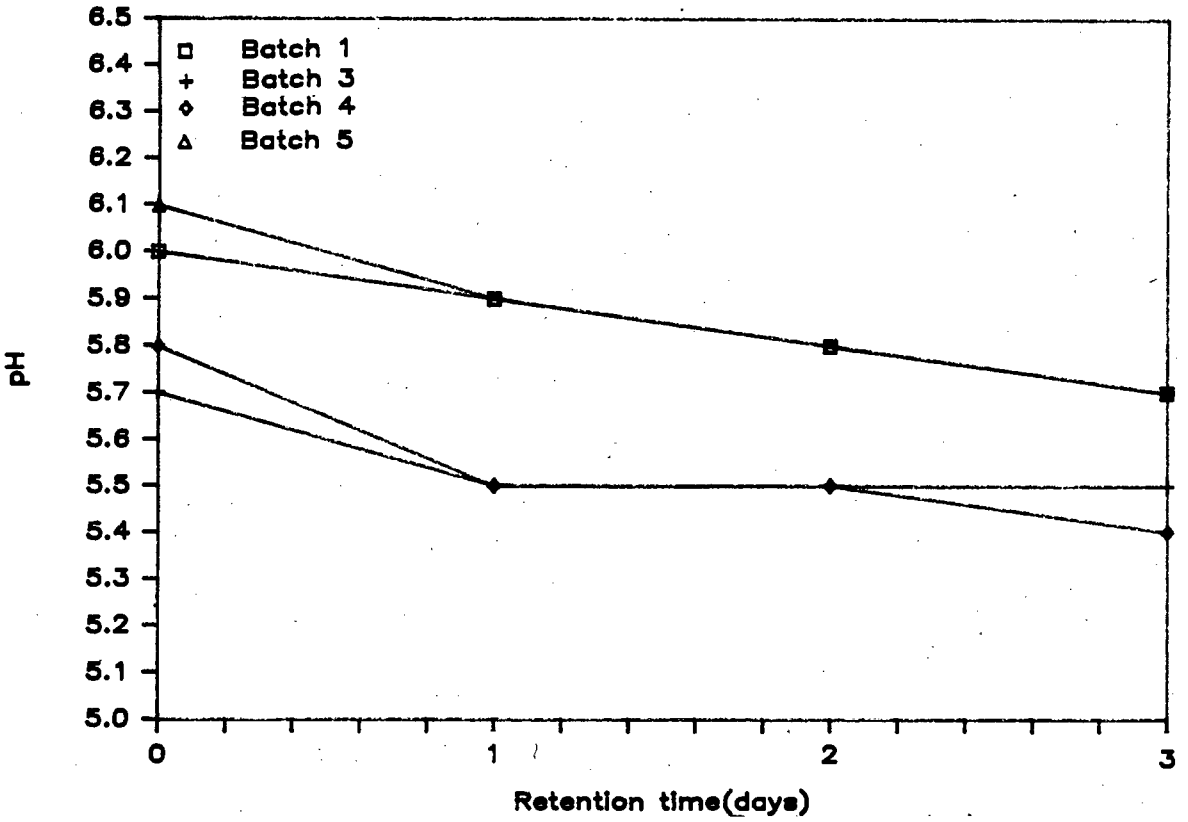

Fig 4.2: Average pH in each completely mixed, semi-continously fed, in-series reactor versus total retention time, for all batches of sludge.

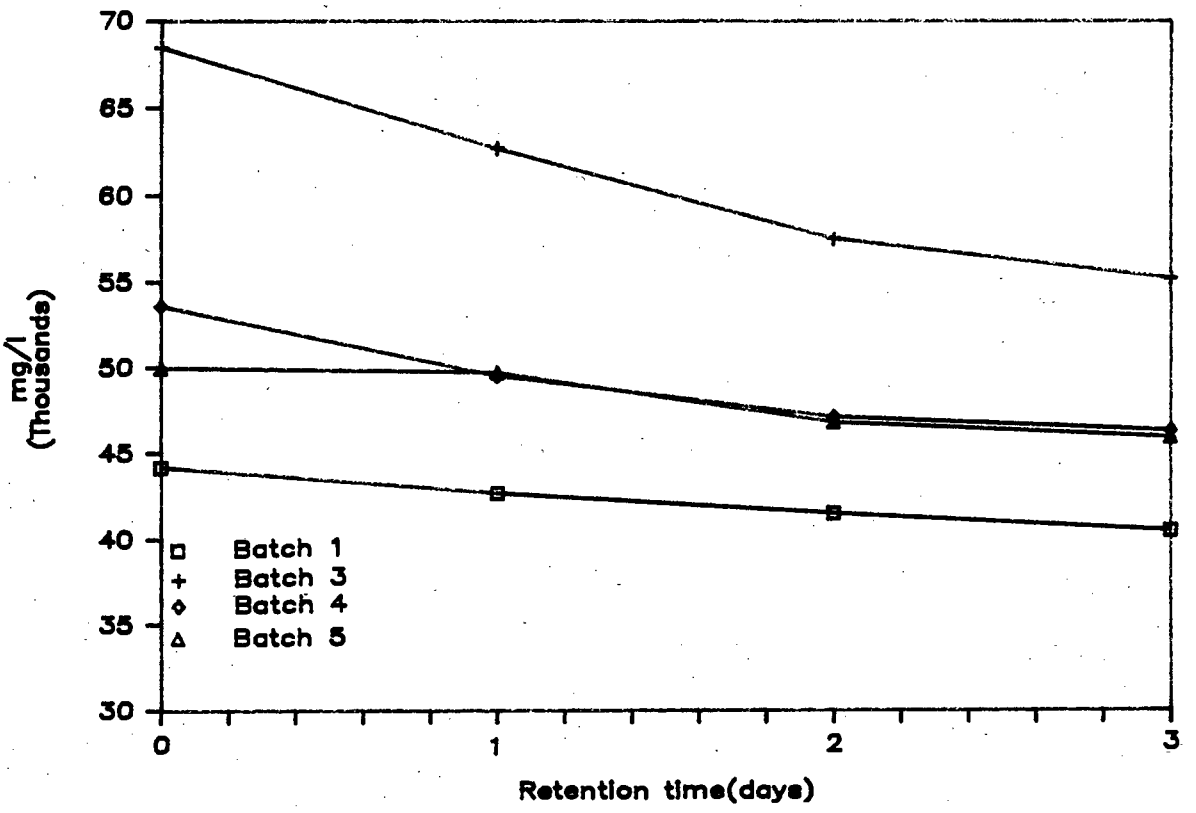

Fig 4.3(a): Average TSS concentration in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sldge.

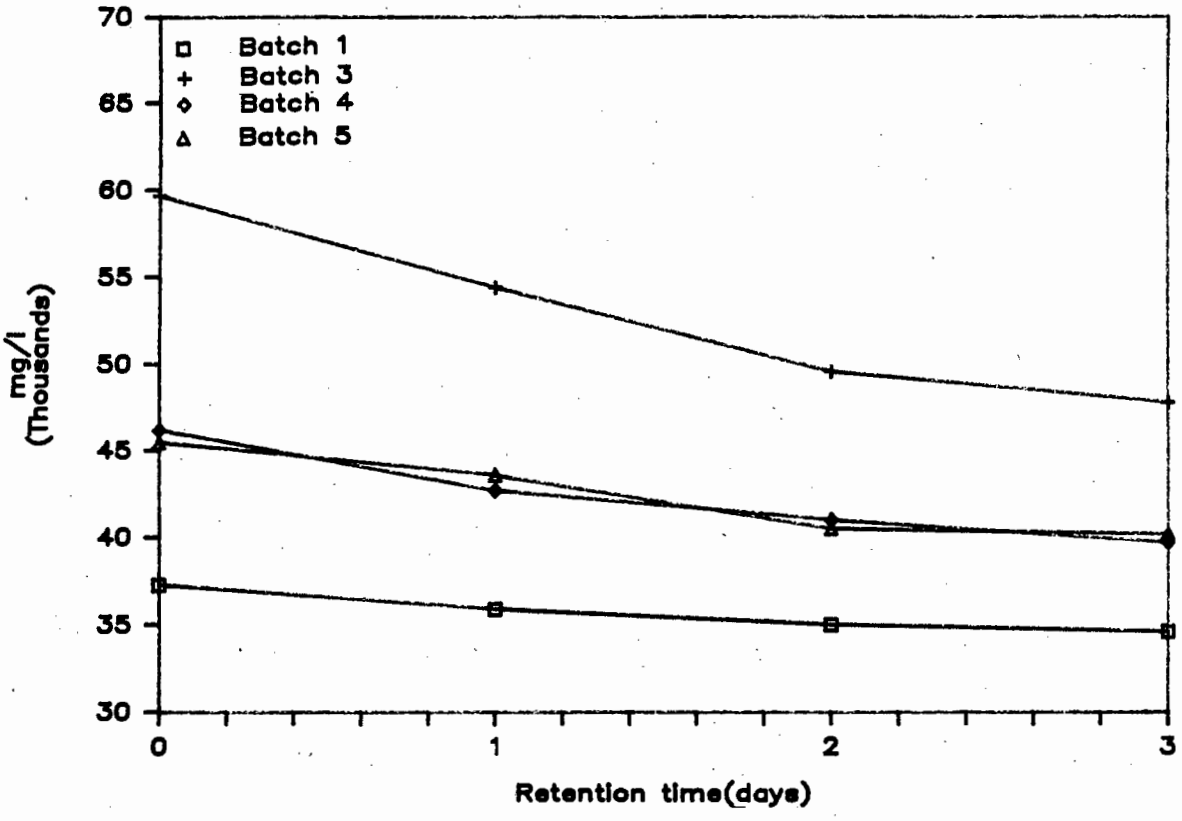

Fig 4.3(b): Average VSS concentration in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sldge.

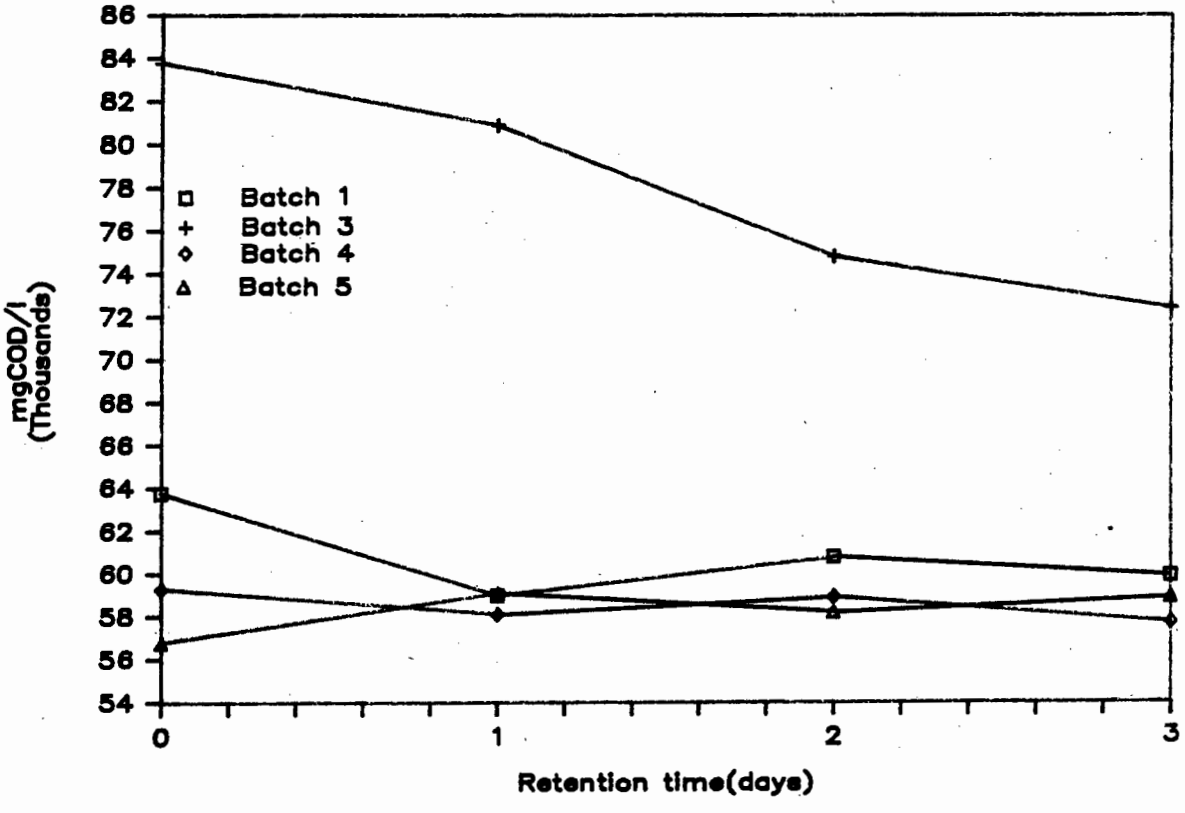

Fig 4.4: Average COD of the VSS concentrations in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sludge.

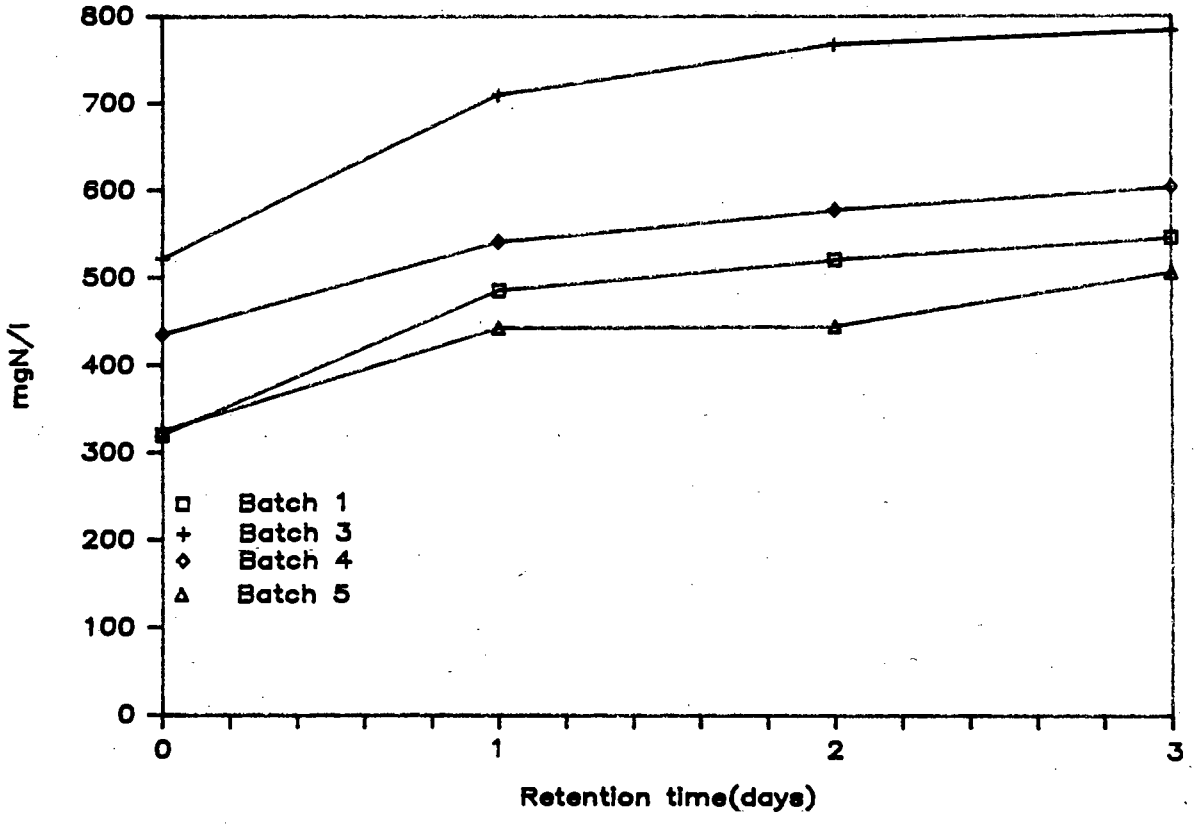

Fig 4.5(a): Average TKN concentration of the –0,45μm filtrate in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sludge.

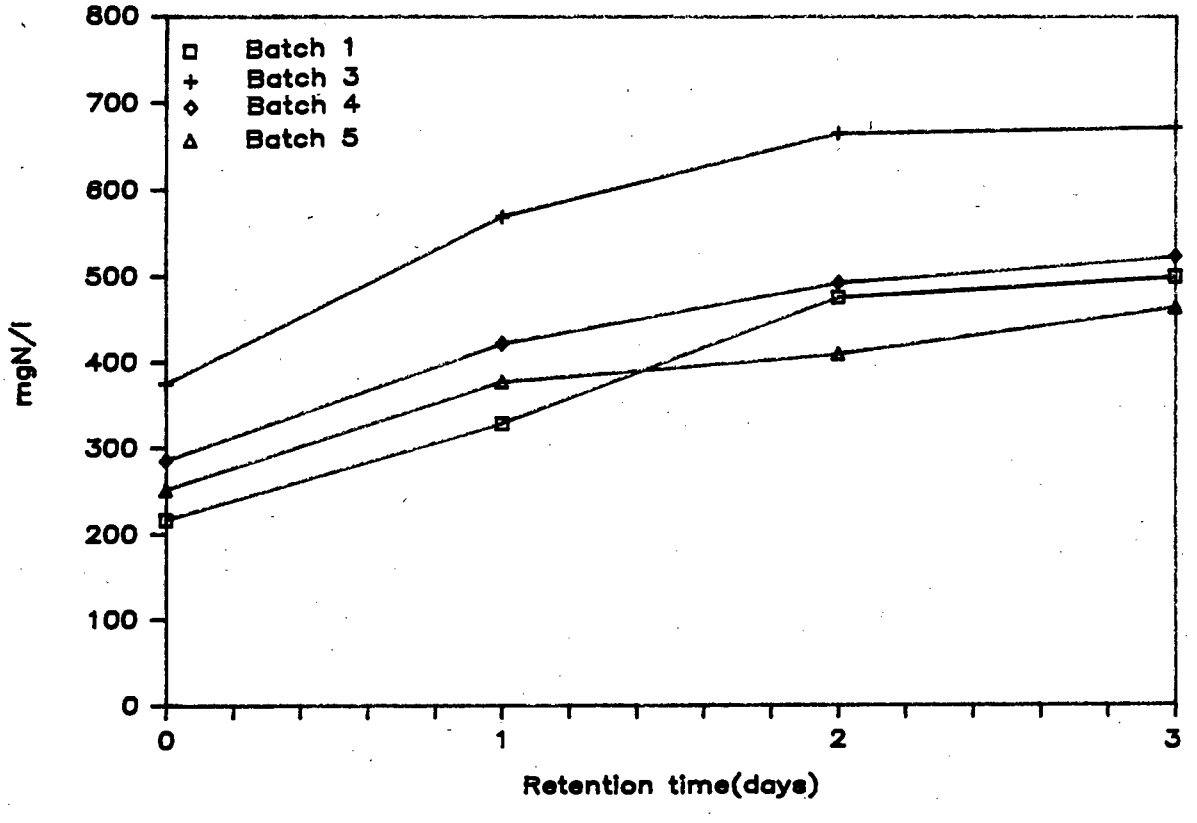

Fig 4.5(b): Average NH_3-N concentration of the –0,45μm filtrate in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sludge.

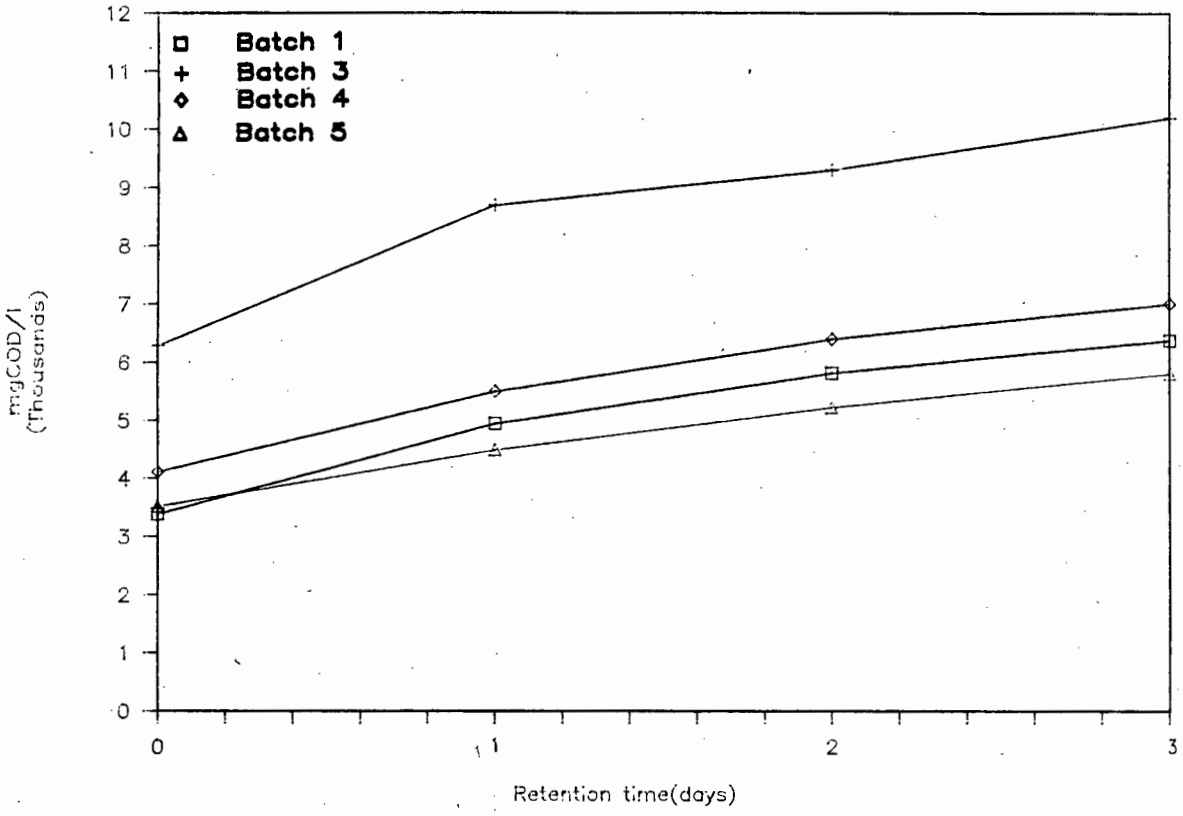

Fig 4.6: Average –0,45μm COD concentration in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sludge.

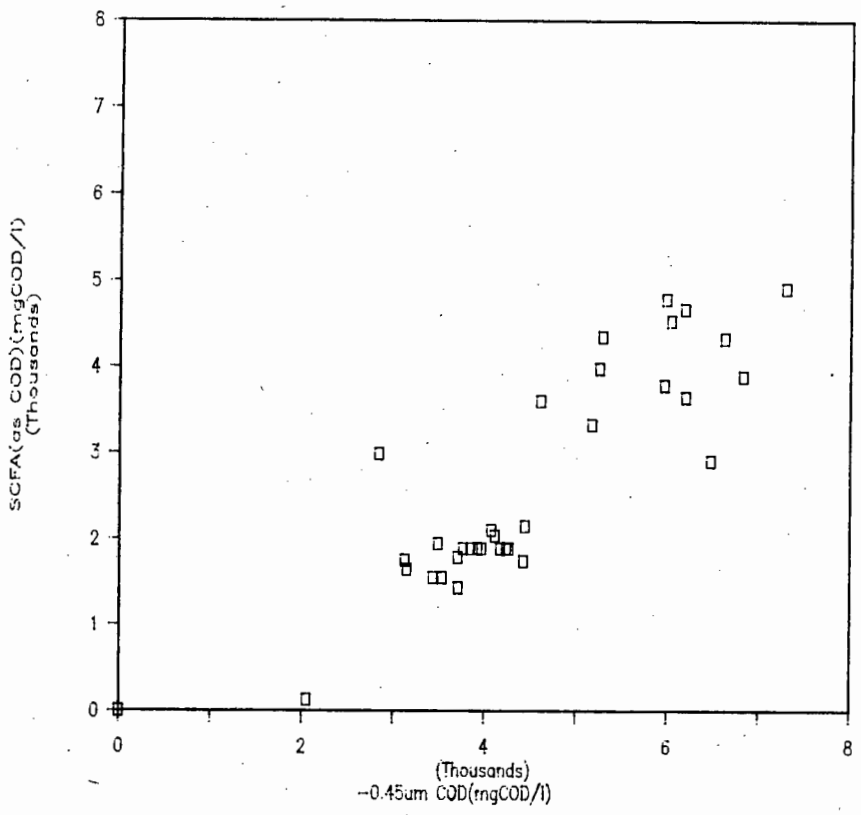

Fig 4.7(a): SCFA (as COD) concentration of the –0,45μm filtrate versus the COD of the –0,45μm filtrate for the influent raw sludge of a 3 in-series completely mixed reactor system (each reactor of 1 day retention time).

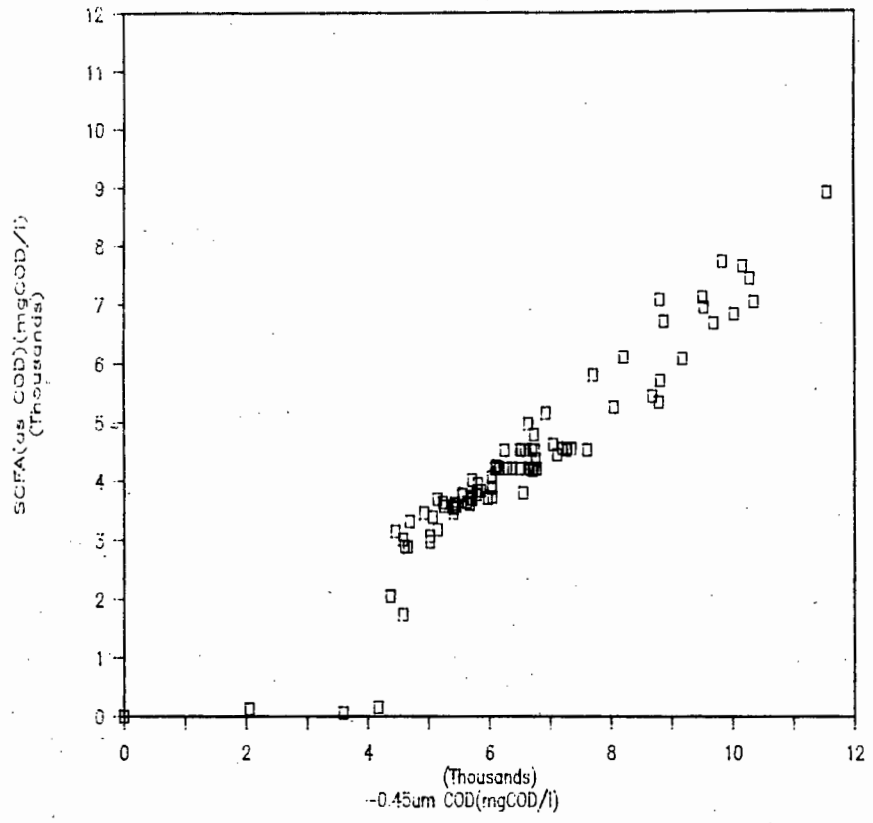

Fig 4.7(b): SCFA (as COD) concentration of the –0,45μm filtrate versus the COD of the –0,45μm filtrate for a 3 in-series completely mixed reactor system (each reactor of 1 day retention time).

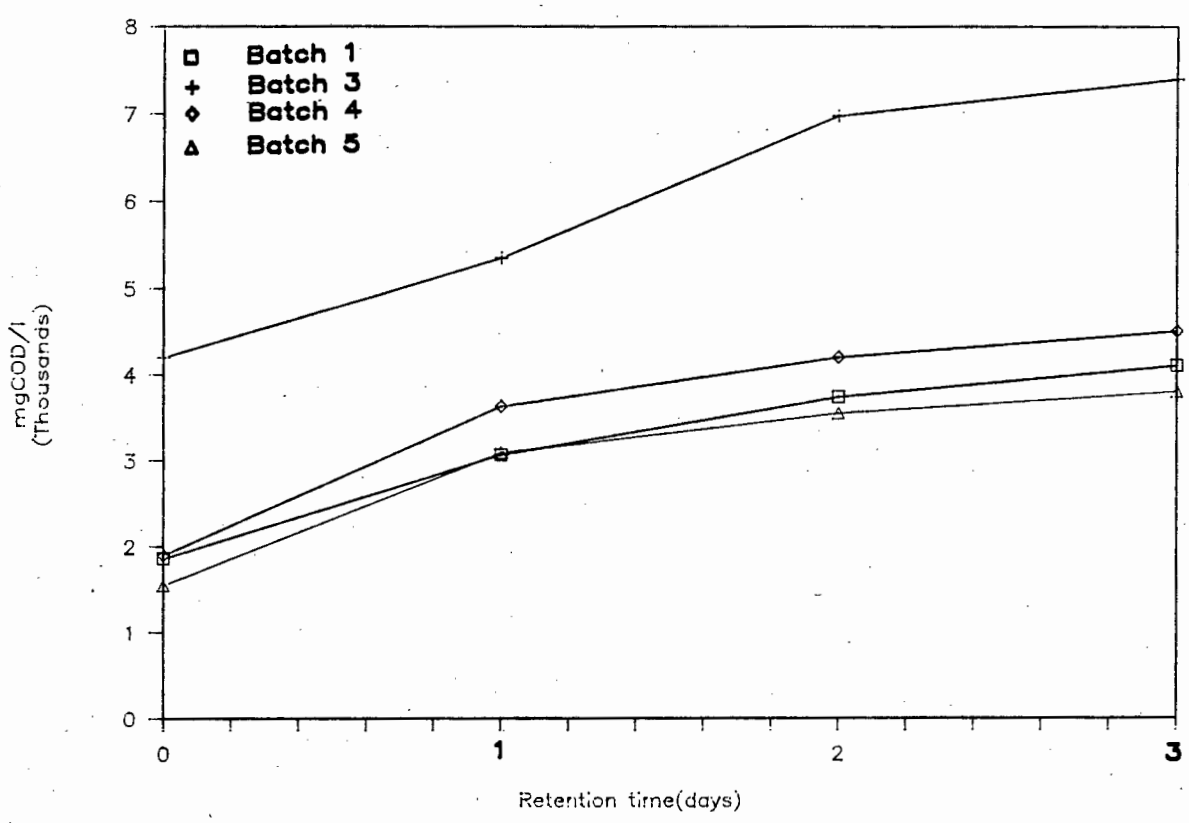

Fig 4.8: Average SCFA (as COD) concentration in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sludge.

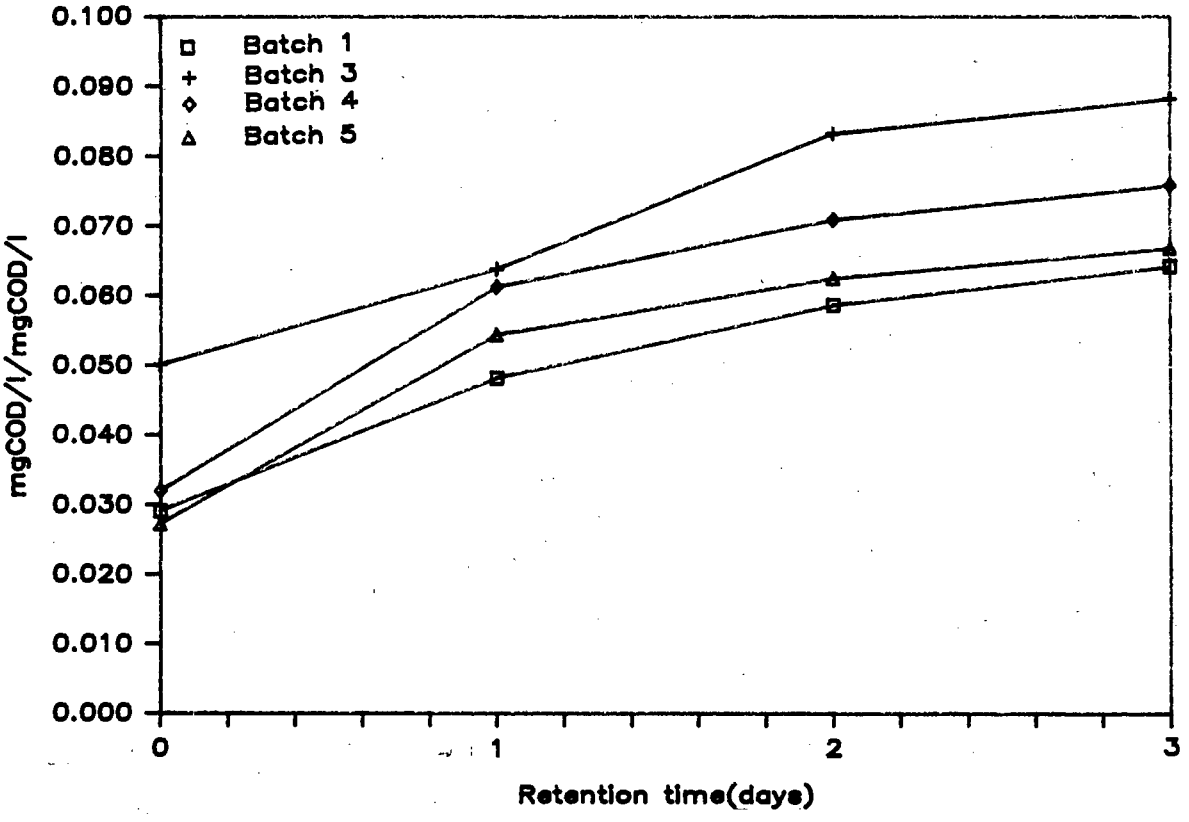

Fig 4.9: Average mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{tvo}$) ratios in each completely mixed, semi-continuously fed, in-series reactor versus total retention time, for all batches of sludge.

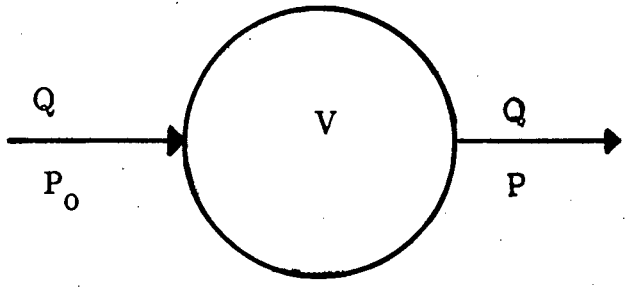

Fig 4.10: Single completely mixed, continuously fed reactor depicting influent and effluent flow rates and acid generation potentials.

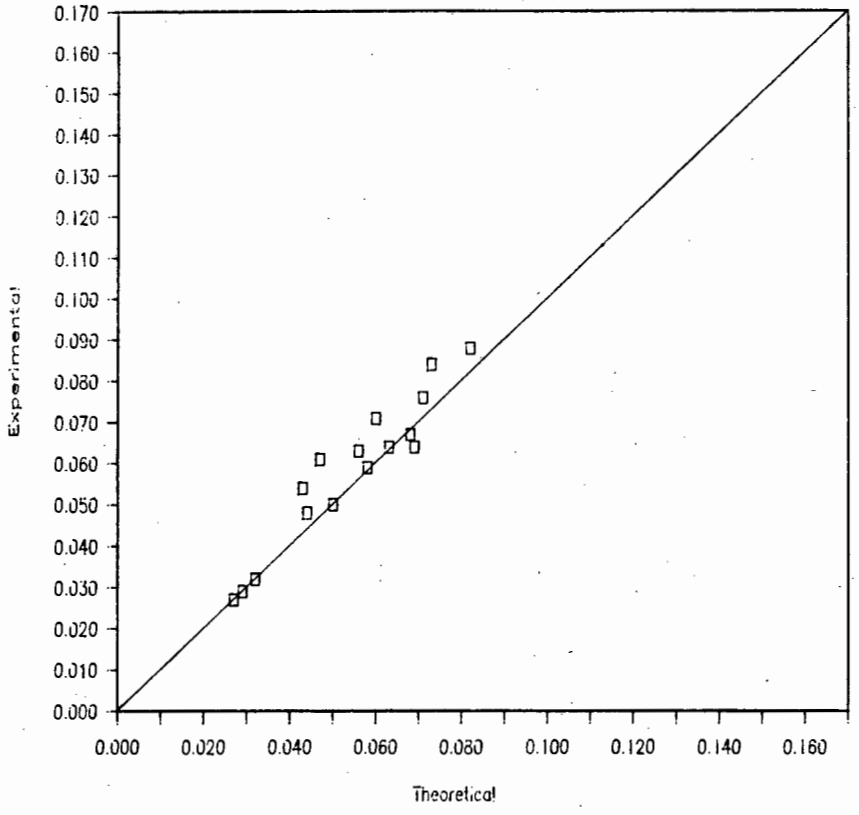

Fig 4.11: Correlation plot of theoretical versus observed mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{nvo}$) ratios for a 3 in-series, completely mixed, semi-continuously fed reactor system, each reactor having a retention time of 1 day [theoretical values from Eq (4.6) where $SCFA'_{pvo}$ = 0,14 mgSCFA (as COD)/mg initial VSS (as COD)].

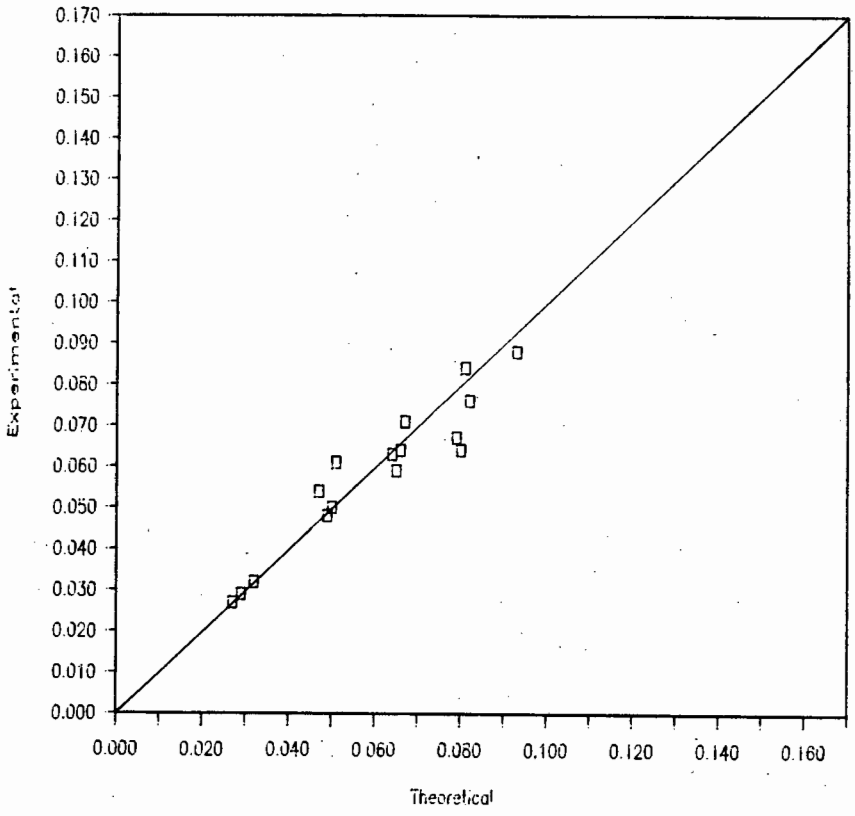

Fig 4.12: Correlation plot of theoretical versus observed mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{nvo}$) ratios for a 3 in-series, completely mixed, semi-continuously fed reactor system, each reactor having a retention time of 1 day [theoretical values from Eq (4.7) where $SCFA'_{pvo}$ = 0,17 mgSCFA (as COD)/mg initial VSS (as COD)].

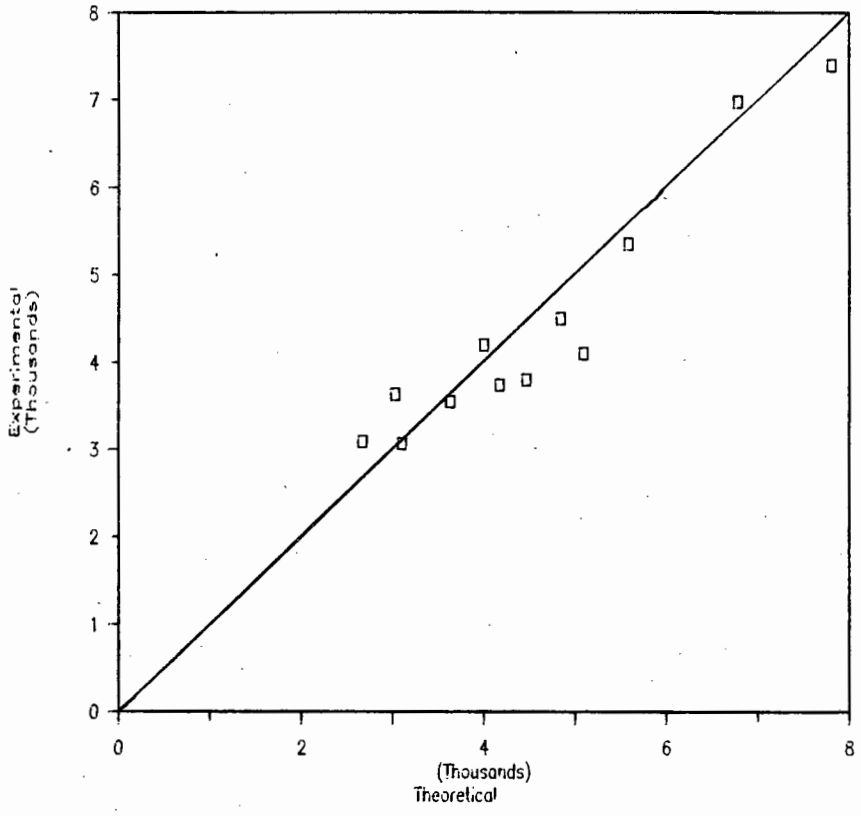

Fig 4.13: Correlation plot of theoretical versus observed mgSCFA (as COD)/ℓ (i.e. $SCFA'_{neff}$) in the effluent of the reactors in a completely mixed, semi-continuously fed reactor system, each reactor having a retention time of 1 day for batches of underflow sludge with different initial VSS (as COD) concentrations.

CHAPTER 5

SINGLE REACTOR, STEADY STATE SYSTEM

5.1 INTRODUCTION

In Chapter 3 acid fermentation in a batch reactor system was investigated, and in Chapter 4, a 3-in-series, completely mixed reactor system receiving a constant daily sludge load. The response behaviour of the first reactor (of 1 day retention time) in the series system showed that in this reactor the major part of the acid generation took place. It was decided therefore to investigate the single completely mixed reactor system more intensively, by enquiring into its behaviour at different retention times. Accordingly the objectives of this task were to:

(1) Measure the rate of acid production in reactors having retention times of 2, 3, 5, 6 and 9 days.

(2) Determine the fractions of the total 'soluble' COD concentration formed by (1) long chain macro-molecules, (2) –0,45μm filtrate and (3) SCFA's.

(3) Determine the sludge settleability at the different retention times.

(4) Check if there is any onset of methanogenesis at retention times of 6 and 9 days.

(5) Evaluate the acid fermentation model against the observed performance of the single reactor steady state system.

5.2 EXPERIMENTAL SET-UP

The apparatus consisted of three 3 litre perspex batch reactors identical to those used in the in-series investigation (see Fig 5.1). Polystyrene discs were floated on the liquid surface to prevent oxygen entry to the liquid medium. The apparatus was operated in a temperature controlled room at 20° C.

5.3 OPERATION

The investigation was done in two stages; in the first stage, the 3 reactors were operated at retention times of 2, 3 and 5 days and the second stage the 3 reactors

were operated at retention times of 3, 6 and 9 days. Each reactor was operated independently.

Seventy five litres of raw primary sludge were collected from the underflow primary sedimentation tank at the Mitchell's Plain Treatment Works (just prior to desludging at 10h00). On arrival at the laboratory the raw sludge was divided into approximate daily feed volumes and stored in plastic bags at –14° C. The frozen feed sludge was defrosted in the cold room, at 4° C, for 3 days prior to being fed into the reactors. The VSS of the sludge batches collected at the plant ranged from 36 000 to 53 000 mgVSS/ℓ, see Table 5.1, and were used undiluted.

To initiate the system, each reactor was filled to the 2,6 litre mark with the underflow sludge obtained from the full scale works. Feeding was twice daily as follows: Due to the viscous nature of the primary sludge, there was a measure of uncertainty to the efficiency of mixing. Thus, just prior to feeding (and sampling and wasting) the contents of each reactor were drained (from the bottom) and poured back into the top of the reactor to ensure a well mixed medium.

Depending on the retention time of a reactor, an appropriate volume of sludge was drained from the bottom of each reactor i.e. for 5 days retention time a total of 520 mℓ (i.e. 2600/5) of sludge was drained per day; feeding was twice a day i.e. 260 mℓ of sludge drained at every feed. Each reactor was then topped up to the 2,6 litre mark with raw sludge. From the volumes drained, two 50 mℓ samples were taken and centrifuged for testing; the remaining sludge used to measure the sludge settleability via the diluted sludge volume index (DSVI) test.

Testing was as follows: Influent and reactor 1 on one day, reactors 2 and 3 the following day, and the following parameters measured:

(1) pH.

(2) DSVI of the sludge.

(3) TSS and VSS concentrations of the sludge pellet obtained after centrifugation.

(4) VSS (as COD) concentration of the sludge pellet.

(5) Total 'soluble' COD of the supernatent obtained from (3) above after filtration through a Whatman's No.1 filter.

(6) COD of the filtrate from (5) above after filtration through a –0,45μm filter. On filtering through a –0,45μm filter a 'blinding effect' on the –0,45μm filter was observed. This 'blinding effect' appeared to be caused by the presence of long chain macro-molecules blocking up the –0,45μm filter paper. In order to determine the long chain macro-molecule concentration, the –0,45μm COD concentration was subtracted from the total 'soluble' COD concentration.

(7) TKN and NH_3-N concentrations of the –0,45μm filtrate, and

(8) SCFA concentrations of the –0,45μm filtrate.

Sampling techniques and measurement procedures are set out in Appendix A.

5.4 RESULTS

A total of 5 batches of raw sludge were tested; three batches under stage 1, and two batches under stage 2; the stages were run for 49 days and 51 days respectively. The results of all 5 batches are listed in Tables D.1 to D.8 in Appendix D. As stated before, the COD's of the total SCFA concentrations listed in Tables D.1 to D.8 were calculated using the conversion factors of Eastman and Ferguson (1981) listed in Table 3.1. Plots with respect to time of the following parameters were made for each raw sludge and each reactor and are shown in Appendix D:

(1) pH,
(2) DSVI,
(3) TSS and VSS concentrations,
(4) COD of the VSS concentrations,
(5) TKN and NH_3-N concentrations,
(6) Total 'soluble' COD, –0,45μm COD and SCFA (as COD) concentrations, and
(7) Acetic, propionic, butyric and valeric acid concentrations.

For each batch of raw sludge, average values for the above parameters were calculated and are listed in Table 5.1. From the data listed in Table 5.1 and plots of

these versus retention time (Figs 5.2 to 5.17), the following general observations can be made:

(1) pH – The pH decreased with increasing retention time [see Fig 5.2(a) and (b)]. The minimum pH observed in a reactor was 5,0.

(2) DSVI – Settleability improved with increasing retention time [see Fig 5.3(a) and (b)]. The DSVI's of the influent sludge and the fermented mixed liquor are extremely low, the low DSVI of the influent sludge most certainly was caused by freezing of the sludge batches, which was done to prevent fermentation in storage. The DSVI of the reactor contents, therefore, cannot be accepted as reflecting the settling behaviour of the influent sludge direct from a treatment plant without prior freezing. However, from the literature it can be inferred that acid fermentation does improve in settleability and compactability (Pitman and Lötter, 1986).

(3) TSS and VSS – The TSS and VSS concentrations decreased with increasing retention time [see Figs 5.4(a) and (b) and 5.5(a) and (b)].

(4) VSS (as COD) – The COD of the VSS concentration decreased with increasing retention time [see Fig 5.6(a) and (b)].

(5) TKN and NH_3-N – Both these concentrations increased with increasing retention time [see Figs 5.7(a) and (b) and 5.8(a) and (b)].

(6) Total 'soluble' COD – The total 'soluble' COD concentration increased with increasing retention time [see Fig 5.9(a) and (b)]. From correlation plots of –0,45μm COD versus total 'soluble' COD (see Figs 5.10 and 5.11), a close correlation is evident. The –0,45μm COD constitutes approximately 88 percent of the total 'soluble' COD of the raw sludge (see Fig 5.10). In the individual reactors, the –0,45μm COD constitutes approximately 63 percent of the total 'soluble' COD (see Fig 5.11) – there is an increase in long chain macro-molecule concentrations of approximately 25 percent upon anaerobic fermentation of the raw sludge.

(7) –0,45μm COD – The –0,45μm COD concentration increased with increasing retention time [see Fig 5.12(a) and (b)].

(8) SCFA – The SCFA (as COD) concentration increased with increasing retention time [see Fig 5.13(a) and (b)]. Further important observations are:

(i) No lag or delay period in SCFA generation was observed during this investigation.

(ii) In Figs 5.14 and 5.15, correlation plots of the SCFA (as COD) versus total 'soluble' COD concentrations are shown for the influent and reactor contents respectively. There is a close correlation between the SCFA (as COD) and total 'soluble' COD for the reactors contents, but only a poor correlation for the influent sludge. For the reactor contents the SCFA (as COD) constitutes about 53 percent of the total 'soluble' COD (see Fig 5.15).

(iii) In Figs 5.16 and 5.17, correlation plots of the SCFA (as COD) versus –0,45μm COD concentrations are shown. As found in the in-series experiment, there is a close correlation between these parameters for the reactor contents, whereas for the influent the correlation was much poorer. In the raw sludge the SCFA's (as COD) formed approximately 66 percent of the –0,45μm COD (see Fig 5.16), and in the individual reactors 85 percent (see Fig 5.17). In the in-series experiments these values were 58 and 67 percent respectively. It is difficult to find a reason why the in-series and single reactor studies show such large differences. The only significant differences that can be noted were in the feed sludge constitution – in the single reactor study the butyric and valeric acid concentrations were high compared to the in-series reactor, study, see (iv) below.

(iv) Acetic and propionic acids were the major acids generated; other acids generated were butyric and valeric. In the reactors the averaged ratios of acetic:propionic:butyric:valeric acids (as COD) were 1:1,4:0,5:0,6. In the raw sludge, of batches 1, 2 and 3, the ratios of acetic:propionic:butyric:valeric acids (as COD) were 1:1,4:1,4:1,0.

(v) No decrease in SCFA concentration with time was observed in any of the tests. It is unlikely therefore that methanogenesis was operational during these experiments, possibly due to inhibition of the growth of methanogenes caused by the low pH's. A white fungus grew on the top of the polystyrene discs floating on the liquid surface, but this did not appear to affect the SCFA concentration. The fungus was cleaned off approximately once a week.

5.5 MODELLING OF SCFA GENERATION

In Chapter 4 (section 5.1) the basic model for an in-series acid fermenter reactor system was developed, (Eq 4.7) i.e.

$$SCFA'_{nvo} = (0{,}17 - SCFA'_{ovo})\left(1 - \frac{1}{(1+0{,}16R)^n}\right) + SCFA'_{ovo}$$

where

$SCFA'_{nvo}$ = mgSCFA (as COD)/mg initial VSS (as COD) in the effluent from the n^{th} reactor.

$SCFA'_{ovo}$ = mg initial SCFA (as COD)/mg initial VSS (as COD) concentration.

R = retention time in each reactor, d.

n = number of reactors.

In Fig 5.18, the mgSCFA (as COD)/mg initial VSS (as COD) ratios in reactor effluent for each batch of raw sludge are shown plotted against retention time for the single completely mixed reactor system. From a visual observation of Fig 5.18, it appears that SCFA (as COD) generation is a first order type reactor similar to that of the in-series, completely mixed, reactor system. Thus theoretically, Eq (4.7) also should be valid for a single reactor system i.e. n = 1.

$$SCFA'_{nvo} = (0{,}17 - SCFA'_{ovo})\left(1 - \frac{1}{(1+0{,}16R)}\right) + SCFA'_{ovo} \qquad (5.1)$$

From Fig 5.18, a mean value for $SCFA'_{ovo}$ was estimated at 0,048 mg initial SCFA (as COD)/mg initial VSS (as COD).

In Fig 5.19, a correlation plot is shown of the theoretical $SCFA'_{nvo}$ values versus the experimentally observed values for the 2, 3, 5, 6 and 9 day retention time. Also

included is the theoretical and experimental values for the 1st reactor in the in-series system, at 1 day retention time, from Chapter 4. From Fig 5.19 a very good correlation is evident. Also, as

$$SCFA_{neff} = SCFA'_{nvo} \cdot X'_{vo} \quad (5.2)$$

(see Eq 4.8), the associated theoretical $SCFA'_{neff}$ concentrations can easily be determined. In Fig 5.20, a correlation plot of the theoretical $SCFA_{neff}$ values versus experimental $SCFA_{neff}$ values is shown. Again a good correlation is obtained.

5.6 CONCLUSIONS

In the investigation into the production of SCFA's in single steady state reactors, the following conclusions are pertinent:

(1) No lag period in SCFA generation was observed for sludge age as low as 2 days.

(2) Throughout the period the system was in operation, the pH never declined below 5,3 for raw sludge VSS concentrations ranging from 36 000 to 53 000 mgVSS/ℓ.

(3) The responses in the single reactors of different retention times were as consistent as the responses observed down the in-series reactor system.

(4) As the retention time increased

- (i) The VSS concentration decreased.
- (ii) The sludge settleability improved i.e. the DSVI decreased.
- (iii) The VSS (as COD) concentration decreased.
- (iv) The TKN and NH_3-N concentrations increased.
- (v) The total "soluble", –0,45μm and SCFA COD concentrations increased.

(5) There were close correlations between the total "soluble" COD and (i) –0,45μm COD, and (ii) total SCFA's (as COD) in the reactor contents

(6) The long chain macro-molecule concentration increased by about 25 percent

upon anaerobic fermentation of primary sludge.

(7) A close correlation exists between the –0,45μm COD and the SCFA (as COD). The SCFA's (as COD) constitute approximately 66 percent of the raw sludge –0,45μm COD and 85 percent of the –0,45μm COD in the reactors.

(8) The major acids produced were acetic and propionic with butyric and valeric acids also present. The averaged ratios of acetic:propionic:butyric:valeric acids (as COD) were 1:1,4:0,5:0,6.

(9) No decrease in SCFA concentration due to methanogenesis was observed during the time period the system was operational.

(10) The rate of SCFA (as COD) generation in the single reactor of different retention times could be estimated closely by the steady state model developed for the in-series reactor system, i.e. Eq (5.1)

$$SCFA'_{nvo} = (0,17 - SCFA'_{ovo})\left(1 - \frac{1}{(1+0,16R)}\right) + SCFA'_{ovo}$$

where R = retention time in days and $SCFA'_{ovo} = 0,048$.

Table 5.1: **Results on a single completely mixed reactor.**

Reactor and Batch number	pH	DSVI ml/g	TSS mgTSS/l	VSS mgVSS/l	VSS (as COD) mgCOD/l	TKN mgN/l	NH3-N mgN/l	Total "soluble" COD mgCOD/l	-0.45um COD mgCOD/l	SCFA (as COD) mgCOD/l	Acetic acid mgHAc/l	Propionic acid mgHPr/l	Butyric acid mgHBu/l	Valeric acid mgHVa/l
Stage 1														
Influent														
1	5.6	59.1	45000	39900	57400	255	169	4300	3800	3170	665	757	443	251
2	5.9	61.5	46700	41000	60200	366	210	4690	4380	2860	510	556	473	308
3	6.0	59.3	40600	36300	50534	291	187	3960	3645	2920	619	616	434	256
REACTOR 1	R=2 DAYS													
1	5.4	57.2	40200	35800	52600	363	300	9800	5640	4800	1127	1327	442	380
2	5.2	61.7	40900	36300	54000	434	367	10150	6060	4590	1210	1284	390	341
3	5.5	56.5	37900	33900	43300	349	294	8230	5460	4794	1153	1345	428	341
REACTOR 2	R=3 DAYS													
1	5.2	55.9	41000	36600	56400	362	316	10380	5840	5120	1280	1446	429	400
2	5.2	60.7	42000	36800	59600	424	370	9920	6360	5100	1433	1362	425	392
3	5.4	57.7	37000	33400	50200	334	297	8760	5340	4950	1333	1321	439	350
REACTOR 3	R=5 DAYS													
1	5.2	57.5	39000	34900	53100	367	326	11940	6780	5860	1468	1723	470	396
2	5.0	50.0	40900	35400	59000	437	370	11880	7200	5860	1708	1550	466	438
3	5.4	56.6	34200	30500	43000	370	323	10060	6100	5500	1452	1590	617	496
Stage 2														
Influent														
1	6.1	62.0	41600	36500	50200	287	203	4100	3700	2200	598	660	208	96
2	6.1	54.0	61800	53100	67900	389	229	6200	5300	2300	612	657	252	90
REACTOR 1	R=3 DAYS													
1	5.4	61.6	37500	33000	49500	350	304	8800	5600	5000	1442	1287	411	361
2	5.6	53.8	60250	52100	59400	458	398	11000	7700	6200	1554	1665	523	498
REACTOR 2	R=6 DAYS													
1	5.4	58.4	37600	33200	44500	361	325	10600	6700	6000	1652	1625	461	435
2	5.6	50.5	57600	49800	60600	513	452	11700	8200	6800	1774	1829	564	547
REACTOR 3	R=9 DAYS													
1	5.3	56.3	37800	33400	48700	393	354	11900	7400	6500	1776	1796	514	474
2	5.5	47.5	56900	48700	50500	549	482	13100	9100	7400	1880	2038	610	613

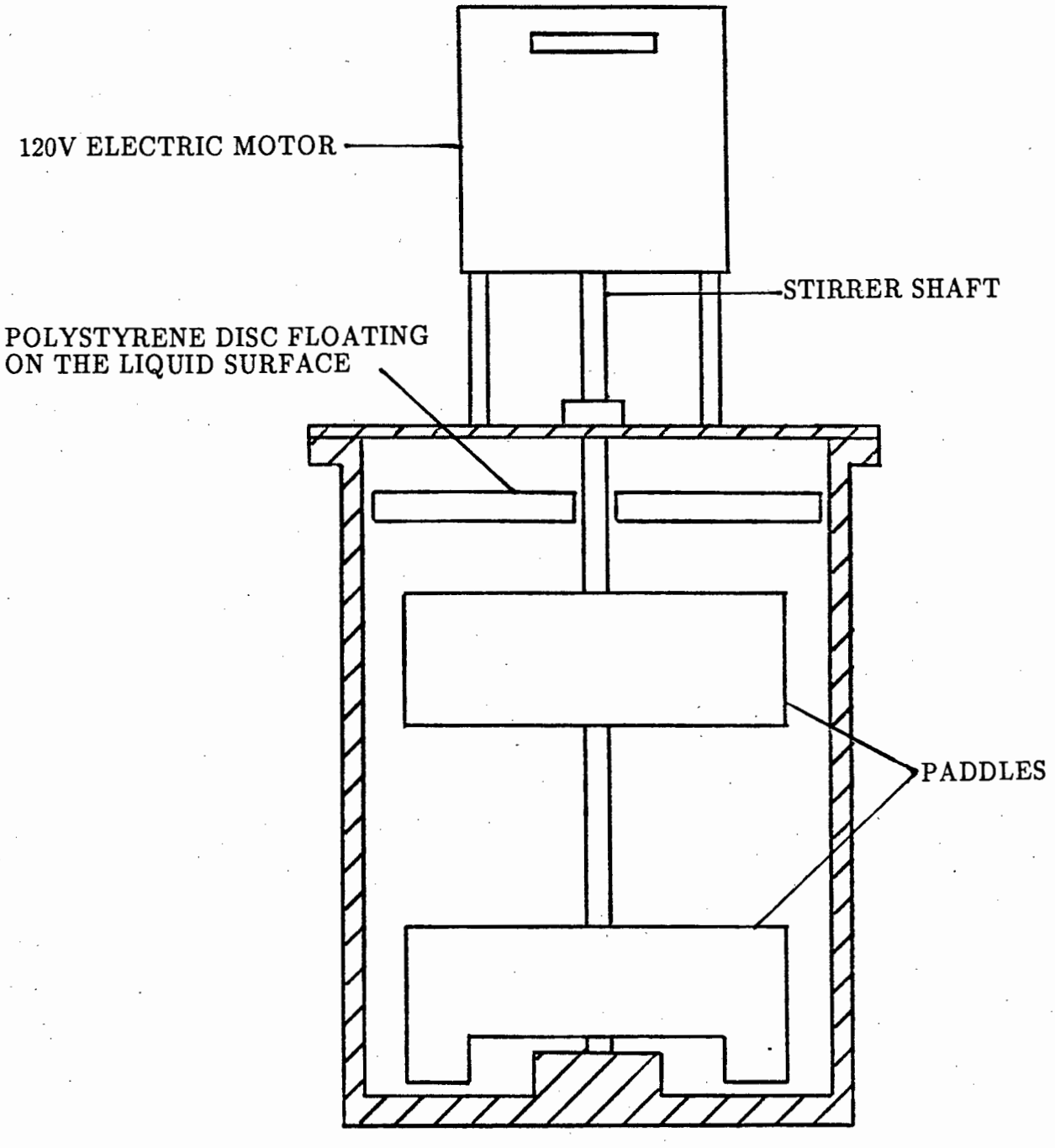

Fig 5.1: Schematic of one of the 3 litre perspex reactors used in the single reactor, steady state investigation.

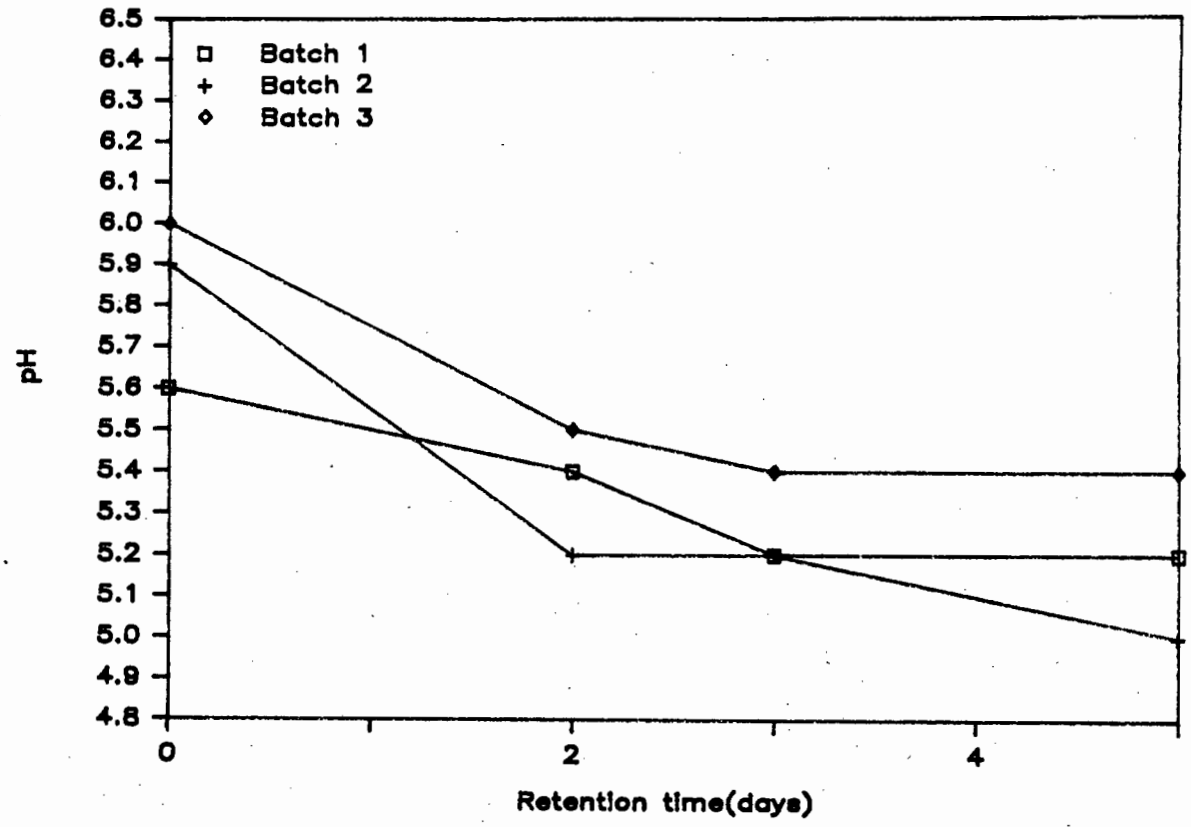

Fig 5.2(a): Average pH versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

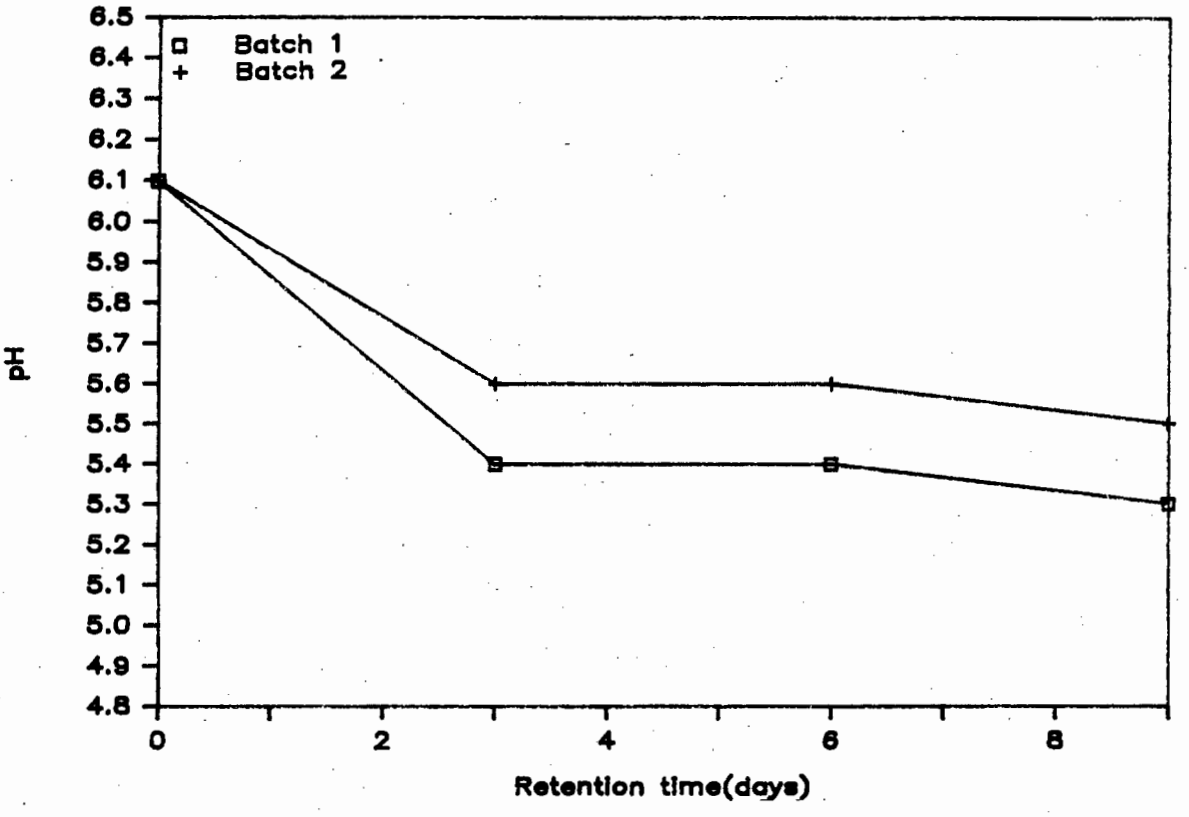

Fig 5.2(b): Average pH versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

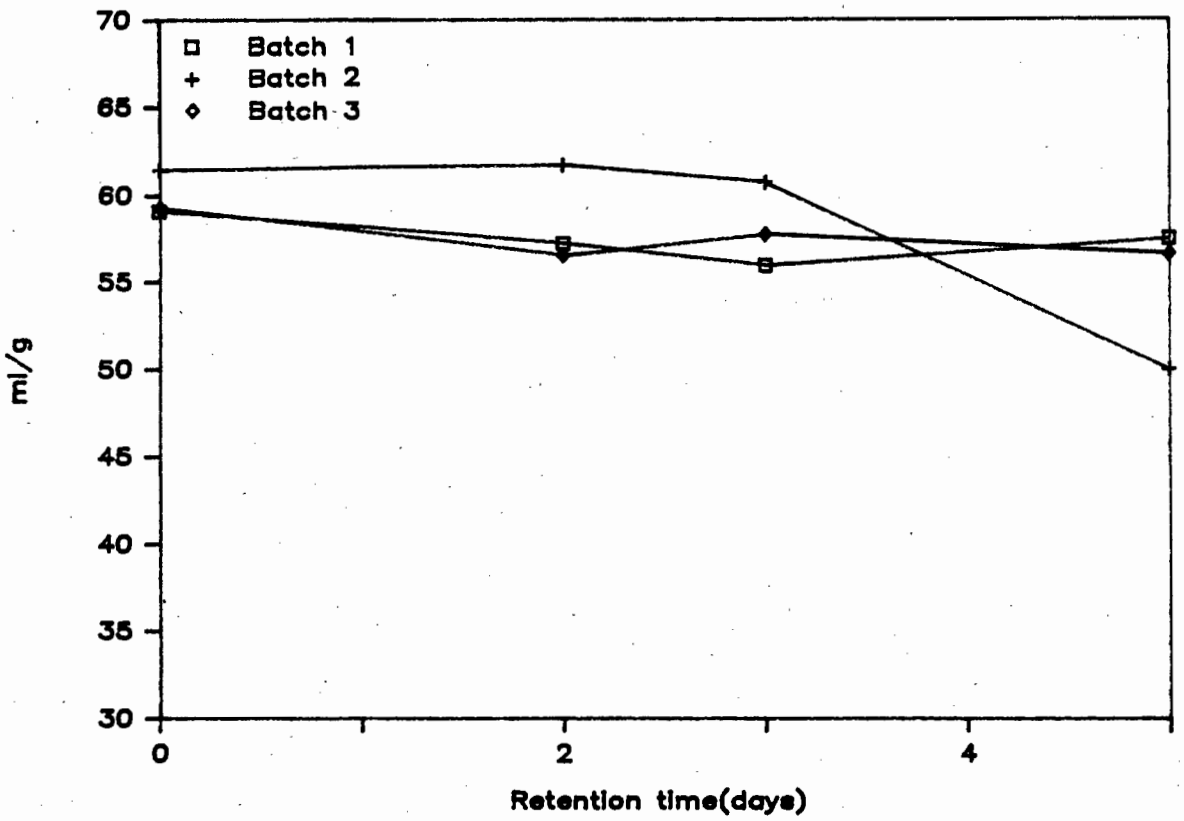

Fig 5.3(a): Average DSVI versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

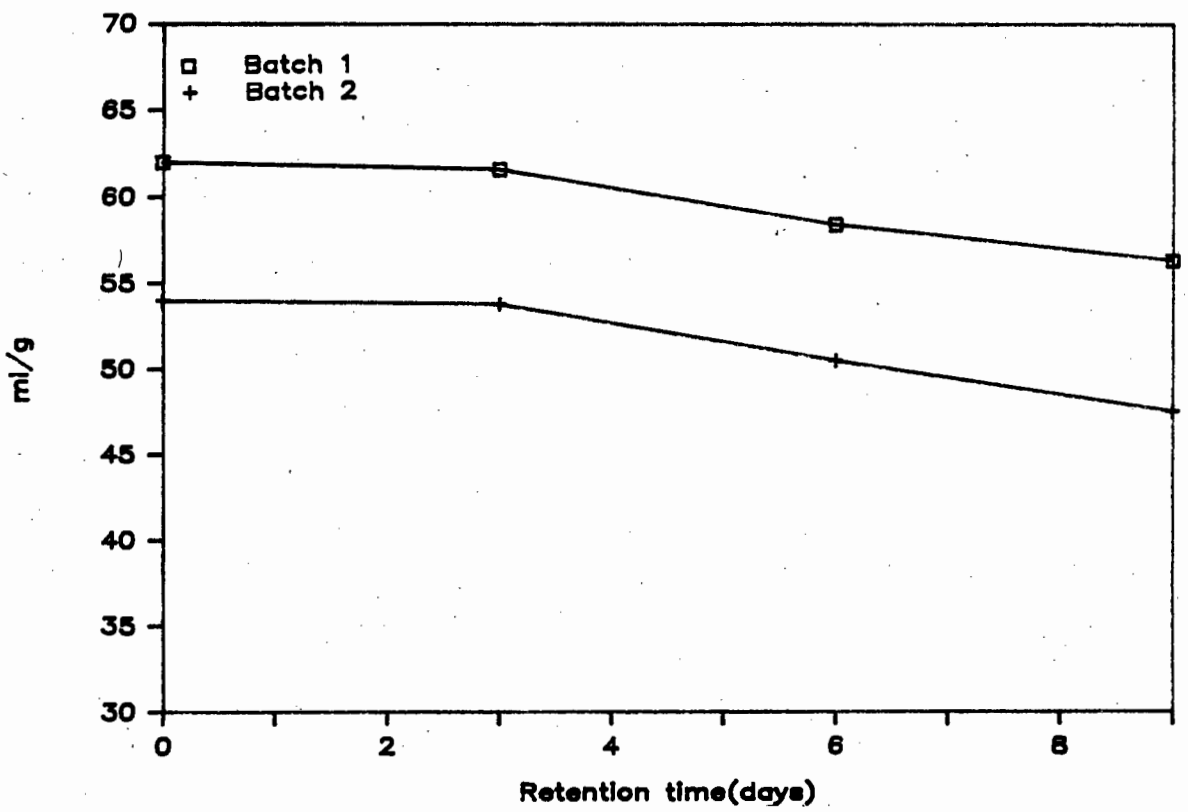

Fig 5.3(b): Average DSVI versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

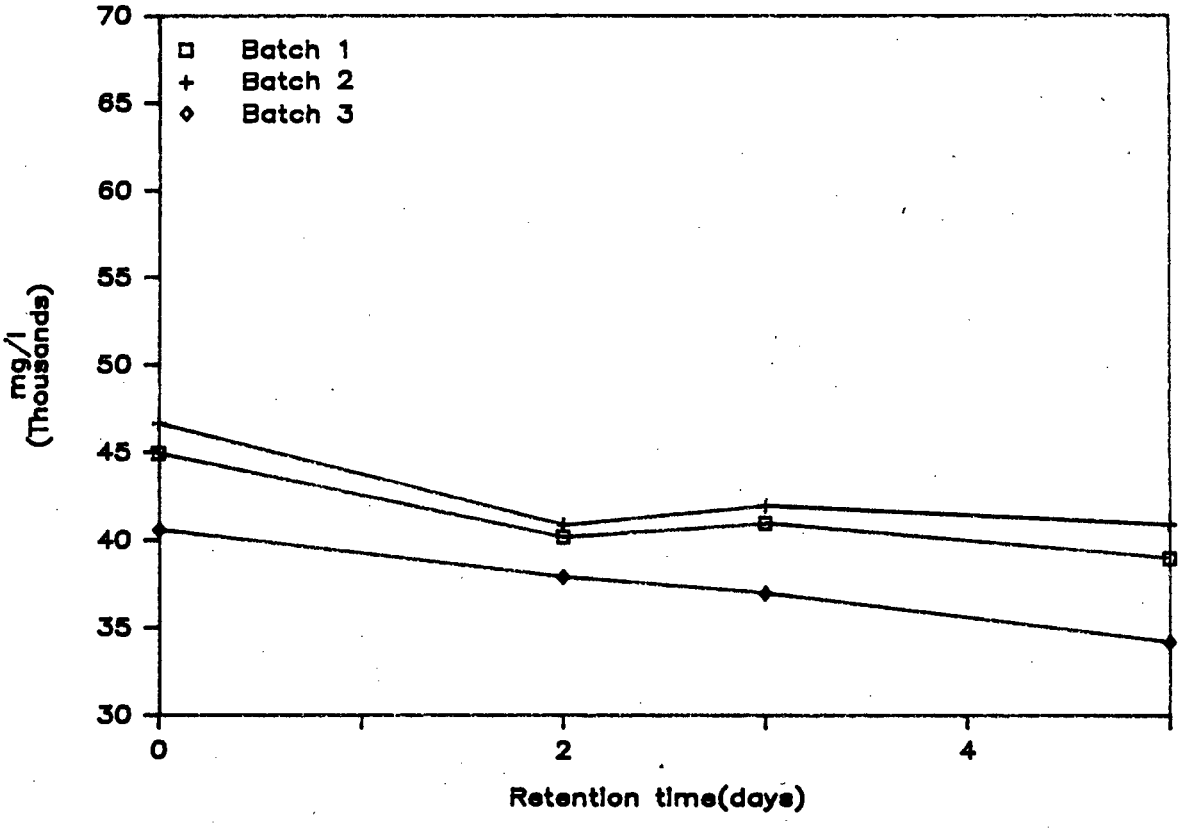

Fig 5.4(a): Average TSS concentrations versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

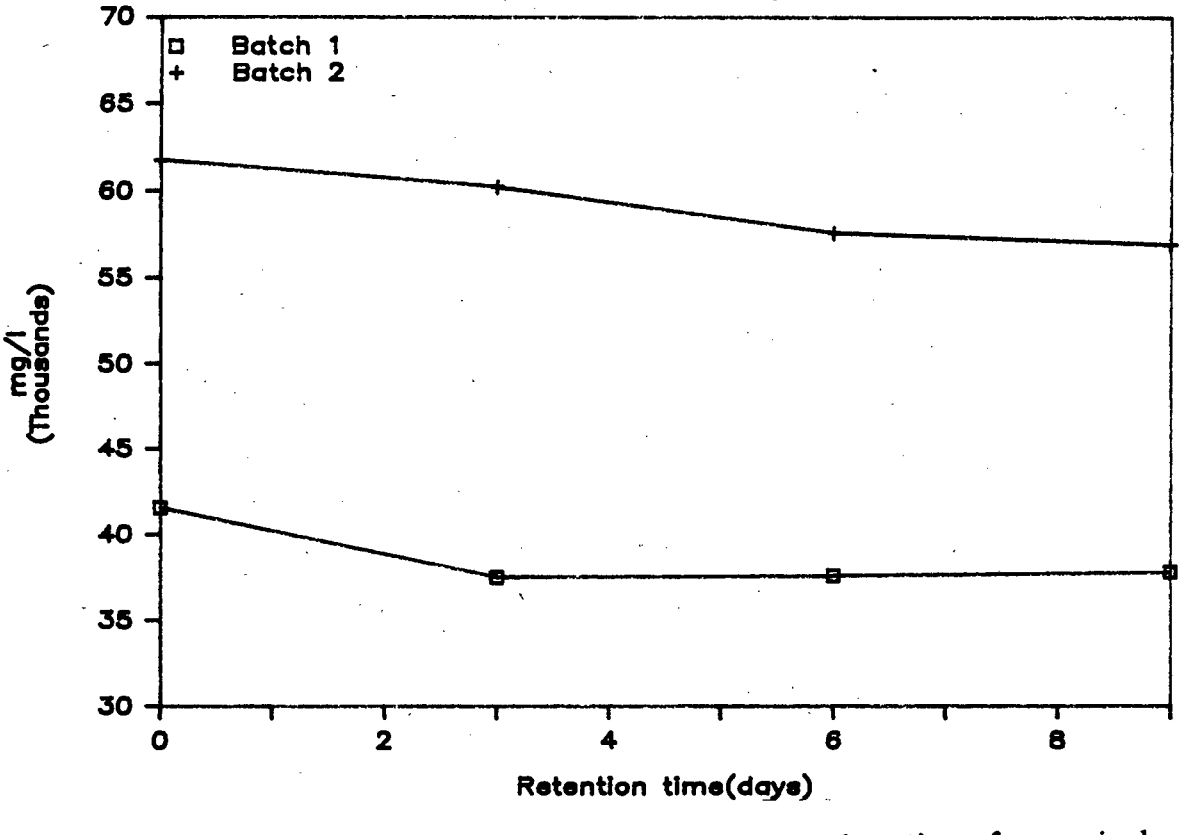

Fig 5.4(b): Average TSS concentrations versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

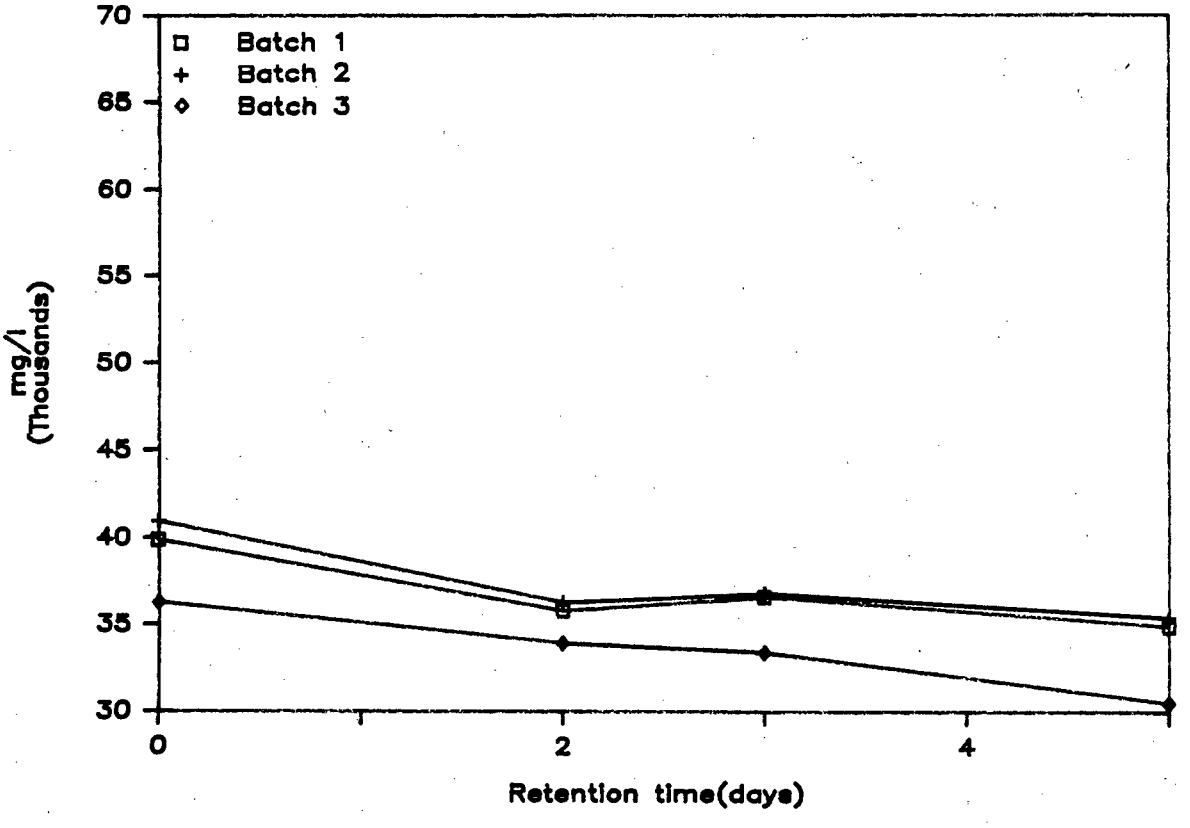

Fig 5.5(a): Average VSS concentrations versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

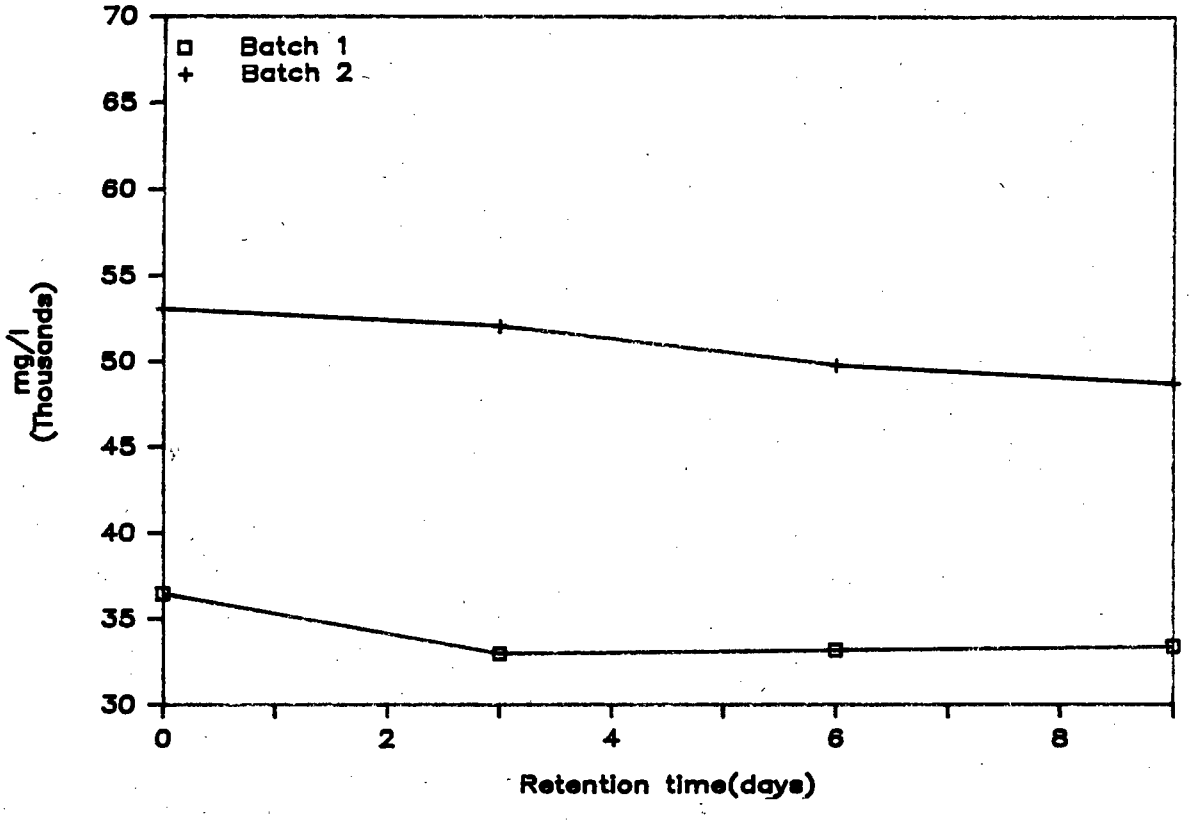

Fig 5.5(b): Average VSS concentrations versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

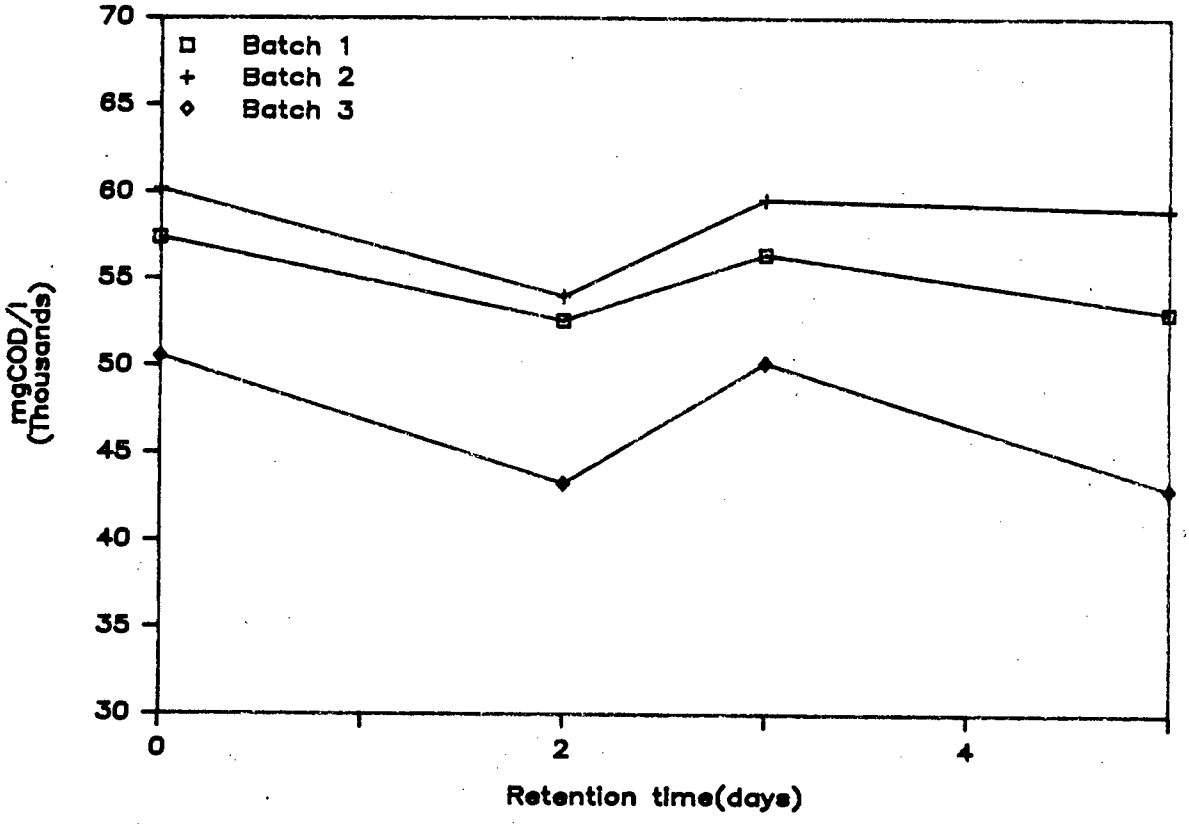

Fig 5.6(a): Average COD of the VSS concentrations versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

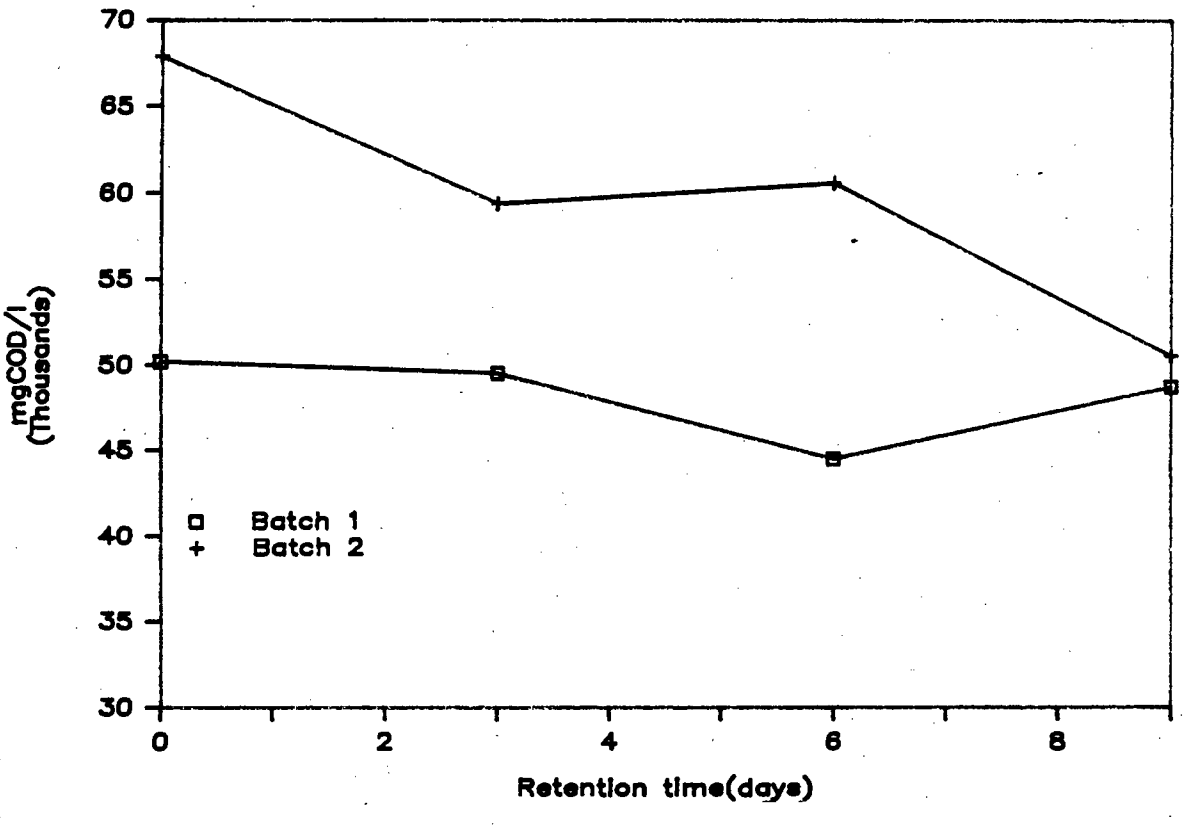

Fig 5.6(b): Average COD of the VSS concentrations versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

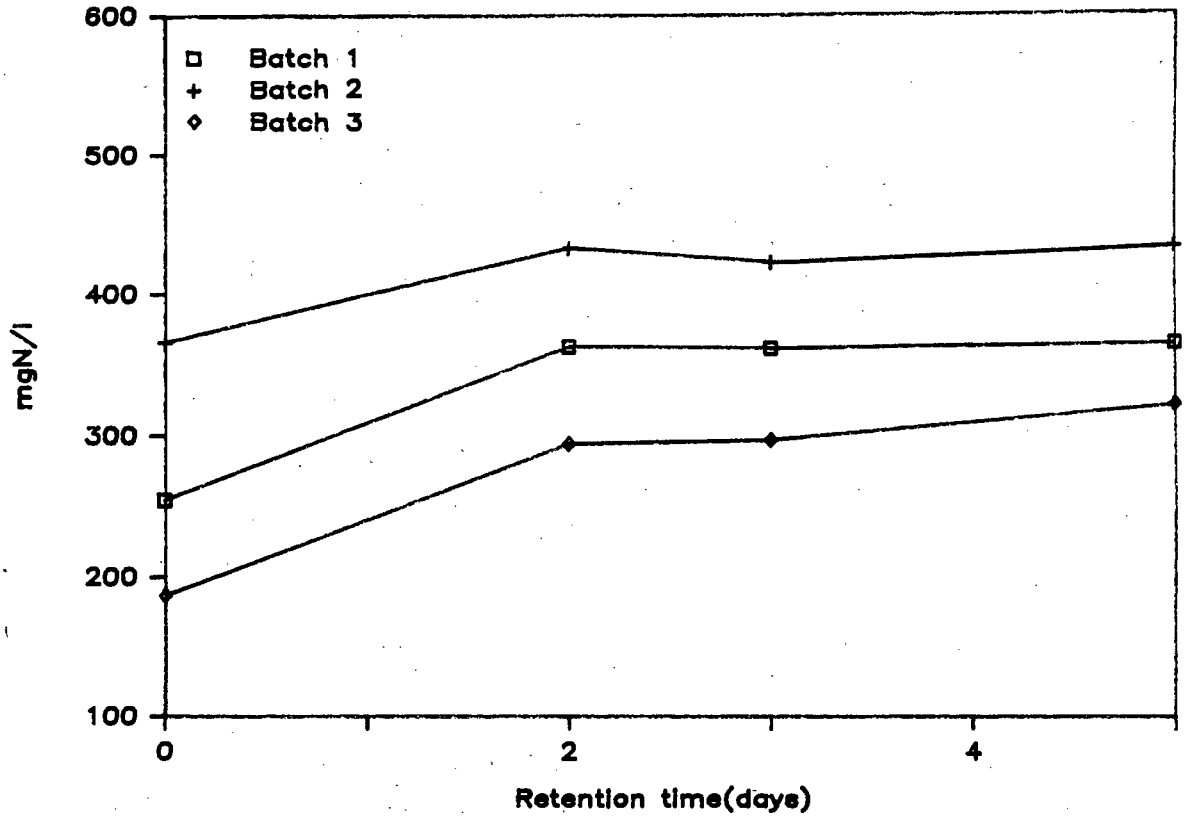

Fig 5.7(a): Average TKN concentrations of the –0,45μm filtrate versus retention time for a single, completely mixed reactor system of retention times 2, 3, and 5 days, for all batches of sludge.

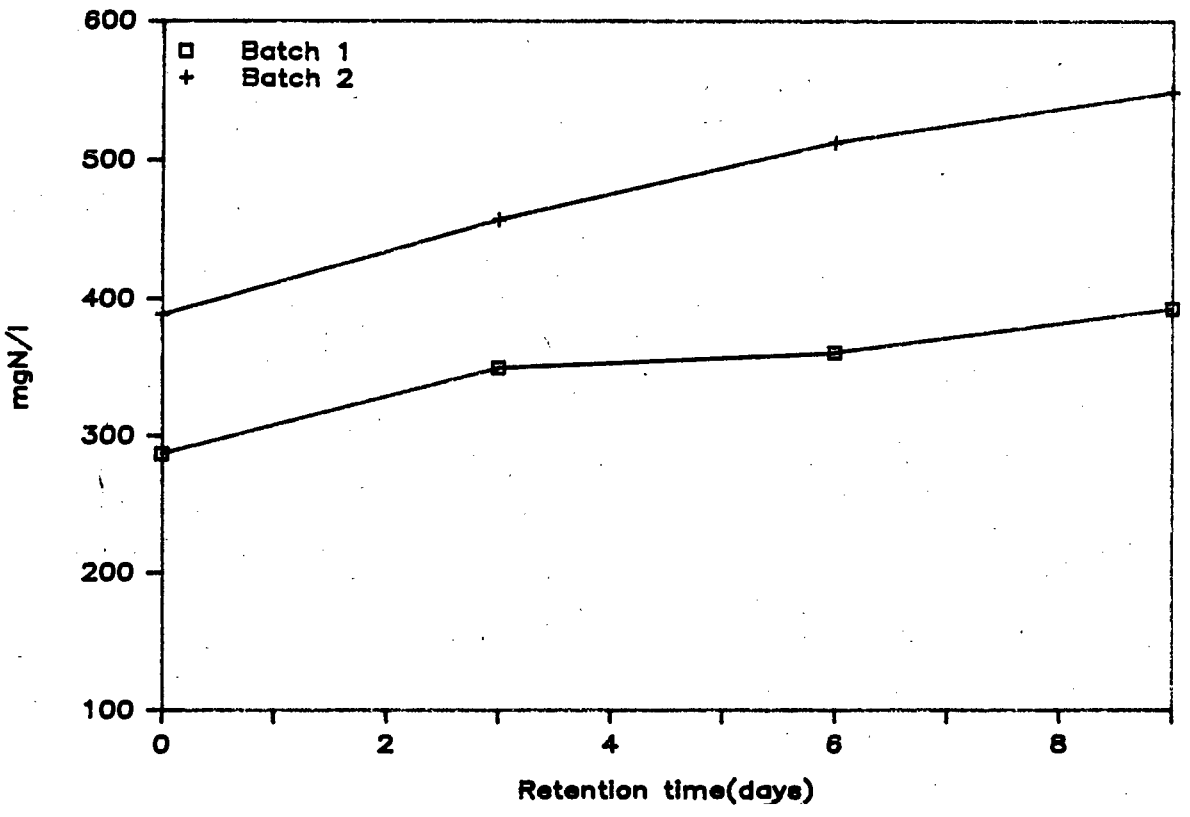

Fig 5.7(b): Average TKN concentrations of the –0,45μm filtrate versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

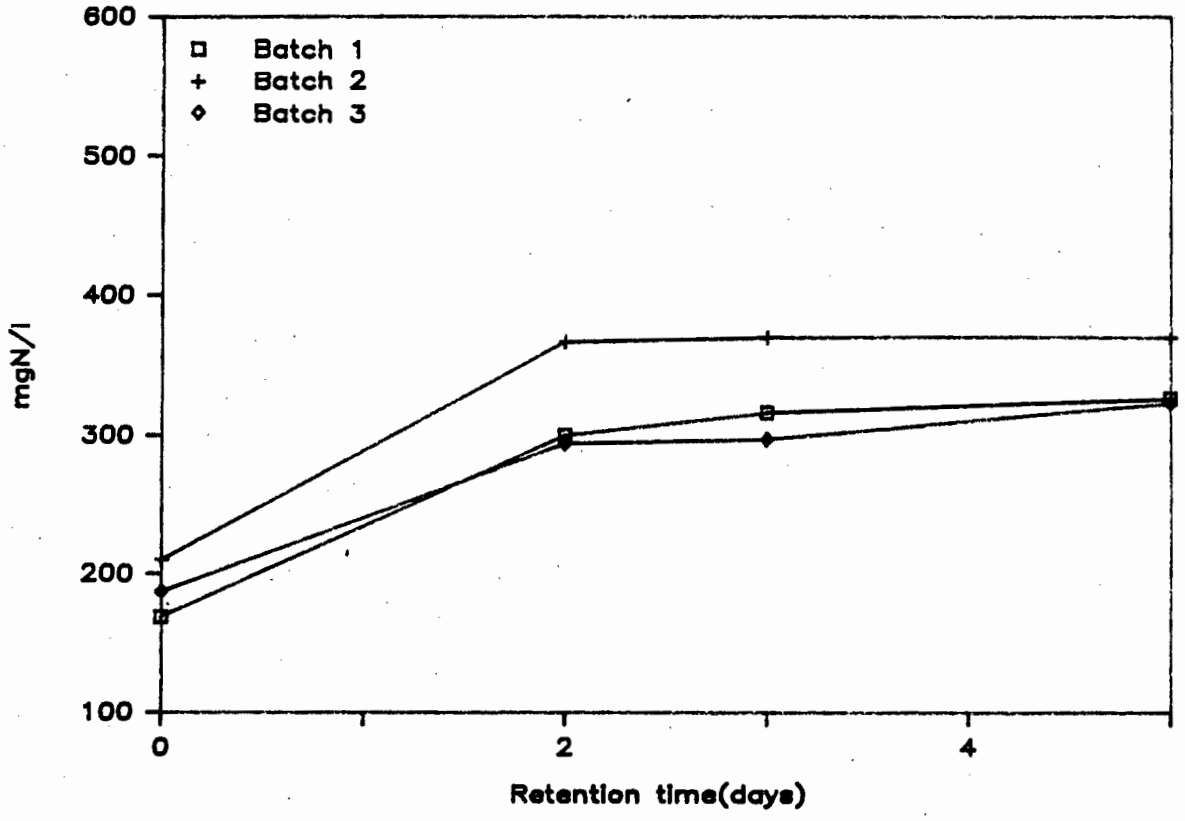

Fig 5.8(a): Average NH_3-N concentrations of the –0,45μm filtrate versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

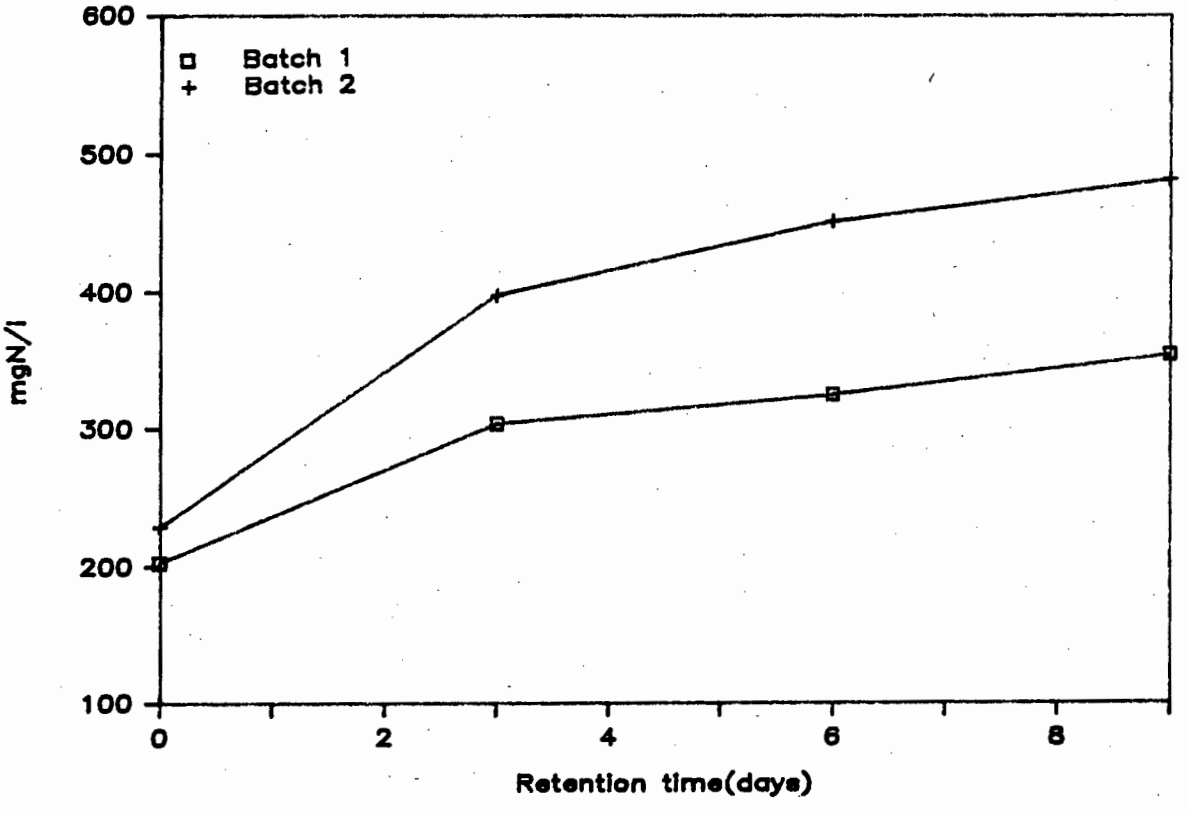

Fig 5.8(b): Average NH_3-N concentrations of the –0,45μm filtrate versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

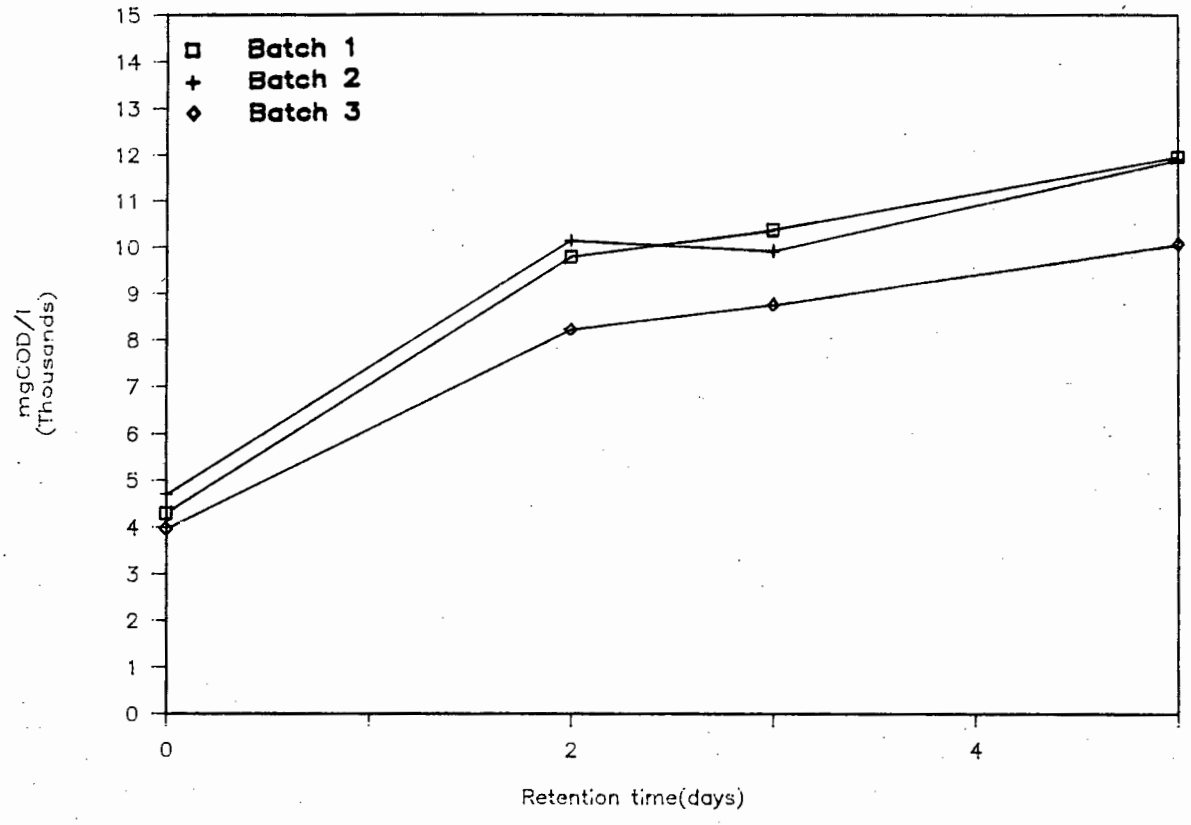

Fig 5.9(a): Average total 'soluble' COD concentrations versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

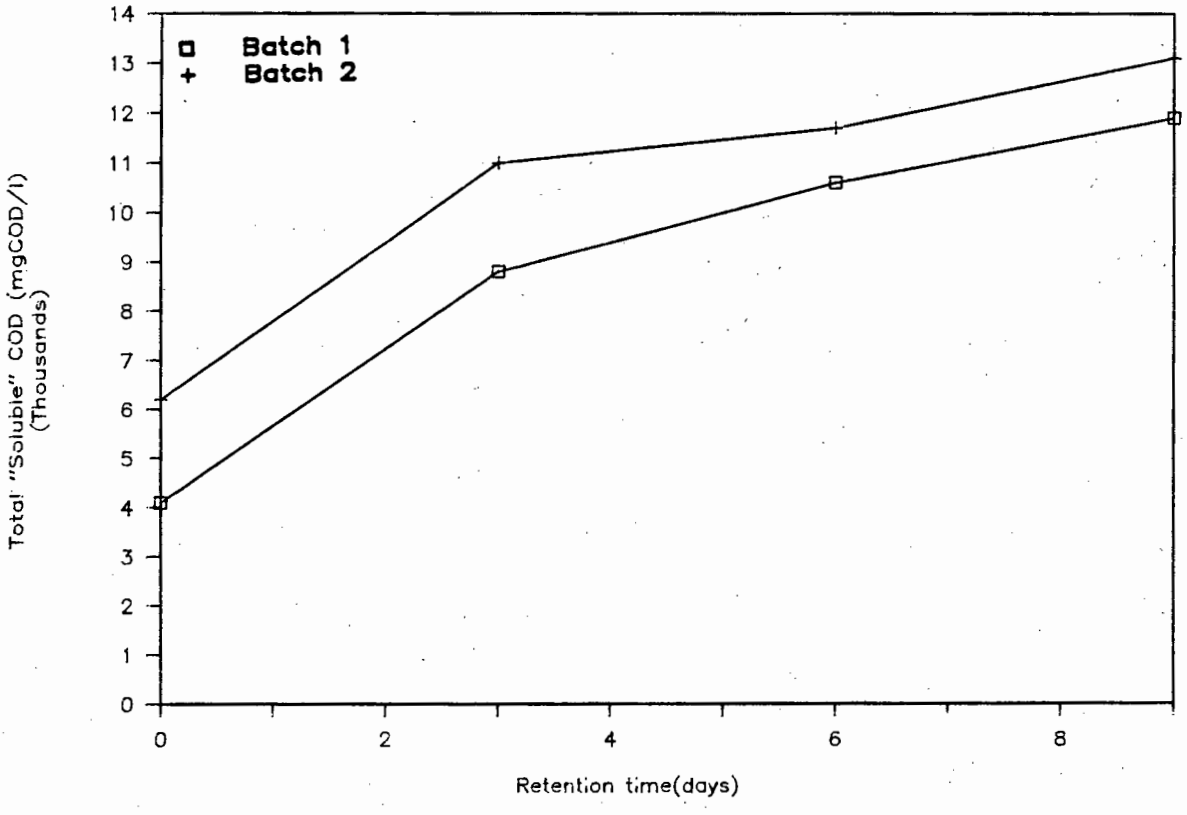

Fig 5.9(b): Average total 'soluble' COD concentrations versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

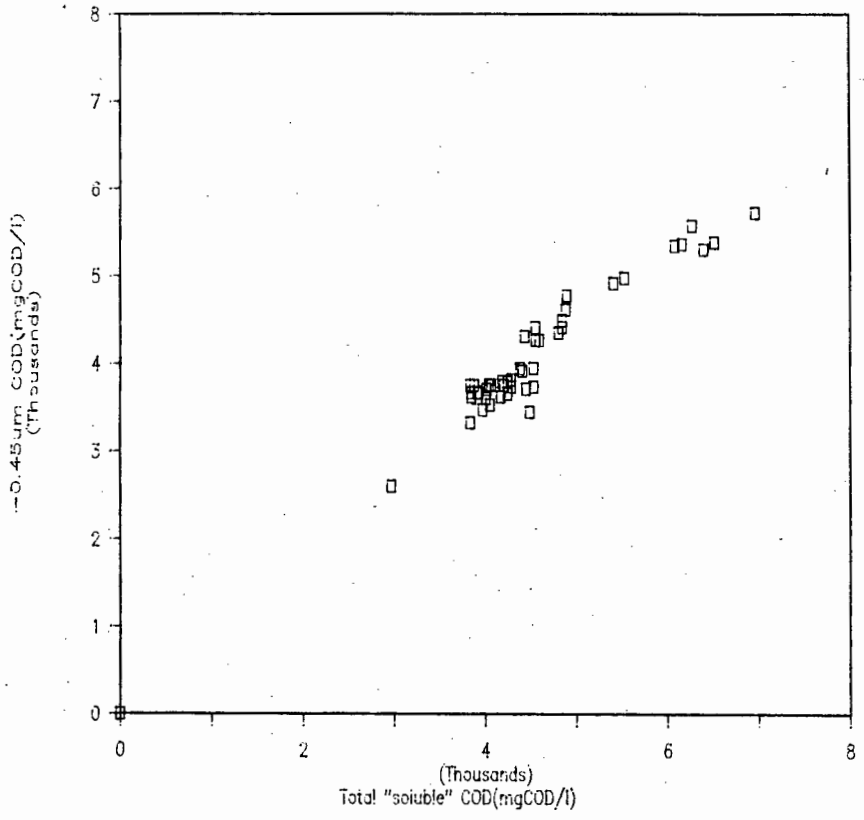

Fig 5.10: Correlation plot of the average –0,45μm COD concentrations versus average total 'soluble' COD concentrations for the influent of a single, completely mixed reactor system, for all batches of sludge.

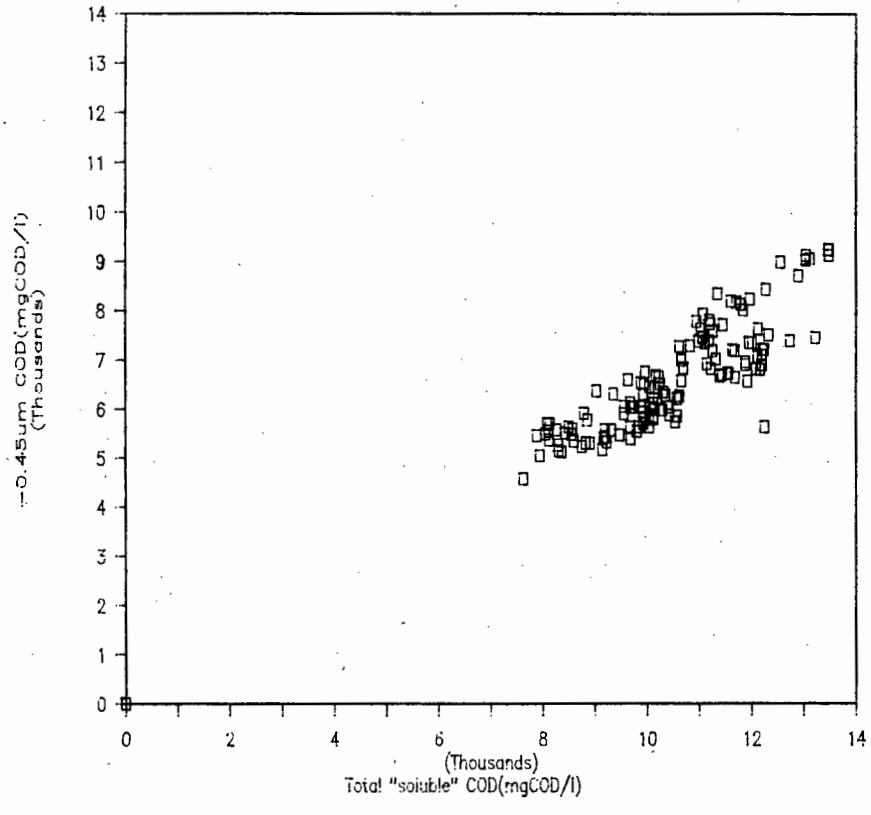

Fig 5.11: Correlation plot of average –0,45μm COD concentrations versus average total 'soluble' COD concentrations of a single, completely mixed reactor system of 2, 3, 5, 6 and 9 days retention time, for all batches of sludge.

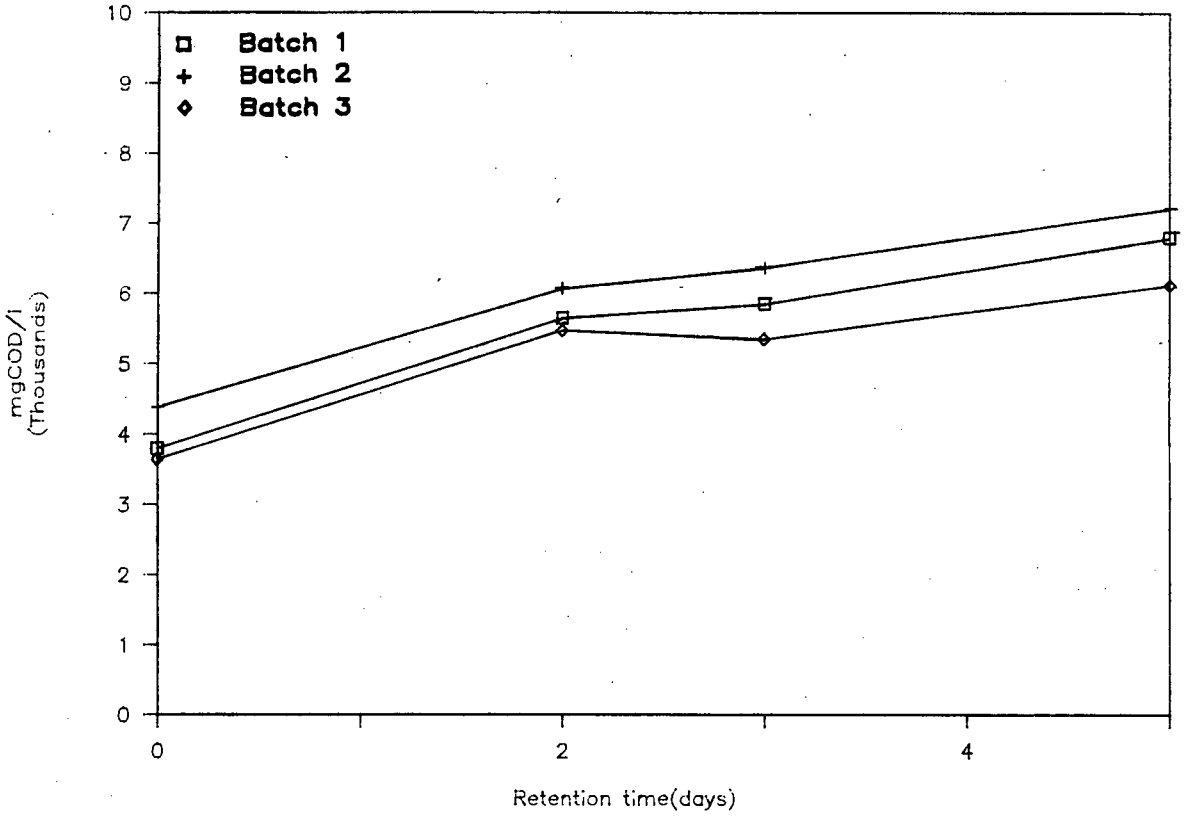

Fig 5.12(a): Average –0,45μm COD concentrations versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

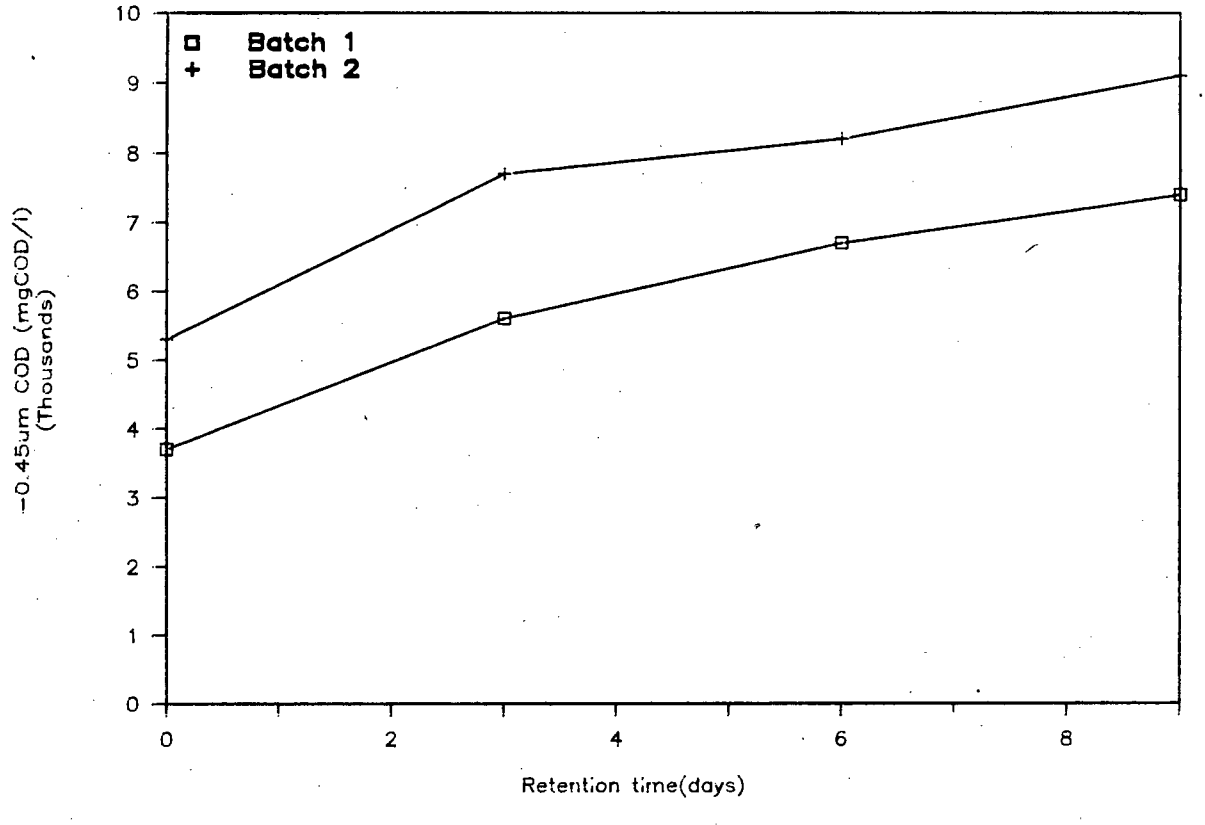

Fig 5.12(b): Average –0,45μm COD concentrations versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

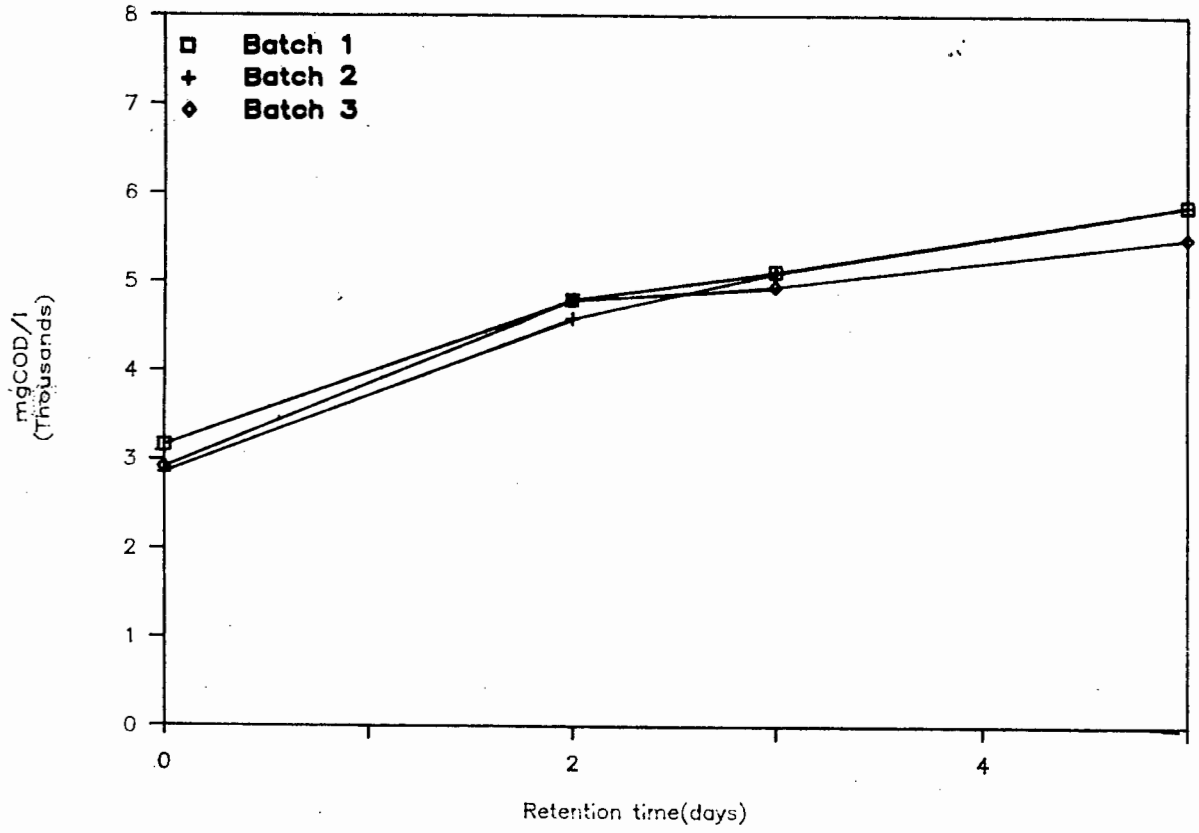

Fig 5.13(a): Average SCFA (as COD) concentrations versus retention time for a single, completely mixed reactor system of retention times 2, 3 and 5 days, for all batches of sludge.

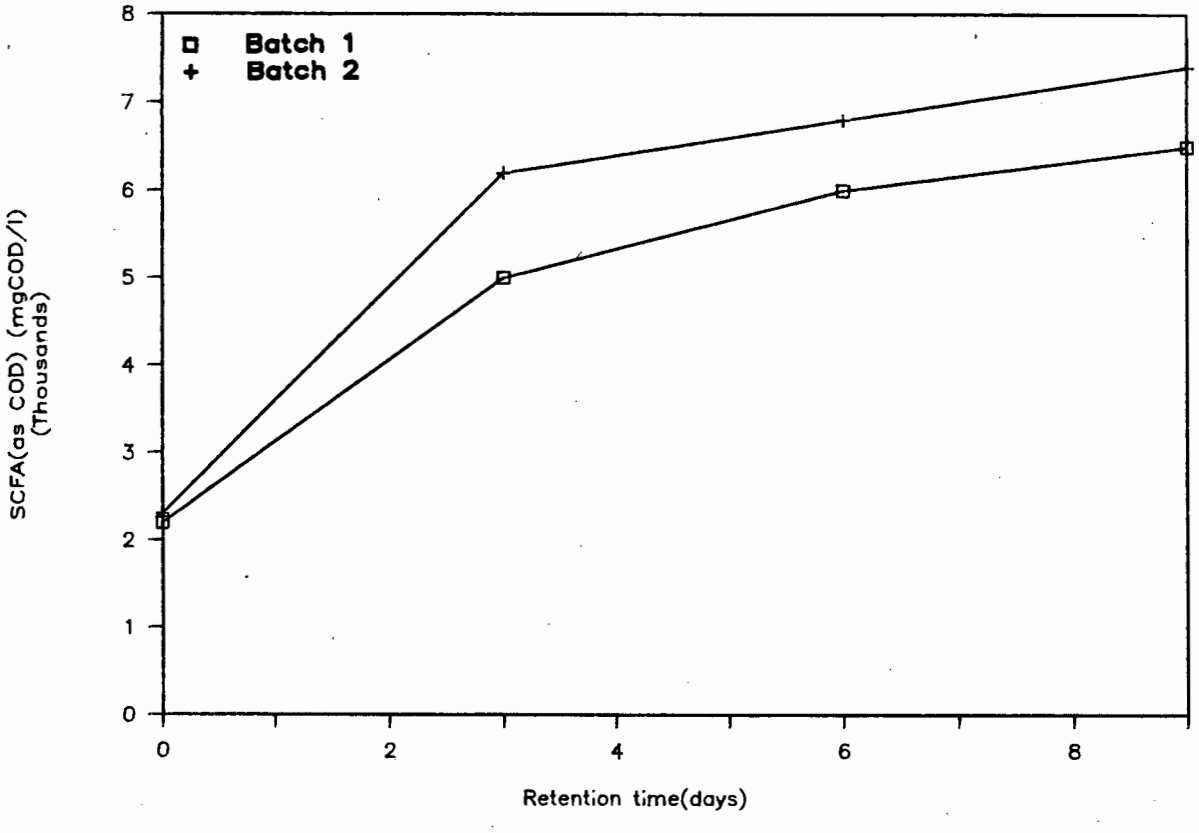

Fig 5.13(b): Average SCFA (as COD) concentrations versus retention time for a single, completely mixed reactor system of retention times 3, 6 and 9 days, for all batches of sludge.

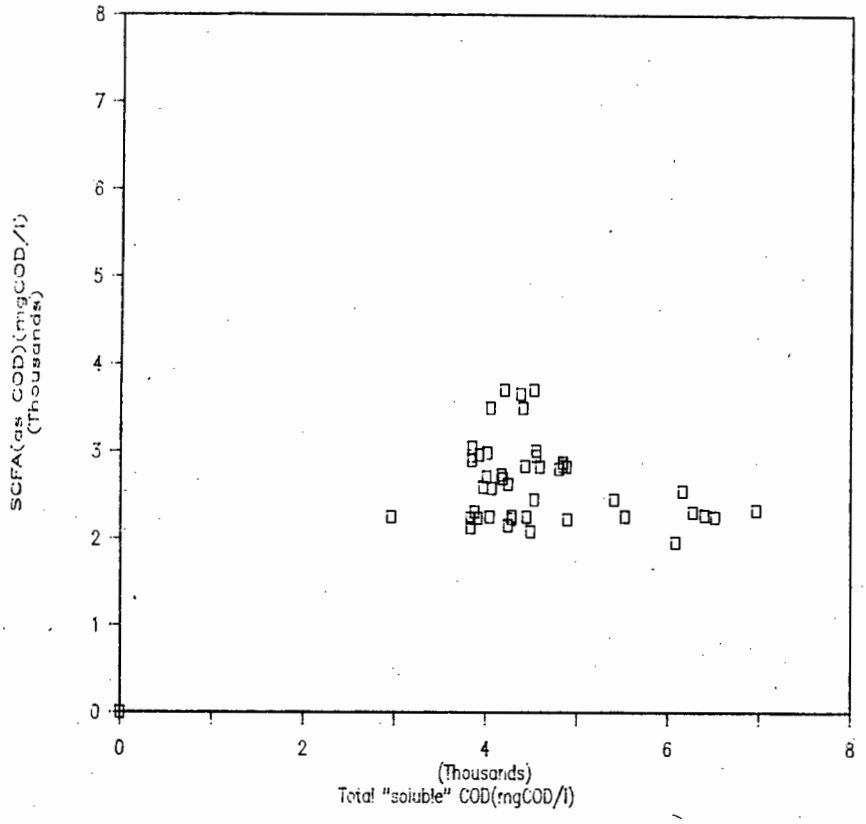

Fig 5.14: Correlation plot of average SCFA COD concentrations versus average total 'soluble' COD concentrations for the influent of a single, completely mixed reactor system, for all batches of sludge.

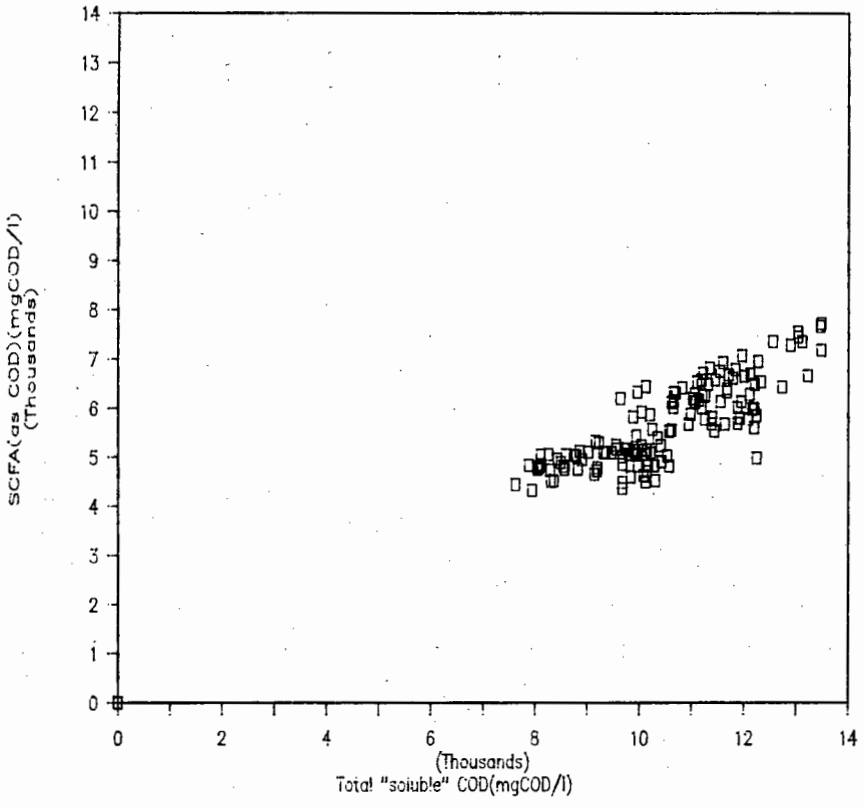

Fig 5.15: Correlation plot of average SCFA COD concentrations versus average total 'soluble' COD concentrations of a single, completely mixed reactor system of 2, 3, 5, 6 and 9 days retention time, for all batches of sludge.

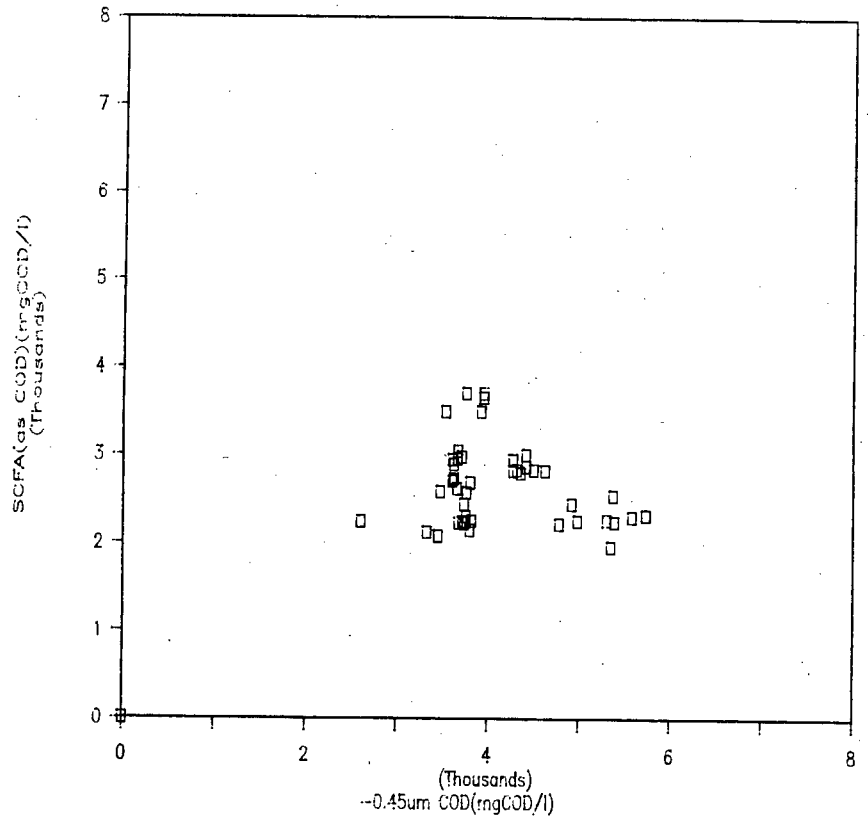

Fig 5.16: Correlation plot of average SCFA COD concentrations versus average –0,45μm COD concentrations for the influent of a single, completely mixed reactor system, for all batches of sludge.

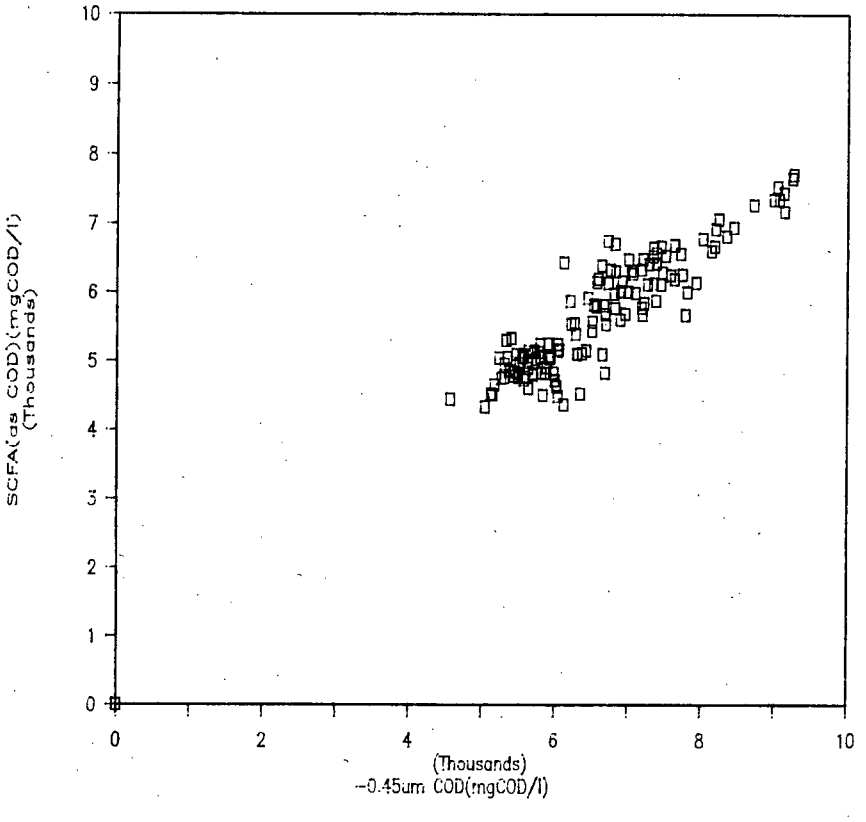

Fig 5.17: Correlation plot of average SCFA COD concentrations versus average –0,45μm COD concentrations of a single, completely mixed reactor system of 2, 3, 5, 6 and 9 days retention time, for all batches of sludge.

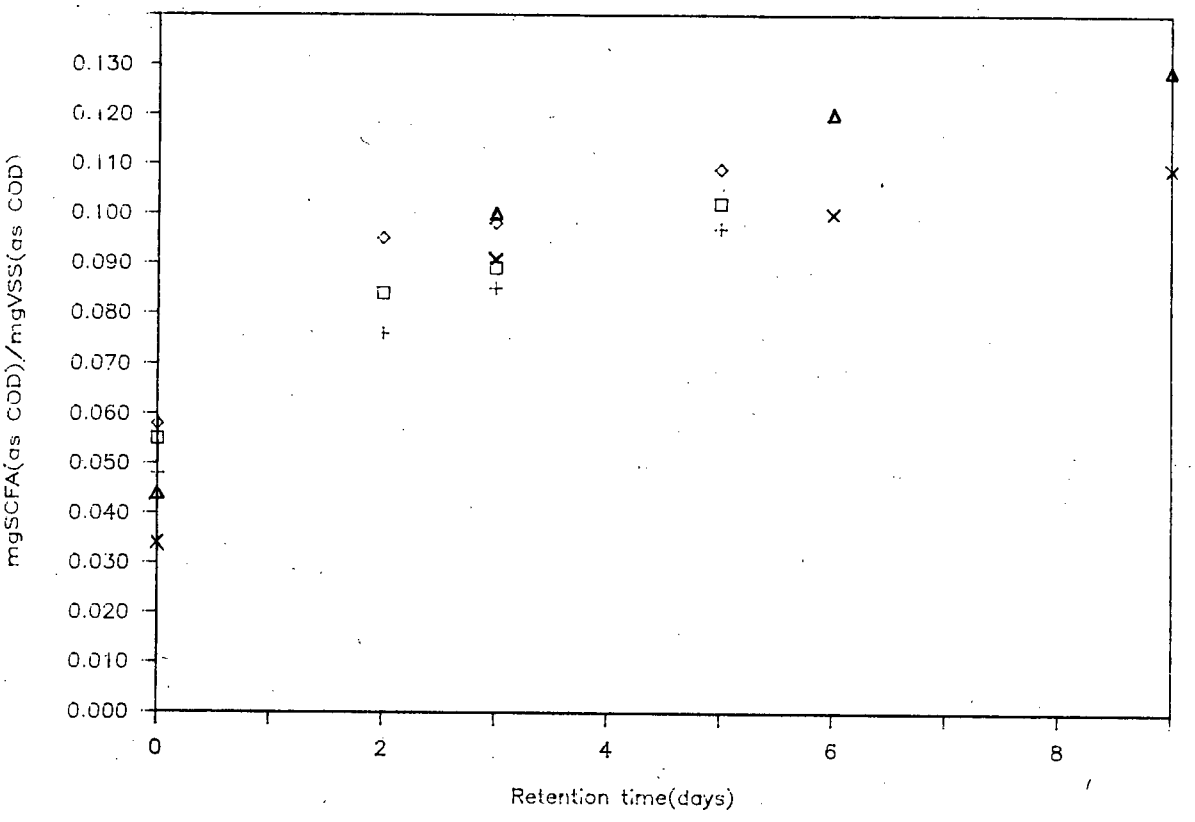

Fig 5.18: mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{nvo}$) ratios versus retention time for a single, completely mixed reactor system of 2, 3, 5, 6 and 9 days retention time, for all batches of sludge.

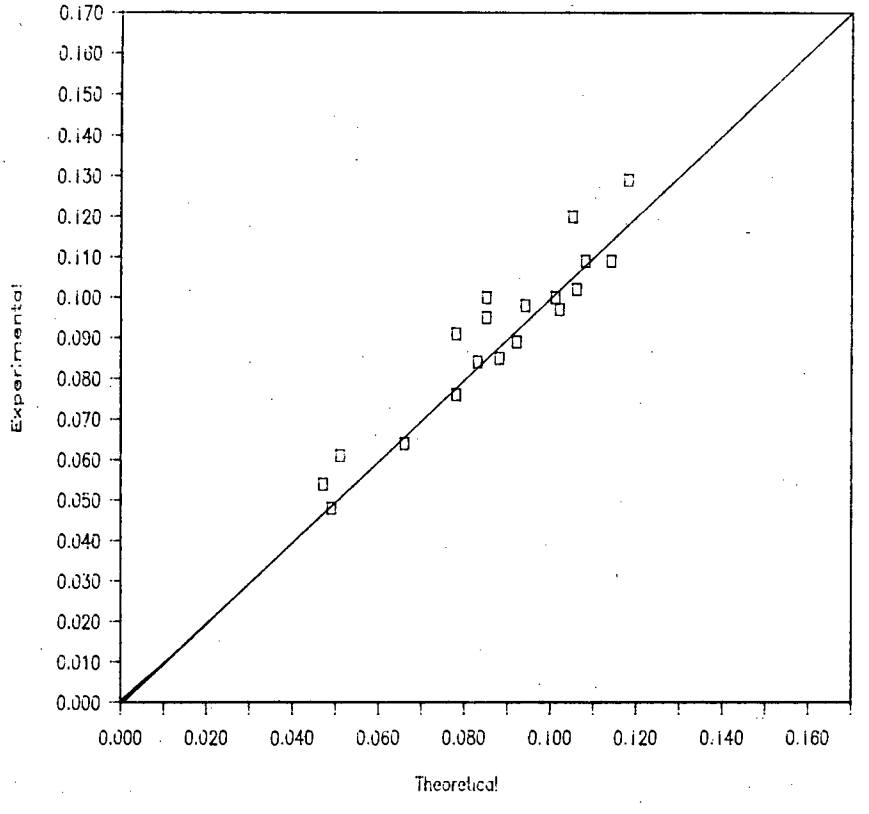

Fig 5.19: Correlation plot of theoretical versus measured mgSCFA (as COD)/mg initial VSS (as COD) (i.e. $SCFA'_{nvo}$ ratios for a system of single, completely mixed reactors with retention times of 1, 2, 3, 5, 6 and 9 days [theoretical $SCFA_{nvo}$ values from Eq (5.1)].

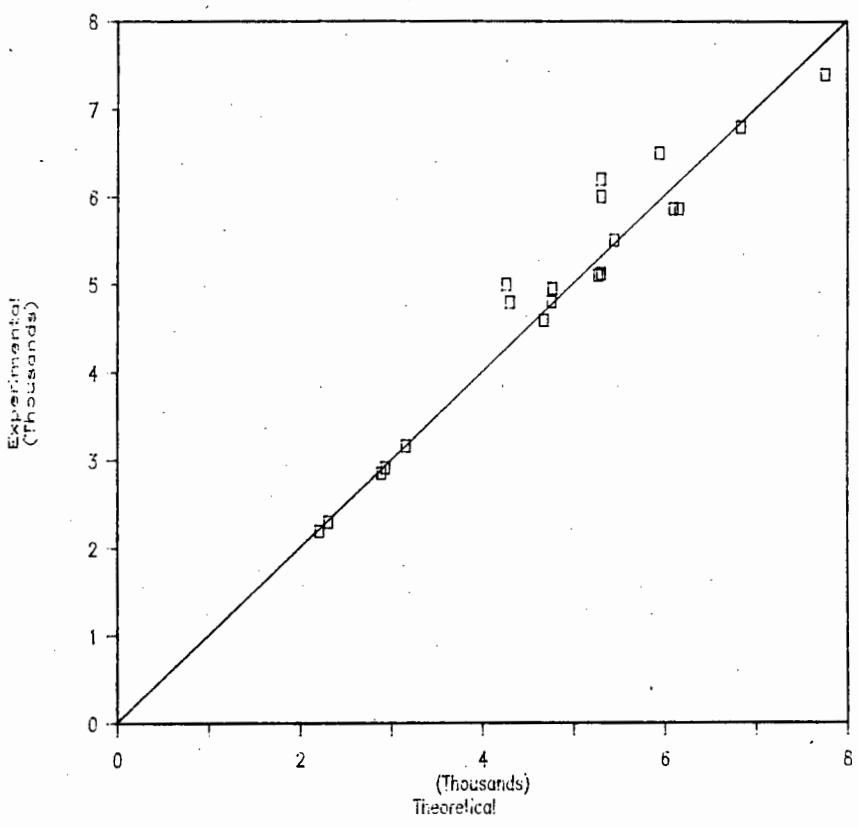

Fig 5.20: Correlation plot of theoretical versus measured mgSCFA (as COD) (i.e. $SCFA'_{neff}$) concentrations for a system of single, completely mixed reactors with retention times of 1, 2, 3, 5, 6 and 9 days [$SCFA'_{neff} = SCFA'_{nvo} \cdot X'_{vo}$, $SCFA'_{nvo}$ from Eq (5.2)].

CHAPTER 6

DESIGN EQUATIONS FOR ACID FERMENTATION

6.1 INTRODUCTION

In this chapter the focus will fall on the development of design equations for acid fermentation.

The basic theory for modelling acid fermentation of the underflow from a primary settling tank (PST) was developed in Chapter 3. Solutions were developed for the batch system in Chapter 3, the in-series reactor system with constant flow and load in Chapter 4, and the single reactor system with constant flow and load in Chapter 5.

The fermentation systems, in which these solutions would find application, may not cover the spectrum of systems that have been developed in practice. It is useful, therefore, to review briefly the various systems that have been developed and assess whether these can be brought within the ambit of the basic solution equations.

(1) The pilot scale fermentation system developed by Rabinowitz *et al.* (1985, a and b) consisted of 1 in-series reactors operated either (i) as a flow through system or (ii) a system with a fermenter settler and recycle so that the sludge age and hydraulic retention time could be independent in which event the supernatant from fermenter settler could be discharged directly to the BEPR system, or recombined with the wasted sludge and discharged to the BEPR system.

In the study by Rabinowitz *et al.* the underflow COD concentration from the PST to the fermenter system was very low and this was the main reason why it was possible to operate the fermenter system with a sludge age different from the hydraulic retention time. In South Africa with the high COD concentrations in the underflow from the PST to the fermenter it is unlikely that the system could be operated other than as a flow through one. It would still be feasible to incorporate a fermenter settler but now the function of the settler would be to separate the acid rich liquid from the sludge solids. The acid rich supernatant from the fermenter settler then

could discharge to the BEPR and the underflow discharge to the anaerobic digesters. The model for this system has been described in Chapters 4 and 5. Rabinowitz (1985a and b) operated a two in-series fermenter reactor system. For design, an important practical aspect would be to resolve whether an in-series fermenter reactor system has a significant advantage over a single reactor system for the same total retention time.

(2) At full scale Pitman (1986) operated a single reactor system in which the daily PST underflow sludge production was discharged to a single fermenter reactor over a period of 8h. The daily sludge production was accumulated over 2 to 3 days. Each day the reactor was mixed for 4 to 6h. At the end of the 2 to 3 day period the fermenter contents were settled and over the next 3 days the supernatent was pumped to the BEPR system. The settled sludge was pumped to the anaerobic digesters, and the cycle recommenced. To have a continuous supply of acid supernatant, two reactors would be required, operated in parallel but out of phase. For convenience we shall designate this fermentation system an *accumulating batch fermentation system.* An important practical advantage of this system is that it does not require a fermenter settling tank.

A model describing the behavior of the accumulation batch fermentation system can be developed from the basic acid fermentation equation for the single reactor system in Chapter 5; this will be done in Section 2 of this chapter.

(3) Pitman *et al.* (1986) utilized the primary settling tank as an acid fermenter. The settled sludge accumulated in the PST over a period of about 3 days. Each day the sludge was recycled from the underflow to the influent point of the PST in this manner elutriating the acid generated to the supernatant of the PST. The enriched supernatant was discharged to the BEPR plant. The accumulated sludge tended to settle as a dense mass, to such a degree that on occasion the scraper mechanism failed. Sludge holding times could not be extended beyond about 3 days because methane fermentation commenced with loss of SCFA. Also, the sludge turned black, probably because a low redox potential developed in the mass causing sulphates to be reduced to sulfides, a situation that may have been aggravated by elutriation because then a continuous supply of sulphate from the raw sewage would

come in contact with the sludge. For this system insufficient experimental data is available to allow a behavioural model to be developed.

6.2 ACCUMULATING BATCH FERMENTATION REACTOR SYSTEM

The model for this system is developed as follows:

Let Flow to the fermentation reactor/day = $Q(\ell/d)$
VSS (as COD) in the influent = X'_v (mg/ℓ)
Thus the daily mass of VSS (as COD) in the influent = $\Delta MX'_v = X'_v \cdot Q$ (mg/d)

If $\Delta MX'_v$ is fed as a batch at the beginning of day 1, the mass potential of SCFA (as COD) per unit mass of VSS (as COD) is $SCFA'_{pvo}$. At the end of day 1 the potential has been reduced due to the production of SCFA. The potential remaining, P_{r1}, can be found from Eq (3.7),

$$P_{r1} = (SCFA'_{pvo} - SCFA'_{ovo})\ \Delta MX_v e^{-k\Delta t} \tag{6.1}$$

At the end of two days, feeding $\Delta MX'_v$ at the beginning of the second day, accumulating the first and second days' feed in the reactor, the mass potential of SCFA (as COD) at the end of day 2 is

$$\begin{aligned} P_{r2} &= \left[(SCFA'_{pvo} - SCFA'_{ovo})\ \Delta MX_v e^{-k\Delta t}\right] \\ &\quad + \left[(SCFA'_{pvo} - SCFA'_{ovo})\ \Delta MX_v e^{-k\Delta t}\right] e^{-k\Delta t} \\ &= (SCFA'_{pvo} - SCFA'_{ovo})\ \Delta MX_v \left[e^{-k\Delta t} + e^{-2k\Delta t}\right] \end{aligned} \tag{6.2}$$

Continuing in this fashion the potential remaining at the end of n days is

$$P_{rn} = (SCFA'_{pvo} - SCFA'_{ovo})\ \Delta MX_v \left[e^{-k\Delta t} + e^{-2k\Delta t} + ... + e^{-nk\Delta t}\right] \tag{6.3}$$

It can now be shown readily that the *mass* of SCFA *generated* (as COD) per unit mass of influent VSS (as COD)

$$= (SCFA'_{pvo} - SCFA'_{ovo})\ \Delta MX_v \left[n - e^{-k\Delta t} - e^{-2k\Delta t} - ..... - e^{-nk\Delta t}\right] \quad (6.4)$$

and the mgSCFA (as COD)/mgVSS (as COD) in the rector after n days, $SCFA'_n$ will be

$$SCFA'_n = (SCFA'_{pvo} - SCFA'_{ovo}) \left[n - e^{-k\Delta t} - e^{-2k\Delta t} - ..... - e^{-nk\Delta t}\right]/n + SCFA'_{ovo} \quad (6.5)$$

[Note division by n because the volume is n times the daily flow]

In the raw sewage influent with influent COD = S_{ti}, let a fraction, f, pass to the underflow to the acid fermenter, then the concentration of SCFA generated per litre of *influent raw sewage flow*, $SCFA_n$, is

$$SCFA_n = f \cdot S_{ti} \cdot SCFA'_n \quad \text{mgSCFA (as COD)}/\ell \text{ influent flow} \quad (6.6)$$

6.3 SUMMARY OF BASIC DESIGN EQUATIONS

In summary the following prediction equations for SCFA generation have been derived:

1. **Batch fermentation reactor (Chapter 3)**

$$SCFA'_{tvo} = (SCFA'_{pvo} - SCFA'_{ovo})\ (1 - e^{-0,16t}) + SCFA'_{ovo} \quad (3.7)$$

where

$SCFA'_{tvo}$ = mgSCFA (as COD)/mg initial VSS (as COD) at batch time t

$SCFA'_{pvo}$ = potential mgSCFA (as COD)/mg initial VSS (as COD). From experimental work $SCFA'_{pvo}$ approximately equal 0,14

$SCFA'_{ovo}$ = mg initial SCFA (as COD)/mg initial VSS (as COD).

The $SCFA_{tvo}$ with regard to the raw sewage flow will be, from Eq (6.6)

$$SCFA_{tvo} = f \cdot S_{ti} \cdot SCFA'_{tvo} \quad [\text{mgSCFA (as COD)}/\ell \text{ influent flow}]$$

2. <u>In-series fermentation reactor system, with n reactors each with the same retention time R, receiving a constant flow and load (Chapter 4)</u>

$$SCFA'_{nvo} = (SCFA'_{pvo} - SCFA'_{ovo})\left(1 - \frac{1}{(1 + 0{,}16R)^n}\right) + SCFA'_{ovo} \tag{4.7}$$

where

$SCFA'_{nvo}$ = effluent mgSCFA (as COD)/mg initial VSS (as COD) from the n^{th} reactor

$SCFA'_{pvo}$ = potential mgSCFA (as COD)/mg initial VSS (as COD)

$SCFA'_{ovo}$ = mg initial SCFA (as COD)/mg initial VSS (as COD).

The SCFA with regard to the raw sewage flow will be, from Eq (6.6),

$$SCFA_{nvo} = f \cdot S_{ti} \cdot SCFA'_{nvo} \quad [\text{mgSCFA (as COD)}/\ell \text{ influent flow}]$$

3. <u>Single fermentation reactor receiving a constant flow and load (Chapter 5)</u>

The single reactor system constitutes a subset of the in-series reactor system, by inserting in the in-series equation, n=1,

$$SCFA'_{1vo} = (SCFA'_{pvo} - SCFA'_{ovo})\left(1 - \frac{1}{(1 + 0{,}16R)}\right) + SCFA'_{ovo} \tag{5.1}$$

where

$SCFA'_{1vo}$ = effluent mgSCFA (as COD)/mg initial VSS (as COD)

$SCFA'_{pvo}$ = potential mgSCFA (as COD)/mg initial VSS (as COD)

$SCFA'_{ovo}$ = mg initial SCFA (as COD)/mg initial VSS (as COD).

The SCFA with regard to the raw sewage flow will be, from Eq (6.6),

$$SCFA_{1vo} = f \cdot S_{ti} \cdot SCFA'_{1vo} \quad [\text{mgSCFA (as COD)}/\ell \text{ influent flow}]$$

4. <u>Accumulating batch fermentation reactor, accumulating underflow sludge for n days</u>

$$SCFA'_n = (SCFA'_{pvo} - SCFA'_{ovo}) \left[n - e^{-k\Delta t} - e^{-2k\Delta t} - ..... - e^{-nk\Delta t}\right]/n + SCFA'_{ovo} \qquad (6.5)$$

$SCFA'_n$ = effluent mgSCFA (as COD)/mg initial VSS (as COD) at the end of n days, accumulating sludge on a daily basis

$SCFA'_{pvo}$ = potential mgSCFA (as COD/mg initial VSS (as COD).

The SCFA with regard to the raw sewage flow will be from Eq (6.6)

$$SCFA_n = f \cdot S_{ti}\ SCFA'_n \quad [\text{mgSCFA (as COD)}/\ell \text{ influent flow}] \qquad (6.6)$$

Where experimental work on the systems had been undertaken (batch system, Chapter 3, in-series system, Chapter 4, single reactor system, Chapter 5), experimentally derived values for $SCFA'_{ovo}$ and $SCFA'_{pvo}$ were determined, as follows:

System	$SCFA'_{ovo}$	$SCFA'_{pvo}$
Batch system	0,042	0,14
In-series system	0,035	0,17
Single reactor system	0,048	0,17

The in-series and single reactor systems appear to give values for $SCFA'_{pvo}$ that differ significantly from that obtained on the batch system. Accordingly we have retained $SCFA'_{pvo}$ of 0,14 for the batch system and 0,17 for the in-series and single reactor systems. The average value for $SCFA'_{ovo}$, based on all the systems, is

$SCFA'_{ovo} = 0,042$; this value might differ substantially between waste waters and probably will be affected significantly by the length of the sewer lines.

6.4 DEVELOPMENT OF 'EQUIVALENT' REACTOR

The estimated mean value of $SCFA'_{ovo}$, can be utilized directly, or approached indirectly by assuming that $SCFA'_{ovo}$ has been generated in an 'equivalent' fermentation reactor, upstream of the 'real' fermentation system. The retention time of this 'equivalent' reactor is chosen to give an effluent $SCFA'_{nvo}$ value equal to the default $SCFA'_{ovo}$ value. There is a slight advantage in this approach in that the method of calculation of SCFA' becomes uniform irrespective of whether only the 'equivalent' or the 'equivalent' plus 'real' reactor system are present. This will become apparent in developing design equations for the 'equivalent' reactor approach.

6.4.1 Batch operation

The formulated $SCFA'_{tvo}$ equation, derived from the mean experimental results on batch systems, describes the curve shown in Fig 6.1. The theoretical curve could be extrapolated to $SCFA'_{tvo} = 0$ at $t = -\Delta t$ (i.e. when $t = -\Delta t$, $SCFA'_{ovo} = 0$) and Eq (3.7) can be written as

$$SCFA'_{tvo} = 0,14\ (1 - e^{-0,16\ (t\ +\ \Delta t)}) \qquad (6.7)$$

From Fig 6.1, when $t = 0$, $SCFA'_{tvo} = 0,042$ mgSCFA (as COD)/mg Initial VSS (as COD). Substituting into Eq (6.7)

$$0,042 = 0,14\ (1 - e^{-0,16\ (0\ +\ \Delta t)})$$

Solving for Δt:

$$\Delta t = \frac{\ln\ (\ -\frac{0,042}{0,14}\ )}{-\ 0,16}$$

yields $\Delta t = 2,23$ days.

Substituting back into Eq (6.7) yields

$$SCFA'_{tvo} = 0,14\ (1 - e^{-0,16\ (t\ +\ 2,23)}) \qquad (6.8)$$

We now have an equation which predicts $SCFA'_{tvo}$ at any time t in a batch system – the system consists of an 'equivalent' batch rector with a retention time of 2,23 days in series with a 'real' batch reactor with a retention time of t days.

In Fig 6.2 a correlation plot is shown, predicted versus observed $SCFA'_{tvo}$ values for a batch reactor system, with retention times, t, ranging from 1 to 16 days (predicted values from Eq (6.8), and observed data from Chapter 3). Evidently the theoretically predicted and observed values of $SCFA'_{tvo}$ correlate reasonably well. Consequently Eq (6.8) can be accepted as a design equation for $SCFA'_{tvo}$ generation under batch conditions.

6.4.2 In-series reactor operation

The 'equivalent' reactor approach now can be applied to the in-series reactor system. The $SCFA'_{ovo}$ present in the influent of a 'real' reactor system can be considered to have been generated in a small 'equivalent' completely mixed reactor, upstream of the 'real' series of completely mixed reactors. The retention time of the mythical or 'equivalent' reactor is equal to R_o. Consequently the $SCFA'_{ovo}$ concentration in the effluent from the 'equivalent' reactor can be written as

$$SCFA'_{ovo} = 0{,}17 \left(1 - \frac{1}{(1+kR_o)} \right) \tag{6.9}$$

For an equivalent reactor, o, in series with a set of real reactors 1, 2, 3 ... n, Eq (4.7) reduces to

$$SCFA'_{nvo} = 0{,}17 \left(1 - \frac{}{\prod_{i=o}^{n}} \frac{1}{(1+kR_i)} \right) \tag{6.10}$$

where R_o is the retention time of the equivalent reactor, o, and R_1, R_2 ... R_n are given by V_1/Q, V_2/Q ...V_n/Q and V_1, V_2 ... V_n = volumes of reactors 1, 2 ... n.

If the retention times in each of the reactors 1, 2 ... n are equal, then

$$SCFA'_{nvo} = 0{,}17 \left(1 - \frac{1}{(1+kR_o)} \cdot \frac{1}{(1+kR)^n} \right) \tag{6.11}$$

Later we shall show that, with very little error, one may accept the retention time of

the equivalent completely mixed reactor as equal to the retention time of the equivalent batch reactor. Hence, assuming $R_o = t = 2,23$ days, then for $k = 0,16$ we have

$$\frac{1}{(1+kR_o)} = \frac{1}{1,357} = 0,737$$

Substituting into Eq (6.11) yields

$$SCFA'_{nvo} = 0,17 \left(1 - \frac{0,737}{(1+0,16R)^n} \right) \qquad (6.12)$$

In Fig 6.3 a correlation plot is shown of predicted versus observed $SCFA'_{nvo}$ values for the 3 in-series "real" reactor system, each reactor of 1 day retention time, (predicted values from Eq (6.12) and observed data from Chapter 4). It would seem that Eq (6.12) slightly over predicts the $SCFA'_{nvo}$ generated.

6.4.3 Single reactor operation

In a single reactor, steady state system, Eq (6.10) with $n = 1$, can be written as

$$SCFA'_{nvo} = 0,17 \left(1 - \frac{1}{(1+kR_o)} \cdot \frac{1}{(1+kR)} \right) \qquad (6.13)$$

Assume $R_o = \Delta t = 2,23$ days, then for $k = 0,16$/day

$$SCFA'_{nvo} = 0,17 \left(1 - \frac{0,737}{(1+0,16R)} \right) \qquad (6.14)$$

In Fig 6.4 a correlation plot is shown, predicted versus observed $SCFA'_{nvo}$ values for the single reactor system over a range of sludge ages from 1 to 9 days (predicted values from Eq (6.14) and observed data from the $R = 1$ day observation in Chapter 4 and $R = 2$, 3, 5, 6 and 9 days from Chapter 5). It appears that Eq (6.14) slightly under predicts the $SCFA'_{nvo}$ generated.

To illustrate the correspondence between the predicted and observed mgSCFA/mg initial VSS, both as COD, for the single reactor system, the following mean $SCFA'_{nvo}$ values are shown plotted against "real" reactor retention time in Fig 6.5:

(1) Experimental mean values for the influent (corresponding to the 'equivalent' reactor retention time R_o = 2,23 days) and the 'real' single reactor with retention times R = 0, 1, 2, 3, 5, 6 and 9 days.

(2) Experimental mean values obtained by Rabinowitz and Oldham (1985b), at real retention times of 2,5, 3,5, 5 and 10 days, suitably transformed to units used in this investigation [i.e. mgSCFA (as COD)/mg initial VSS (as COD)].[1] No data is supplied by Rabinowitz whereby the experimental values at R = 0 can be calculated.

(3) Predicted $SCFA'_{nvo}$ curve using Eq (6.14).

The data of Rabinowitz and Oldham (1985b) plots slightly higher than those from this investigation. However, the trends exhibited by their data conform very well to that in this investigation, with one exception at 10 days retention time – the low experimental value observed by Rabinowitz and Oldham (1985b) very likely was due to the development of methane fermentation.

From the observations above, the assumption of the equivalent or mythical retention time of 2,23 days to determine the $SCFA'_{ovo}$ in the influent appears to be an acceptable one, or, alternatively one may simply accept $SCFA'_{ovo}$ = 0,042.

6.5 GRAPHICAL ANALYSIS

The design formula Eqs (6.8, 6.12 and 6.14) can be recast readily to depict the behaviour graphically. These equations in essence describe the SCFA' generated as the potential SCFA' less the potential SCFA' remaining. Accordingly the percentage potential remaining ($SCFA'_r$) can be formulated as follows:

Batch system:
$$\frac{SCFA'_r}{SCFA'_{pvo}} = 100\, e^{-0,16t} \qquad (6.15)$$

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[1]Note the data by Rabinowitz and Oldham is in terms of total COD of the underflow, *not* the COD of the VSS of the underflow i.e. VSS after centrifugtion. The mean total COD/VSS COD in our investigation was 1,08 so that for the purpose of plotting Rabinowitz' data, their $SCFA'_{nvo}$ value was multiplied by 1,08 before plotting.

Single reactor:
$$\frac{SCFA'_r}{SCFA'_{pvo}} = \frac{100}{1+0,16R} \qquad (6.16)$$

In Fig 6.6(a) are shown the relationship depicting the percentage of the potential SCFA (as COD)/mg initial VSS (as COD) remaining, ($SCFA'_r$), for a batch system and for a single completely mixed reactor system versus retention time. The axis for percentage $SCFA'_r$ is logarithmic. Also shown, in the right hand side of the figure, is the percentage SCFA' generated. This plot in effect assumes that the potential $SCFA'_{pvo}$ is the same for the two systems. With these two curves, it is possible to determine, completely graphically, the behaviour of in-series systems: Assume we have an in-series completely mixed reactor system with two reactors each of 5 days retention time. The effluent from the first reactor is given by the value at R = 5 days (point 1) in Fig 6.6(b). To determine the effluent from the second reactor, draw a straight line from the origin through point 1 and continue for a further 5 days. At total R = 10 days, effluent of the second reactor is given by point 2.

The procedure above is for equal volume reactors; for unequal volumes, the procedure is as follows: Assume two reactors in-series, the first stage, say, 2 days retention time, the second 8 days retention time (total of 10 days retention time). The effluent from the first reactor is given at R = 2 days (point 1) in Fig 6.6(c). The effluent from the 8 day reactor is found as follows: On the curve determine the effluent value for a single reactor at 8 days retention time (point 2), join the origin to point 2. From point 1 draw a line parallel to the line from the origin to point 2 (shown dotted) for a further 8 days retention time, to give point 3, the effluent value of the in-series system of 2 plus 8 days retention time.

6.5.1 "Equivalent" reactor

From Fig 6.6(a) it can be seen that at a retention time of 2,23 days there is very little difference in $SCFA'_{tvo}$ remaining between the batch reactor and the single completely mixed reactor, that is, the assmption made earlier that setting Δt = 2,23 days, from the batch tests equal to R_o in the single reactor and in-series completely mixed reactor systems, is acceptable.

6.5.2 Single versus in-series reactor systems

From the work by Rabinowitz and Oldham (1985b) (plotted in Fig 6.5) it seems that there is a danger of methane fermentation occurring at flow through retention times (sludge ages) approaching 10 days. To reduce the possibility of methanogenesis, it

would be safer to operate a fermentation system at flow through retention times, say, shorter than 6 days. At a retention time 6 days, the problem for a designer downstream of the 'equivalent' reactor (of 2,23 days retention time), is whether to have a single completely mixed reactor of 6 days 'real' retention time, or two in-series completely mixed reactors of say 3 days each i.e. whether the system should consist of 2 reactors ('equivalent' plus one 6 day reactor) or of 3 reactors ('equivalent' plus two 3 day reactors).

The graphical method of analysis of this problem is as follows: We apply the method for an in-series system with reactor retention times of 2,23, 3 and 3 days (2,23, 5,23 and 8,23 total retention times) and for a single reactor system of 2,23 and 6 days (2,23 and 8,23 total retention times). The graphical solutions to the two systems, using the procedure described in Section 3.0, are shown in Fig 6.7.

From Fig 6.7, the percentage $SCFA'_{nvo}$ remaining for the one equivalent and two in-series reactor system is 33,5%, and the percentage $SCFA'_{nvo}$ remaining for the one equivalent and one reactor system, is 37,5%.

Clearly there is little merit in replacing the 6 day 'real' retention time reactor by two in-series 3 day 'real' retention time reactors (a difference of 4 percent in $SCFA'_{nvo}$ remaining).

One may check the graphical solution by applying Eqs (6.12 and 6.14):

For the in-series reactor system of 2,23; 3 and 3 days 'real' retention times: the percentage $SCFA'_{nvo}$ generated is 66,3 percent i.e. 33,7 percent remaining and in the 2,23 and 6 day 'real' retention time the values are 62,4 and 37,6 percent respectively. These values are the same as those determined graphically.

6.6 CONCLUSIONS

(1) A number of design equations suitably calibrated, have been developed to determine the steady state SCFA generated in batch, single flow through, in-series flow through, and accumulating batch reactor systems.

(2) The predicted SCFA yield for the steady state single reactor system compares favourably with experimental results reported by Rabinowitz *et al.* (1985b).

(3) Theoretically the most efficient system for SCFA generation is the batch type system. In this experimental study, however, the data would indicate that the potential yield for SCFA production is lower than that for the completely mixed in-series and single reactor systems.

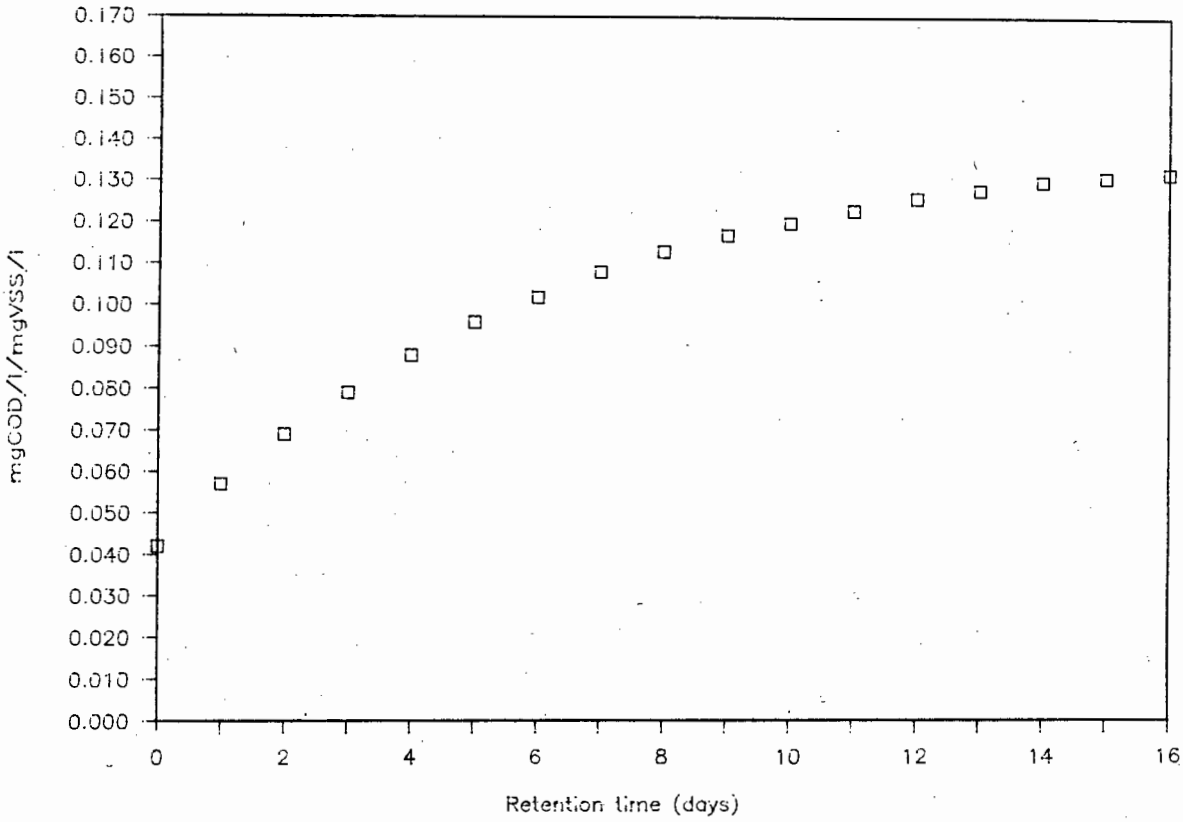

Fig 6.1: Theoretical equation for predicting $SCFA'_{tvo}$ values (Eq 3.7) versus retention time for a batch reactor system.

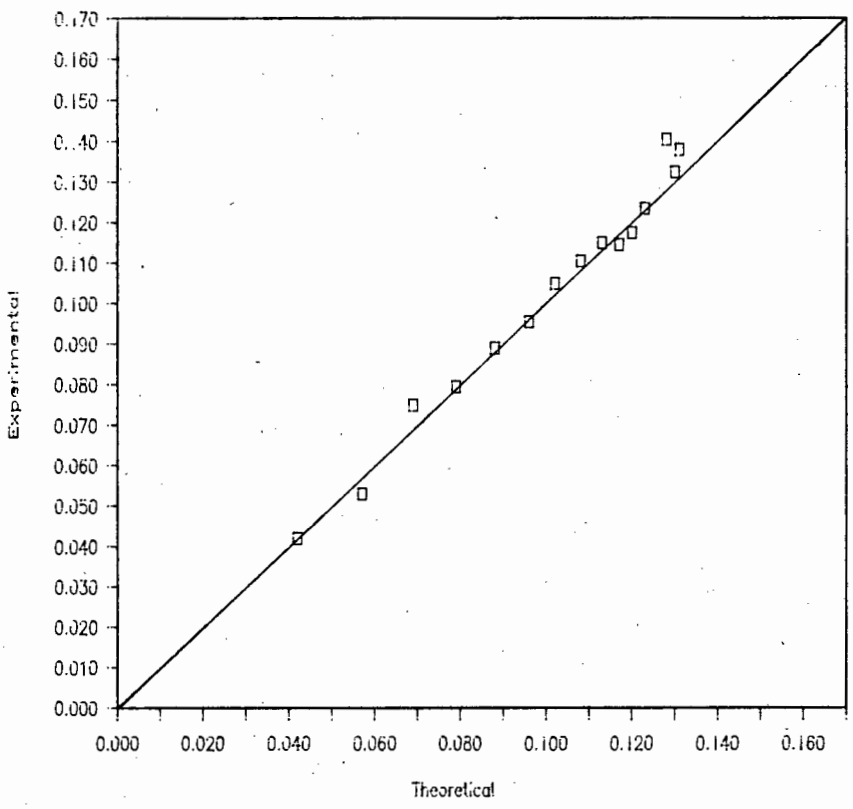

Fig 6.2: Correlation plot of predicted versus observed $SCFA'_{tvo}$ values for the batch system (predicted values from Eq (6.8) and observed values from Chapter 3).

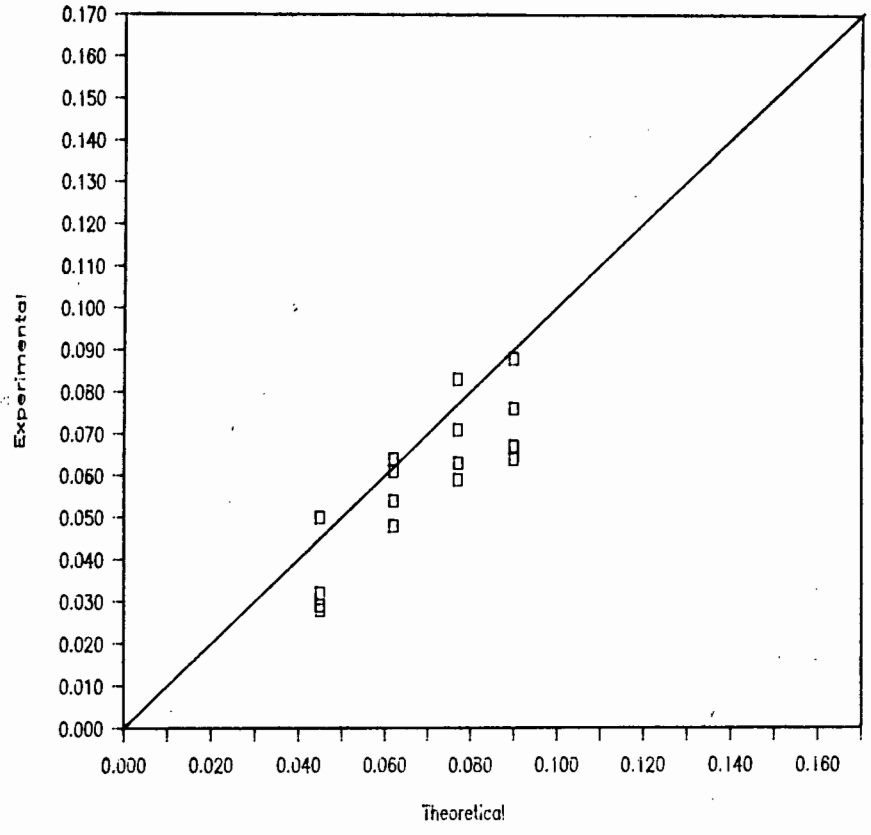

Fig 6.3: Correlation plot of predicted versus observed $SCFA'_{nvo}$ values for the 3 in-series, semi-continuously fed completely mixed reactor system [predicted values from Eq (6.12) and observed data from Chapter 4)].

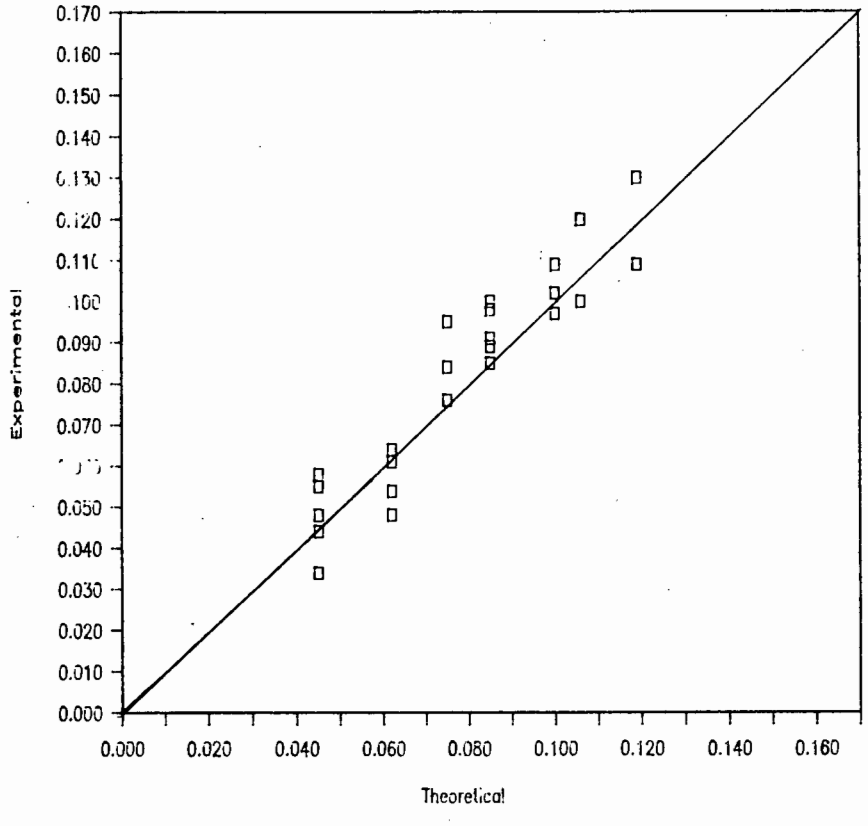

Fig 6.4: Correlation plot of predicted versus observed $SCFA'_{nvo}$ values for the single, completely mixed reactor system [predicted values from Eq (6.14) and observed data from Chapters 4 and 5].

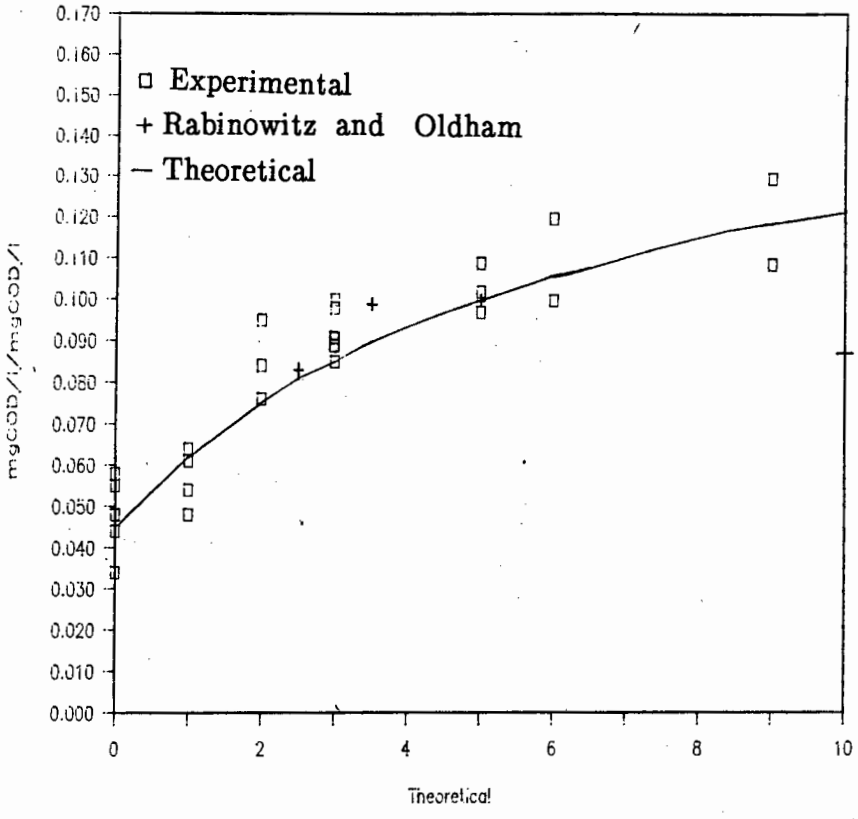

Fig 6.5: Predicted and observed $SCFA'_{nvo}$ values of a single completely mixed reactor versus "real" reactor retention time. Also shown is the $SCFA'_{nvo}$ values obtained by Rabinowitz *et al.* (1985b).

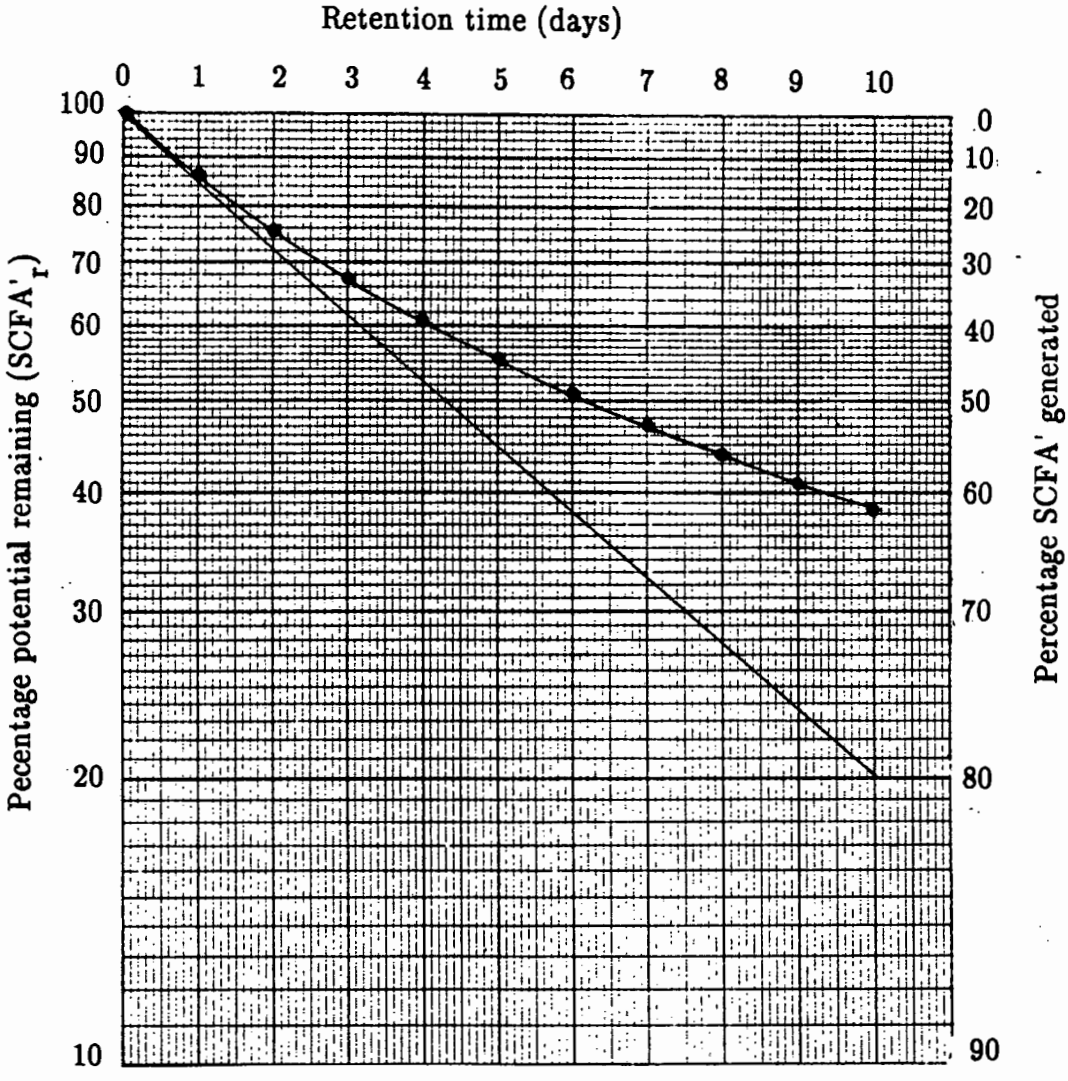

Fig 6.6(a): Relationship depicting the percentage of the SCFA' potential remaining, $SCFA'_r$, versus retention time, for the batch and single completely mixed reactor systems.

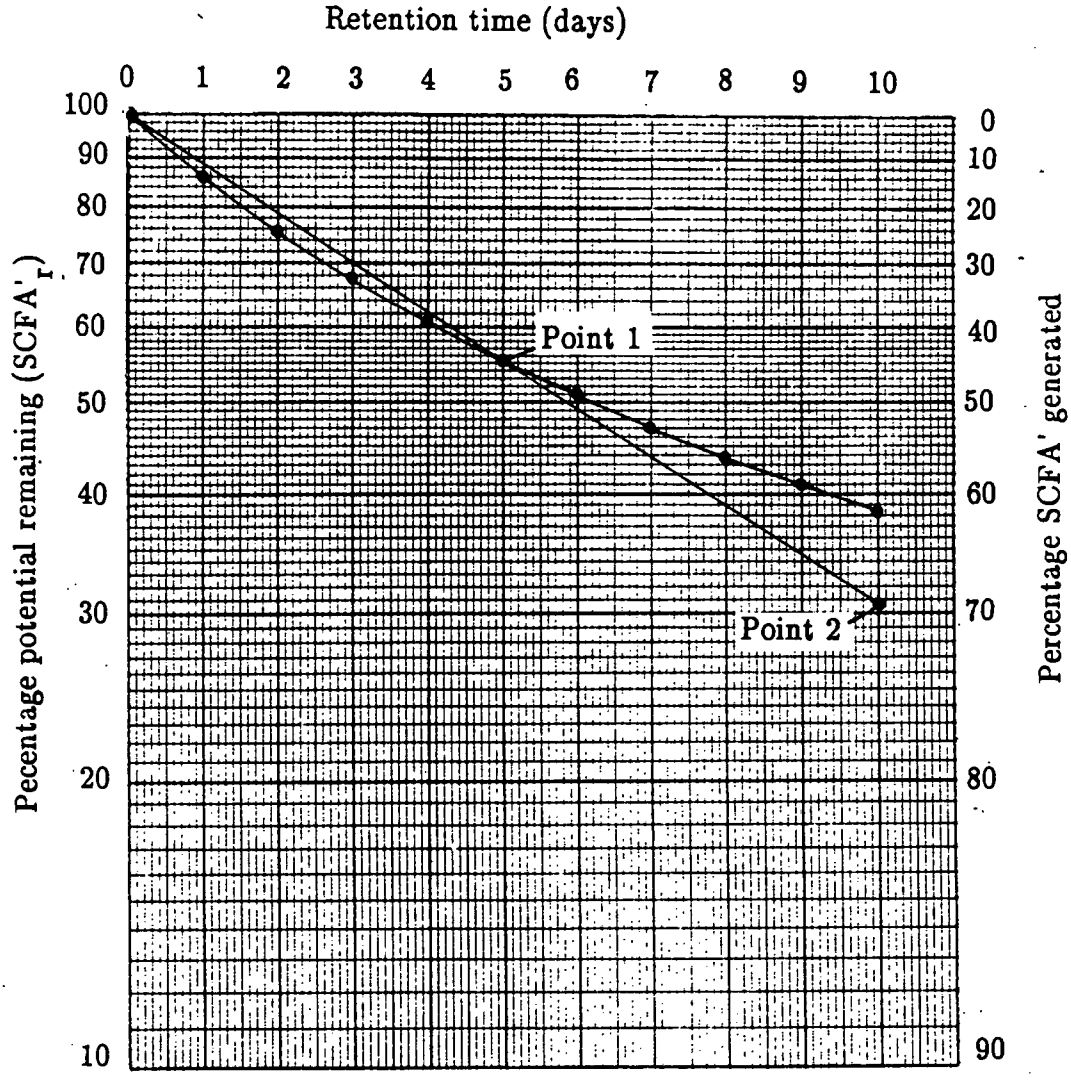

Fig 6.6(b): Graphical analysis for determining the effluent $SCFA'_{nvo}$ value from a 2 in-series, completely mixed reactor system, each reactor having a retention time of 5 days.

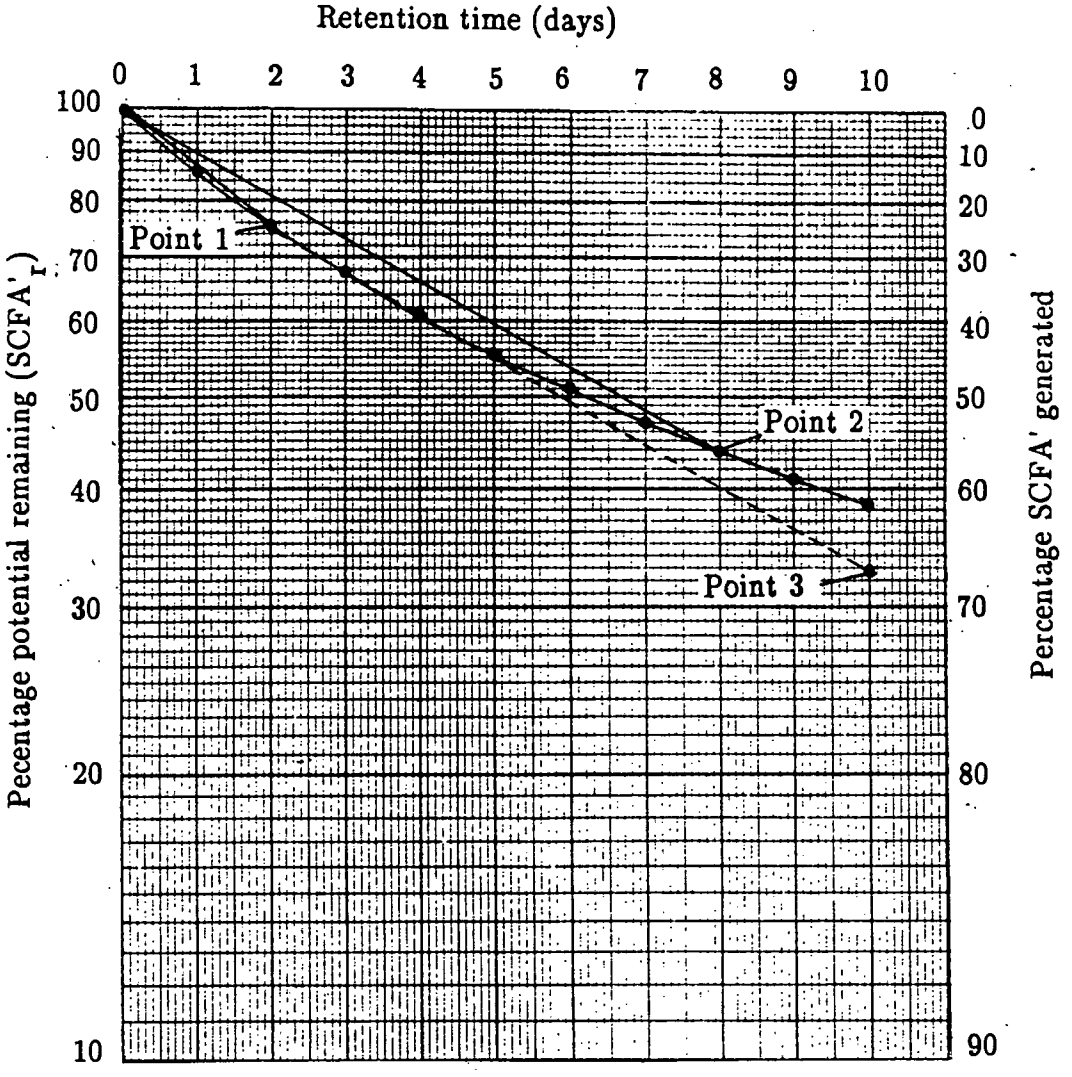

Fig 6.6(c): Graphical analysis for determining the effluent $SCFA'_{nvo}$ value from a 2 in-series, completely mixed reactor system, of 2 and 8 day reactor retention times.

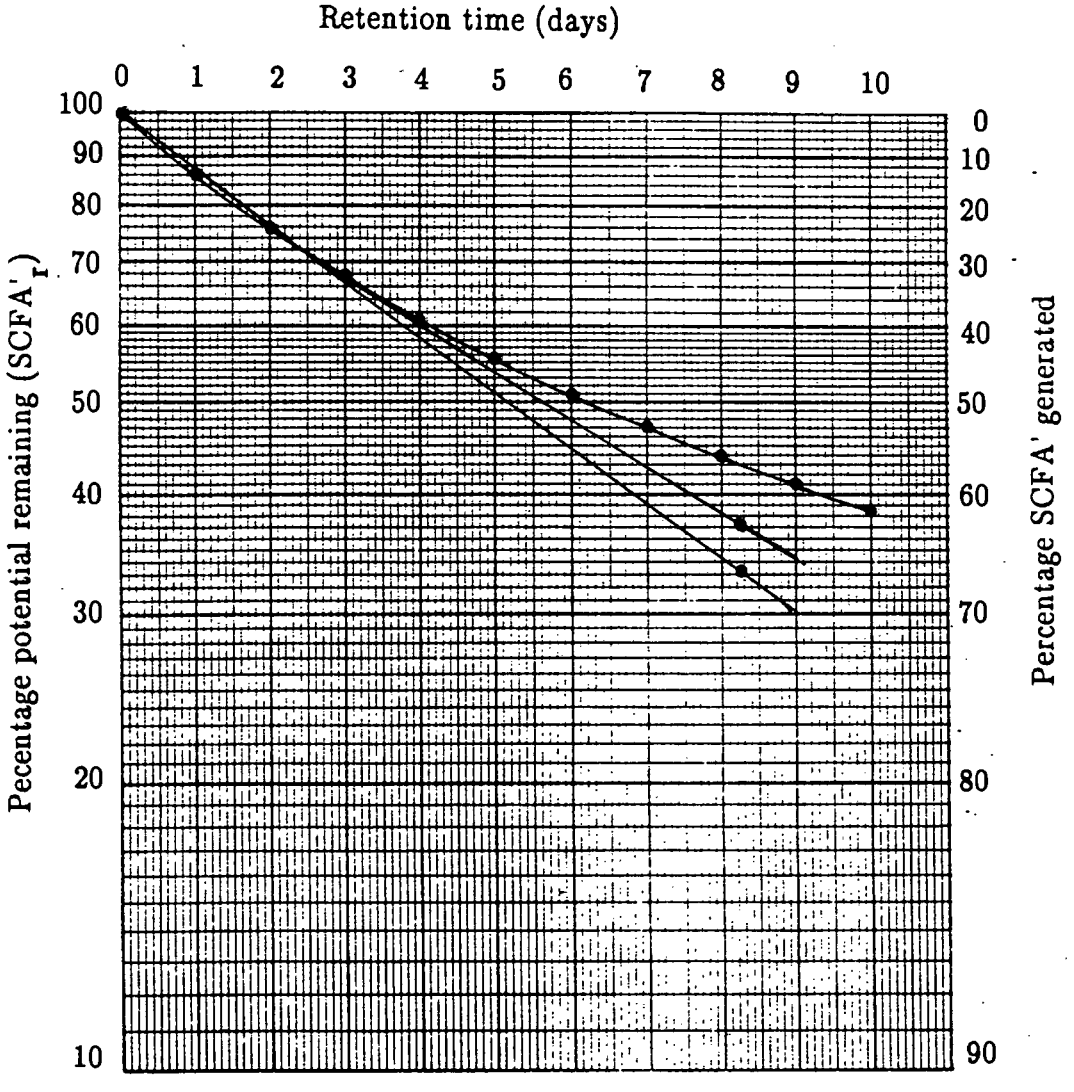

Fig 6.7: Graphical method of comparing the effluent $SCFA'_{nvo}$ values from a 2 in-series completely mixed reactor system of 2, 23 and 6 days reactor retention times with that of a 3 in-series reactor system with 2, 23, 3 and 3 day reactor retention times.

CHAPTER 7

BIOLOGICAL EXCESS P REMOVAL

7.1 INTRODUCTION

In Chapter 6 design models have been presented for determining short chain fatty acids (SCFA) generation, when fermenting the underflow from the primary settler. In this chapter it is the intention to explore the influence of the SCFA generated on the P removal in a biological excess P removal (BEPR) system.

Wentzel *et al.* (1989) proposed a steady state BEPR model by means of which it is possible to determine P removal from BEPR systems. The predictions of this model have been evaluated against sets of experimental data obtained on 30 laboratory scale units covering a range of sludge ages (4 to 30 days), influent COD (500 to 1000 mgCOD/ℓ) for the Phoredox (non-nitrifying) systems, and the three and five stage modified Bardenpho, UCT and MUCT (nitrifying) systems. The model makes provision for the presence of SCFA's in the influent.

The BEPR model is quite complex and there is little merit to be gained in attempting to summarize its contents or calculation procedures. Accordingly we will accept that the reader is familiar with the model. We will only report the predictions using the model to evaluate the effects of a number of fermenter/BEPR combinations.

7.2 ACID FERMENTATION AND BEPR

In order to make a comparative study of the various fermentation/BEPR combinations it is necessary to set down the conditions that form the basis for all calculations:

(1) Raw sewage with COD = 1000 mgCOD/ℓ which has mean characteristics as suggested in the WRC Manual (1984). The Manual suggests default values for unbiodegradable soluble COD = 0,03, unbiodegradable particulate COD = 0,13, slowly biodegradable COD = 0,76, readily biodegradable COD (RBCOD) = 0,2 with respect to the raw sewage COD. (In practice this RBCOD fraction should be determined experimentally; as its magnitude can vary between wastewaters and it has a crucial influence on P removal).

(2) No SCFA in the raw sewage before entry to the primary settling tank (PST) or when discharged directly to the BEPR system.

(3) By the time the underflow from the PST enters the fermenter it has already generated some SCFA equal to 0,042 of the underflow COD or equivalently has passed through a 'mythical' reactor with a retention time of 2,23 days, as described in Chapter 6.

(4) The PST removes 40 percent of the raw COD to the underflow. (In practice this fraction will depend on the design of the settling tank).

(5) The acid fermenter is either (i) a *single, completely mixed reactor* receiving a relatively constant underflow rate (say twice a day) with a retention time of 3 or 6 days, or (ii) a single reactor in which the reactor each day receives and retains the daily underflow, accumulates the sludge up to 3 or 6 days, called an *accumulating batch reactor*, and then discharges the contents to the BEPR system at the end of the 3rd or 6th day, (iii) as in (i) above but the liquid is separated from the fermenter sludge and the liquid discharged to the BEPR system; this case is worked out for 3 days retention time only.

(6) In the BEPR system the design is such that no nitrate enters the anaerobic reactor [in the BEPR system, design satisfaction of this requirement is mandatory for efficient P removal, see WRC Manual (1984)].

(7) The BEPR system has a single anaerobic reactor with a sludge mass fraction of 0,15.

(8) The sludge age of the BEPR system is 20 days.

There are two situations to be examined:

(1) The underflow sludge is fermented and returned to the influent flow to the BEPR plant.

(2) The underflow sludge is fermented, settled and the supernatant returned to the BEPR influent.

7.2.1 Underflow sludge fermented and returned to the BEPR influent

Three cases are considered:

Case 1: Raw sewage direct to BEPR system.

From BEPR model, (with no fermentation i.e. SCFA' = 0)
$\Delta P = 21{,}3$ mgP/ℓ

Case 2: Acid fermentation of underflow in a single, completely mixed reactor, fermented contents returned to the BEPR influent.

Influent COD removed in PST
$= 0{,}4 \cdot 1000$
$= 400$ mgCOD/ℓ

(i) Fermentation reactor retention time = 3 days.

Applying Eq (6.14)

$$SCFA'_{nvo} = 0{,}17 \left[1 - \frac{0{,}737}{(1+0{,}16R)} \right]$$

$= 0{,}086$

$SCFA = 0{,}086 \cdot 400$
$= 34{,}1$ mgCOD/ℓ

From BEPR model
$\Delta P = 24{,}3$ mgP/ℓ

(ii) Fermentation reactor retention time = 6 days.

Applying Eq (6.14)

$SCFA'_{nvo} = 0{,}106$
$SCFA = 0{,}106 \cdot 400$
$= 42{,}43$ mgCOD/ℓ

From BEPR model

$\Delta P = 25{,}01$ mgP/ℓ

Case 3: Semi-batch fermenter accumulating underflow sludge for a number of days, fermenter contents returned to BEPR influent.

(i) Sludge fed at the beginning of each day and accumulated for 3 days.

Then from Eq (6.8)

SCFA' $= 0{,}076$
and SCFA $= 0{,}076 \cdot 400$
$= 30{,}5$ mgSCFA (as COD)/ℓ influent flow

From BEPR model

$\Delta P = 24{,}0$ mgP/ℓ

(ii) Fermentation reactor accumulation time = 6 days

Then from Eq (6.8)

SCFA' $= 0{,}094$
and SCFA $= 0{,}094 \cdot 400$
$= 37{,}65$ mgSCFA (as COD)/ℓ influent flow

From BEPR model

$\Delta P = 24{,}6$ mgP/ℓ

The P removal obtained from the 3 cases is given in Table 7.1.

The following conclusions are drawn:

(1) Anaerobic fermentation of the underflow and return the fermented underflow to the BEPR influent flow increased the P removal by 14,1 and 17,4 percent for the 3 and 6 days single completely mixed reactors, and by 12,7 and 15,5 percent for the 3 and 6 day batch accumulation reactors.

(2) From (1) above increase in retention time from 3 to 6 days in the single completely mixed fermentation reactor system increased ΔP only 3,3 percent, and in the accumulative batch fermentation reactor system increased ΔP only 2,8 percent – the increase in retention time from 3 to 6 days hardly seems justified.

(3) Comparing SCFA production the batch accumulation fermenter reactor produces about 10 percent less SCFA than the completely mixed single fermenter reactor when operated at the same retention times. From a practical point of view this difference is not significant enough to be a factor in design – the choice between the two systems will depend on practical operating preferences.

With regard to the completely mixed and batch accumulation reactor systems, at the same retention time the latter has a slightly lower SCFA (as COD)/mgVSS (as COD) production of 3,6 and 4,9 for 3 and 6 days respectively – from a practical point of view about the same efficiency; choice will depend on the practical operating preferences.

7.2.2 Underflow fermented, settled and the supernatant returned to the BEPR influent

The following 2 cases were examined:

Case 1: Raw sewage settled and the settled supernatant discharged to BEPR influent

From BEPR model
$\Delta P = 16,7$ mgP/ℓ

Case 2: Acid fermentation of underflow in a single, completely mixed reactor, of retention time 3 days, the fermented contents settled and the supernatant returned to BEPR settled influent.

From Figs D.13, D.20, D.27, D.41, D.48 and D.55 the total 'soluble' COD formed in the fermenter is closely twice the SCFA formed i.e. the non-SCFA soluble COD is about equal to the SCFA (as COD). Furthermore if the fermented mixed liquor is

allowed to settle in the fermenter, only a fraction of the liquid would be available as supernatant.

The fraction of liquid available as supernatant will depend on the PST underflow VSS, the higher the VSS the lower the supernatant recovery. It would seem therefore that the PST should be operated to discharge an underflow at a relatively low VSS, say 10 000 mg/ℓ. Subsequently when allowed to settle the VSS may increase to say 40 000 mg/ℓ which probably would recover roughly 3/4 of the liquid in the mixed liquor (at present there is no experimental data available as to the liquid recovery fraction). A low PST underflow VSS will demand a larger fermenter volume. To reduce the volume it would be desirable to reduce the retention time of the fermenter to as low a value that is consistent with reasonable SCFA production. From our previous discussion this would indicate a retention time of 3 to 4 days. In the example, assume 3/4 recovery of the liquid and a non-SCFA soluble COD equal in concentration to the SCFA (as COD). Thus

From Eq (6.8)

$$SCFA'_{nvo} = 0{,}086$$

$$SCFA = 0{,}086.400$$
$$= 34{,}1 \text{ mgCOD}/\ell$$

The influent entering the BEPR system is as follows

settled sewage	= 600 mgCODℓ
non-SCFA COD (i.e. 34,1·3/4)	= 25,6 mgCOD/ℓ
SCFA COD (i.e. 34,1·3/4)	= 25,6 mgCOD/ℓ
i.e. S_{ti}	= 651,2 mgCOD/ℓ

From the BEPR model assuming the unbiodegradable particulate COD fraction in the settled sewage is 0,03 (see WRC Manual, 1984)

$$\Delta P = 19{,}07 \text{ mgP}/\ell$$

Comparing the BEPR receiving settled sewage only (ΔP = 16,7 mg/ℓ) with that receiving settled sewage plus fermented underflow supernatant (ΔP = 19,1), addition

of fermented supernatant to the BEPR influent flow increases the P removal by 14,2 percent (for a 3 day fermentation retention time).

7.3 DISCUSSION

The increase in P removals, when acid fermentation of 3 and 6 days retention times were discharged to the BSPR system, were calculated to be about 15 percent. This degree of improvement is somewhat disappointing. Data on laboratory systems (Bagg *et al.*, 1985) and full scale works (Osborn *et al.*, 1986, 1989) have been reported, on the improvement of P removal, when acid fermented underflow has been discharged to the BEPR plant. The impression has been that the improvement is of a much higher degree than that reported here.

One possible explanation is that the non-SCFA soluble (<0,45μm) COD fraction generated during acid fermentation (and is of approximately the same magnitude as the SCFA fraction) contains some RBCOD. If the non-SCFA fraction were totally RBCOD, then the improvement in BEPR would be about 30%. Unfortunately this aspect was not investigated because the implications of this were not recognized. To test the effect of the non-SCFA soluble COD fraction on BEPR would require feeding the acid fermented sludge and supernatant to a laboratory scale nitrification denitrification BEPR system, and noting the improvement in BEPR. This aspect clearly is of importance and should be investigated, preferably at larger scale than laboratory scale. Another explanation is that on the full scale plants investigated, addition of acid fermented material influenced not only P removal but also denitrification. It is possible, for example, that the denitrification before acid addition was such that nitrate was present in the recycle to the anaerobic reactor; after acid addition the nitrate may have reduced to zero. If this should have happened a dramatic improvement in P removal would be observed when the fermented material was added. It is to be hoped that in time reliable data obtained an adequately monitored large scale plant(s) would become available. In the interim it would be most desirable if a pilot scale study on a fermentation/BEPR system is set up to study the interactive response of the two sub systems.

7.4 CONCLUSIONS

(1) When acid fermented primary sludge (or supernatant of the acid fermented sludge) is added to the influent of a BEPR system, the potential increase in P removal predicted by the steady state BEPR model is about 15%. This increase is based on the assumption that only the SCFA generated by acid

fermentation contributes to the additional P removal. Generated with the SCFA is a non-SCFA soluble (<0,45μm) COD fraction approximately equal in concentration to the SCFA fraction. It is possible that some of this COD is RBCOD that can be converted to SCFA in the anaerobic reactor of the BEPR system. If this is so, then the increase in BEPR should be greater than 15%. This may provide an explanation for the increases in P removal of up to 30% that have been observed in full scale BEPR plants with acid fermented sludge and supernatant addition.

(2) There is no significant increase (± 3 percent) in P removal in a BEPR system when the retention time in the acid fermenter is doubled from 3 to 6 days.

Table 7.1: BEPR for the 3 cases examined on the effect of raw sludge fermentation and the fermentation contents directly to the BEPR influent.

Cases	Fermenter system	Phosphorus removal ΔP (mg/ℓ) Fermenter retention time (days)		
		0	3	6
1	None	21,3	–	–
2	Completely mixed, single reactor	–	24,3	25,0
3	Accumulating batch reactor	–	24,0	24,6

CHAPTER 8

CONCLUSIONS

The objectives of this investigation were to investigate, at laboratory scale, (1) generation of short chain fatty acids (SCFA) by acid fermentation of the underflow, (2) development of a model for SCFA generation by acid fermentation of sludge from a primary settling tank and (3) to enquire into the effects of the addition of the acid fermented material on the phosphorus removal in biological excess phosphorus removal systems.

The laboratory investigation comprised studies of, (1) batch systems with batch retention times up to about 10 days for influent volatile solids concentrations ranging from 11 to 42 g/ℓ, (2) 3 in-series completely mixed reactor systems with each reactor having 1 day flow through retention time for influent volatile solids concentrations ranging from 37 to 60 g/ℓ and, (3) single completely mixed reactor systems with flow through retention times of 1, 2, 3, 5, 6 and 9 days for influent volatile solids influent concentrations ranging from 36 to 50 g/ℓ. All the studies were made at 20° C.

From the fermentation studies the following conclusions were formed.

- The raw sludge appears to have an acid fermentation potential for the production of SCFA, of about 17 percent of the influent sludge COD i.e. a specific potential yield of 0,17 mgSCFA as COD/mg influent sludge COD.
- The potential does not appear to be influenced by the concentration of the influent primary sludge.
- The production of SCFA appears to conform to a first order reaction with a reaction rate constant of about 0,16 day^{-1} at 20° C.
- Besides generating SCFA, acid fermentation also generates soluble complex molecules approximately equal in concentration to the concentration of SCFA, i.e. of the total soluble (<0,45μm) COD concentration generated, approximately half is SCFA (as COD) and half is non-SCFA soluble COD. The production rate of the total soluble COD, (and therefore also that of the non-SCFA soluble COD) also approximates a first order rate not influenced by sludge concentration.
- Hydraulic retention time in an acid fermentation system should not exceed about 6 days at 20° C; at longer retention time work (elsewhere) indicates that methane fermentation can take place thereby reducing the net SCFA yield.
- The COD yield of SCFA at 6 days at 20° C is approximately 38 percent of the potential yield, and can be estimated from the specific potential yield (0,17 mgSCFA as COD/mg influent sludge COD by:

$$\text{COD SCFA at 6 days} = 0{,}17(1-e^{0{,}16 \cdot 6}) \text{ COD of influent sludge}$$

giving a yield of 0,065 mgSCFA as COD/mg influent sludge COD. Thus only a minor fraction of the SCFA potential can be generated at these short retention times.

Knowing the potential acid production and the reaction order a model for acid fermentation was constructed and equations developed for SCFA yield at any retention time, for single, in-series and accumulating batch reactor systems. No solutions were developed for acid fermentation in primary settling tanks with underflow recycle to the influent. Applying the model to evaluate the effect of the fermentation systems on the biological excess phosphorus removal (BEPR) systems, it was found that:

- For total retention times up to about 6 days the differences in the SCFA yield between a single reactor, 3 in-series reactors and accumulating batch reactor are small. In consequence the selection of a specific system for acid fermentation will be governed by the cost of construction and the ease of operation.

- From a practical and economic point of view the most appropriate retention time in fermentation systems appears to be about 3 days: With 3 days acid fermentation retention time biological excess phosphorus removal in the BEPR plant will increase by about 15 per cent. Increasing the acid fermentation time to 6 days will improve the phosphorus removal in the BEPR plant only by a further 3 percent. These values apply to BEPR systems treating settled or unsettled influents.

The study reported here did not investigate experimentally, the effects of the addition of the fermented products on BEPR, denitrification and aerobic processes in the nitrification denitrification (ND) BEPR system. Such a study is important because it would give an indication what proportion of the non-SCFA soluble (<0,45μm) COD generated is RBCOD which can be converted to SCFA in the anaerobic rector. The increases in BEPR cited above are those due only to SCFA generation and ignore the possible additional BEPR due to a RBCOD component in the non-SCFA soluble COD fraction. Earlier investigations at laboratory scale (Bagg *et al.*, 1985) and full scale (Osborn *et al.*, 1986, 1989) indicate that the non-SCFA soluble COD does contain RBCOD because the increases in BEPR achieved by acid fermentation are greater than can be accounted for by SCFA generation only. The RBCOD and SCFA generated by acid fermentation also may be important for improving denitrification when a nitrate standard is imposed: Some of the RBCOD/SCFA generated can be passed by the anaerobic reactor (with a concomitant reduction in BEPR) and discharged to anoxic reactors to improve the denitrification. It is most desirable that the combined acid fermentation/NDBEPR system be investigated further. This cannot be done very effectively at laboratory scale and is best investigated at pilot or full scale.

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APPENDIX A

Sampling Techniques and Measurement Procedures

Two 50 mℓ samples of mixed liquor are pipetted into two centrifuge tubes, a few drops of mercuric chloride are added (to stop bacterial action) and the sample centrifuged at 26 000 rev/min for approximately 25 minutes. The following tests are done on the sludge pellets and supernatants:

(1) **COD of VSS, TSS and VSS determinations**

The solids remaining in the centrifuge tubes are retained separately. The sludge pellet of the first centrifuge sample is used to determine the COD of the VSS as follows: The pellet is washed into a macerator with a measured quantity of distilled water and macerated for approximately 15 seconds. A measured sample of this mixture is diluted and the COD of the sludge determined in accordance with Standard Methods (1985).

The sludge pellet from the second centrifuge sample is used to determine the TSS and VSS concentrations in accordance with Standard Methods (1985).

(2) **Total 'soluble' COD, –0,45μm COD, TKN and NH_3-N determination**

The supernatants obtained from the two centrifuged samples are poured off into a single plastic container. The supernatant is filtered through a Whatmans No.1 filter, and when measured a sample taken, diluted and tested. The remaining filtrate is then filtered through a glass fibre –0,45μm filter. The –0,45μm filtrate is diluted and used for COD, TKN and NH_3-N determination in accordance with Standard Methods (1985).

(3) **SCFA determination**

The short chain fatty acid concentrations were measured as follows: A solution of 0,3% phosphoric acid (H_3PO_4) is made up by taking 3g of H_3PO_4 and making it up to 1ℓ with de-ionized water. Separate solutions of acetic, propionic, iso-butyric and iso-valeric acids are made up by taking 1g of each acid and making them up to 1ℓ with the 0,3% H_3PO_4 solution. A set of standard solutions containing known concentrations (50, 100, 150, 200 mgSCFA/ℓ) of acetic, propionic, iso-butyric and iso-valeric acids is made up

from the above solutions and stored in test tubes at 4° C. A further solution of 3% H_3PO_4 is made up by taking 30g H_3PO_4 made up to 1ℓ with de-ionized water and stored at 4° C.

The sample to be measured is made up by taking 9 mℓ of the diluted –0,45μm filtrate, placing it in a test tube, and adding 1 mℓ of 3% H_3PO_4 to ensure an acidic environment and to ensure that approximately the same percentage of H_3PO_4 that is in the standard solutions is present in the sample.

The samples were analyzed using a Packard 417 gas chromatograph fitted with a flame ionization detector and linked to a REC 61 Servograph. A 6ft x 1/8" GP 10% SP-1200 (1% H_3PO_4) on 80/100 Chromasorb WAW glass column (supplied by Supelco, Inc.) is fitted as a detection medium. Prior to measuring, the column is conditioned overnight using the conditioning procedure supplied with the column. To ensure sufficient separation of the different acids, the following operating conditions were used:

(i) Inlet temperature 200° C
(ii) Column temperature 135° C
(iii) Air flow rate 300 mℓ/min
(iv) Hydrogen flow rate 30 mℓ/min
(v) Carrier gas (nitrogen) flow rate 30 mℓ/min

The column is calibrated by injecting 3 $\mu\ell$ samples of known concentrations (i.e. standard solutions) into the column. The samples are analysed by injecting a 3 $\mu\ell$ sample into the column. Each standard solution and sample was analysed at least twice or until a representative value is obtained.

(4) The sludge settleability was measured using the Diluted Sludge Volume Index in accordance with the procedure set out by Ekama and Marais (1984).

APPENDIX B

TABLES AND PLOTS OF THE RESULTS OF THE BATCH REACTOR INVESTIGATION

Table B.1: **Results of all measured parameters in batch test 1.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.4	153	147	13480	12534	19738	3022	461	656	39		1554
1	5.2	189	139	13442	12494	13909	3758	472	661	39		1573
2	5.1	174	137	11964	11260	13702	4245	506	744	39		1735
3	5.0	161	154	11388	10692	13709	4484	750	1039	61		2481
4	5.1	190	162	8828	8252	12456	5252	1089	1511	122		3667
5	5.0	385	127	12144	11382	15362	5398	989	1122	78		2892
6	5.0	161	137	9794	9132	13052	5723	1278	1489	78		3775
7	5.0	164	140	7610	7120	11646	6285	1589	1867	122		4738
8	5.0	171	151	6482	6044	11245	6707	1722	2078	122	233	5674
9	5.0	176	155	5194	4744	9036	7008	1900	2022	78	233	5699
10	5.0	182	164	5270	4982	7229	7068	2011	2156	122	333	6303
11	5.0	171	158	4374	4032	9036	7289	1989	1944	78	233	5676
12	5.0	186	165	3936	3630	6626	7189	2133	1967	122	422	6329
13	5.0	165	174	5970	4952	8634	7389	2233	2044	122	422	6552
14	5.1	181	160	4906	4604	7028	7209	2089	1811	167	422	6128
15	5.1	181	151	5080	4748	7004	7869	2278	2044	144	422	6640
16	5.0	200	175	3532	3466	7828	7704	2444	2089	144	278	6592
17	5.0	193	176	4684	4358	8446	7931	2267	1778	111	278	5873
18	5.1	192	181	4398	4050	6386	8158	2322	1867	144	333	6238
19	5.1	206	179	4012	3728	7210	8199	2967	2278	167	422	7770

Table B.2: Results of all measured parameters in batch test 2.

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
0	5.4	60	81	4302	4042	4934	1100	194	311	28	44	818
1	5.3	69	57	3974	2798	5647	1215	289	394	28		955
2	5.3	90	67	4324	4118	7889	1370	333	478	28		1129
3	5.0	97	71	1824	1692	3944	1432	333	444	28	44	1167
4	5.3	97	74	3060	2900	3529	1578	389	533	56		1322
5	5.2	167	77	2622	2436	3737	1723	367	433	56		1148
6	5.0	57	73	2170	2022	2610	1847	478	667	56		1620
7	5.1	60	45	2062	1946	3213	2108	511	667	56	88	1834
8	5.0	71	66	1972	1852	2410	2309	622	667	56	88	1953
9	5.0	60	42	2310	2136	2811	2450	789	689	56	89	2166
10	5.0	32	50	1790	1676	1606	2771	911	722	56	89	2346
11	5.0	64	56	1486	1384	2610	2470	978	722	56	89	2417
12	5.0	52	63	1746	1624	2424	2831	956	633	56	89	2259
13	5.0	62	41	2100	1940	3815	3032	1200	756	78	89	2745
14	5.0	50	43	1388	1274	3414	2811	1444	811	144	78	3186
15	5.0	59	45	2610	2506	4532	3523	1411	756	189	78	3151
16	5.0	59	63	1632	1512	4120	3090	1333	667	189	78	2932
17	5.0	56	52	2590	2468	4326	3008	1189	533	144	78	2494
18	5.0	41	45	1944	1804	4532	2925	1300	644	144	78	2780
19	5.0	49	53	2852	2734	3502	2946	1544	744	144	78	3191

Table B.3: Results of all measured parameters in batch test 3.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	6.1	161	162	11000	9958	12203	1915	33	22			68
1	5.6	185	182	10008	9152	14518	2630	44	22			80
2	5.2	188	182	8904	8138	13886	3472	33	11			52
3	5.1	186	172	8176	7494	11572	4103	33	756		33	1245
4	5.1	183	179	7570	6954	12624	4650	33	1067		33	1716
5	5.0	186	168	7336	6706	13049	4923	811	1367	89	33	3160
6	5.1	183	169	6558	6082	11059	4833	1078	1367	100	33	3465
7	5.1	179	179	7092	6546	12298	4854	33	1233	89	33	2128
8	5.1	200	189	6770	6310	12083	4916	33	567	66	33	1080
9	5.1	203	193	7438	7132	12288	5059	222	1233	66	33	2288
10	5.1	197	193	6808	6284	11469	4997	1044	1344	89	33	3374
11	5.2	200	197	7216	6652	11059	4915	1078	1344	89	33	3410
12	5.2	202	186	7150	6572	11418	5024					
13	5.1	218	203	7162	6580	13079	4962					

Table B.4: Results of all measured parameters in batch test 4.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	6.2	80	66	3690	3414	5470	652	20	100			173
1	5.9	77	91	3492	3170	4839	905	0	50			76
2	5.4	81	71	3168	2906	3998	1094	0	80			121
3	5.2	81	67	2804	2588	3156	1389	20	20	20		88
4	5.2	90	77	2602	2406	3998	1536	20	20	50		142
5	5.1	63	71	2530	2322	4418	1725	20	20	50		142
6	5.2	74	73	2542	2424	4506	1475	320	500		10	1117
7	5.2	74	73	2408	2254	4096	1720	400	590	20	30	1416
8	5.2	91	77	2272	2126	4506	1741	60	420	20	10	756
9	5.2	85	76	2580	2550	3482	1679	400	550	20	10	1315
10	5.2	81	77	2146	1992	4096	1761	280	450	20	10	1036
11	5.2	84	77	2400	2218	3891	1679	430	590	20	30	1448
12	5.2	85	81	2402	2212	3737	1848	430	550	20	10	1347
13	5.1	94	91	2256	2058	5190	1848	400	610	20	10	1405

Table B.5: **Results of all measured parameters in batch test 5.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.9	179	167	49180	42086	59392	2458	40	30			88
1	5.6	312	266	45006	40536	61723	4170	40	30	20	30	185
2	5.5	322	288	42198	38168	47420	4599	40	30			88
3	5.5	343	319	42742	38882	46194	5232	870	1090	70	80	2866
4	5.4	396	338	41498	37414	62546	6030	70	1170	70	80	2134
5	5.3	385	346	40534	36584	54370	6071	1170	1450	160	130	3995
6	5.3	375	337	37824	34076	65408	6377	1400	1520	140	130	4310
7	5.3	405	356	37134	33804	54370	7583	70	900	140	130	1954
8	5.2	398	381	36488	33266	55296	7352	1630	1820	190	130	5099
9	5.2	440	406	36614	33278	49152	7885	1860	2190	190	180	6006
10	5.2	448	417	36768	33356	56934	8458	2090	2650	320	220	7264
11	5.1	466	441	36550	33138	58163	8745	2200		350	260	
12	5.1	473	449	36283	32506	61440	9318	2120		230	260	
13	5.1	487	451	35872	32498	59145	9306	2060	2920	380	160	7267
14	5.1	532	498	34814	31398	51700	9761	2200	2920	380	160	7776
15	5.1	462	459	34804	31574	53354	9596	1820	2460	320	160	6567
16	5.1	529	512	34392	31256	57077	10547	2100	2640	320	160	7137

Table B.6: Results of all measured parameters in batch test 6.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Prpionic acid	Butyric acid	Valeric acid	SCFA - as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	6.1	63	48	4004	3418	16000	367		100			151
1	5.8	66	52	7586	6936	14309	941		100			151
2	5.5	71	60	10688	9032	12264	852		100			151
3	5.4	69	67	10250	9456	13899	1165		160			242
4	5.3	73	52	9656	8992	12673	1410		160			242
5	5.2	64	56	9858	9564	13082	1288		70			106
6	5.2	60	46	8624	7952	6541	1533		70			106
7	5.2	59	57	8412	7784	12264	2064	30	390			622
8	5.0	53	46	8168	7594	13107	2417	680	1460			2932
9	5.0	50	42	8166	7490	11059	2417	30	30			77
10	5.0	55	42	8008	7366	12698	2682	30	420			667
11	5.0	57	45	7944	7330	12698	2949	370	1000			1906
12	5.0	48	46	7696	6956	12698	2929	750	1030			2357
13	5.0	56	49	7808	7160	10340	3061	800	1060			2456
14	5.0	55	49	7444	6768	8272	2771	710	930			2160
15	5.0	53	52	7270	6698	11994	2937	800	1200			2667
16	5.0	74	46	7266	6662	11994	3164	800	930			2259

Table B.7: Results of all measured parameters in batch test 7.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	6.1	168	144	41414	37044	47923	2744	511	511	67	22	1484
1	5.6	280	230	36798	33700	45466	3686	833	1167	22	22	2737
2	5.5	322	286	33874	30844	43008	4731	1222	1622	122	44	4066
3	5.5	375	333	35358	32462	44646	5509	1144	1278	22	22	3237
4	5.5	393	344	34596	31682	43418	5796	1222	1311	67	22	3451
5	5.4	441	419	35424	32440	51610	6410	1267	1400	67	44	3679
6	5.4	423	417	33528	30802	42924	7318	1633	1911	122	44	4941
7	5.4	477	447	32914		37201	8033	1944	2267	122	44	5911
8	5.3	498	468	32058	29494	41289	7849	1889	1811	44	44	4921
9	5.3	538	482	28752	26222	41698	8340	2222	2489	133	44	6463

Table B.8: Results of all measured parameters in batch test 8.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	6.3	76	60	12146	11094	13936	410	100	122	66		411
1	5.8	90	80	12032	11204	13926	799	144	222	66		609
2	5.7	73	83	12990	11776	14746	1024	278	267	122		922
3	5.7	98	90	11070	10286	13107	1126	333	344	122		1097
4	5.5	106	94	11450	10438	15974	1372	333	433	66		1130
5	5.3	118	106	11008	10052	11469	1536	444	489	122		1434
6	5.2	99	95	10678	10034	12264	1696	555	600	11		1519
7	5.2	99	90	10434	9606	11038	1840	555	611	122	22	1737
8	5.1	106	98	10034	9264	14717	2024	666	733	10		1836
9	5.1	97	81	9472	8674	13082	2678	622	733	66		1891

Table B.9: **Results of all measured parameters in batch test 9.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.7	48	44	18184	16458	18022	1024	356	389			968
1	5.5	60	56	16852	15356	27034	1413	389	467			1121
2	5.4	83	63	16696	15274	17613	1597	433	522			1250
3	5.4	88	81	16386	14914	14746	1782	556	544			1415
4	5.3	91	84	15902	14760	20480	1700	622	556			1503
5	5.3	101	88	17216	15834	16037	1933	644	544			1509
6	5.3	115	105	16756	15432	16448	1953	678	544			1545
7	5.3	112	102	15342	13986	21793	2097	733	589			1672
8	5.3	113	102	15328	14190	19326	1933	733	556			1622
9	5.4	125	104	24202	22628	16448	2138	700	556			1587
10	5.4	132	106	15694	14162	20645	2004	733	556			1622
11	5.4	116	98	16154	14400	21859	1943	678	544			1545

Table B.10: Results of all measured parameters in batch test 10.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.6	111	109	38588	34898	38502	2191	467	600			1405
1	5.4	151	136	34730	31610	39322	3113	667	856			2004
2	5.4	182	161	35208	32294	37274	3768	900	1056			2555
3	5.3	197	178	37866	34596	38093	4567	1122	1133			2910
4	5.3	232	192	35042	32398	33587	4321	1122	1167			2960
5	5.2	232	192	36816	33806	35363	5387	1333	1411			3555
6	5.2	258	223	35762	33002	36186	6004	1444	1622			3993
7	5.2	277	248	35970	32748	39064	6271	1544	1744			4284
8	5.2	280	235	36862	33968	32896	6374	1611	1744			4355
9	5.3	295	272	36354	33172	30018	6620	1611	1744			4355
10	5.2	287	265	34434	31996	31978	6538	1611	1744			4355
11	5.2	295	266	31816	29430	37242	6780	1656	1678			4302

Table B.11: Results of all measured parameters in batch test 11.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.7	110	87	29614	26252	30310	1884	433	544			1295
1	5.6	119	102	25284	22798	31949	2253	556	667			1600
2	5.5	136	120	25768	23338	27853	2847	689	800			1944
3	5.4	140	132	23362	21282	25805	3174	733	878			2109
4	5.3	154	136	23992	21932	30702	3379	911	911			2349
5	5.3	179	146	24392	22496	28372	3701	989	1033			2617
6	5.2	169	146	24562	22354	25496	4215	1078	1122			2846
7	5.2	158	144	23830	21950	25494	4235	1144	1233			3085
8	5.2	172	143	24038	22406	29606	4647	1211	1322			3290
9	5.2	185	161	31272	29576	25906	4749	1256	1422			3489
10	5.2	172	148	22744	21166	27931	5100	1333	1500			3689
11	5.2	160	154	19776	18496	29955	4999	1311	1500			3666

Table B.12: Results of all measured parameters in batch test 12.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.7	116	101	24302	21514	31601	1724	367	467	111	144	1592
1	5.5	133	120	22074	19332	27907	2462	567	633	133		1803
2	5.4	165	141	20802	18956	27497	2914	700	789	156	144	2516
3	5.4	160	139	21114	19602	27853	3215	844	878	167	144	2824
4	5.3	162	140	20242	18848	25804	3584	978	922	167	144	3033
5	5.3	167	140	19512	18176	28672	3994	1089	944	156	144	3165
6	5.3	179	155	17610	15830	22528	4137	1178	1011	156	144	3361
7	5.3	193	178	15384	14142	22118	4301	1278	1200	167	144	3773
8	5.3	188	172	23030	20954	33048	4631	1389	1200	156	211	4008
9	5.3	188	181	21550	19816	28560	4753	1389	1400	167	267	4445
10	5.3	193	174	22326	20532	30192	4957	1444	1344	133	211	4243
11	5.3	210	179	21592	19912	28560	5120	1611	1467	156	211	4649

Table B.13: Results of all measured parameters in batch test 13.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	5.7	87	81	19288	17372	22572	1129	244	278			680
1	5.5	109	98	15102	13628	20520	1703	389	467	111		1322
2	5.4	101	95	15760	14452	20930	1990	444	522	111		1464
3	5.3	111	95	14558	13508	19251	2396	556	600	133		1741
4	5.3	116	109	13568	12646	20480	2621	667	667	133		1961
5	5.3	102	95	13662	12712	20890	2662	778	756	156	144	2549
6	5.3	115	99	15504	14302	16794	2967	811	900	156	144	2802
7	5.3	126	108	14462	13288	20070	3195	911	833	133	144	2765
8	5.3	115	111	15064	13634	22848	3264	1000	900	133	144	2962
9	5.2	119	106	14274	13150	20400	3509	1033	922	133	144	3030
10	5.2	137	106	13434	12300	19584	3937	1089	1000	133	178	3277
11	5.2	116	92	13178	12358	18768	4039	1100	1200	156	178	3633

Table B.14: Results of all measured parameters in batch test 14.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
0	6.0	41	35	14574	13008	15595	759	211	256			612
1	5.8	81	69	11554	10082	18878	1231	322	339			856
2	5.4	83	76	12000	10754	16006	1374	400	422	133		1306
3	5.4	80	66	9958	9080	17203	1679	422	478	133		1414
4	5.3	88	74	9550	8930	14746	1843	533	544	133		1632
5	5.3	77	69	8904	8278	18022	2007	600	578	133		1755
6	5.3	74	66	10516	9828	13517	2109	689	611			1658
7	5.3	83	77	8614	7964	19660	2150	722	644			1743
8	5.3	80	73	9904	9182	22848	2326	778	667			1838
9	5.3	80	73	9218	8464	21216	2346	800	700			1911
10	5.3	74	69	9050	8418	19176	2570	822	744			2001
11	5.3	73	69	9456	8778	11280	2550	844	778			2076

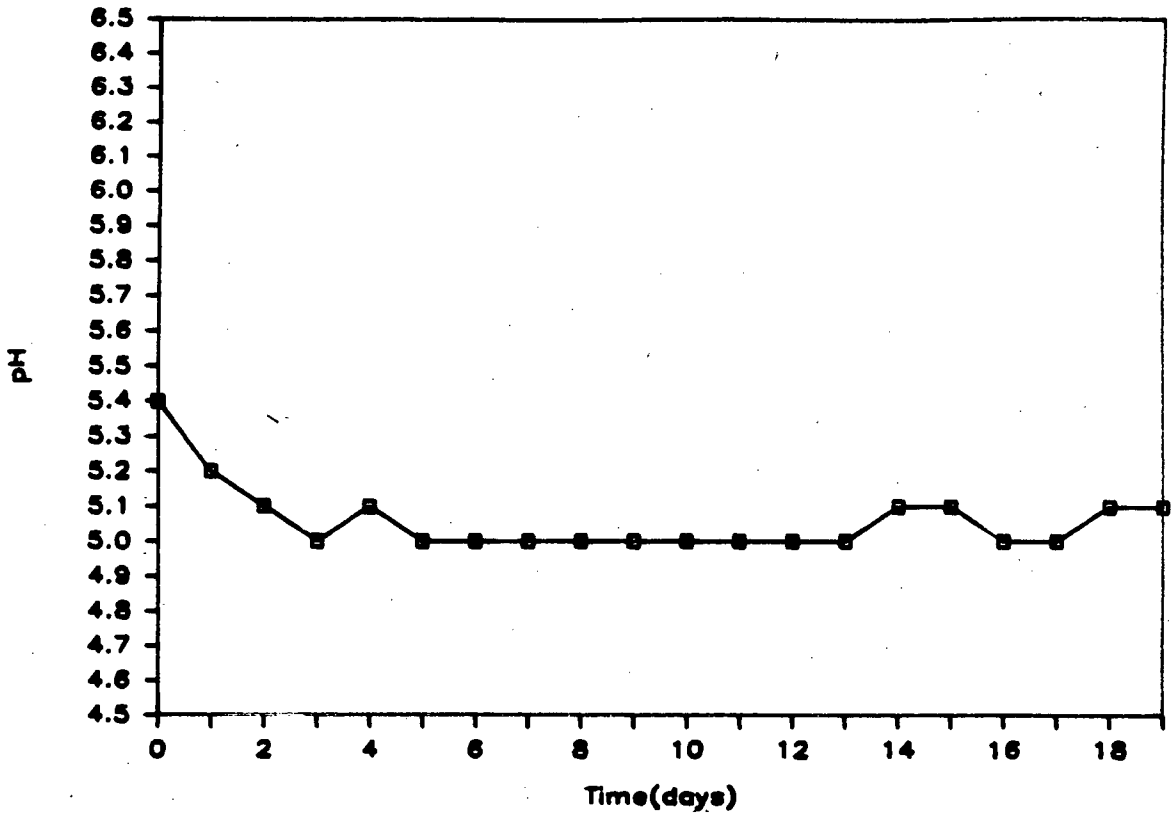

Fig B.1: pH of a batch reactor versus time – batch test 1.

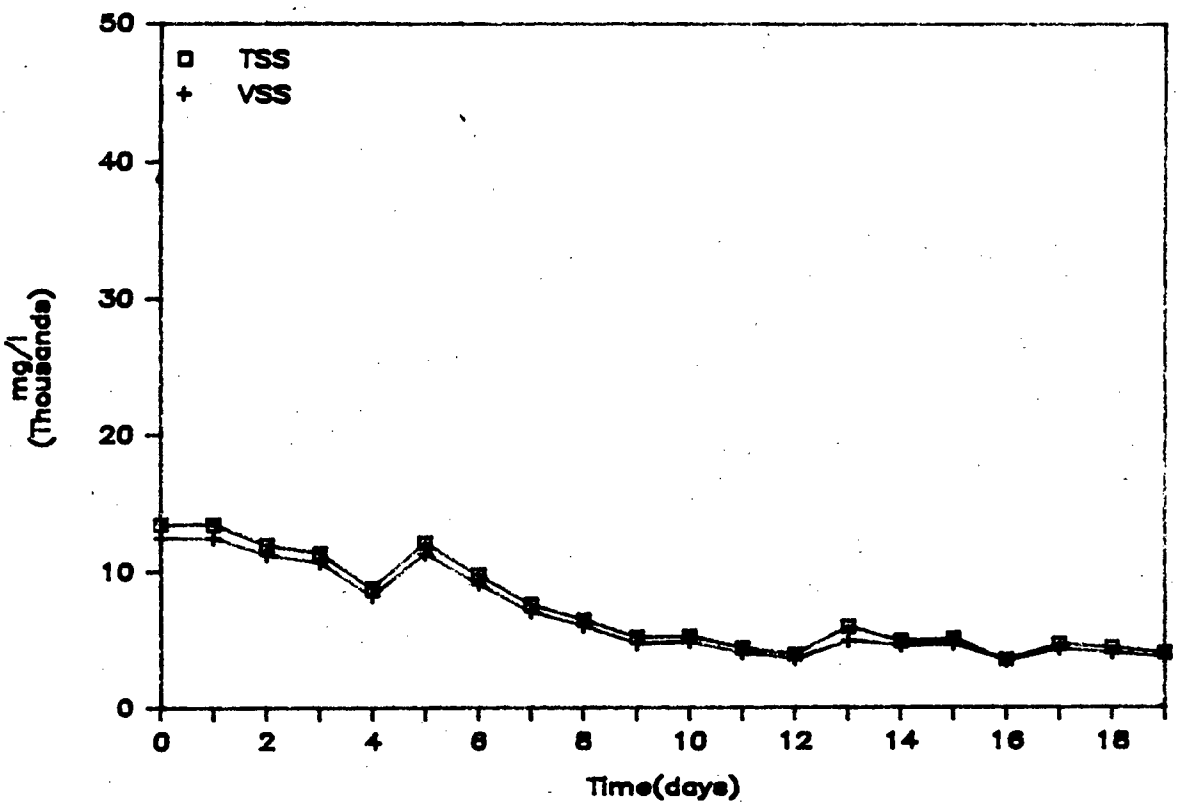

Fig B.2: TSS and VSS concentrations of a batch reactor versus time – batch test 1.

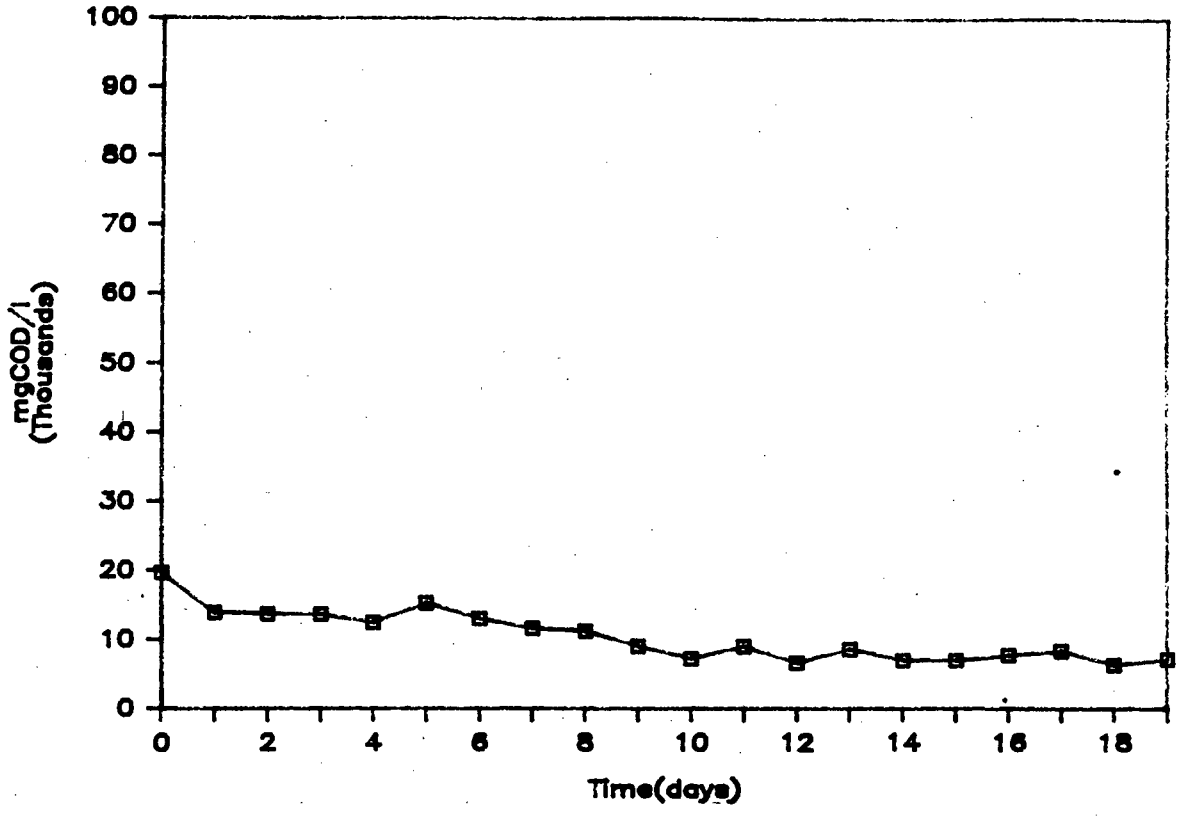

Fig B.3: COD of the VSS concentrations of a batch reactor versus time – batch test 1.

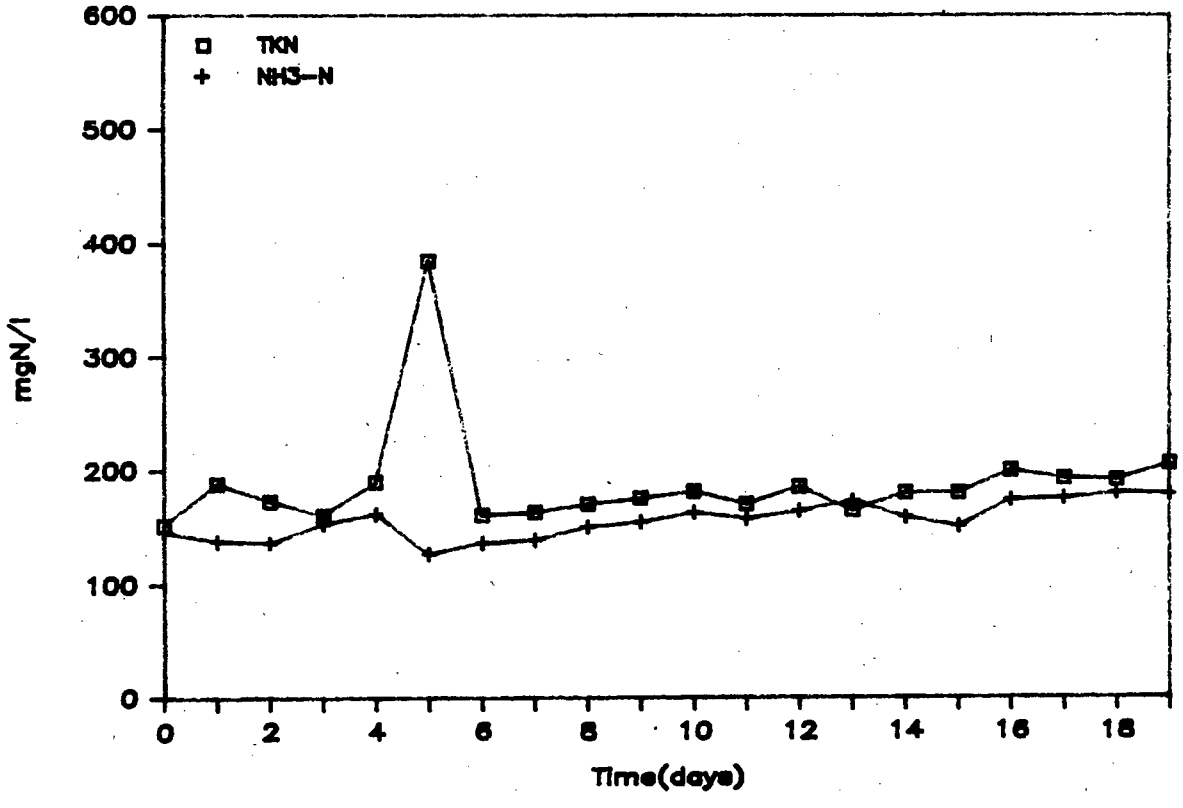

Fig B.4: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 1.

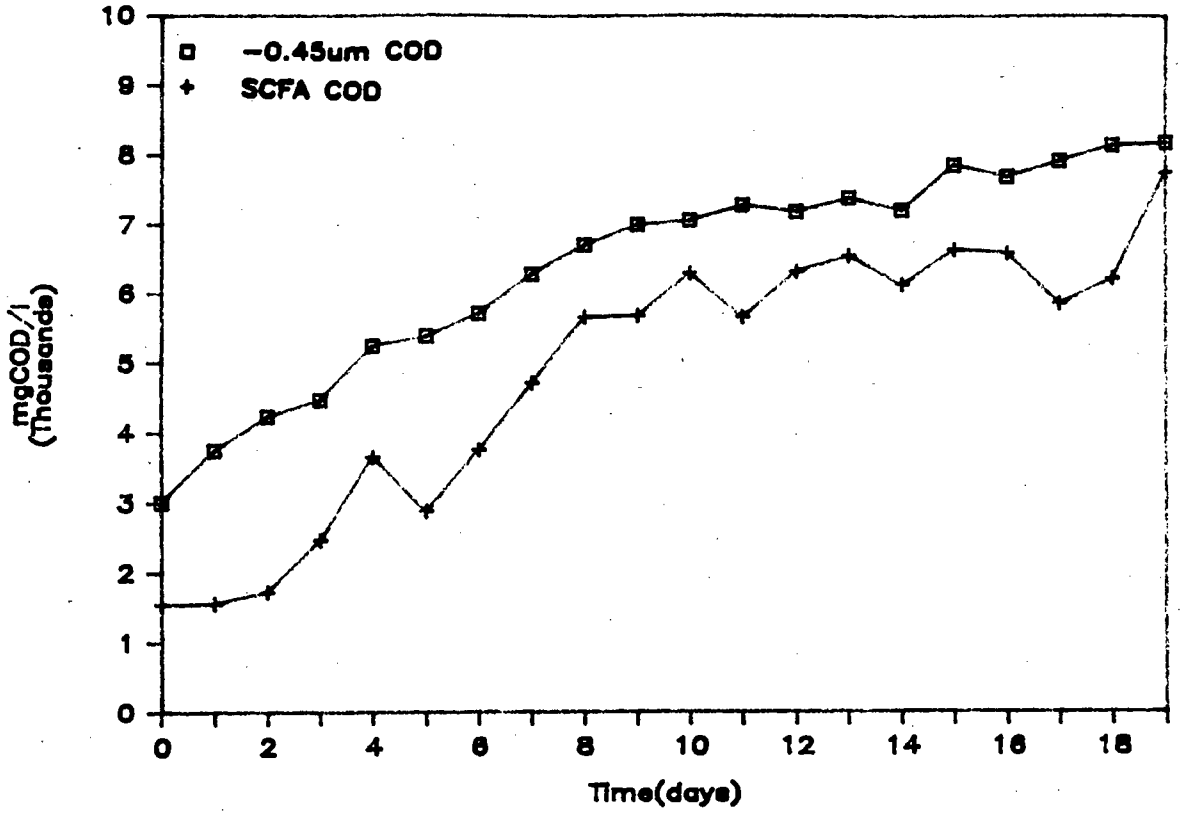

Fig B.5: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 1.

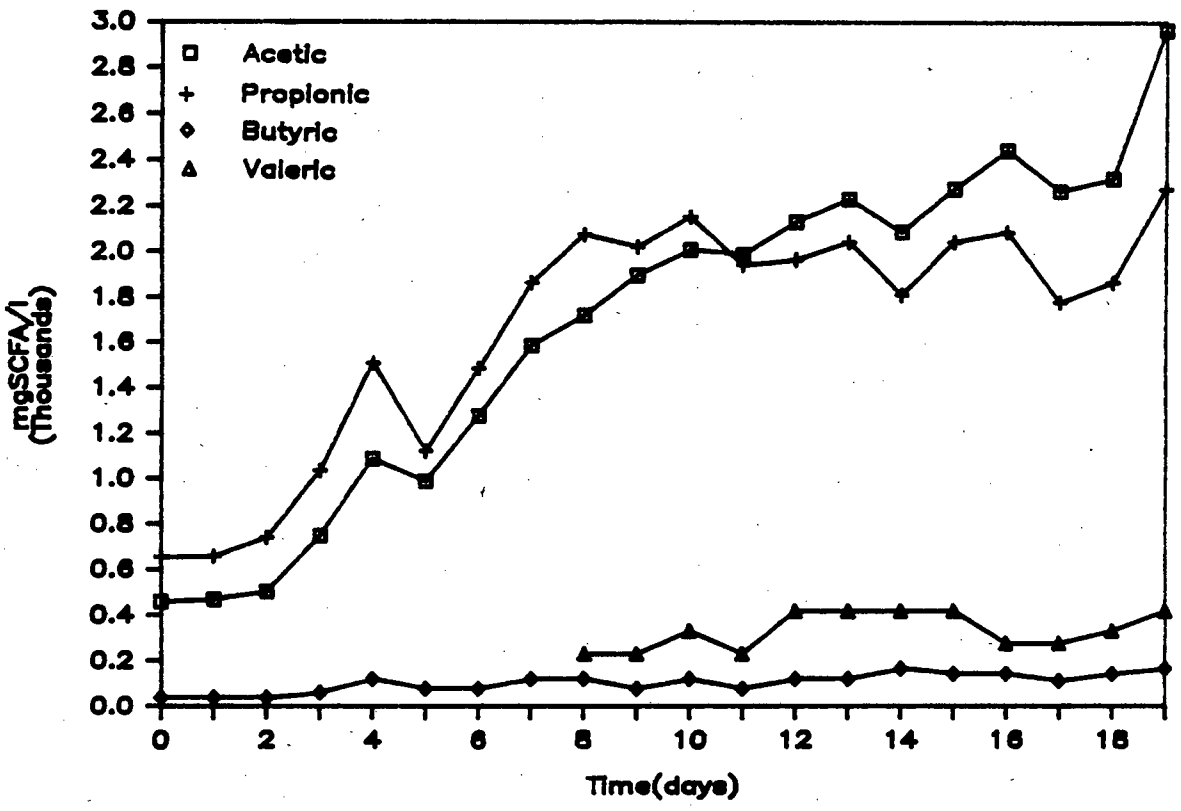

Fig B.6: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 1.

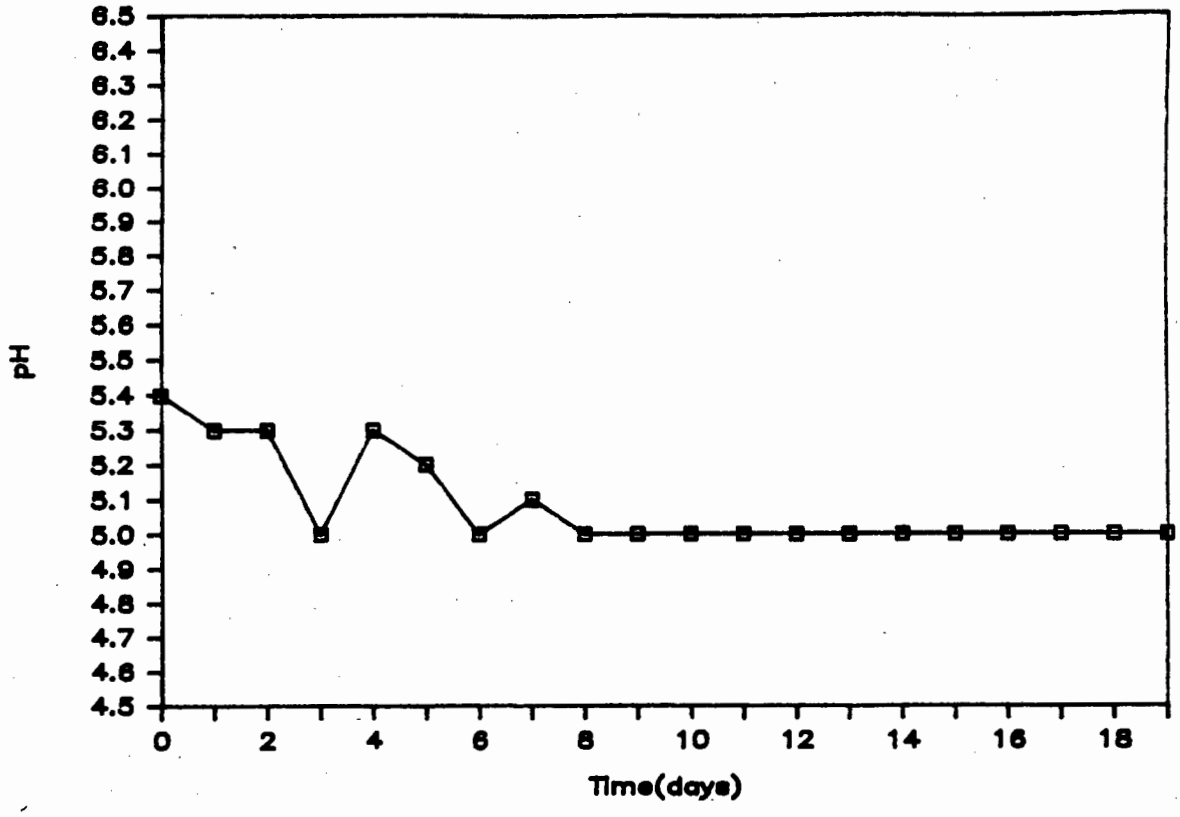

Fig B.7: pH of a batch reactor versus time – batch test 2.

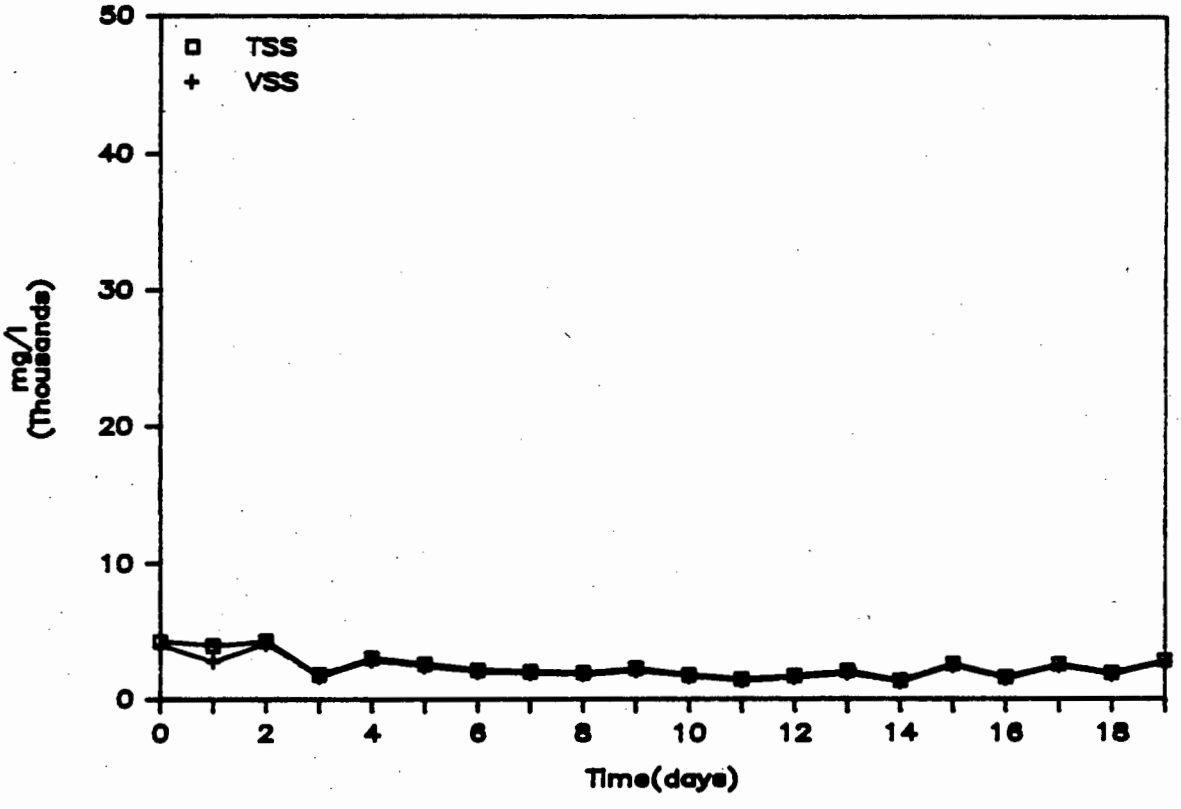

Fig B.8: TSS and VSS concentrations of a batch reactor versus time – batch test 2.

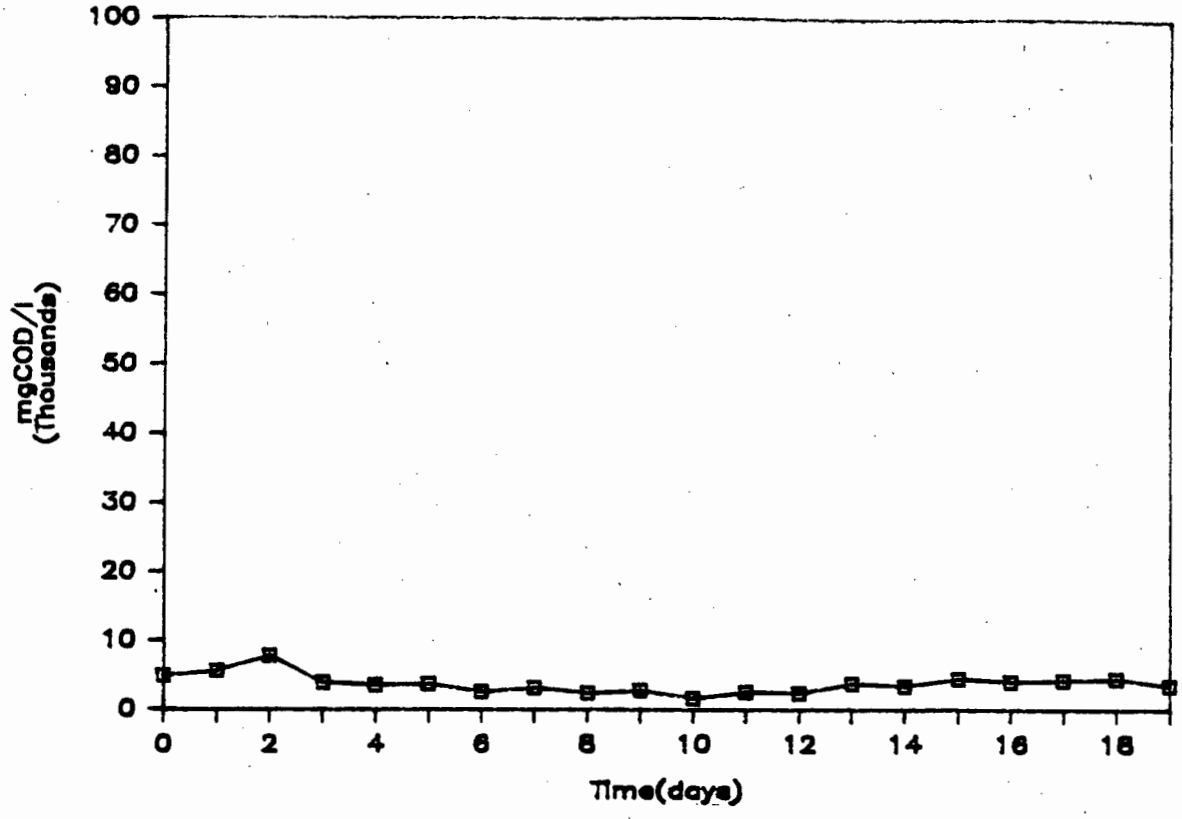

Fig B.9: COD of the VSS concentrations of a batch reactor versus time – batch test 2.

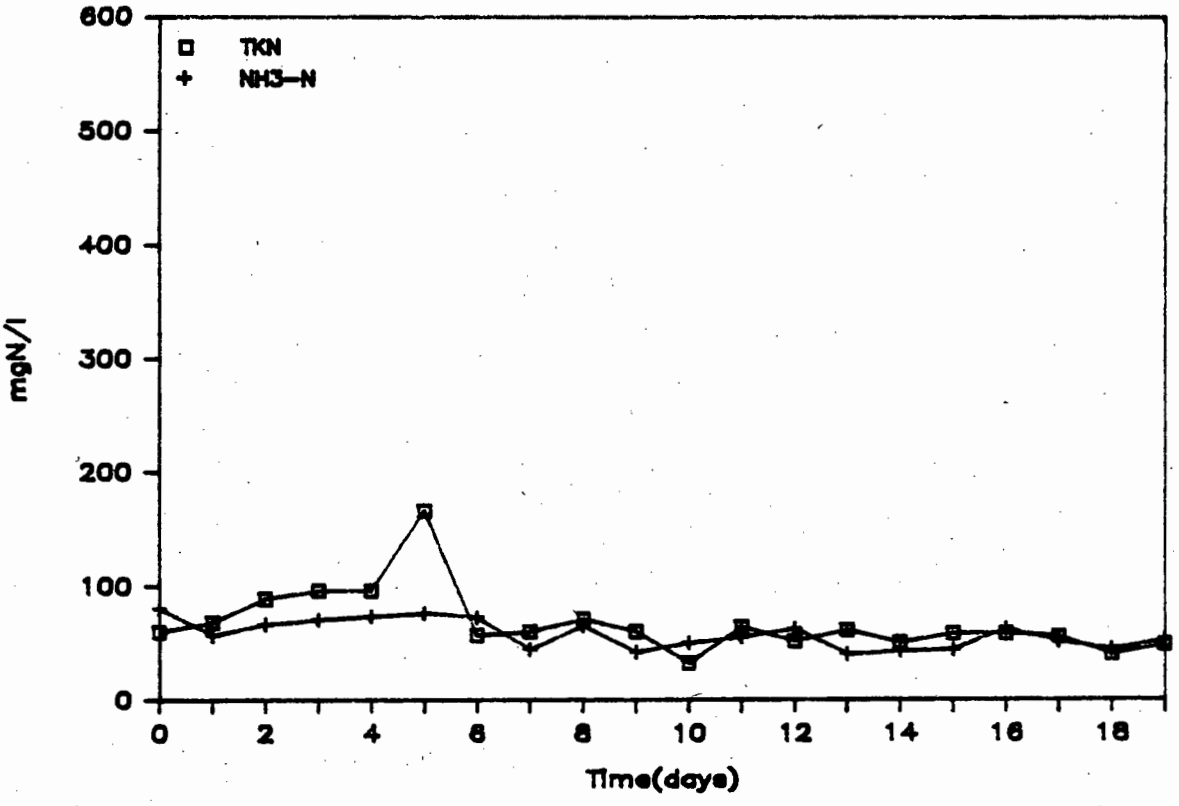

Fig B.10: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 2.

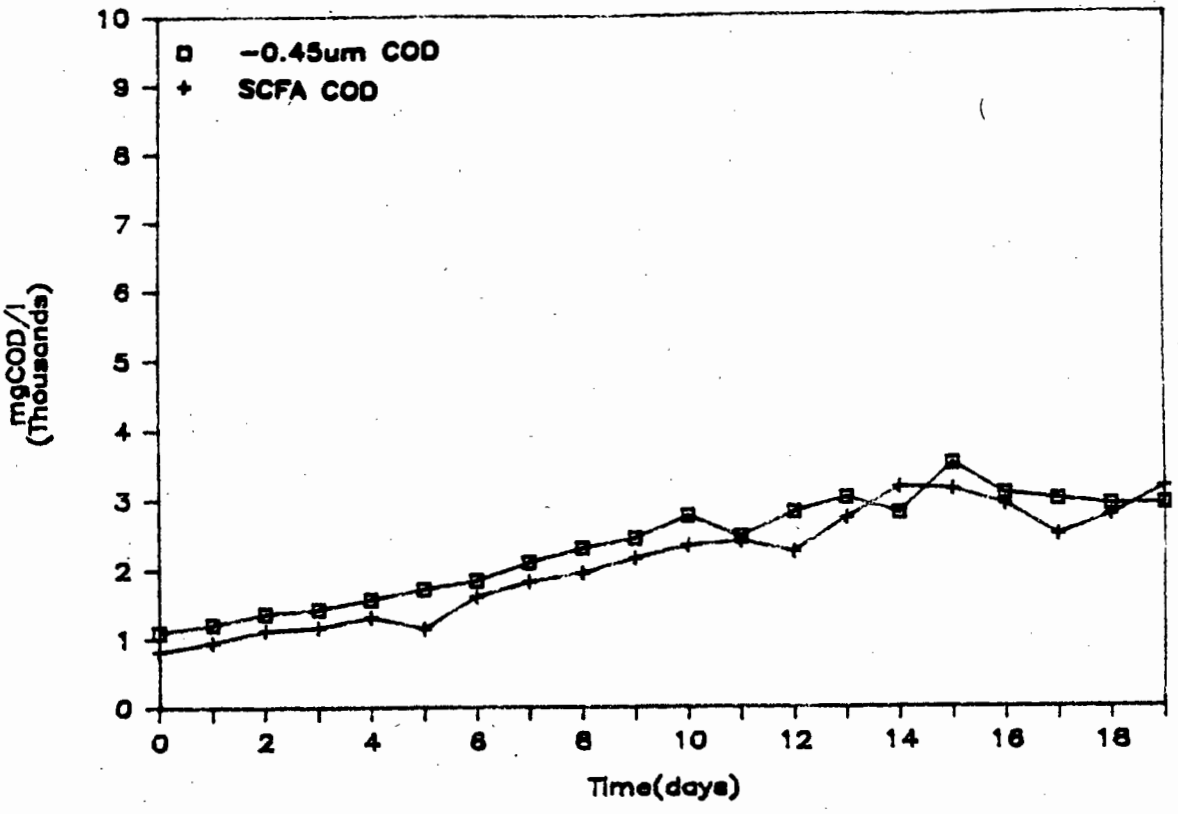

Fig B.11: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 2.

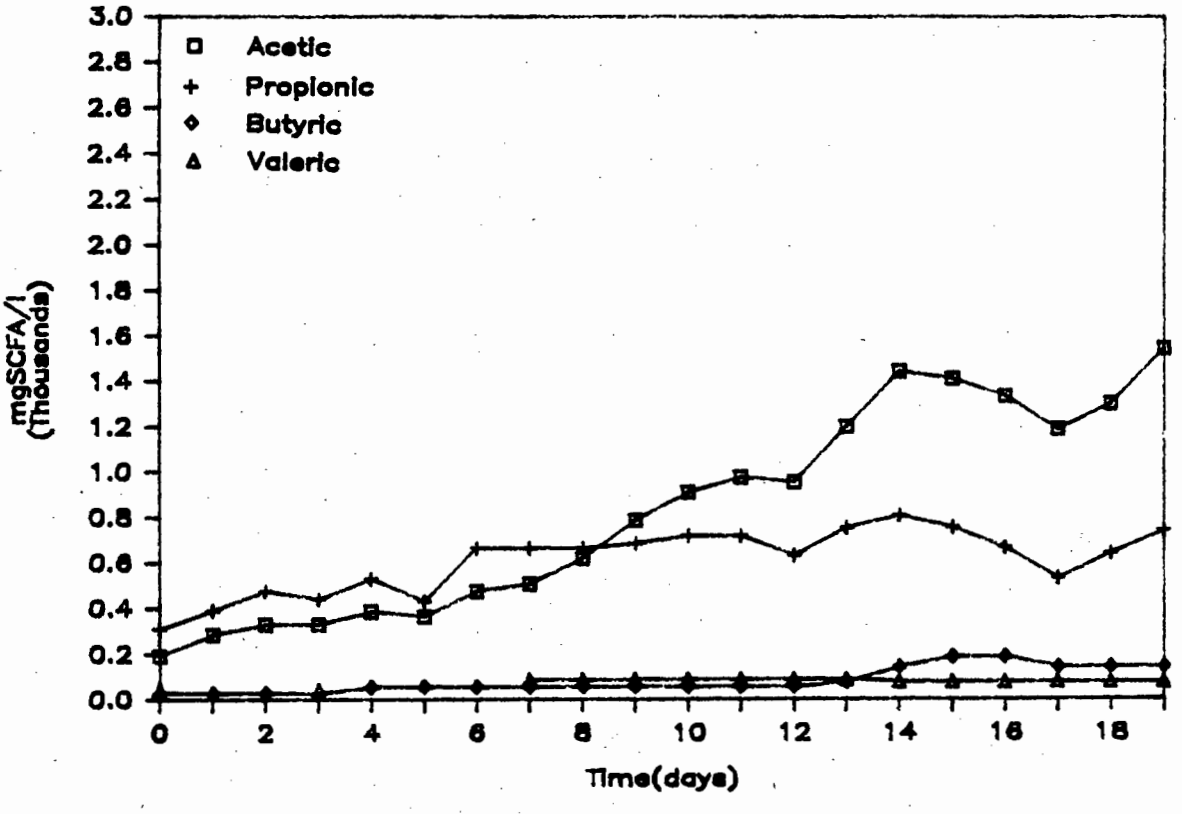

Fig B.12: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 2.

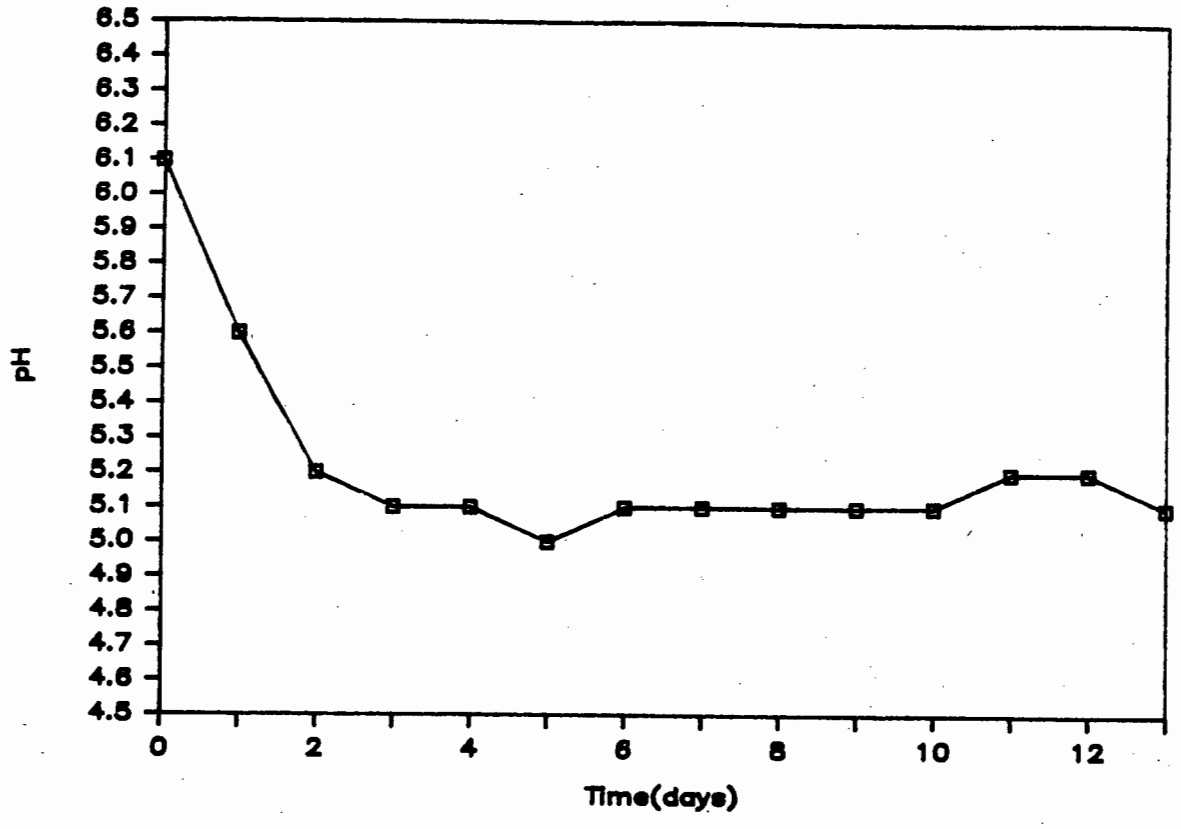

Fig B.13: pH of a batch reactor versus time – batch test 3.

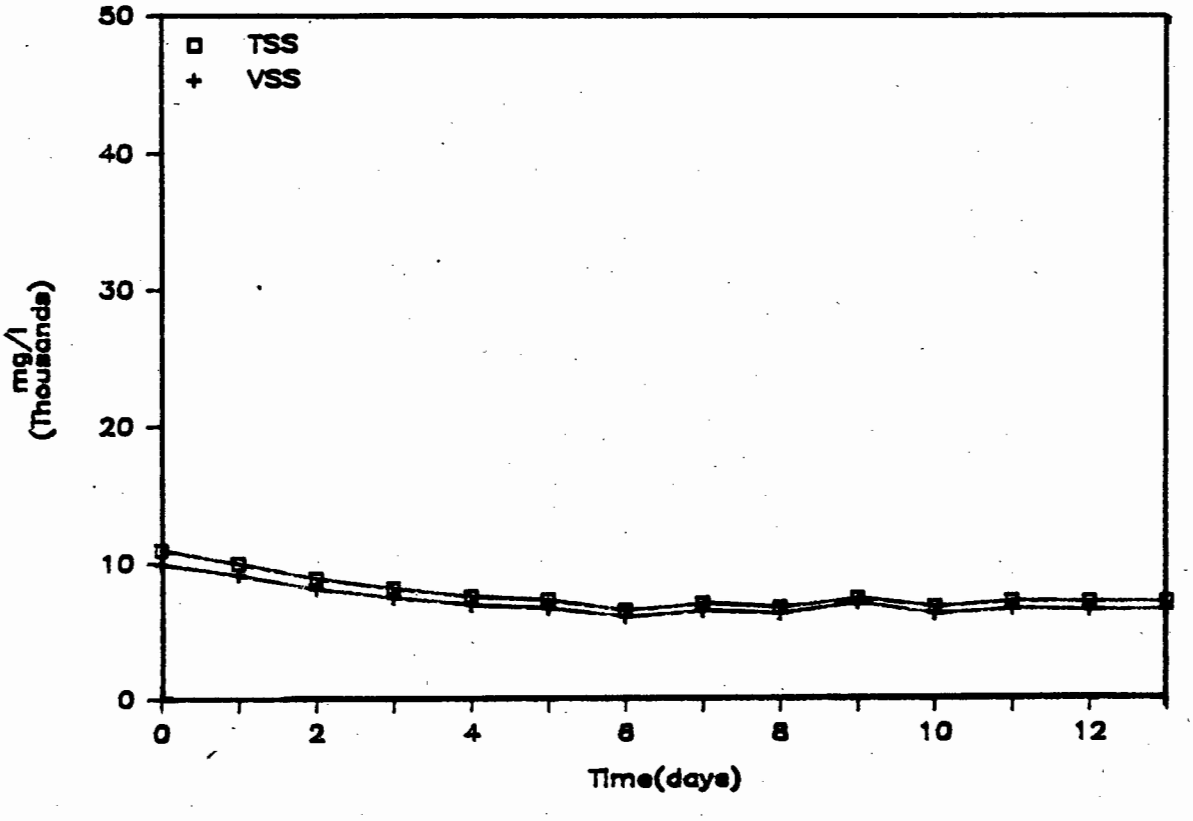

Fig B.14: TSS and VSS concentrations of a batch reactor versus time – batch test 3.

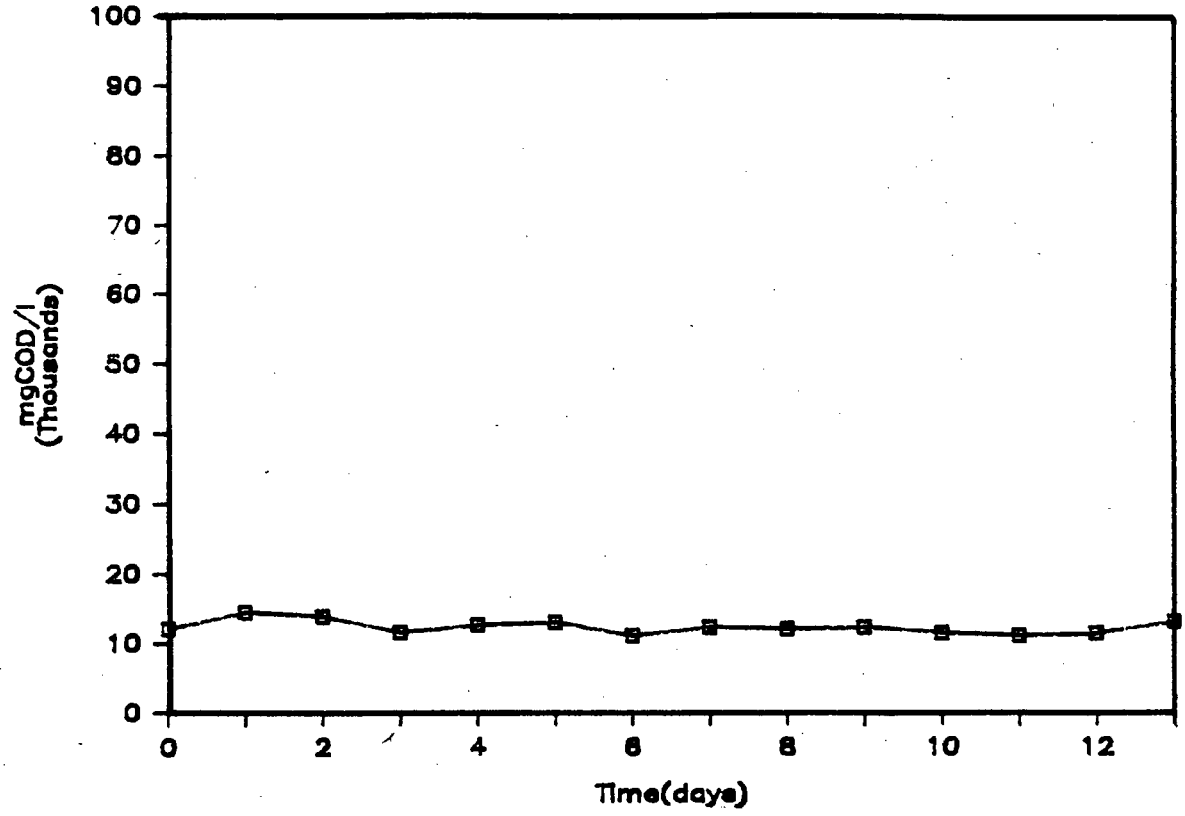

Fig B.15: COD of the VSS concentrations of a batch reactor versus time – batch test 3.

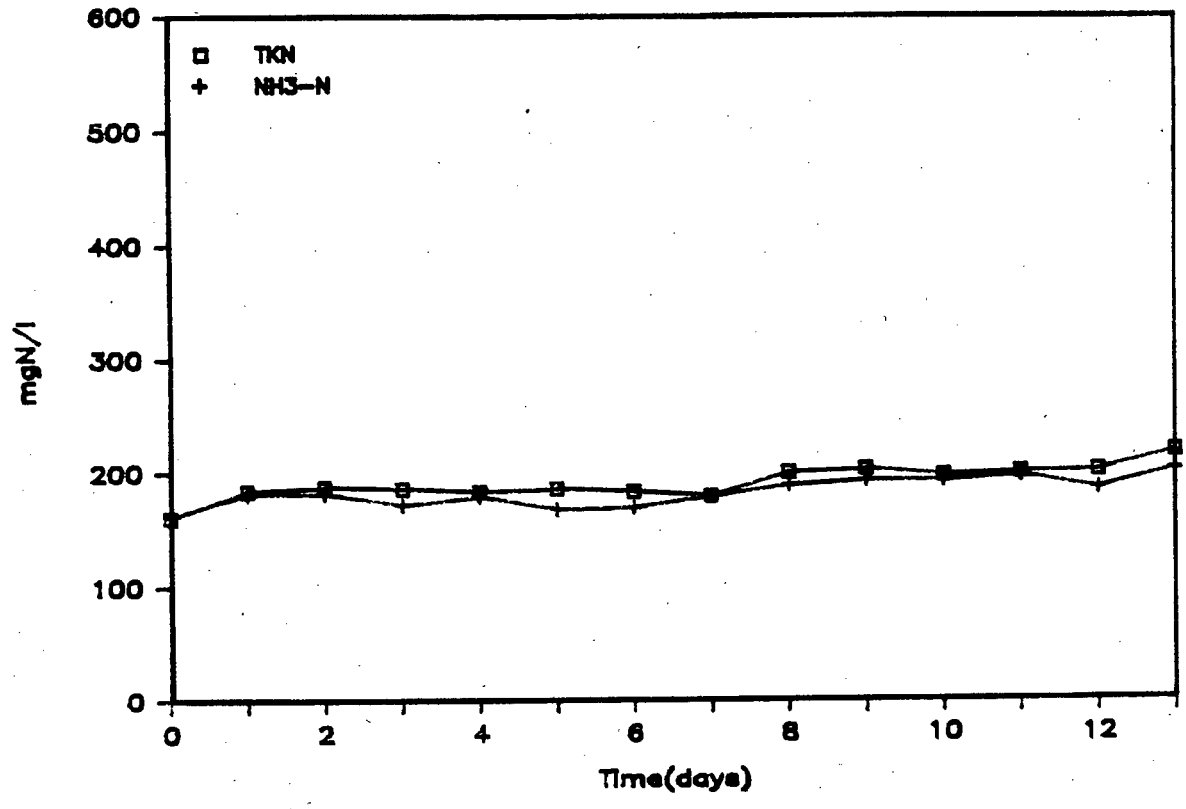

Fig B.16: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 3.

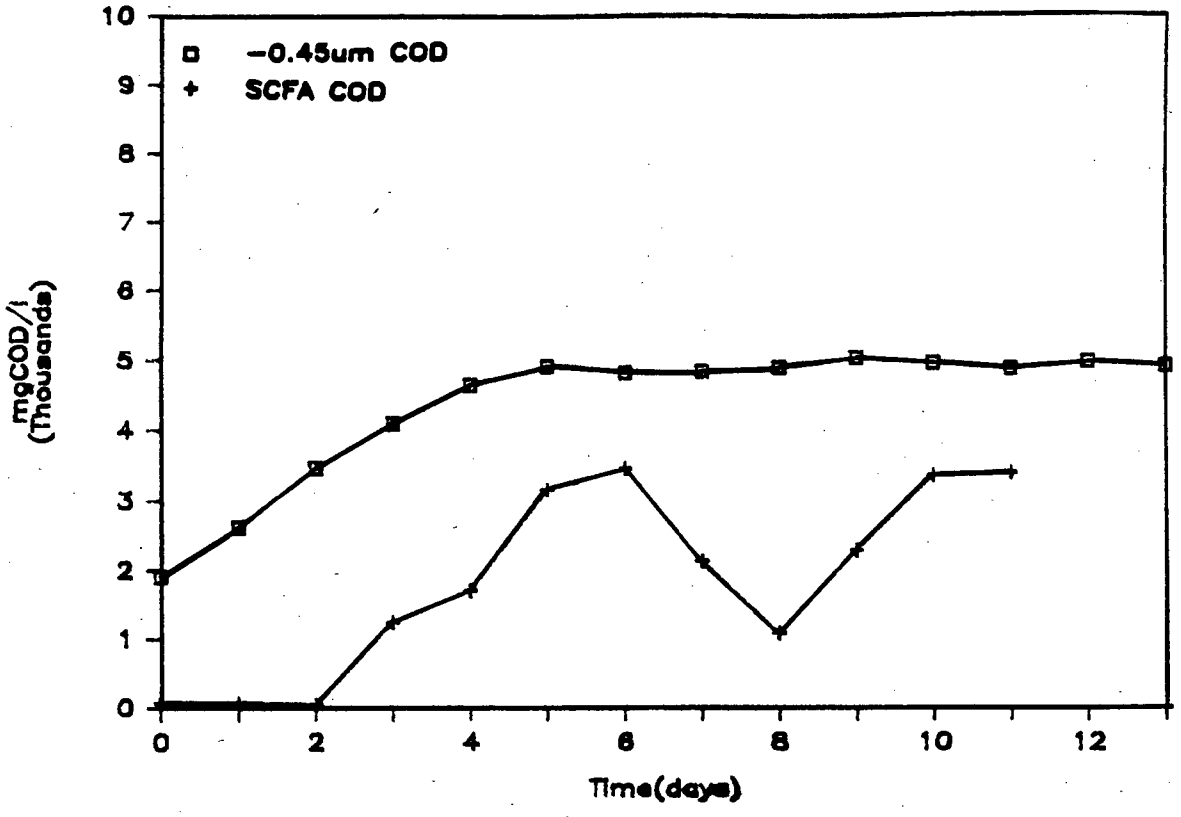

Fig B.17: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 3.

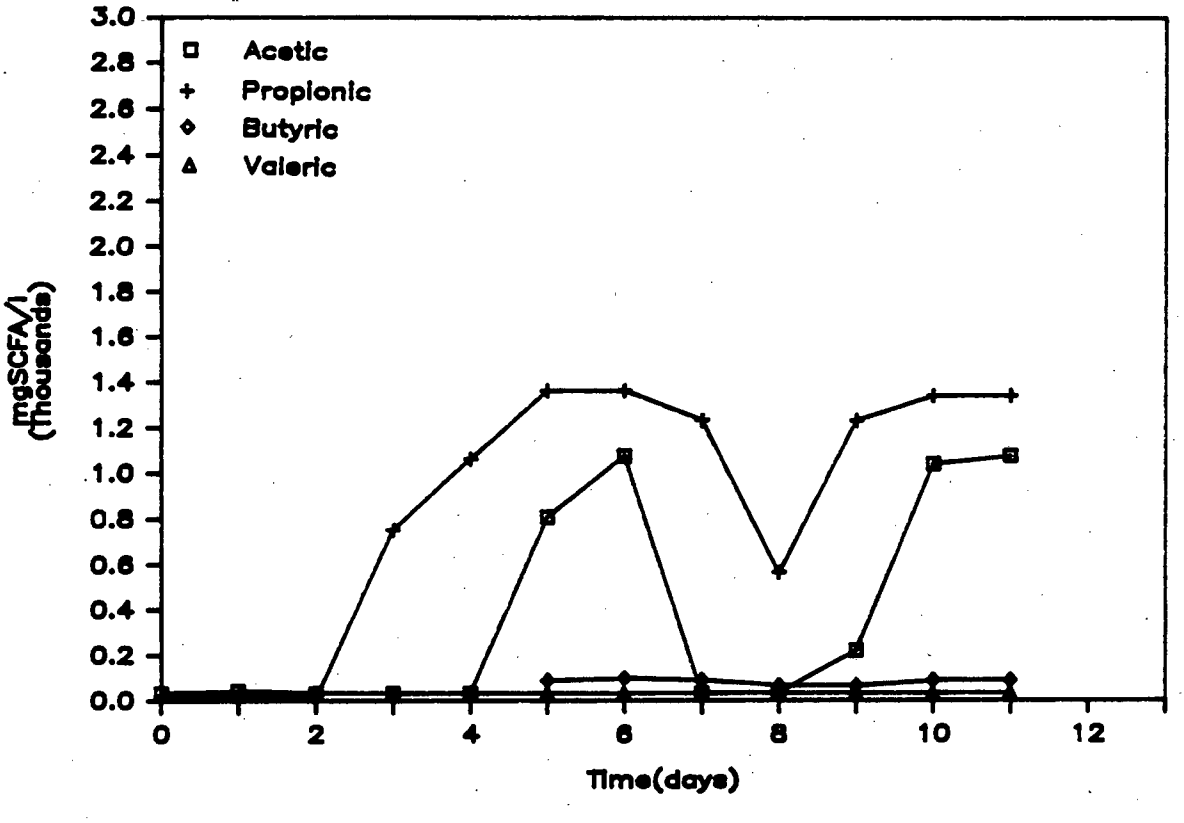

Fig B.18: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 3.

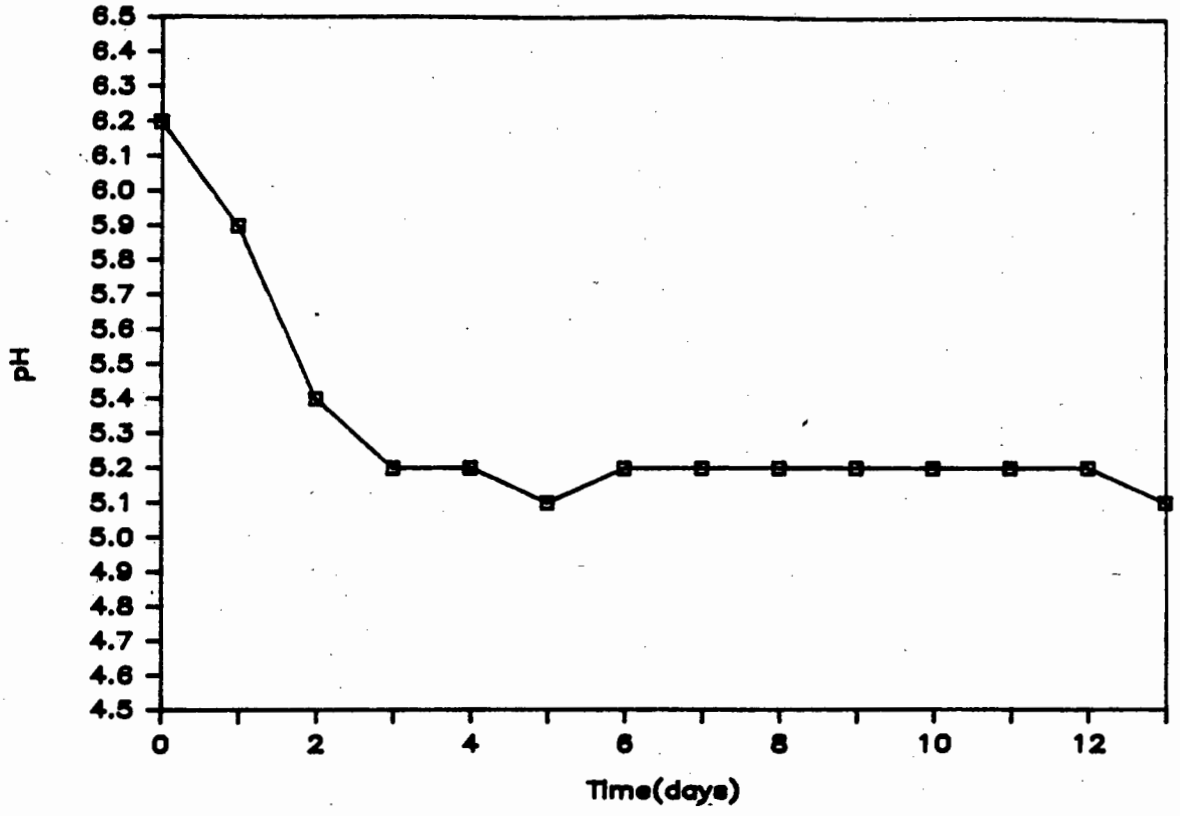

Fig B.19: pH of a batch reactor versus time – batch test 4.

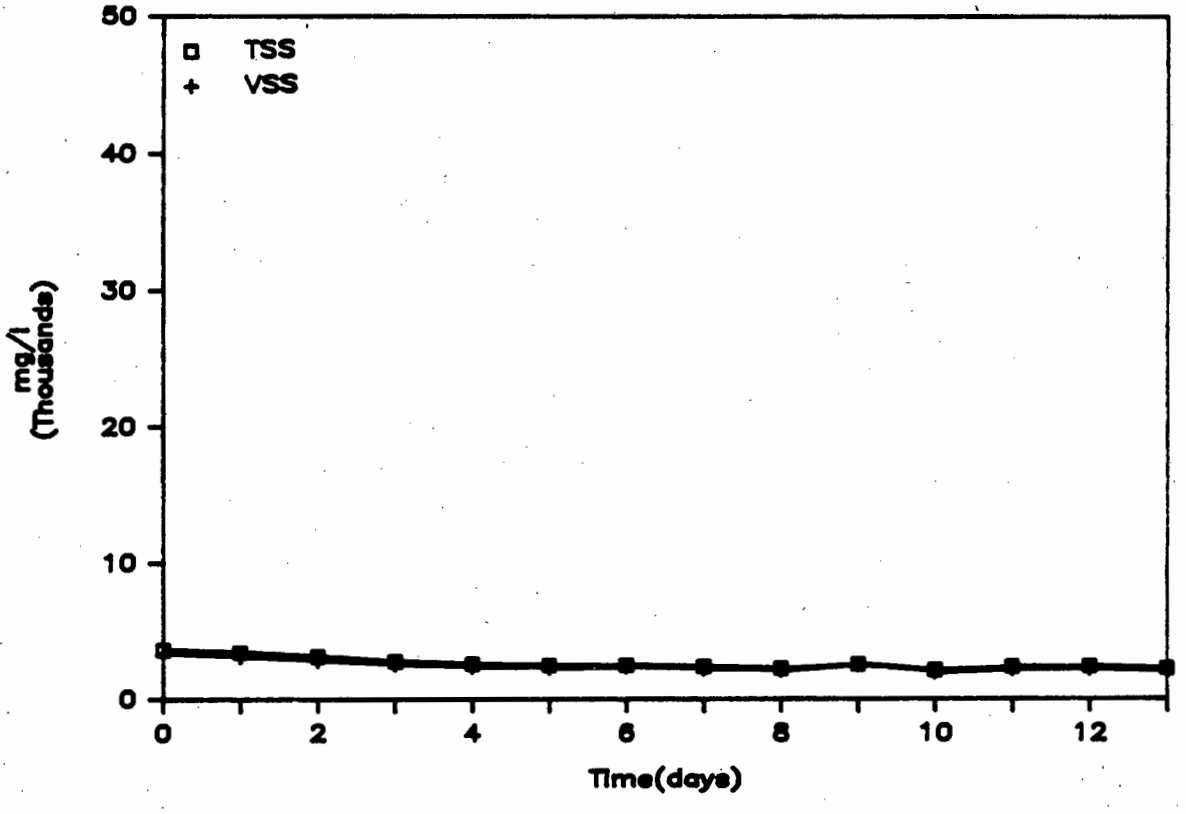

Fig B.20: TSS and VSS concentrations of a batch reactor versus time – batch test 4.

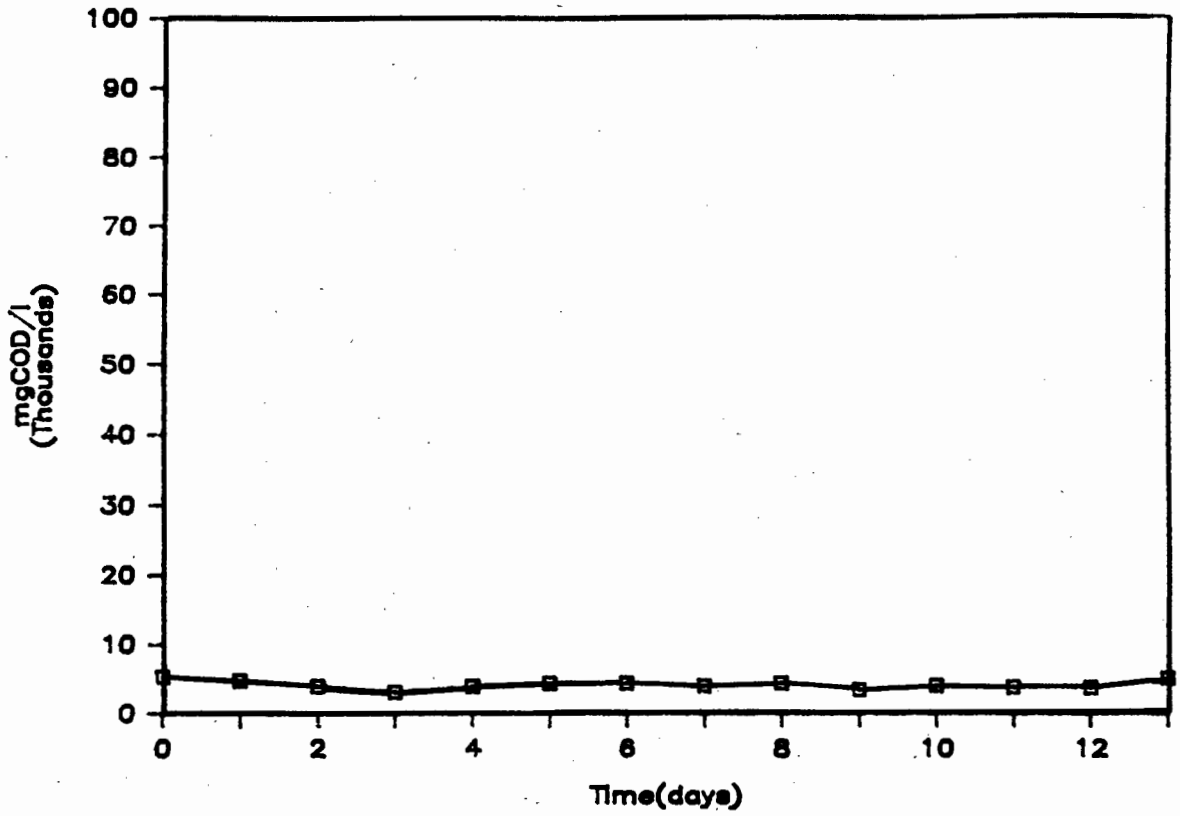

Fig B.21: COD of the VSS concentrations of a batch reactor versus time – batch test 4.

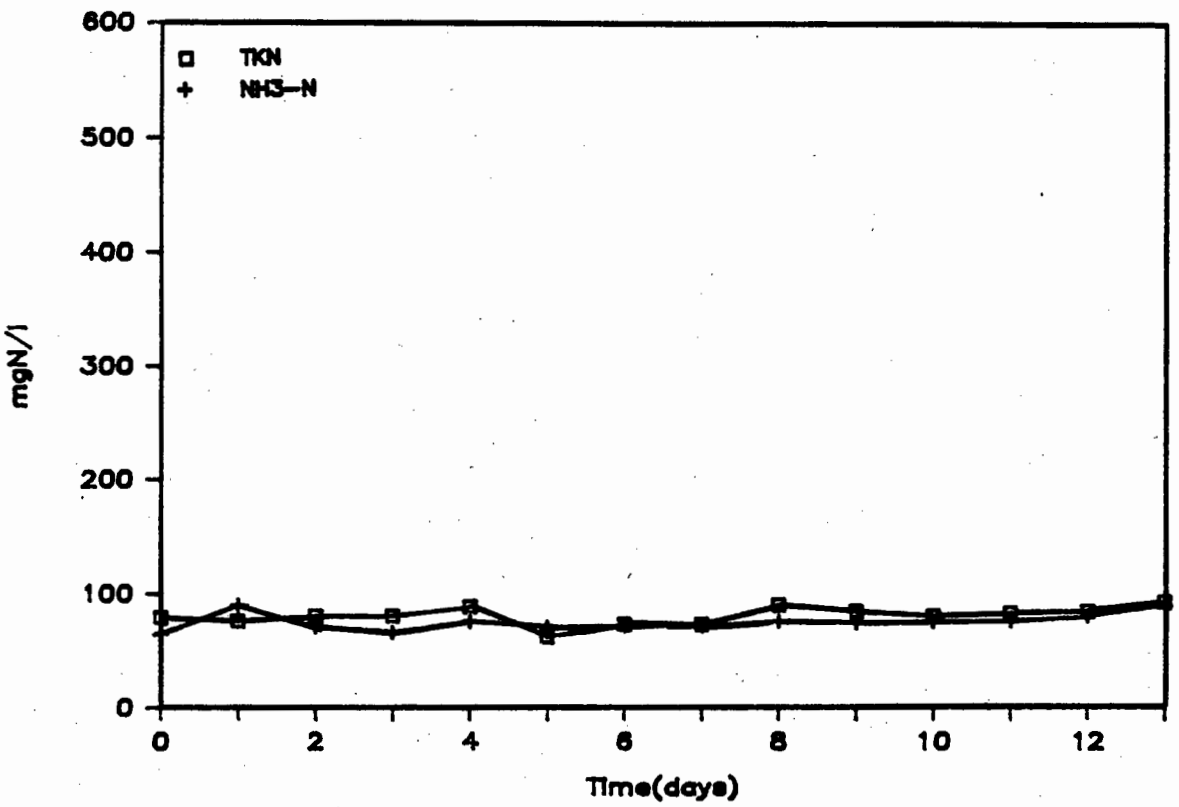

Fig B.22: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 4.

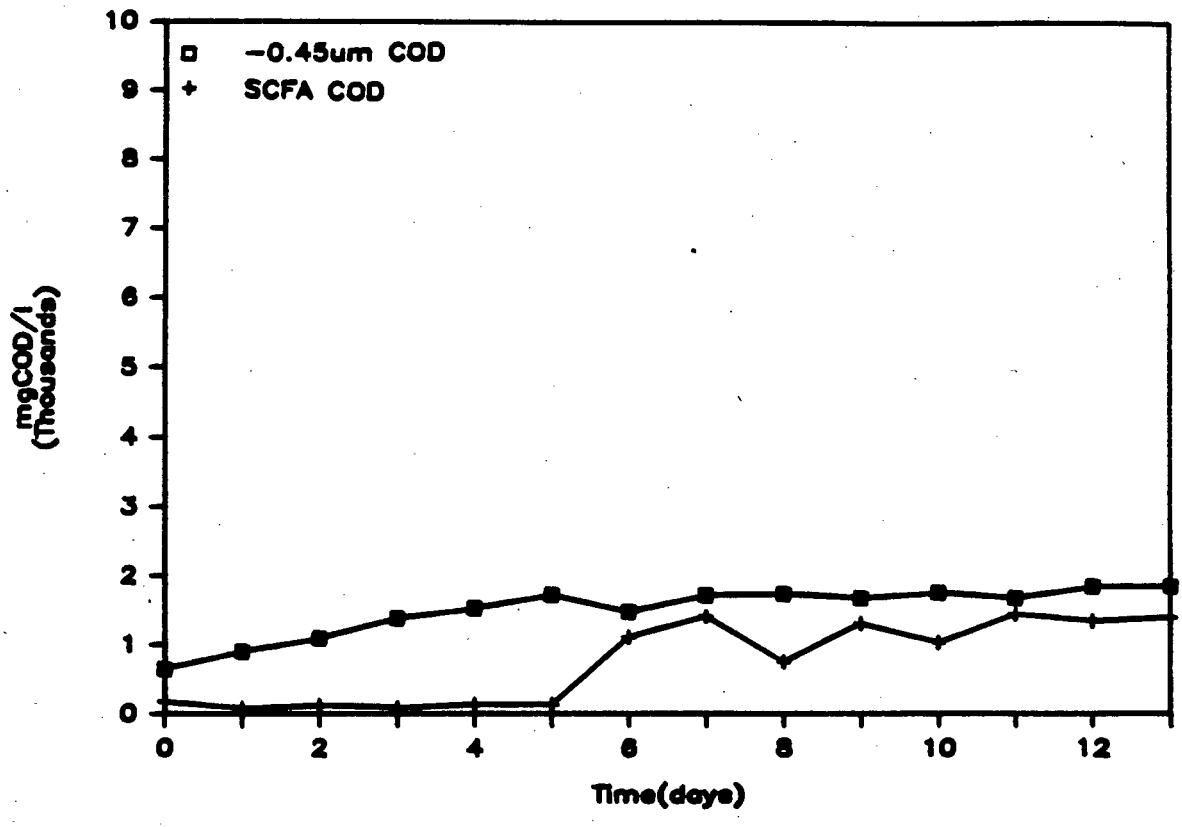

Fig B.23: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 4.

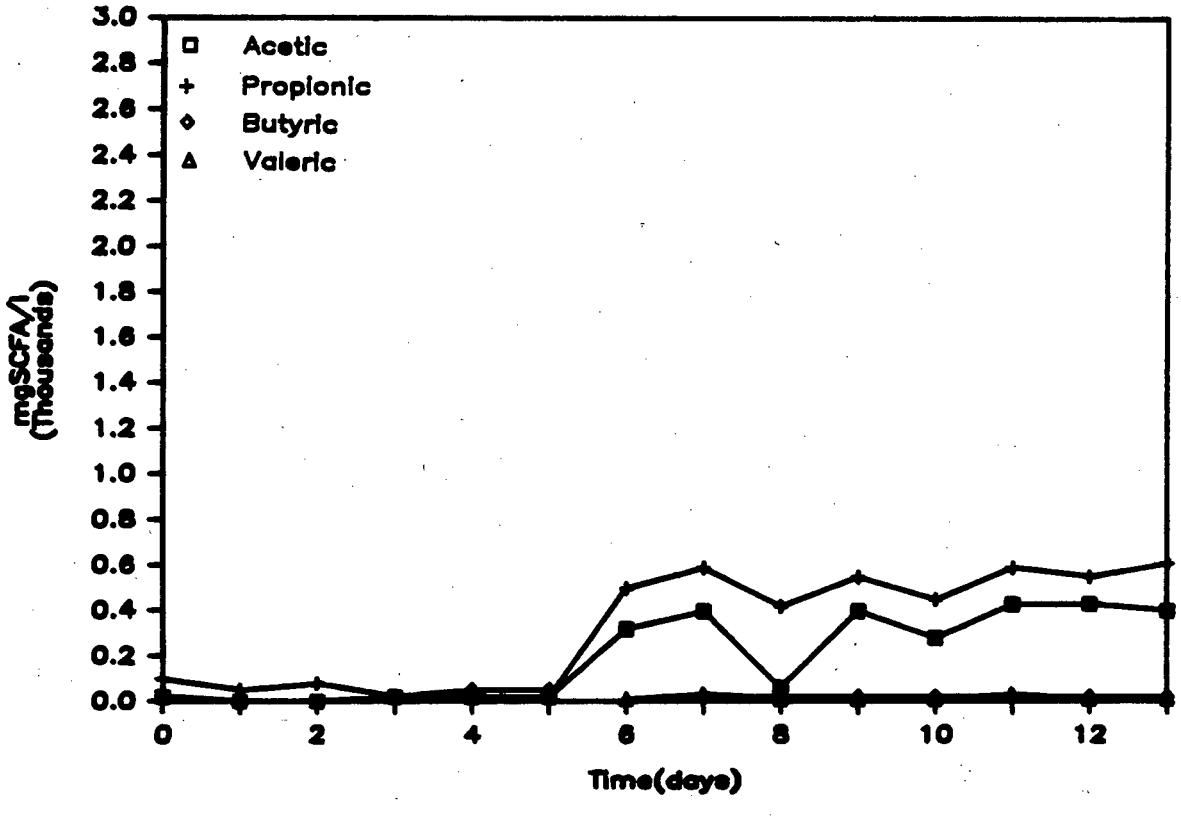

Fig B.24: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 4.

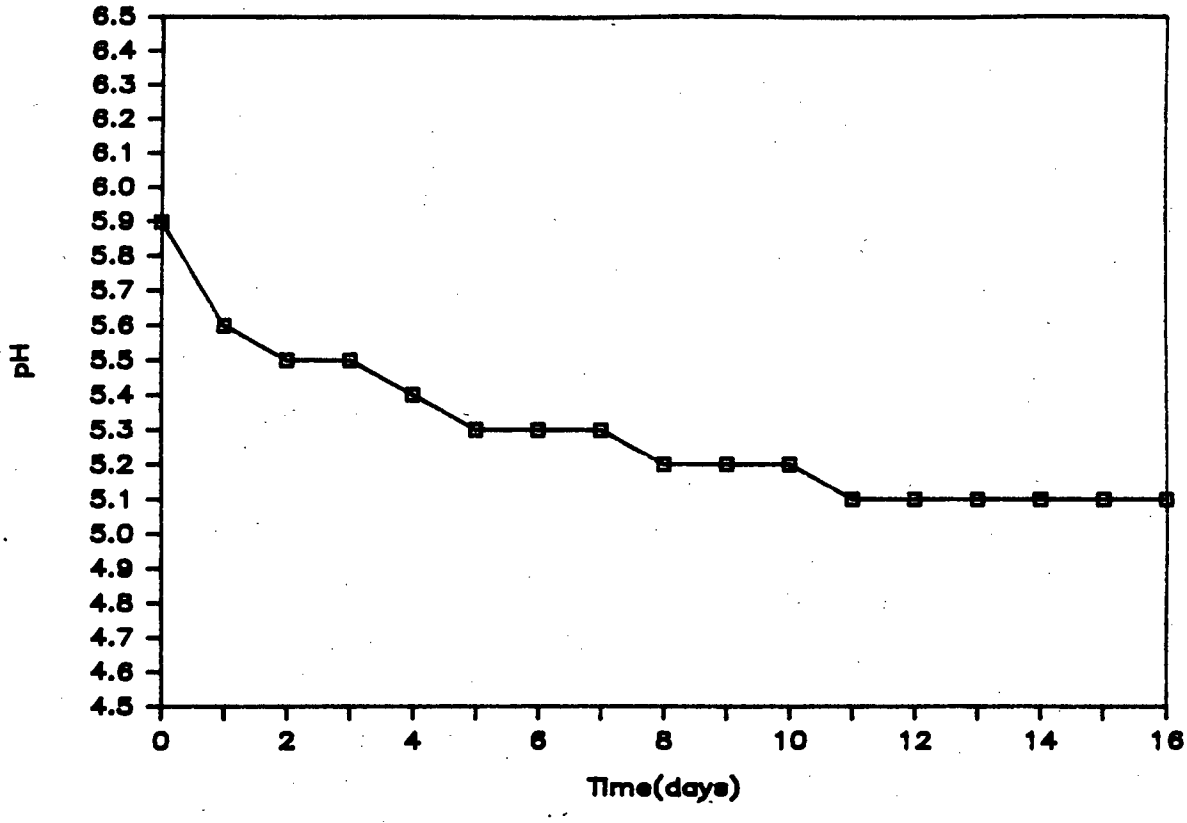

Fig B.25: pH of a batch reactor versus time – batch test 5.

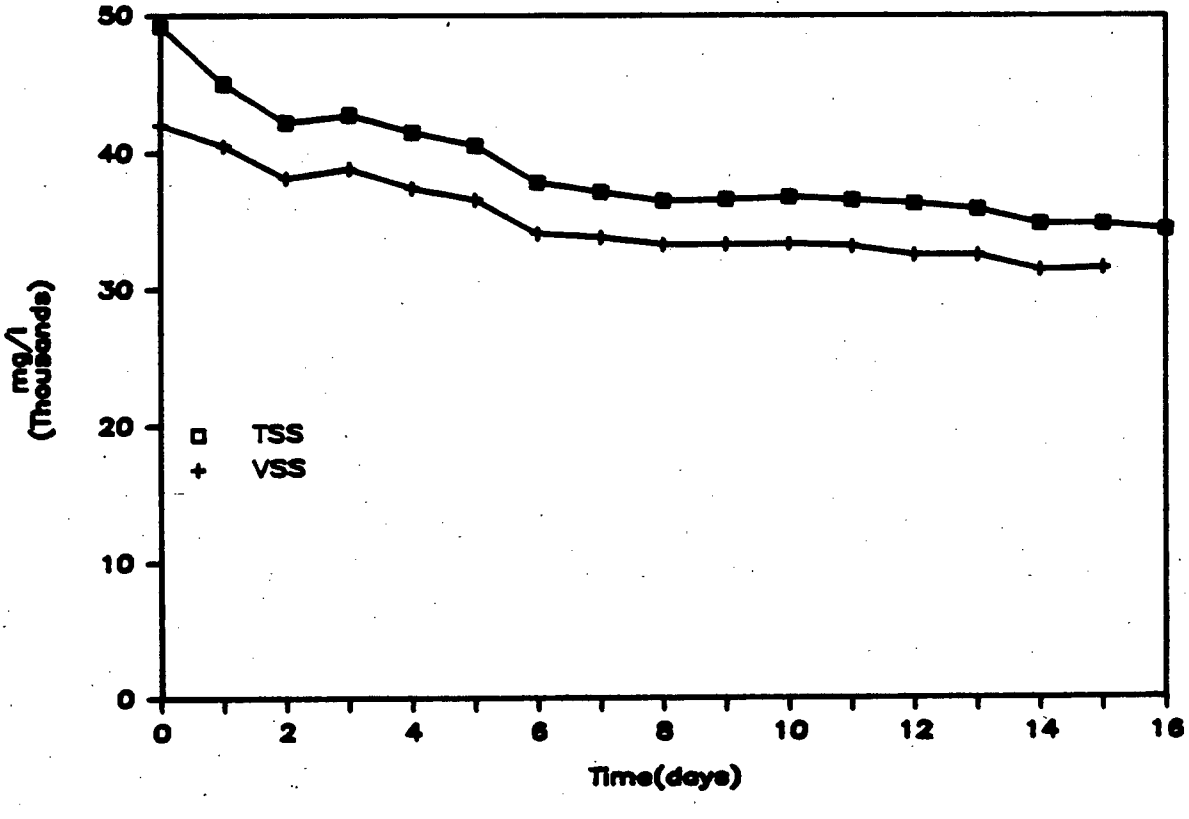

Fig B.26: TSS and VSS concentrations of a batch reactor versus time – batch test 5.

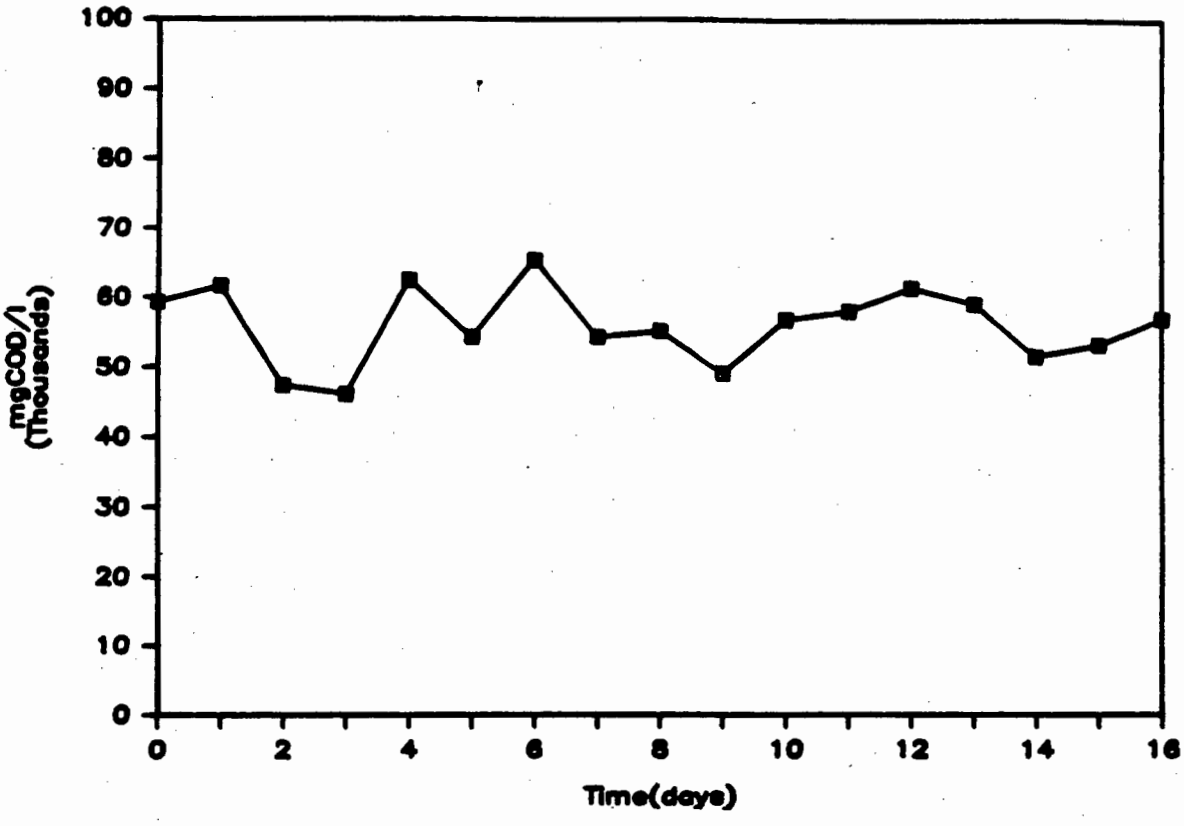

Fig B.27: COD of the VSS concentrations of a batch reactor versus time – batch test 5.

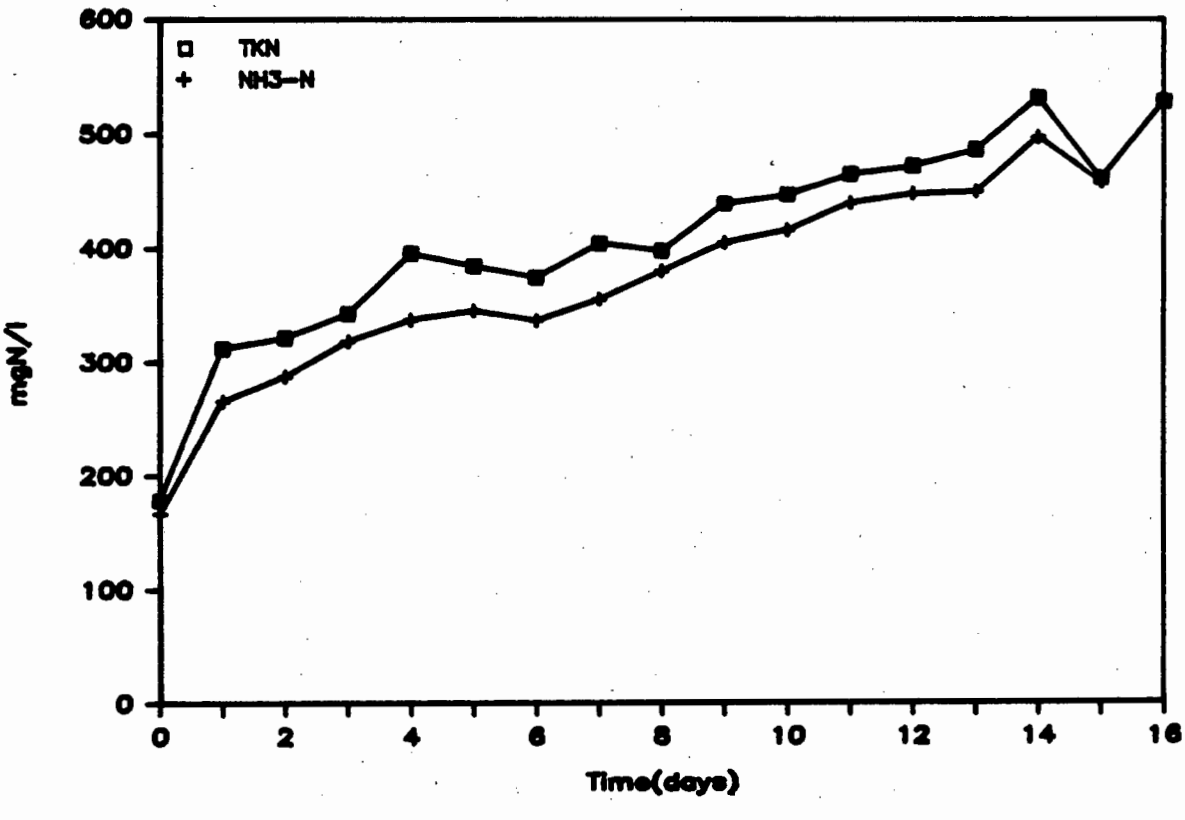

Fig B.28: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 5.

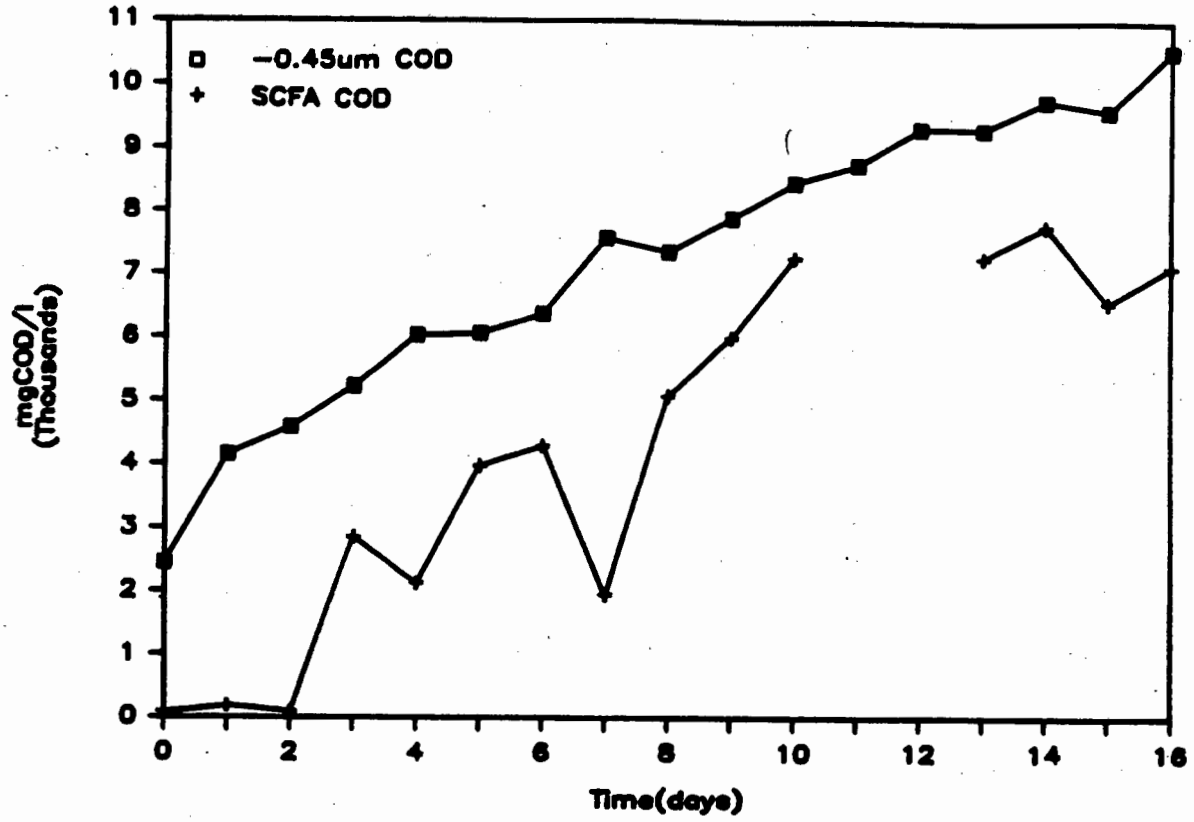

Fig B.29: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 5.

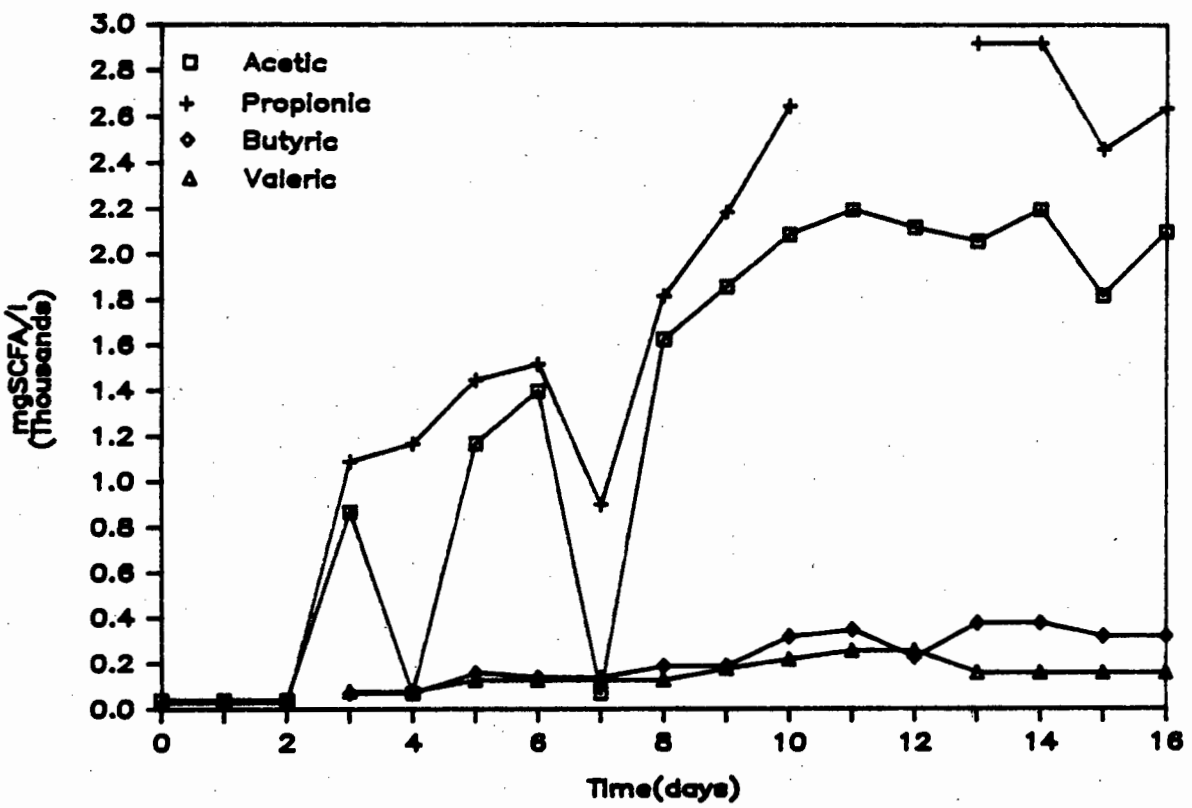

Fig B.30: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 5.

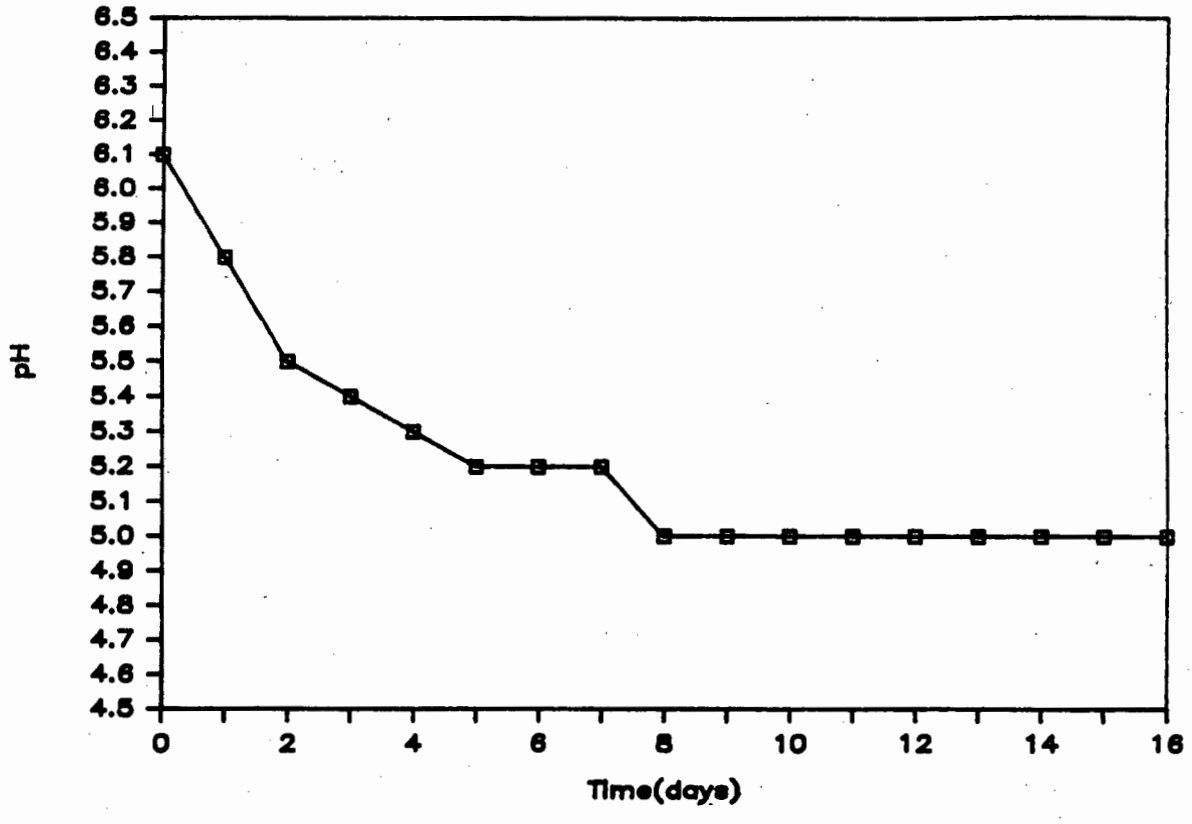

Fig B.31: pH of a batch reactor versus time – batch test 6.

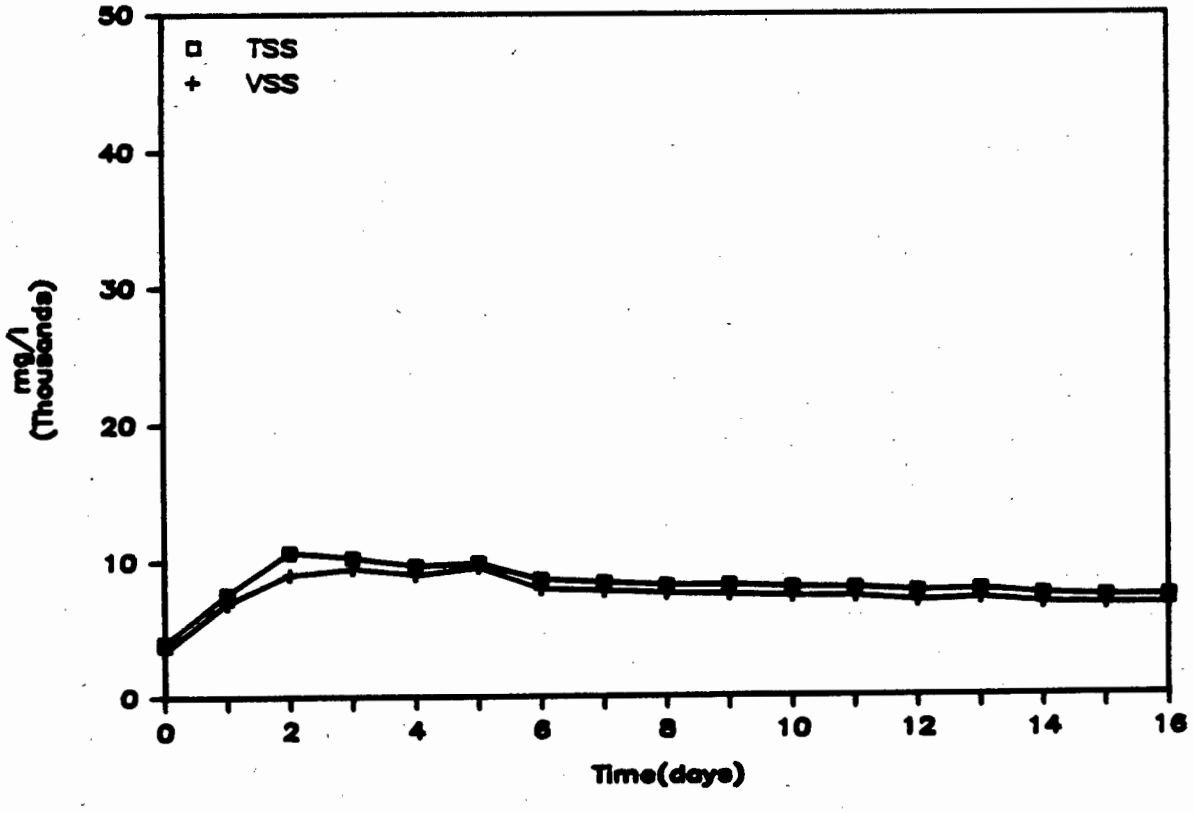

Fig B.32: TSS and VSS concentrations of a batch reactor versus time – batch test 6.

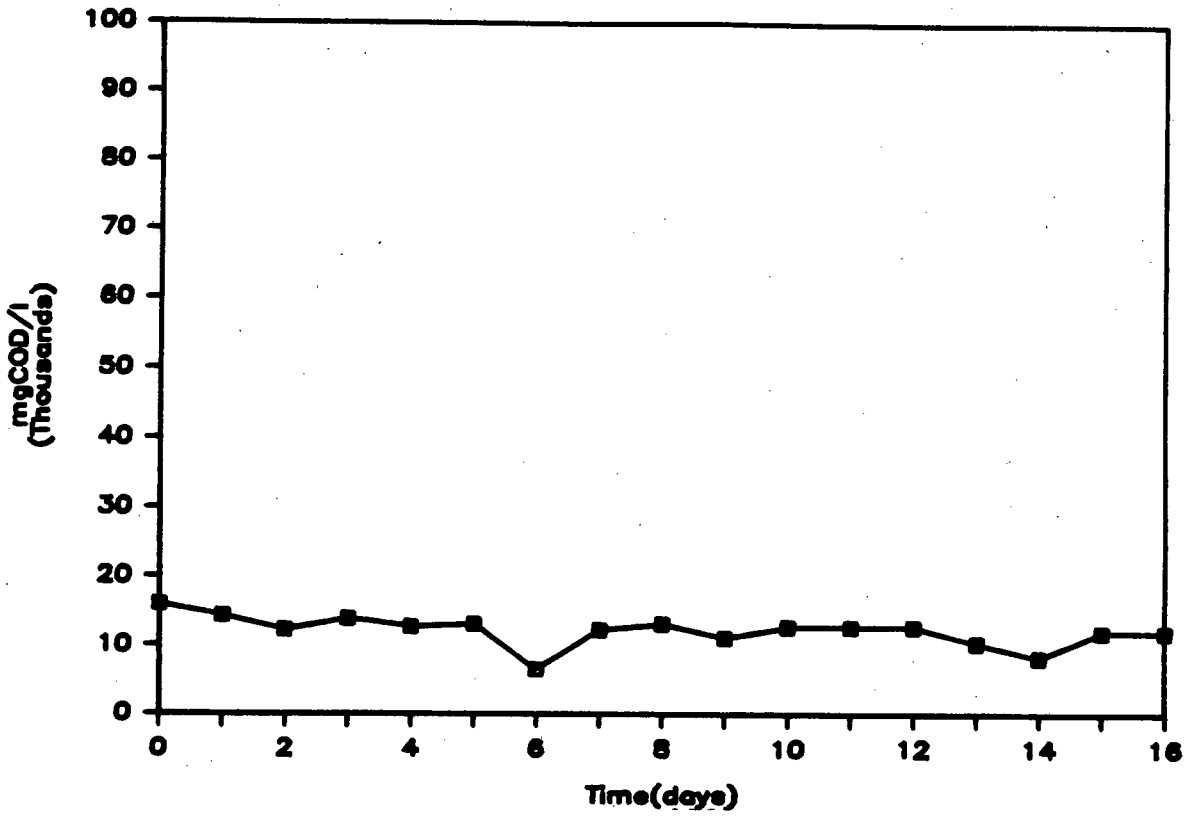

Fig B.33: COD of the VSS concentrations of a batch reactor versus time – batch test 6.

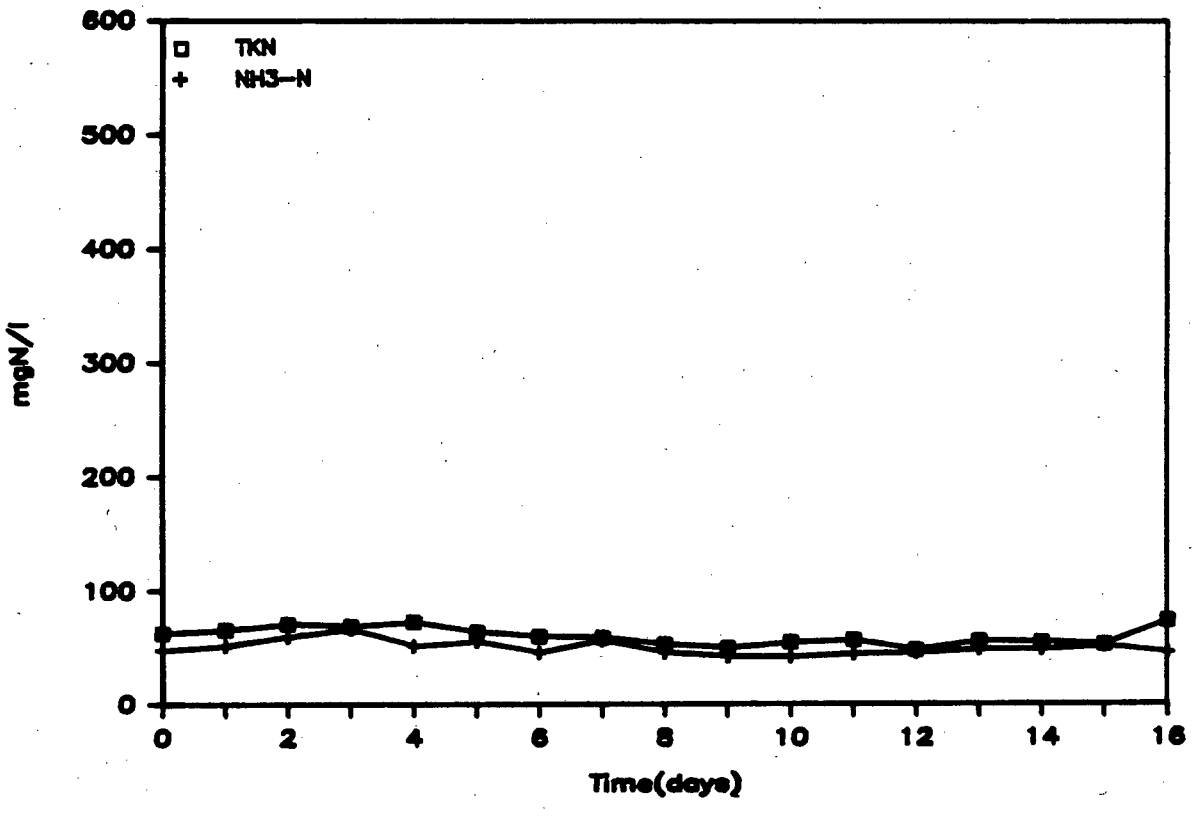

Fig B.34: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 6.

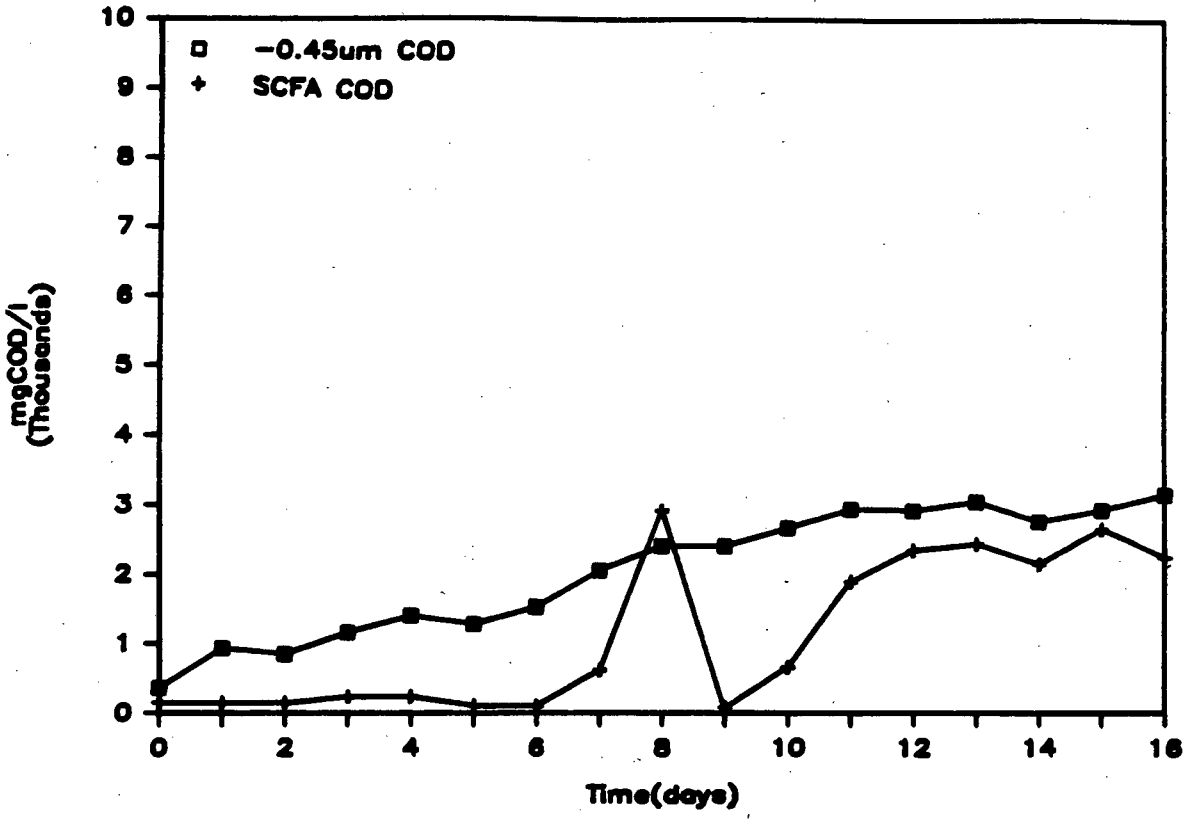

Fig B.35: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 6.

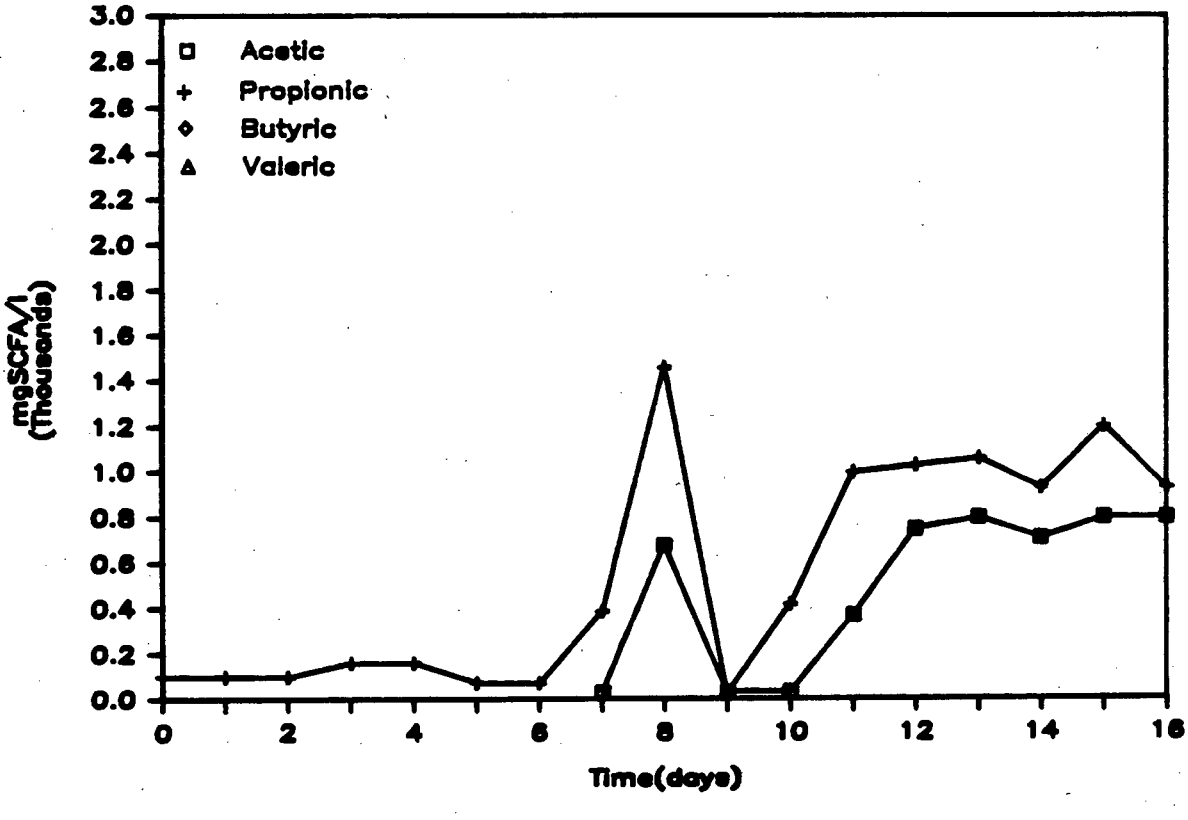

Fig B.36: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 6.

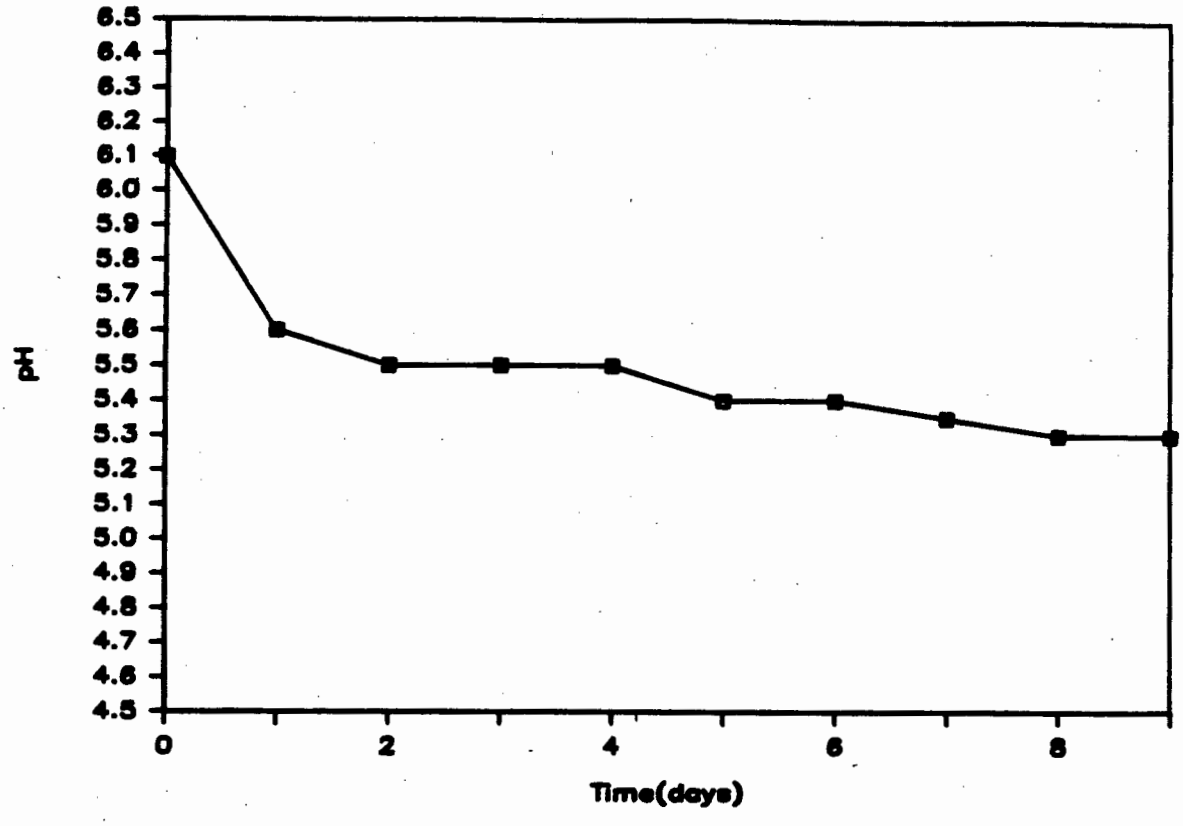

Fig B.37: pH of a batch reactor versus time – batch test 7.

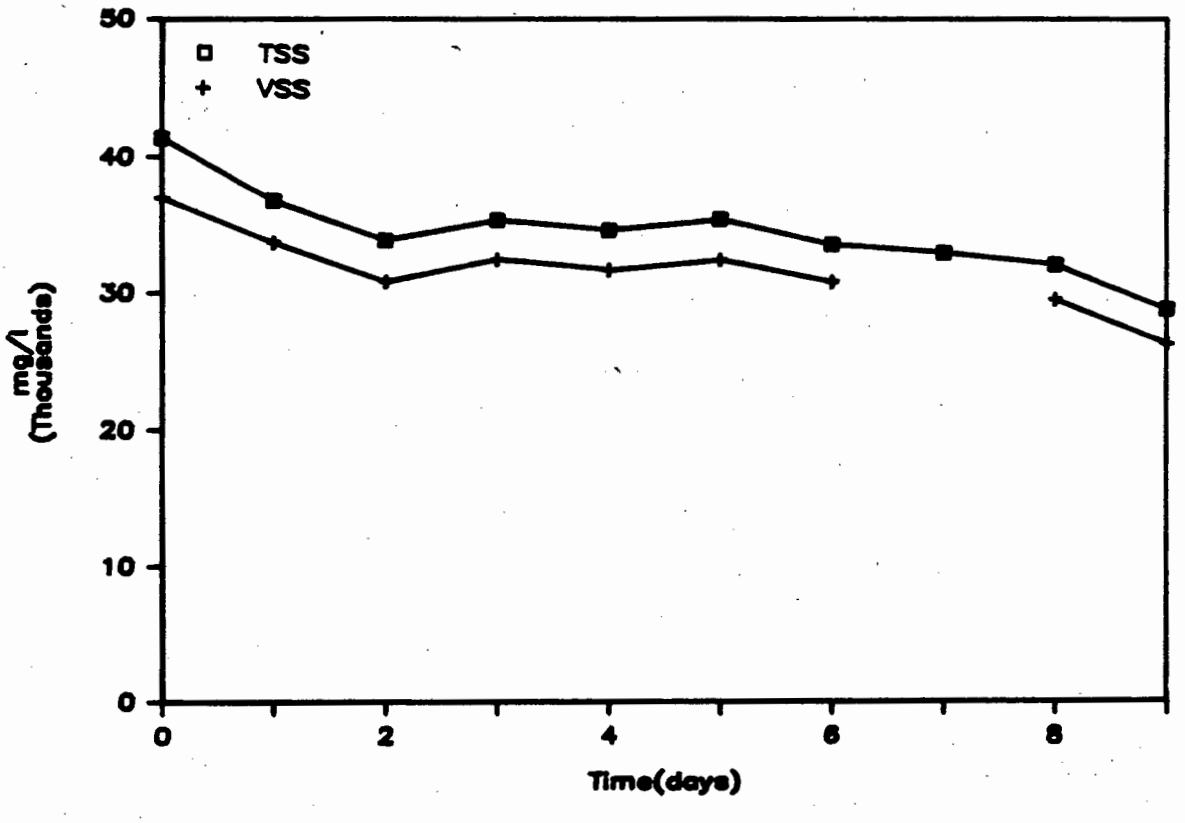

Fig B.38: TSS and VSS concentrations of a batch reactor versus time – batch test 7.

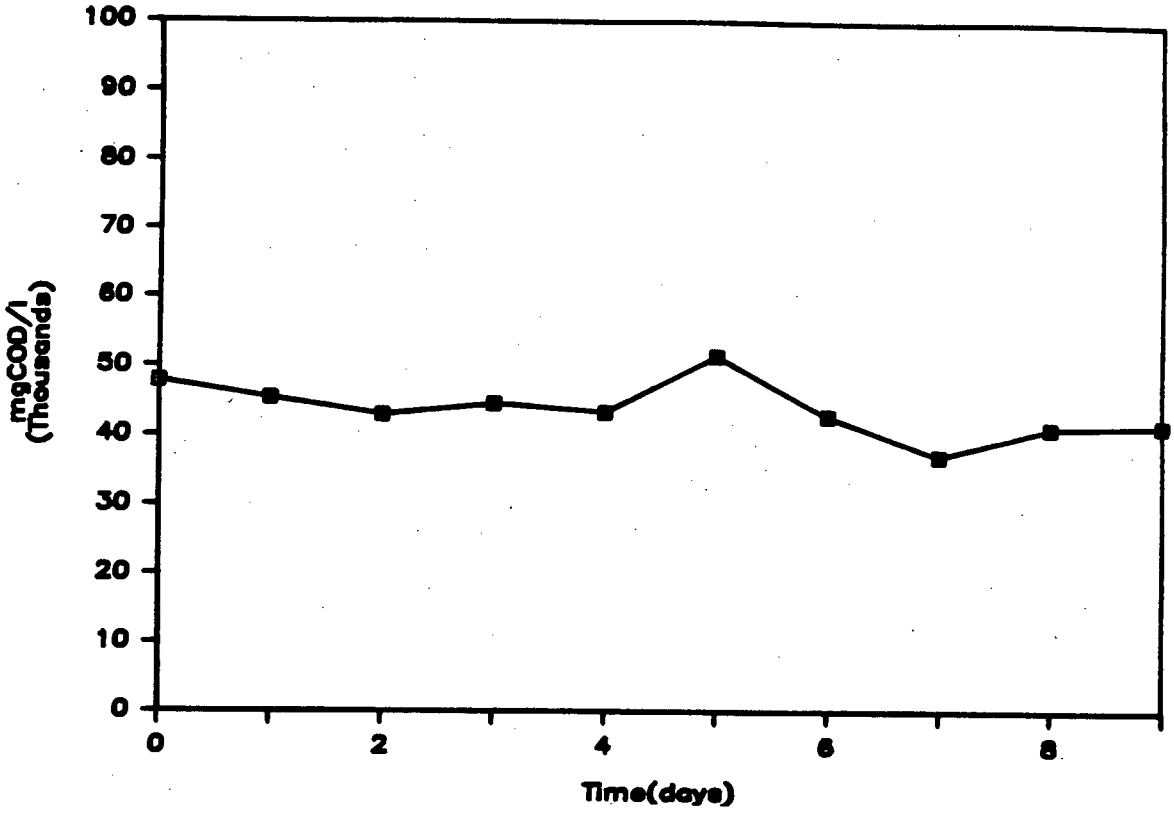

Fig B.39: COD of the VSS concentrations of a batch reactor versus time – batch test 7.

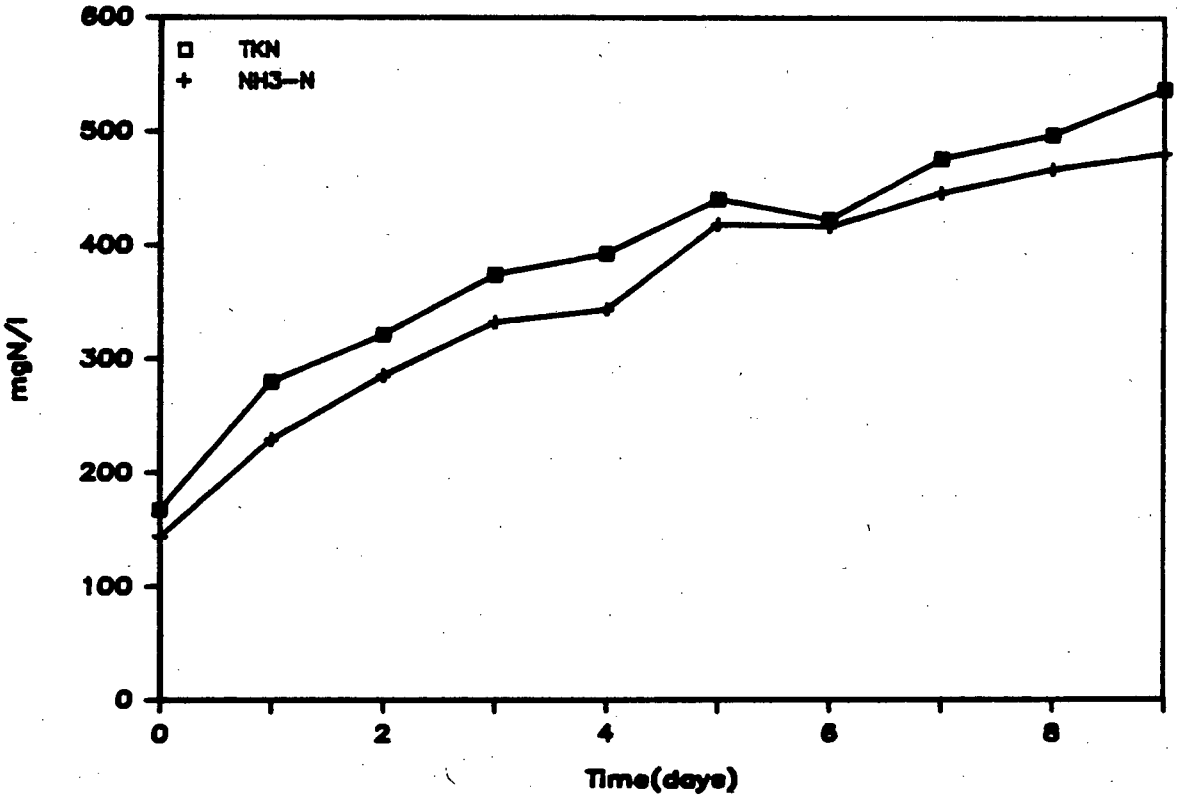

Fig B.40: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 7.

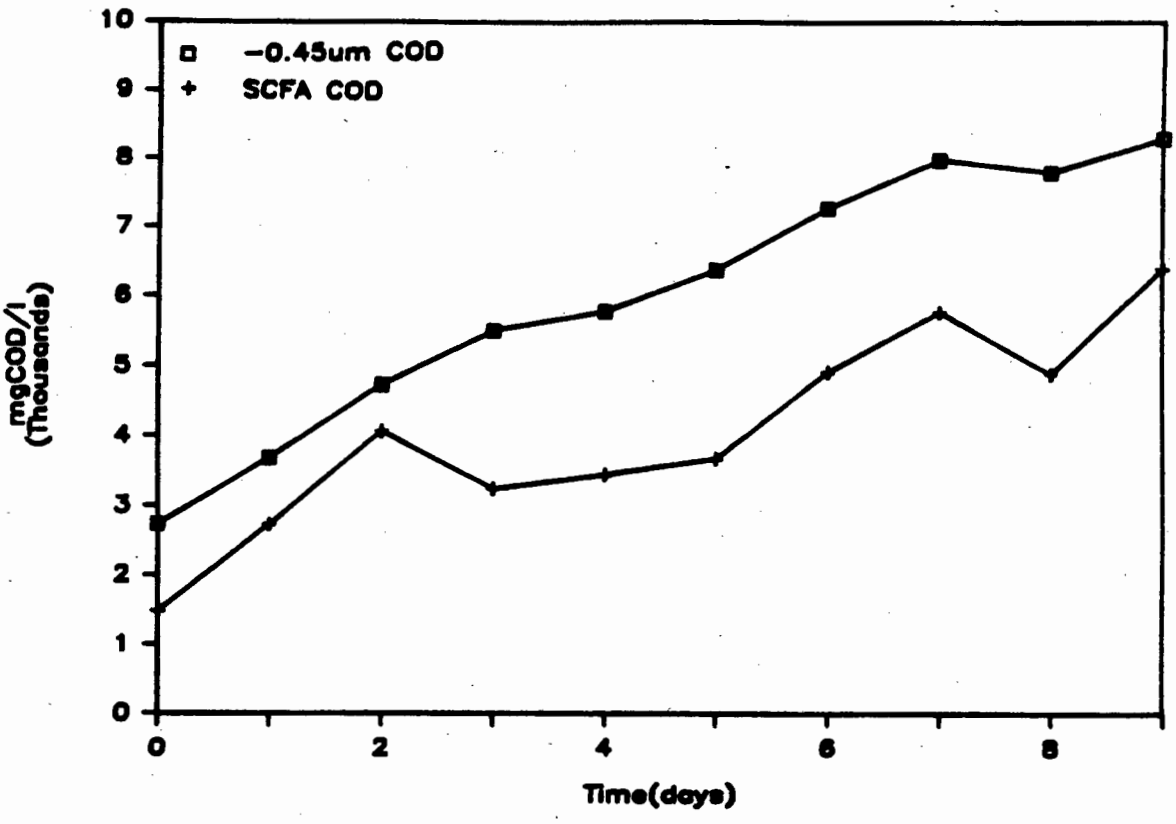

Fig B.41: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 7.

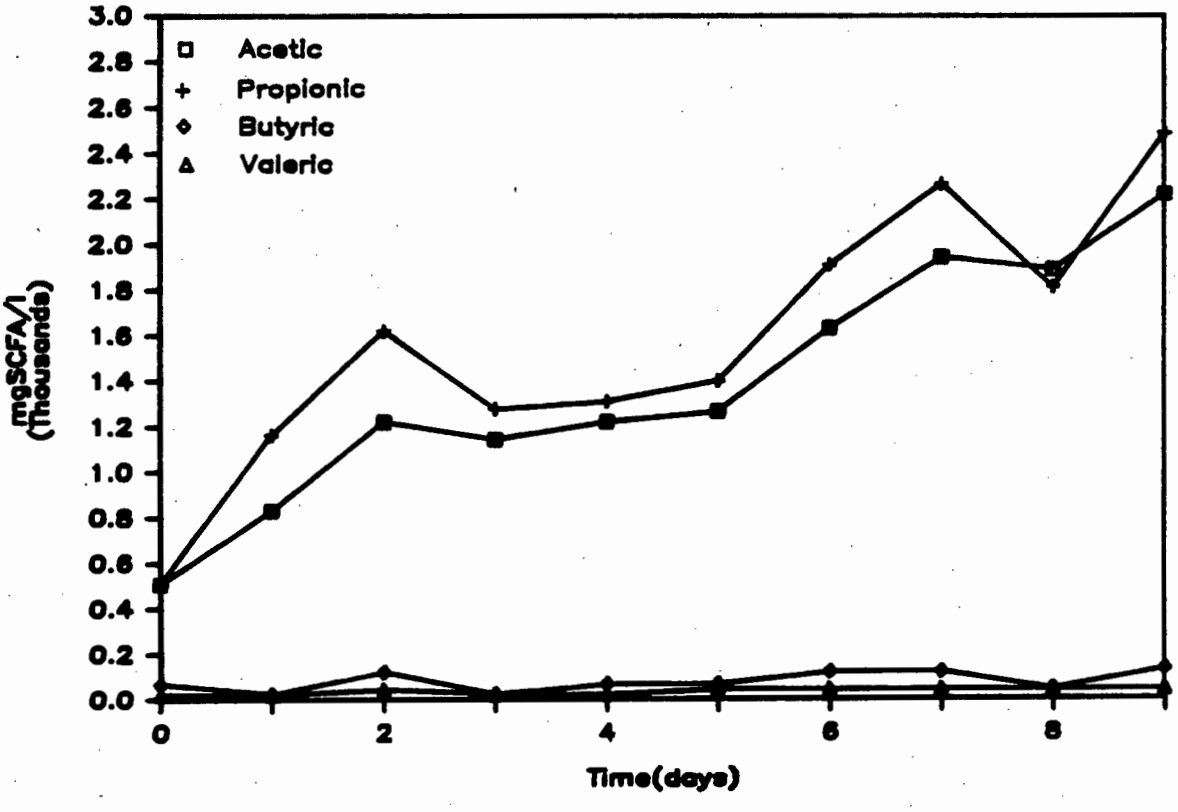

Fig B.42: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 7.

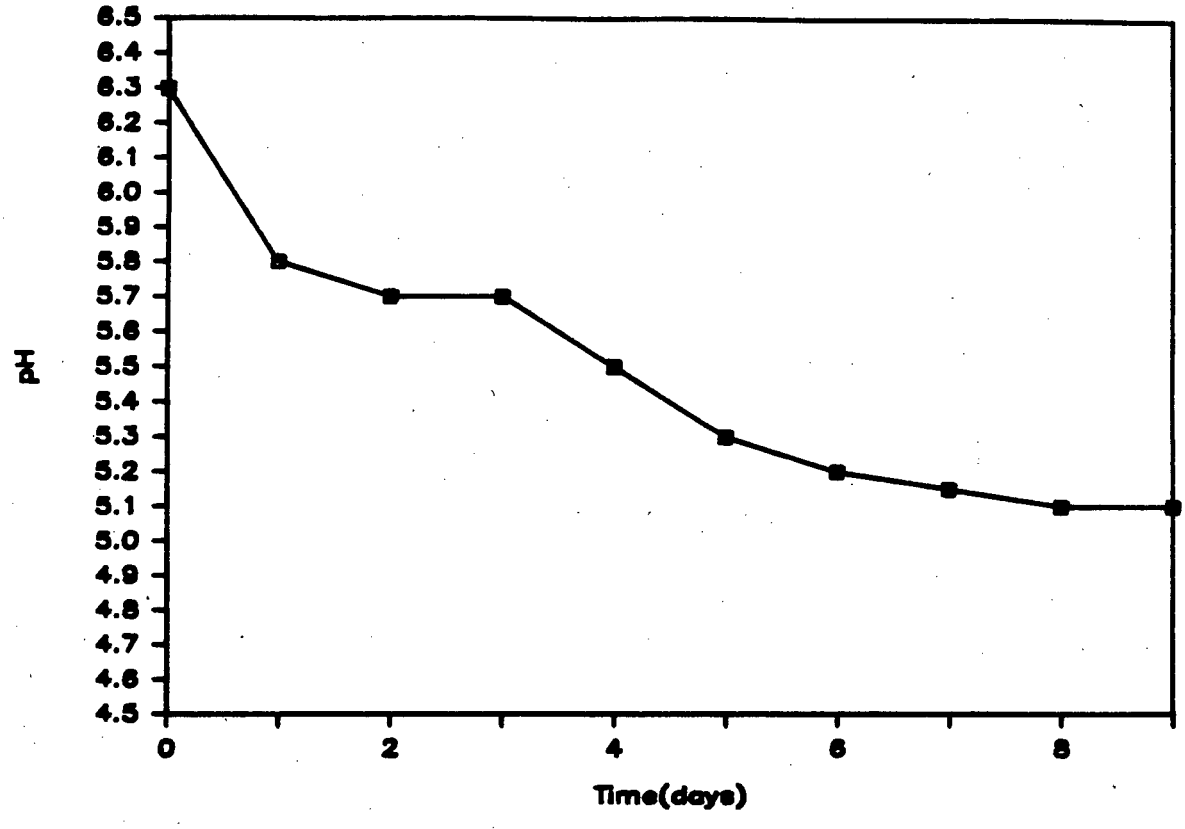

Fig B.43: pH of a batch reactor versus time – batch test 8.

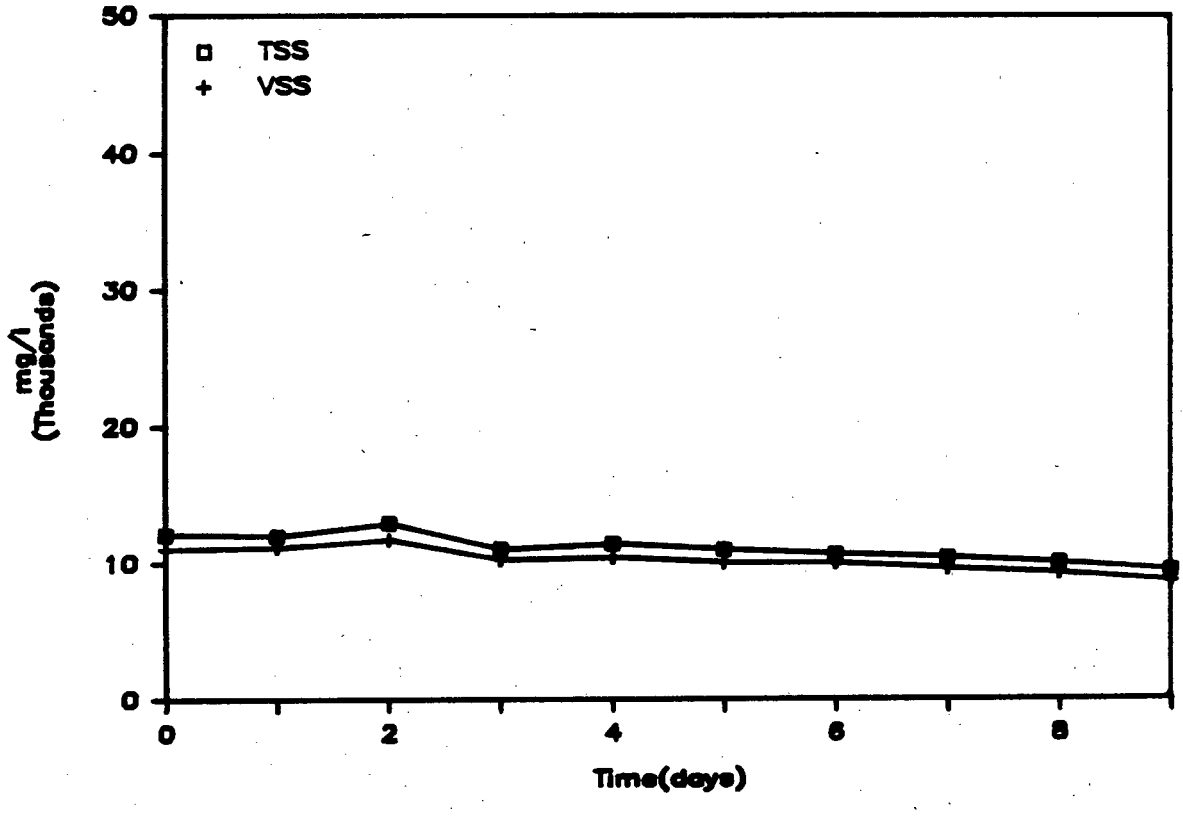

Fig B.44: TSS and VSS concentrations of a batch reactor versus time – batch test 8.

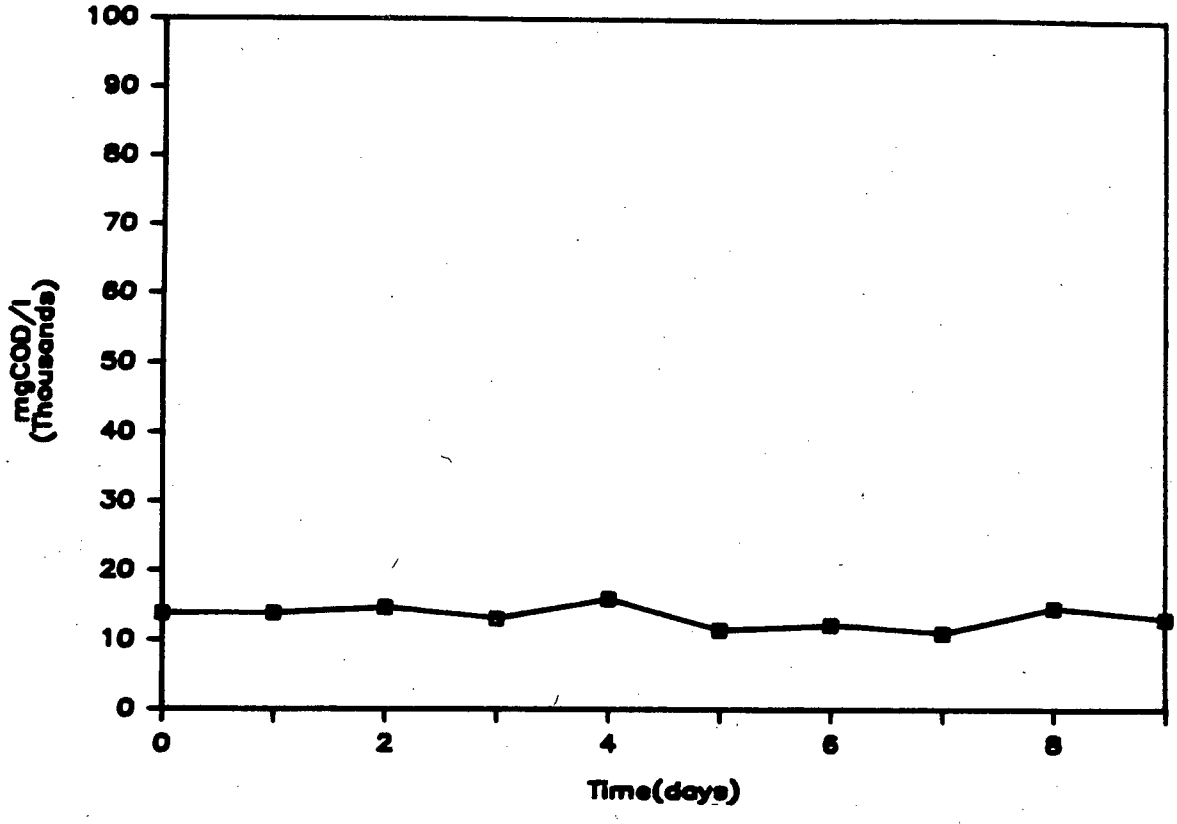

Fig B.45: COD of the VSS concentrations of a batch reactor versus time – batch test 8.

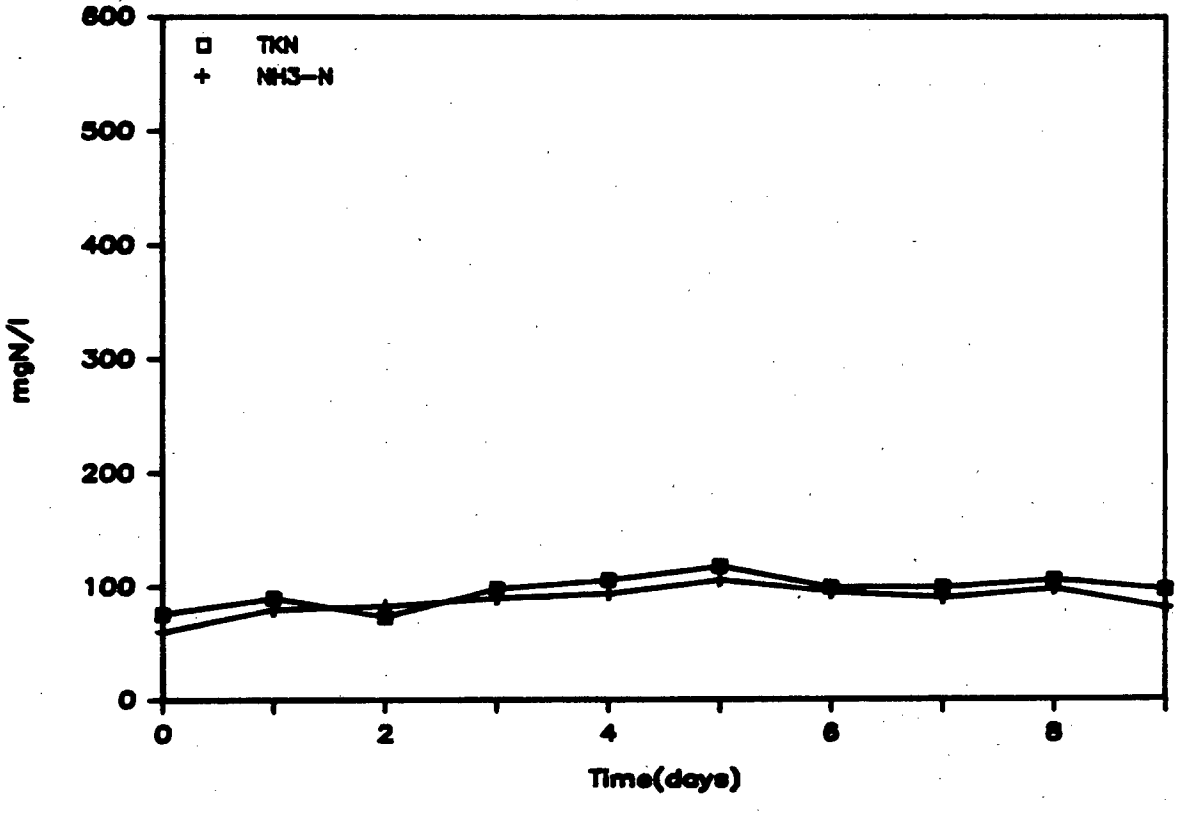

Fig B.46: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 8.

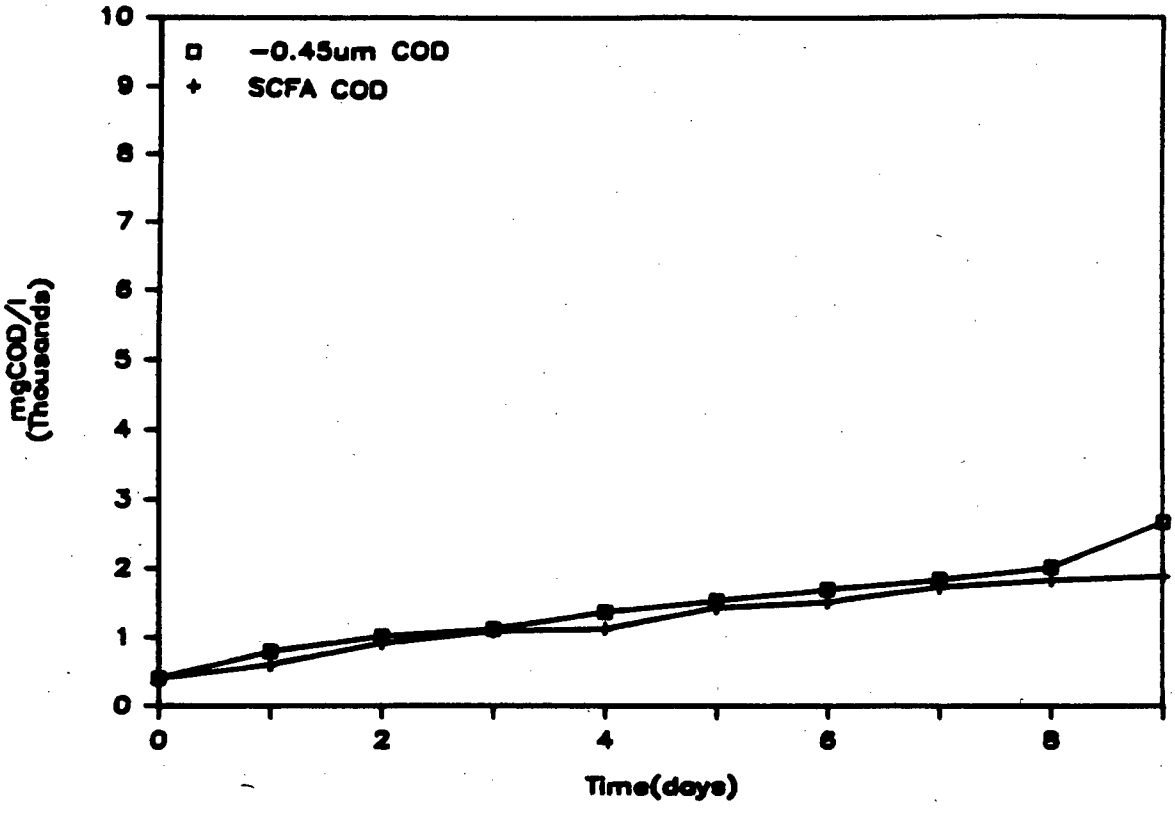

Fig B.47: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 8.

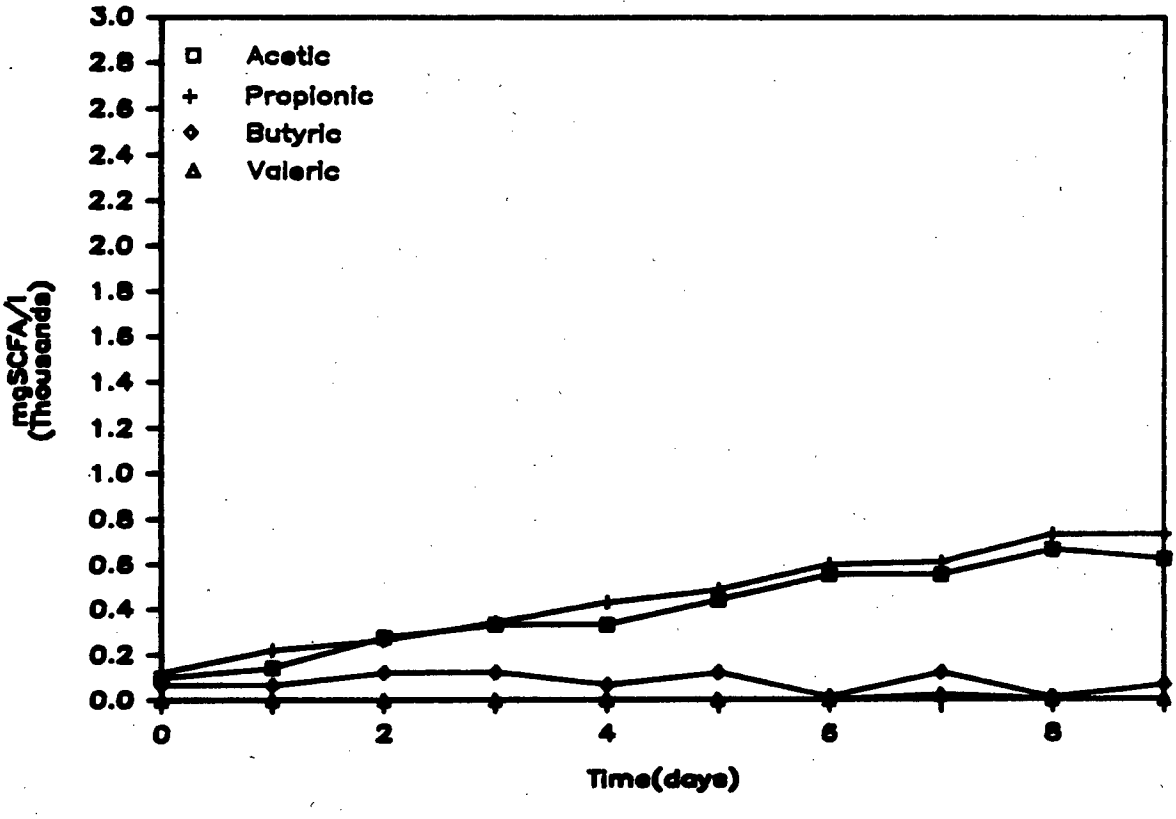

Fig B.48: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 8.

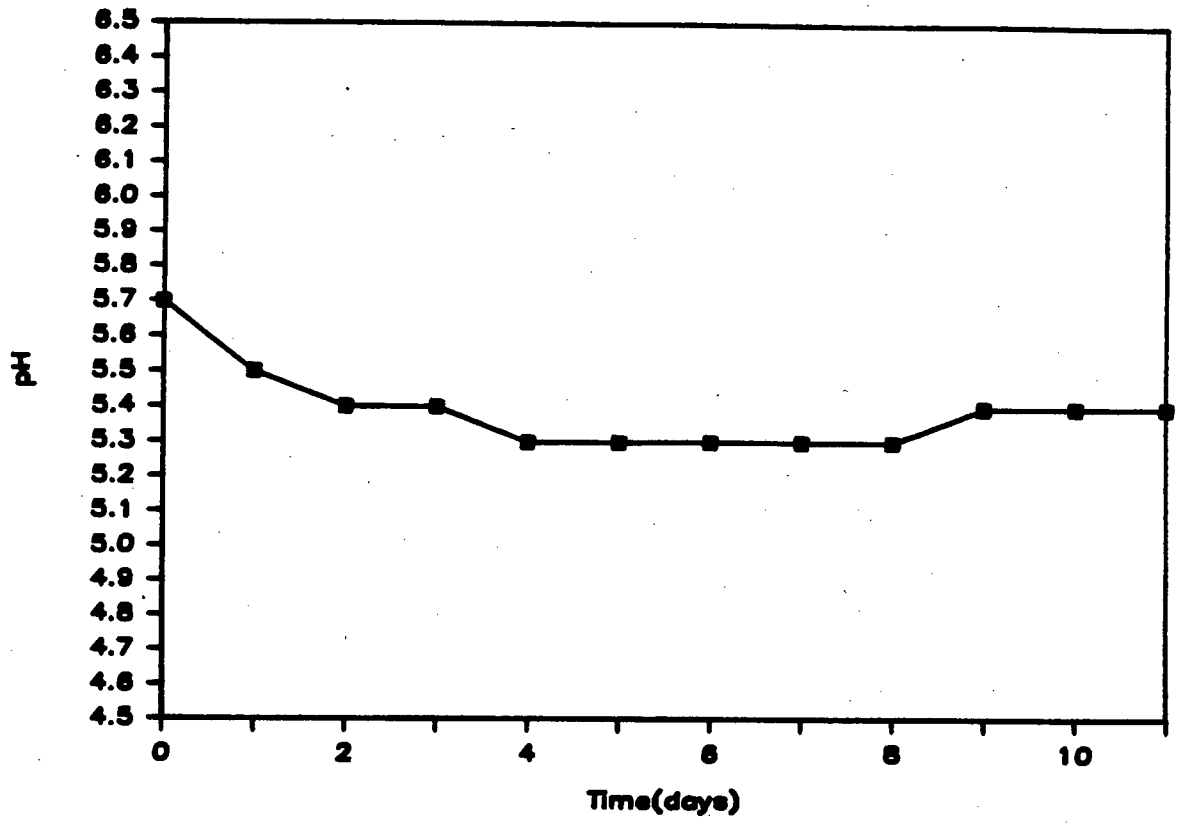

Fig B.49: pH of a batch reactor versus time – batch test 9.

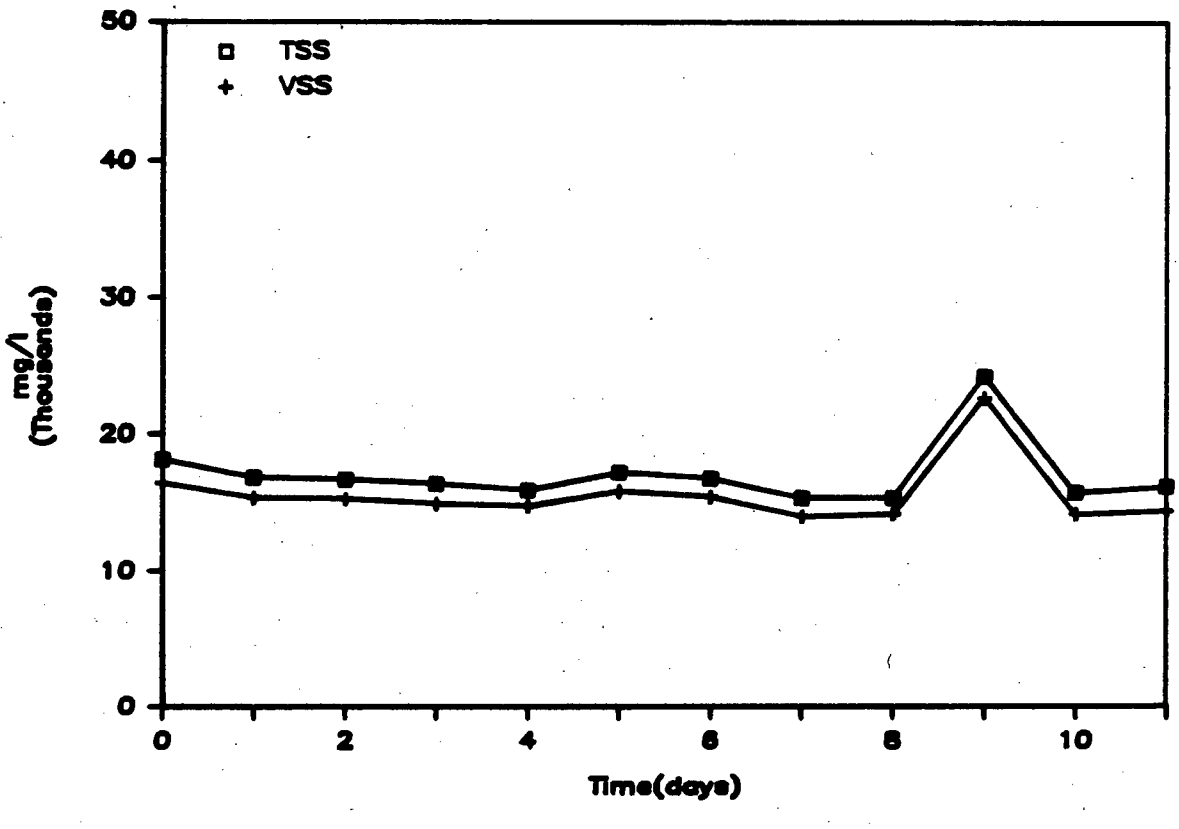

Fig B.50: TSS and VSS concentrations of a batch reactor versus time – batch test 9.

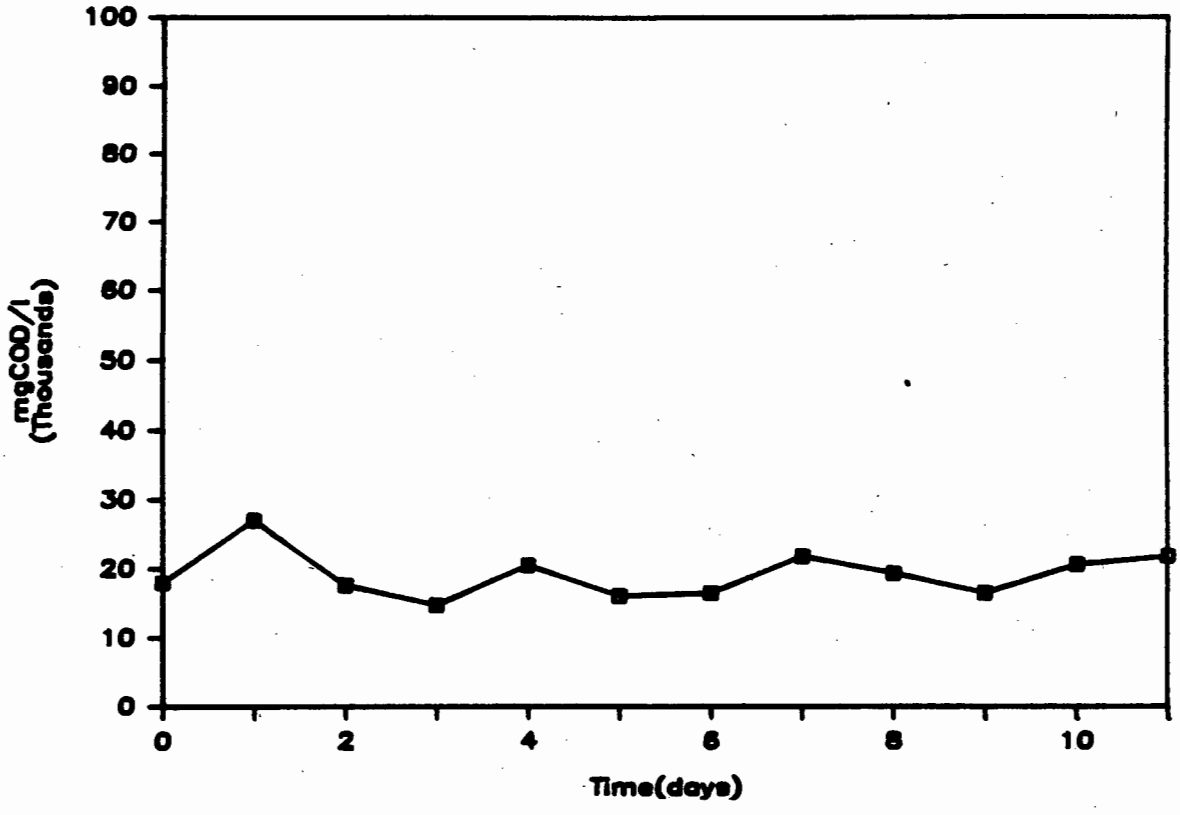

Fig B.51: COD of the VSS concentrations of a batch reactor versus time – batch test 9.

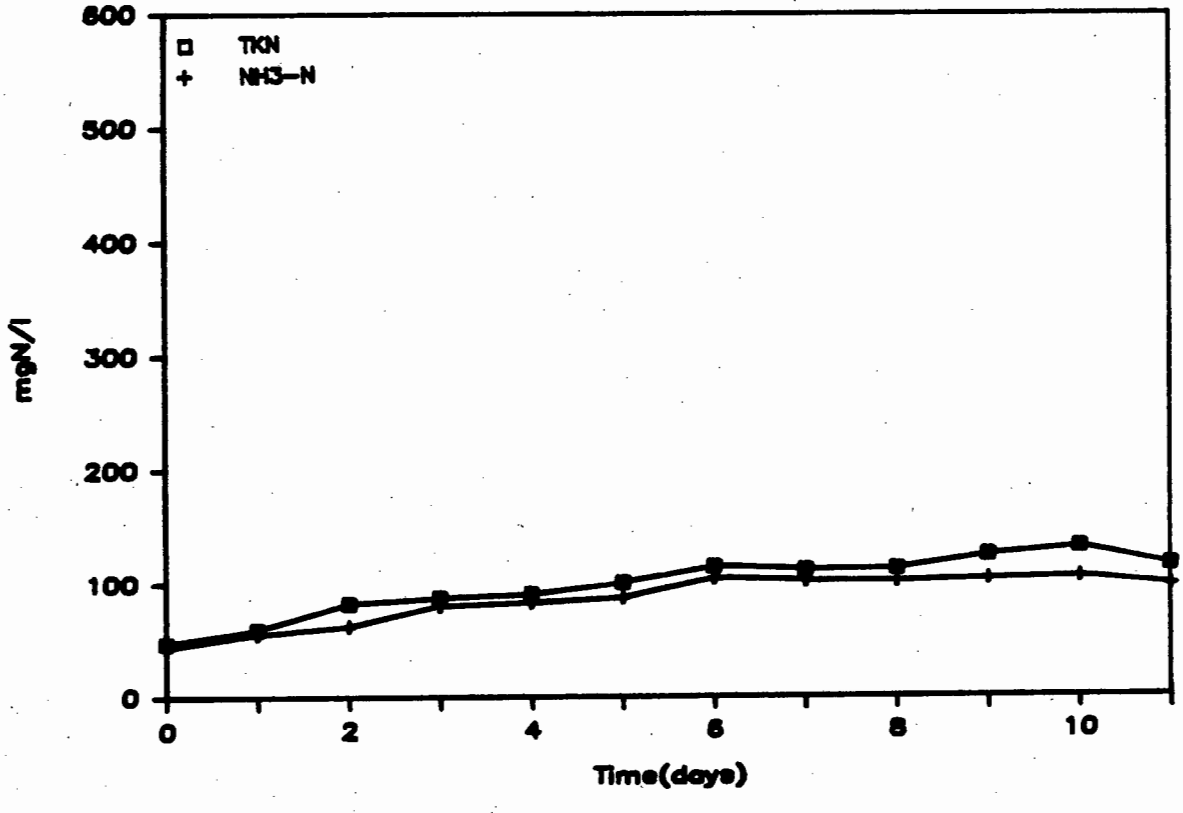

Fig B.52: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 9.

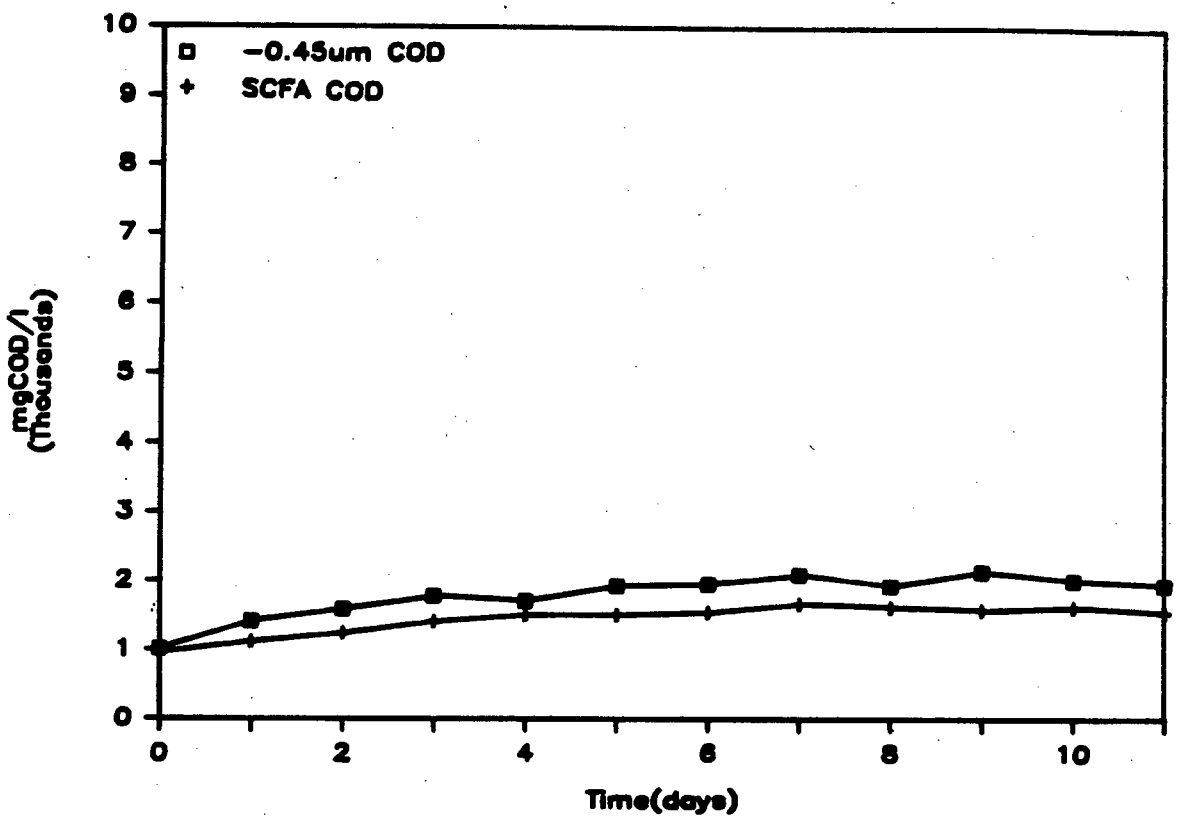

Fig B.53: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 9.

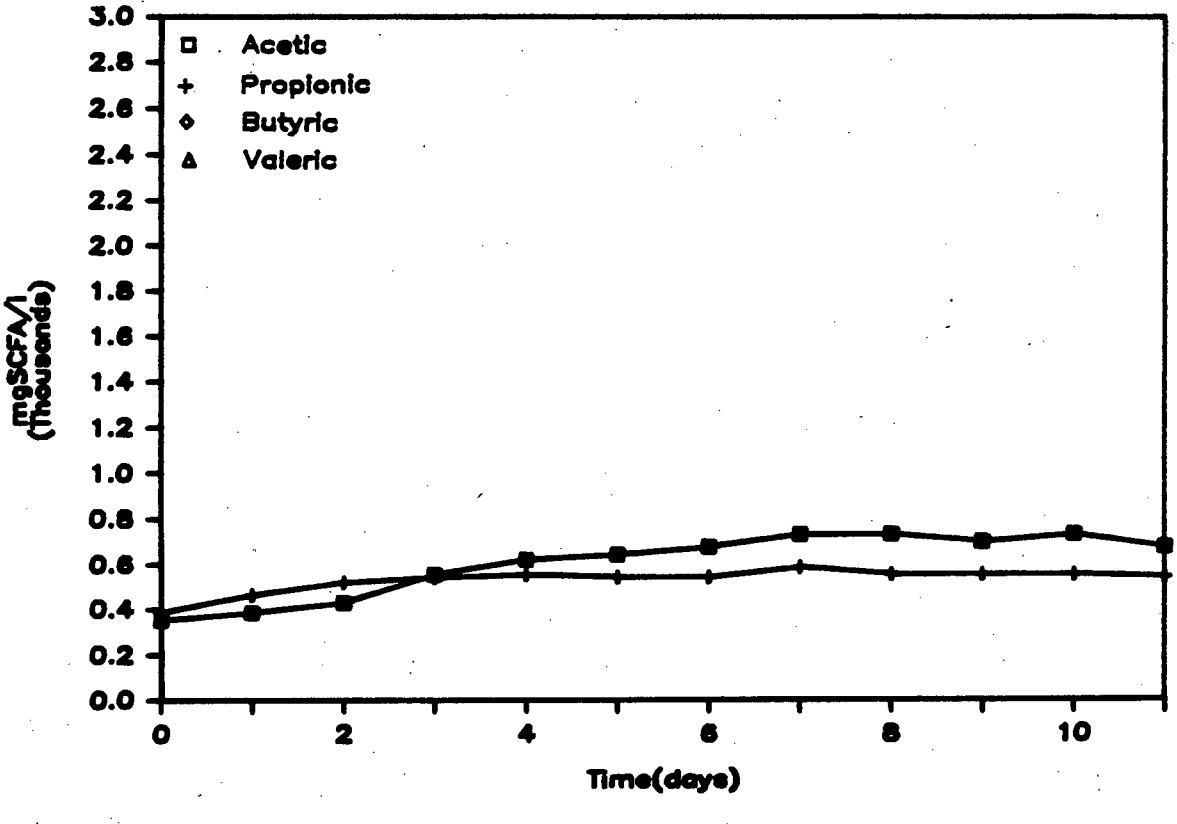

Fig B.54: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 9.

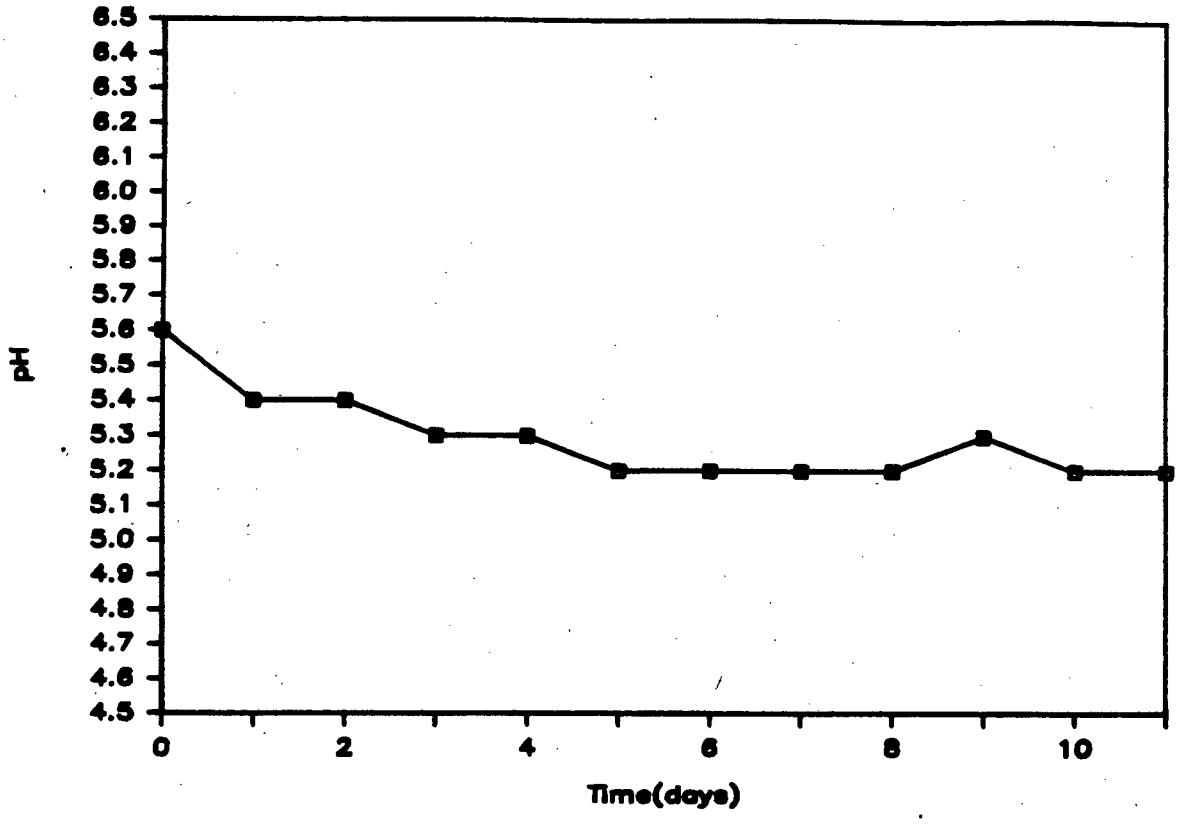

Fig B.55: pH of a batch reactor versus time – batch test 10.

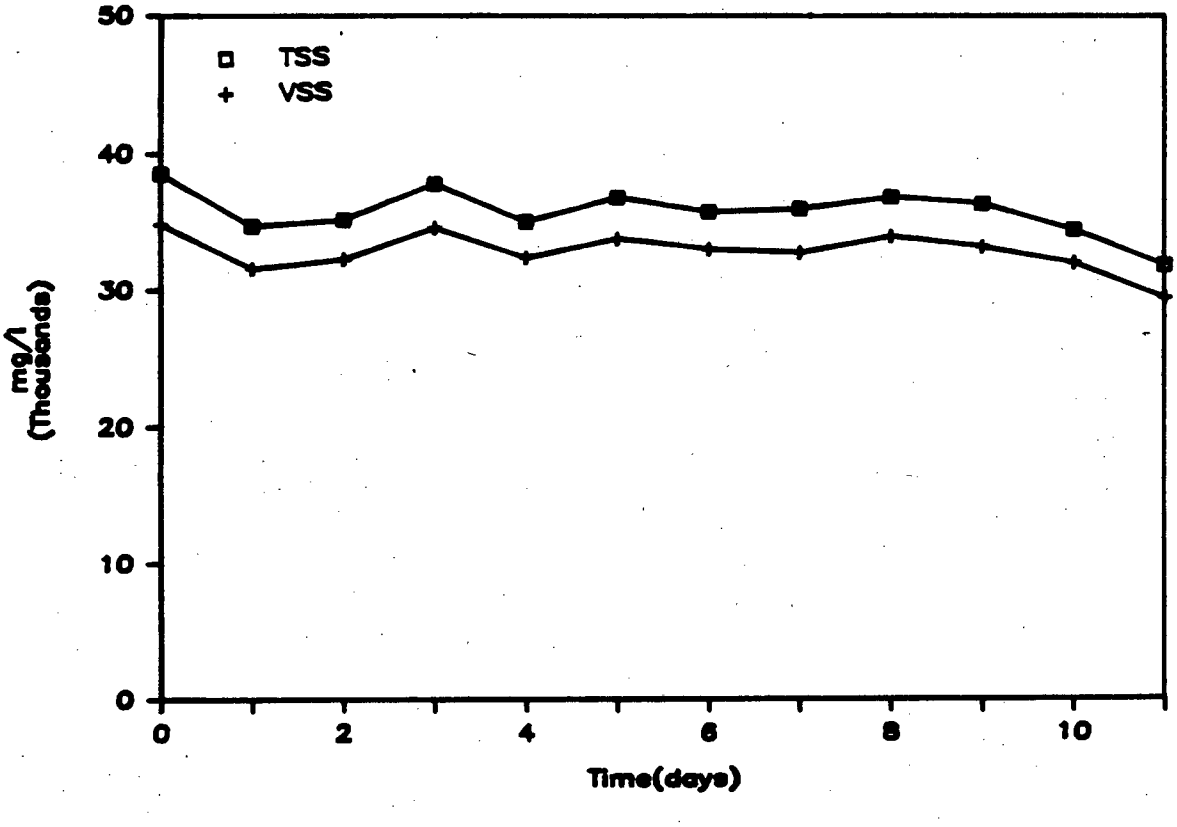

Fig B.56: TSS and VSS concentrations of a batch reactor versus time – batch test 10.

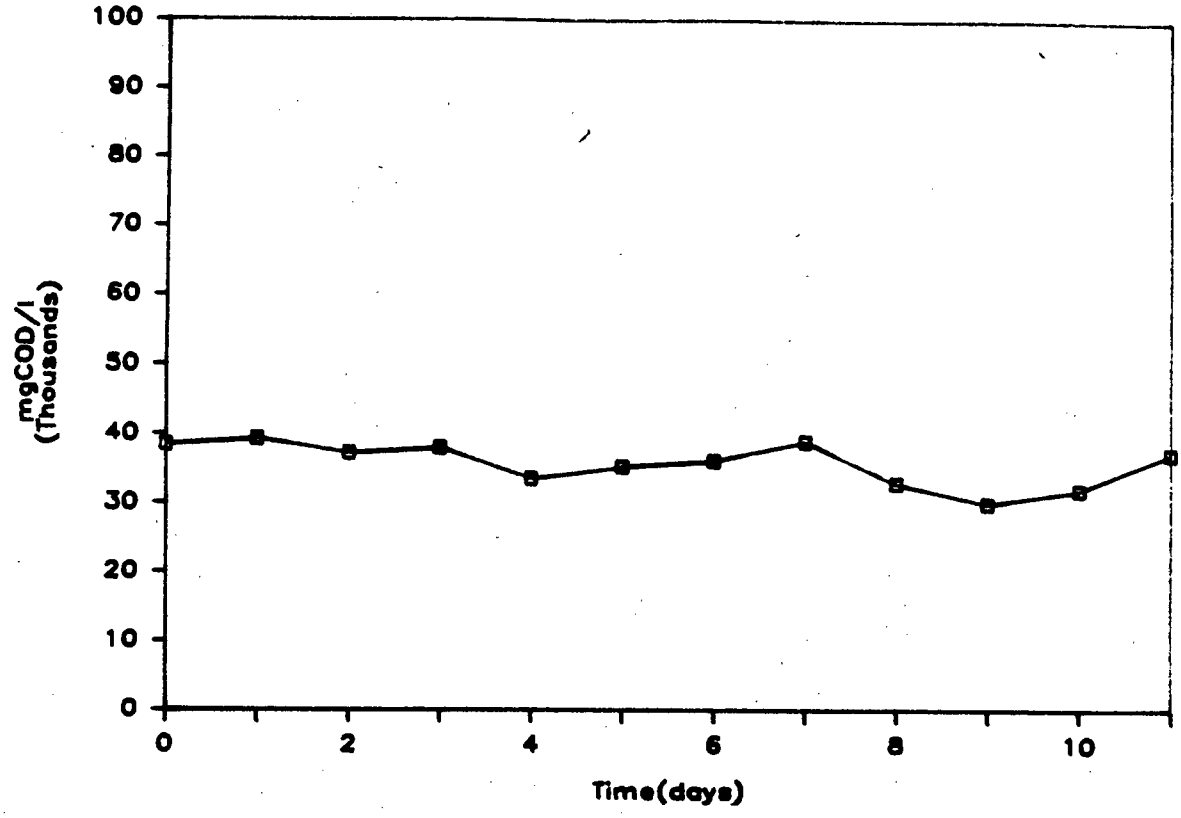

Fig B.57: COD of the VSS concentrations of a batch reactor versus time – batch test 10.

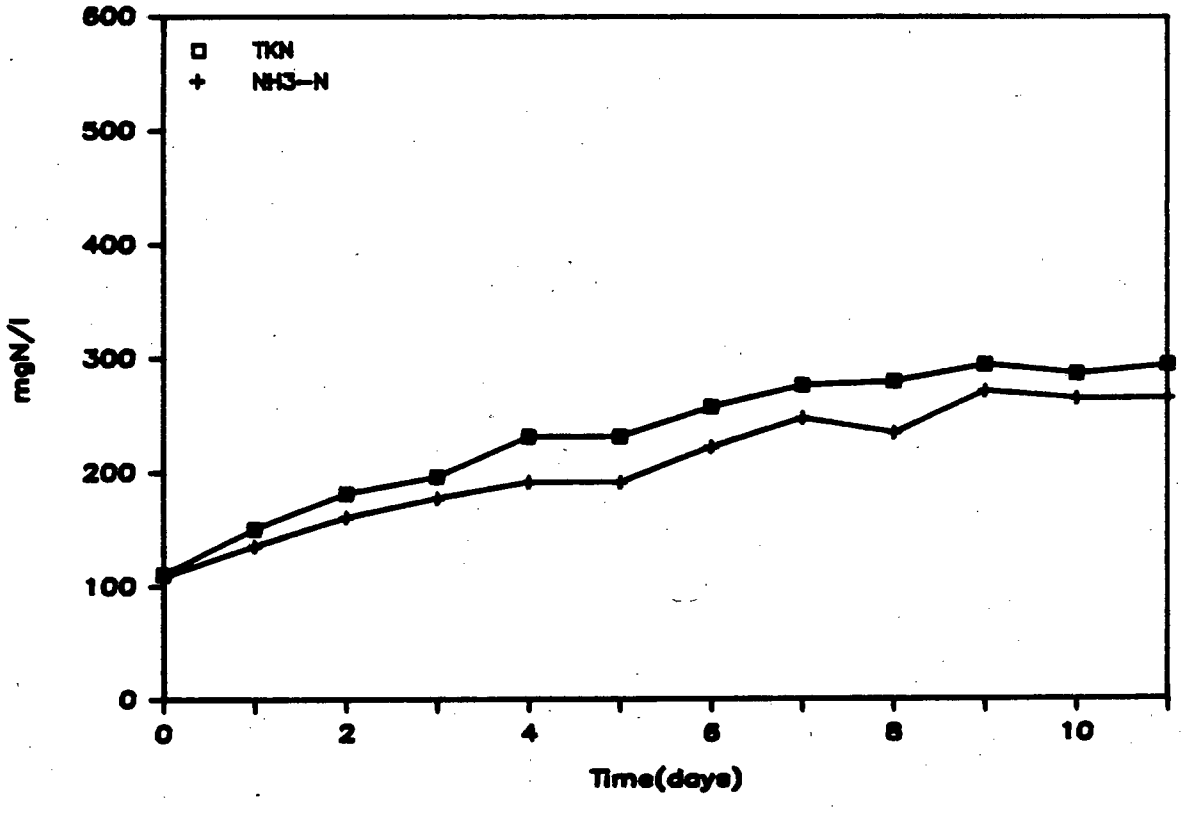

Fig B.58: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 10.

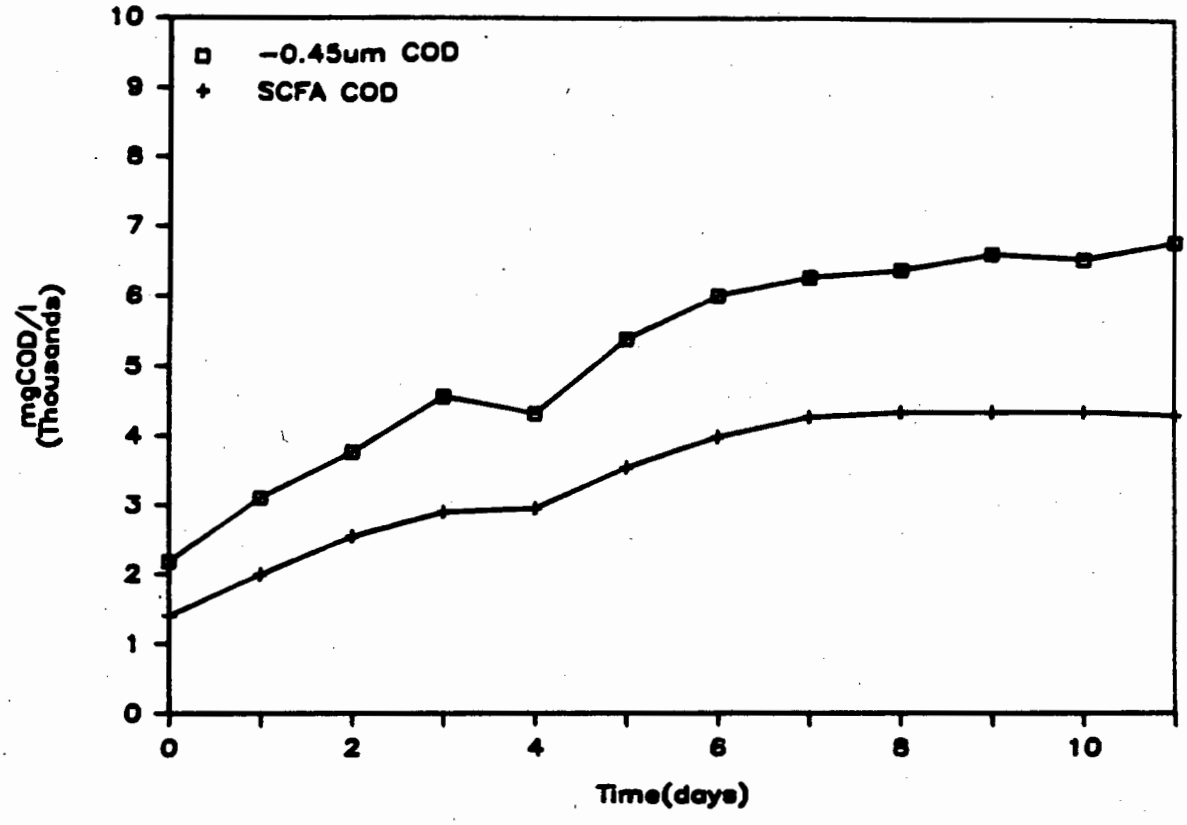

Fig B.59: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 10.

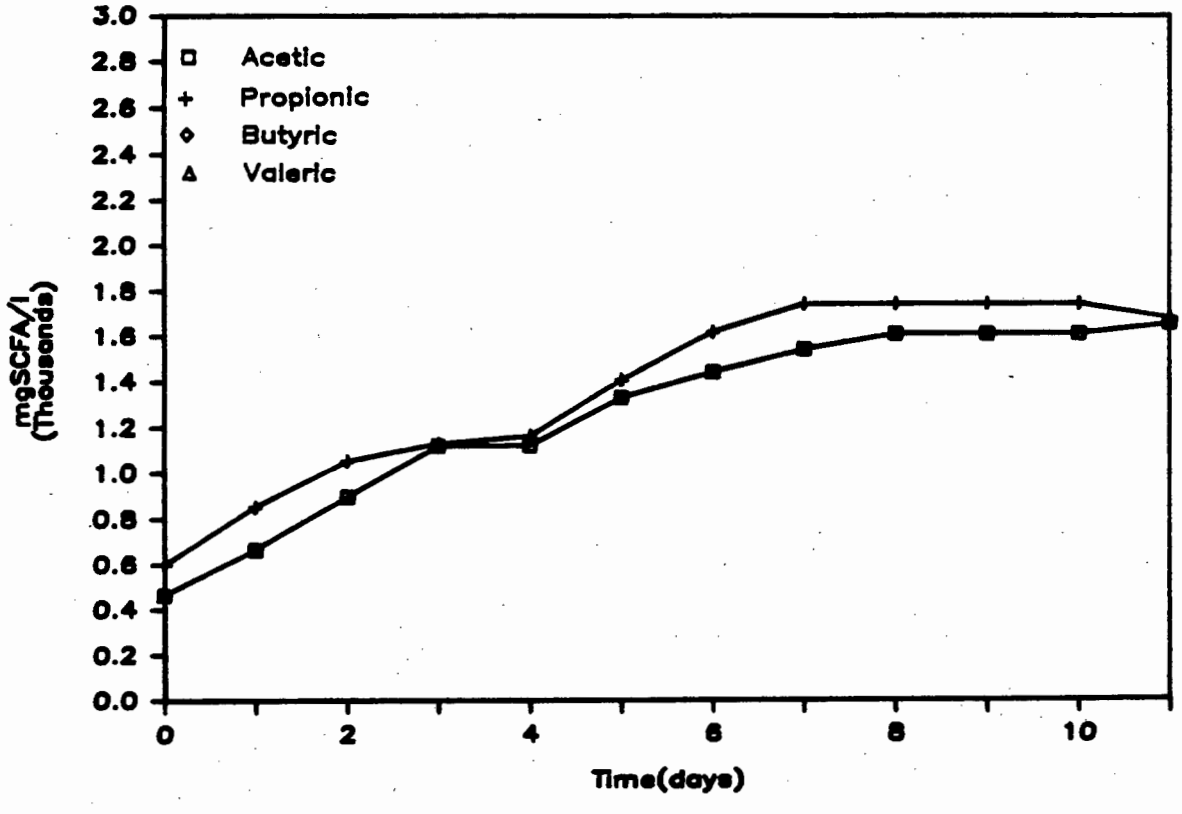

Fig B.60: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 10.

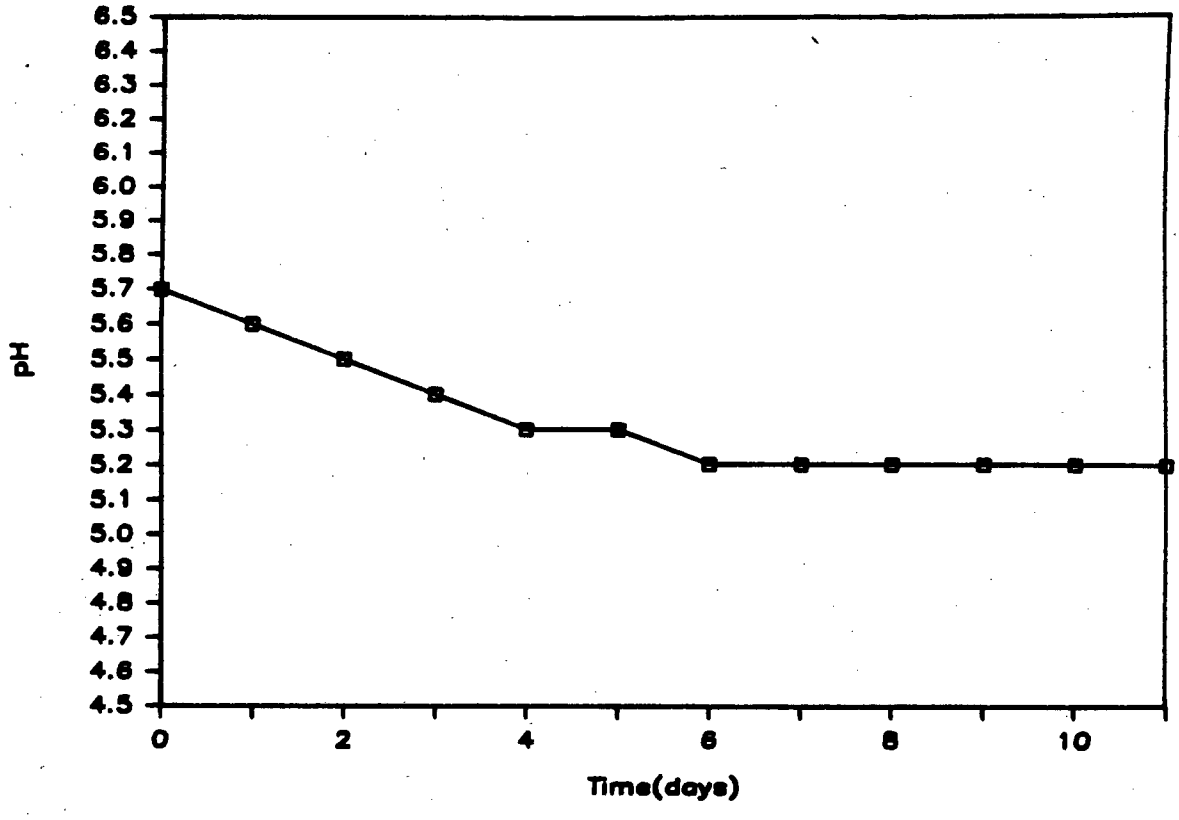

Fig B.61: pH of a batch reactor versus time – batch test 11.

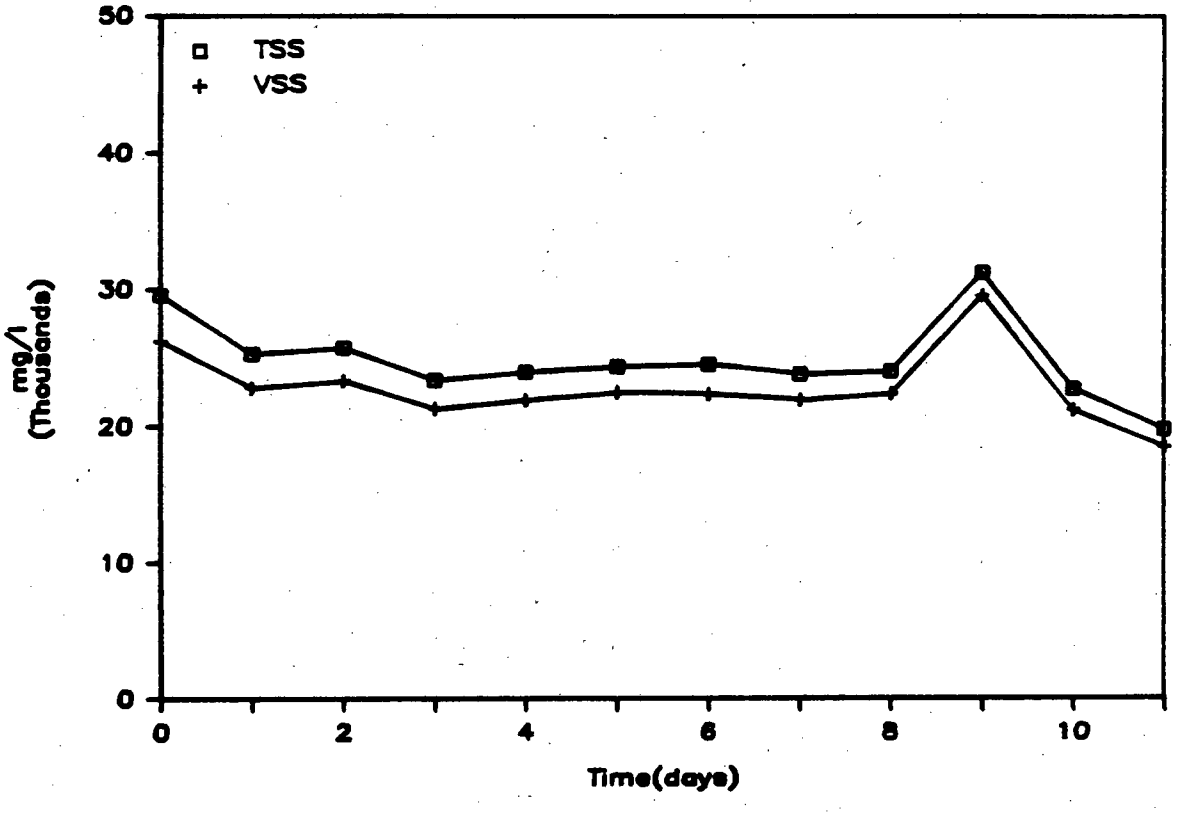

Fig B.62: TSS and VSS concentrations of a batch reactor versus time – batch test 11.

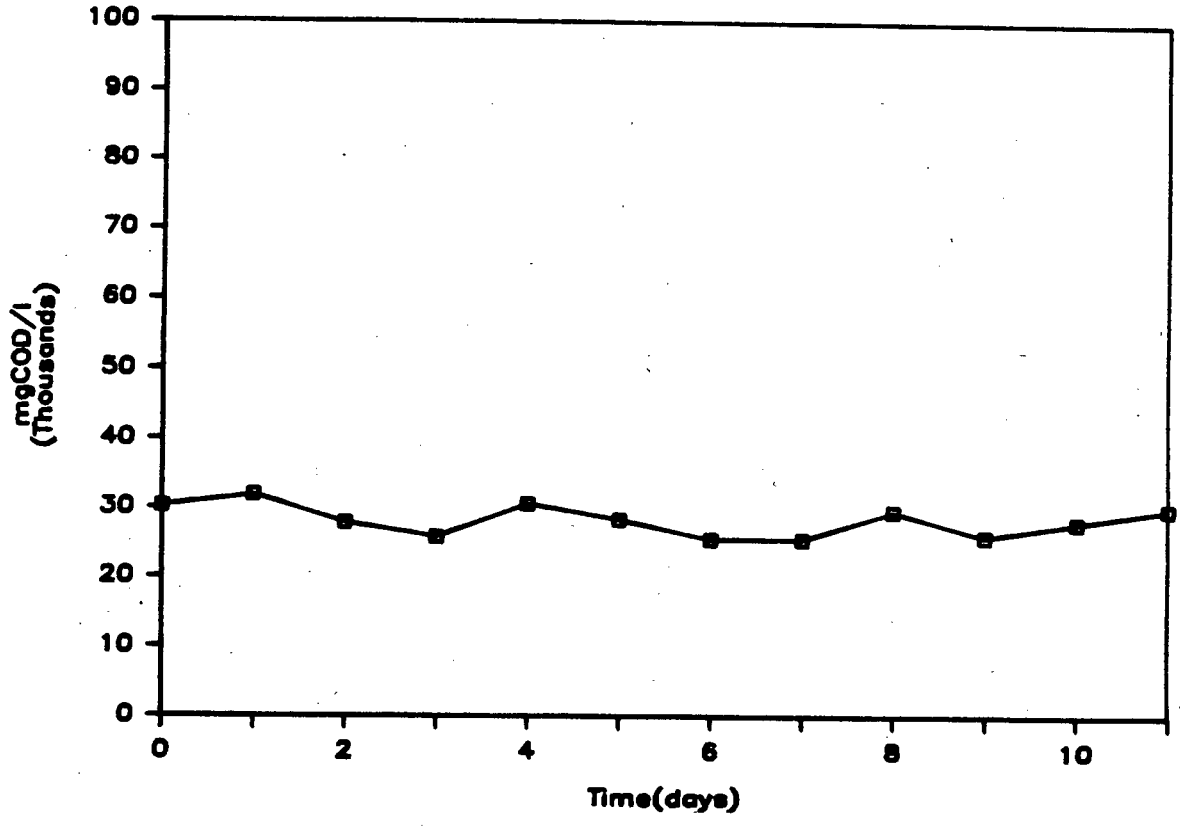

Fig B.63: COD of the VSS concentrations of a batch reactor versus time – batch test 11.

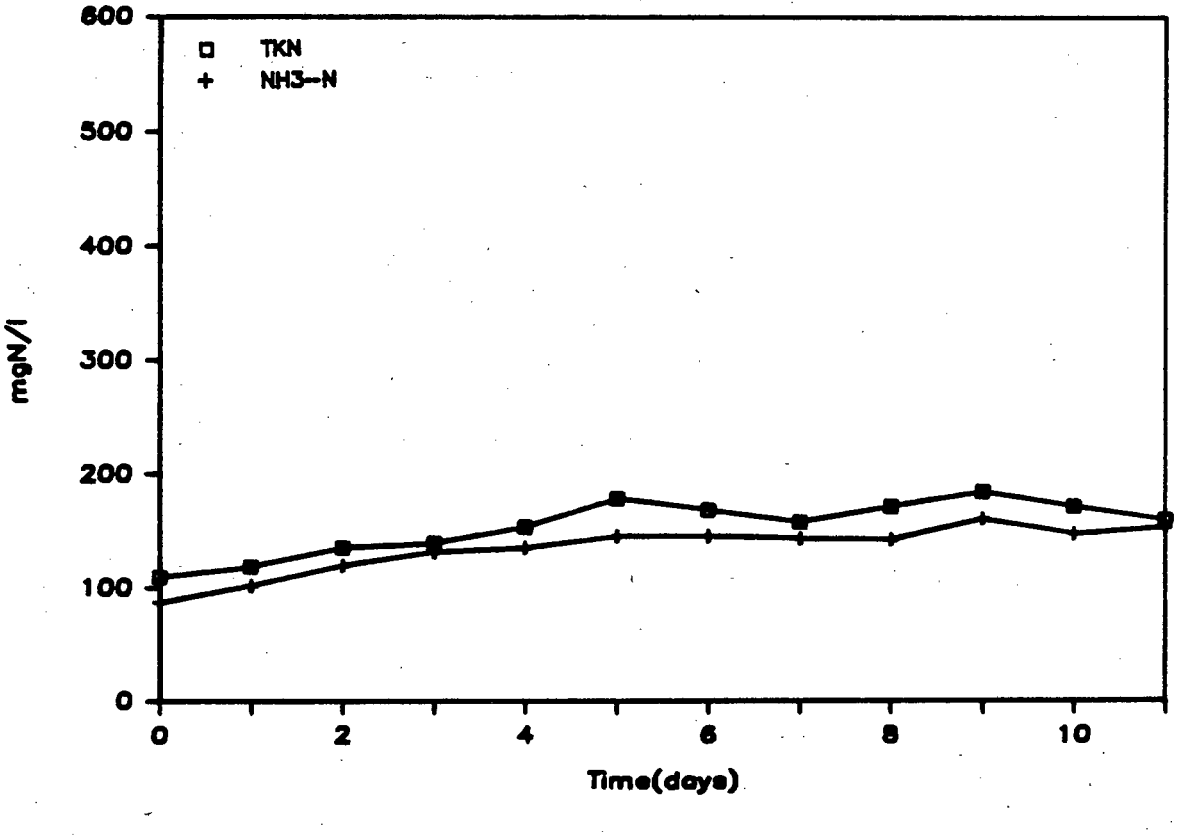

Fig B.64: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 11.

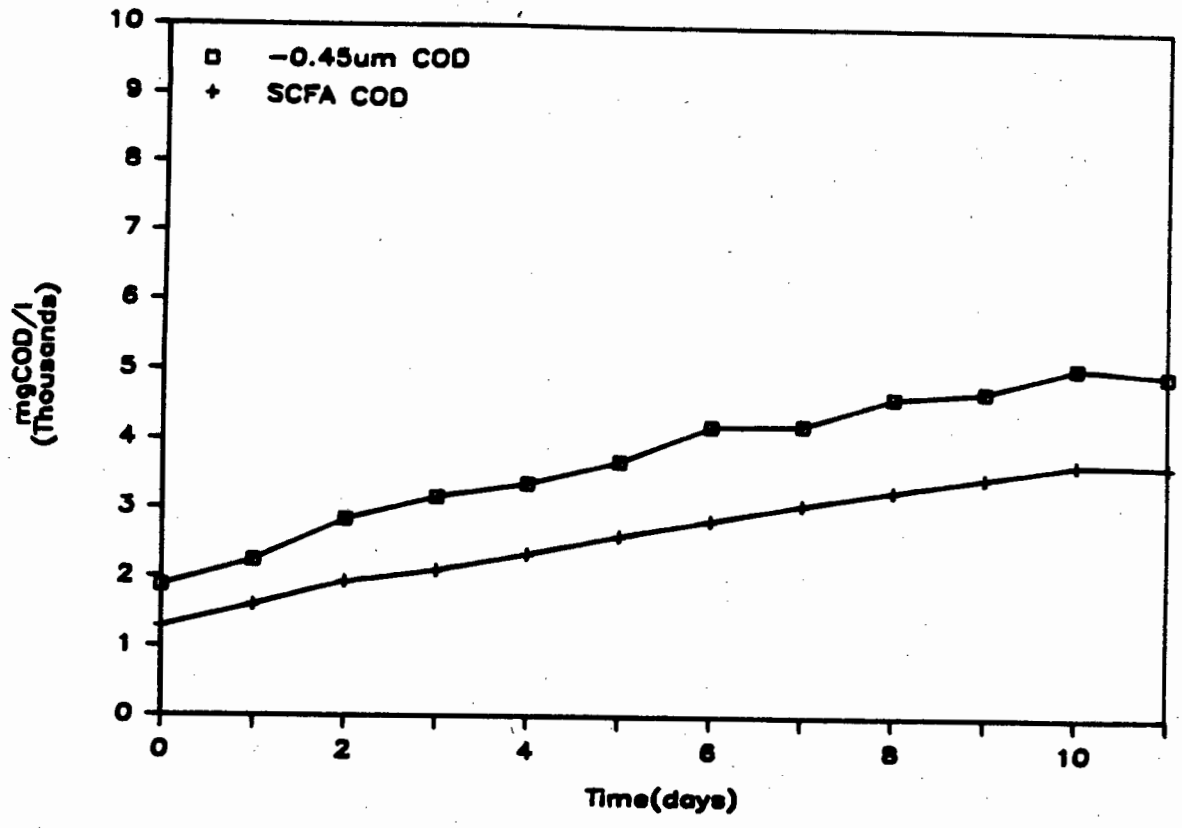

Fig B.65: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 11.

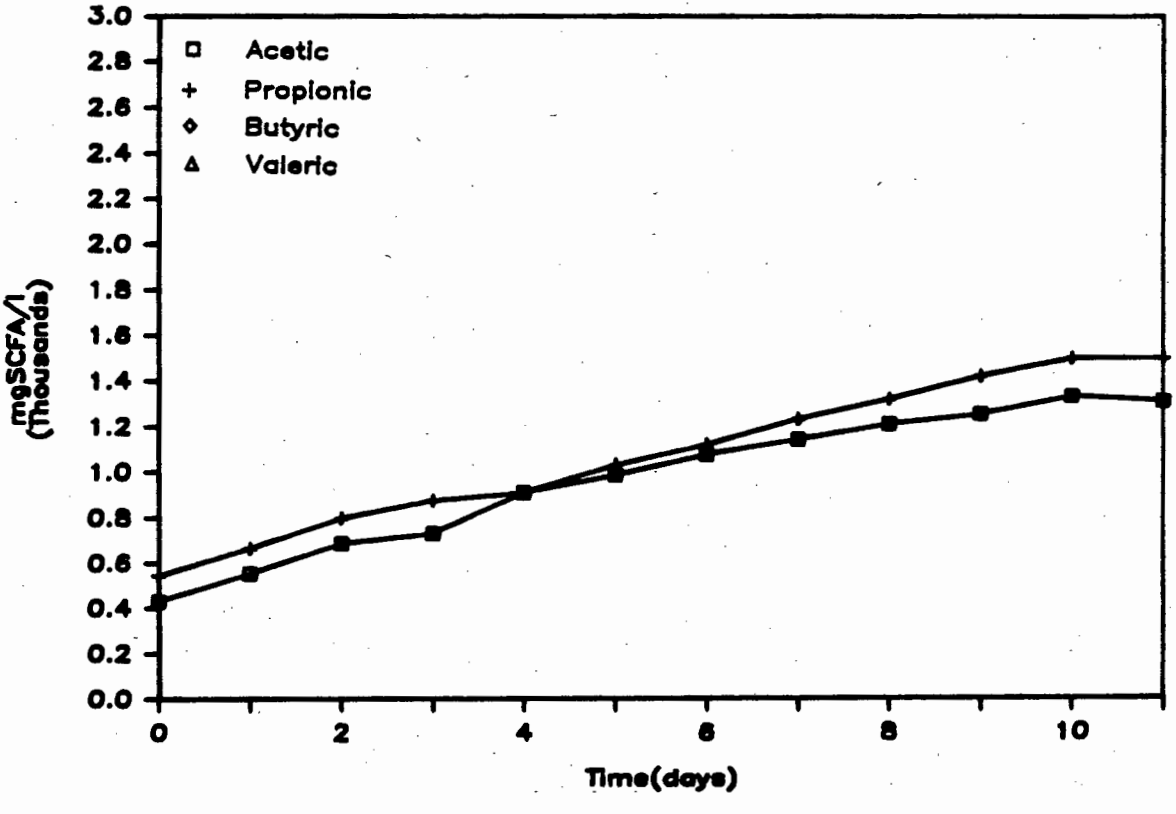

Fig B.66: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 11.

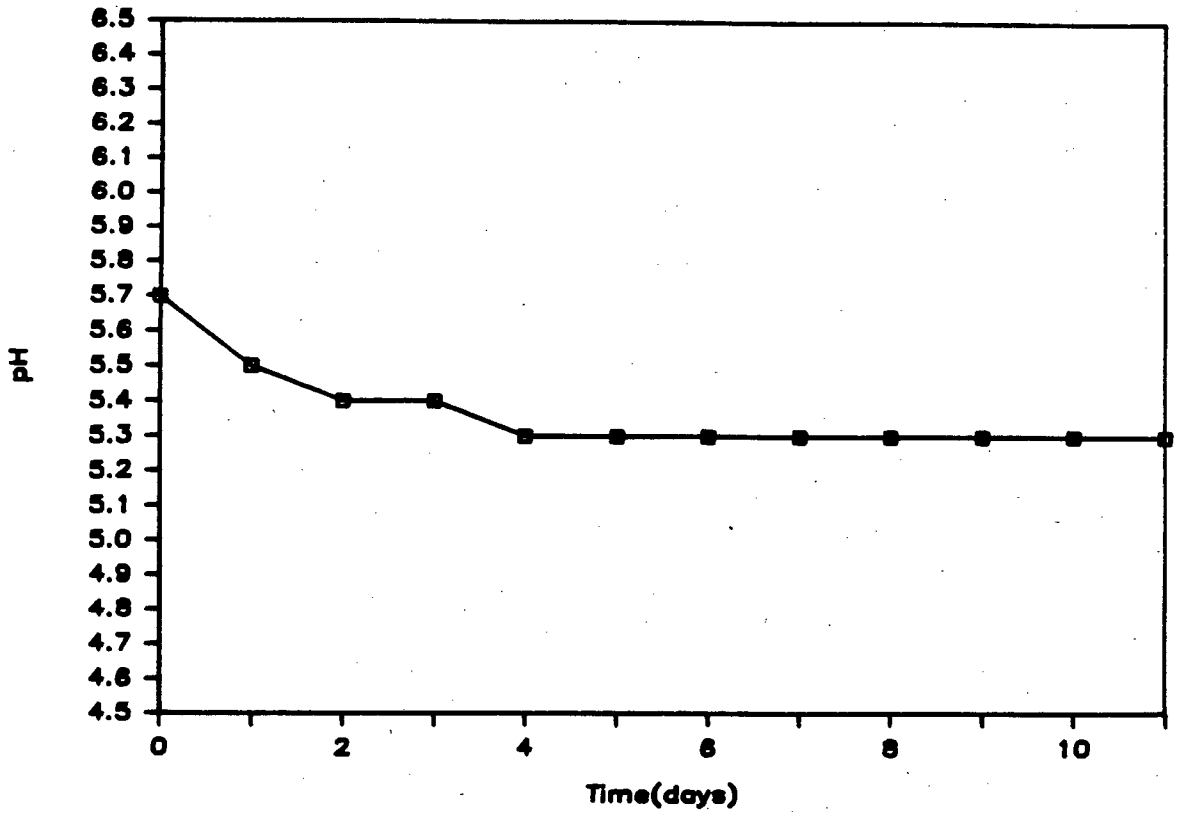

Fig B.67: pH of a batch reactor versus time – batch test 12.

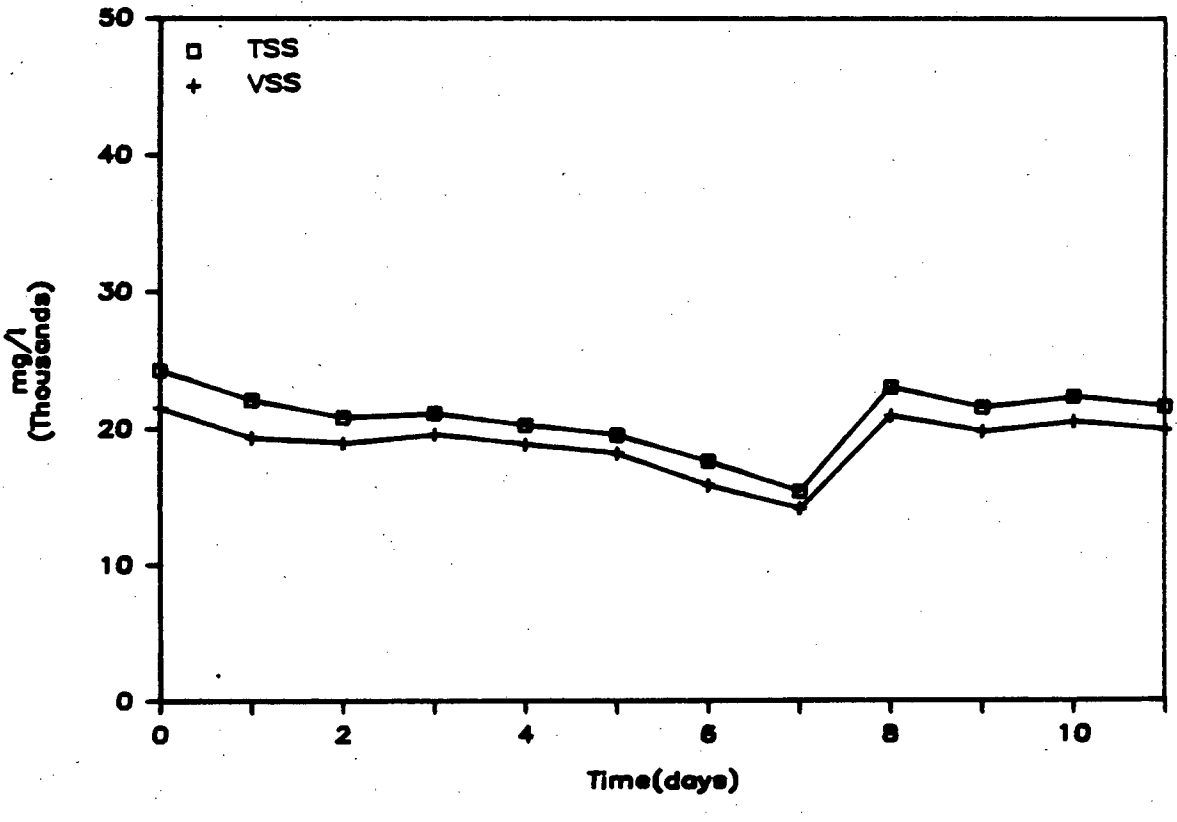

Fig B.68: TSS and VSS concentrations of a batch reactor versus time – batch test 12.

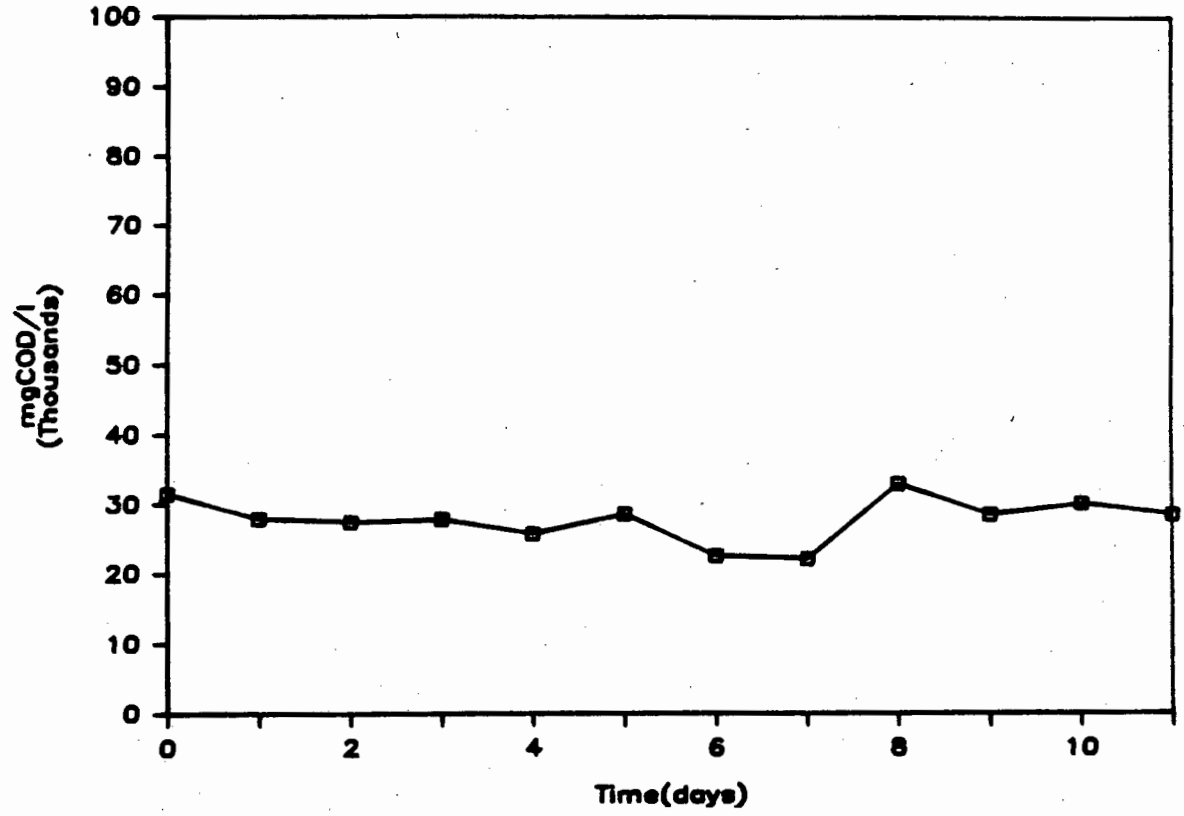

Fig B.69: COD of the VSS concentrations of a batch reactor versus time – batch test 12.

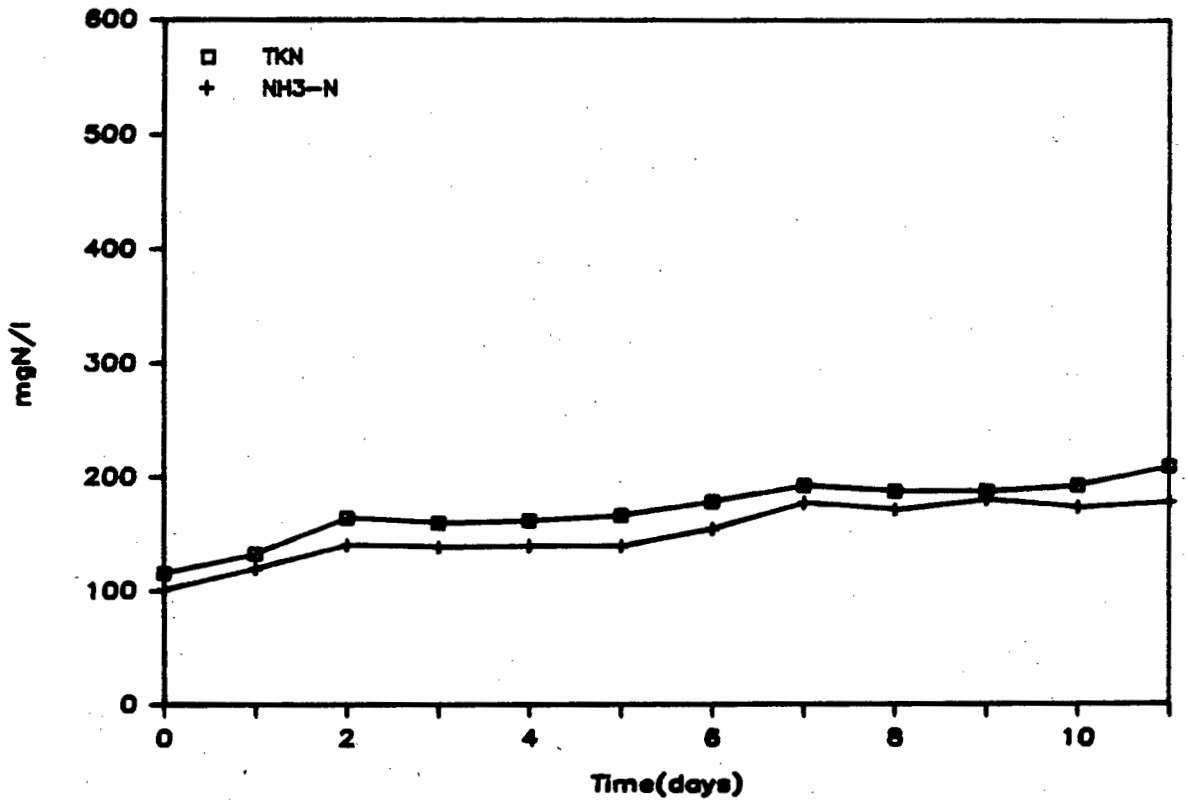

Fig B.70: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 12

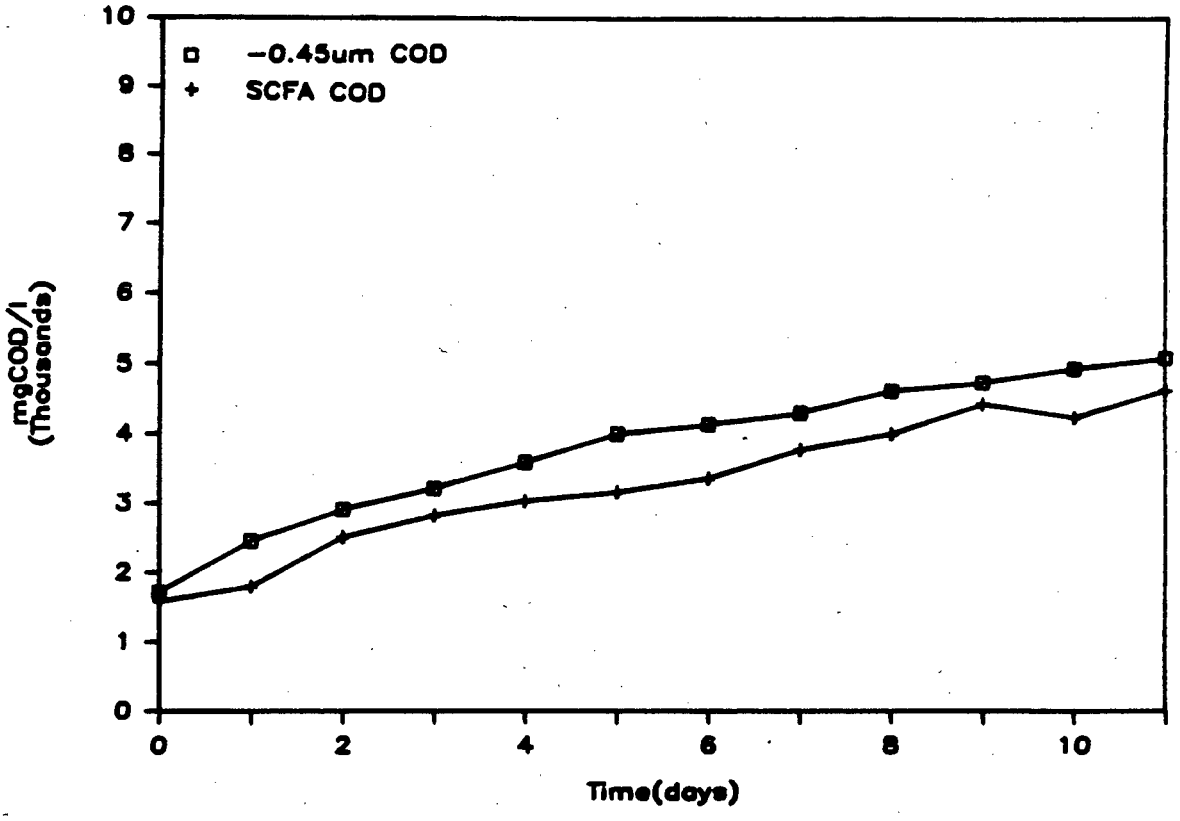

Fig B.71: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 12.

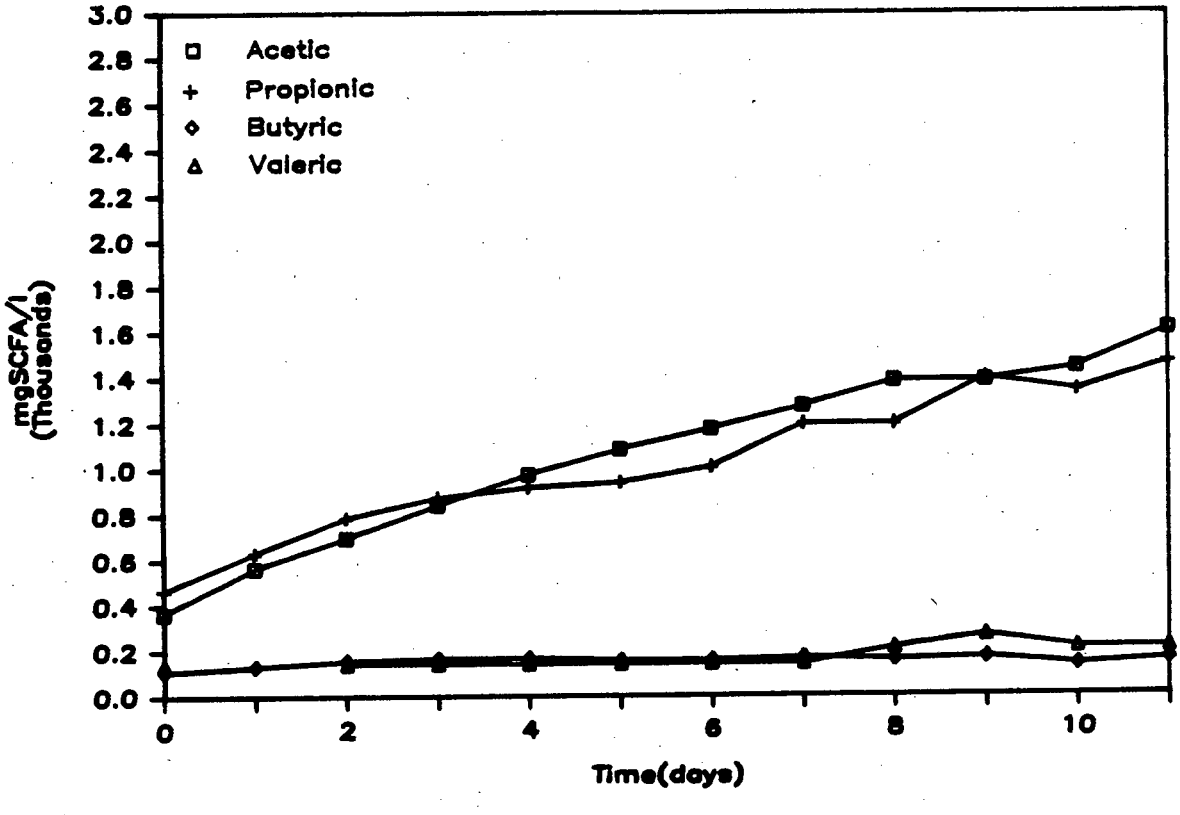

Fig B.72: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 12.

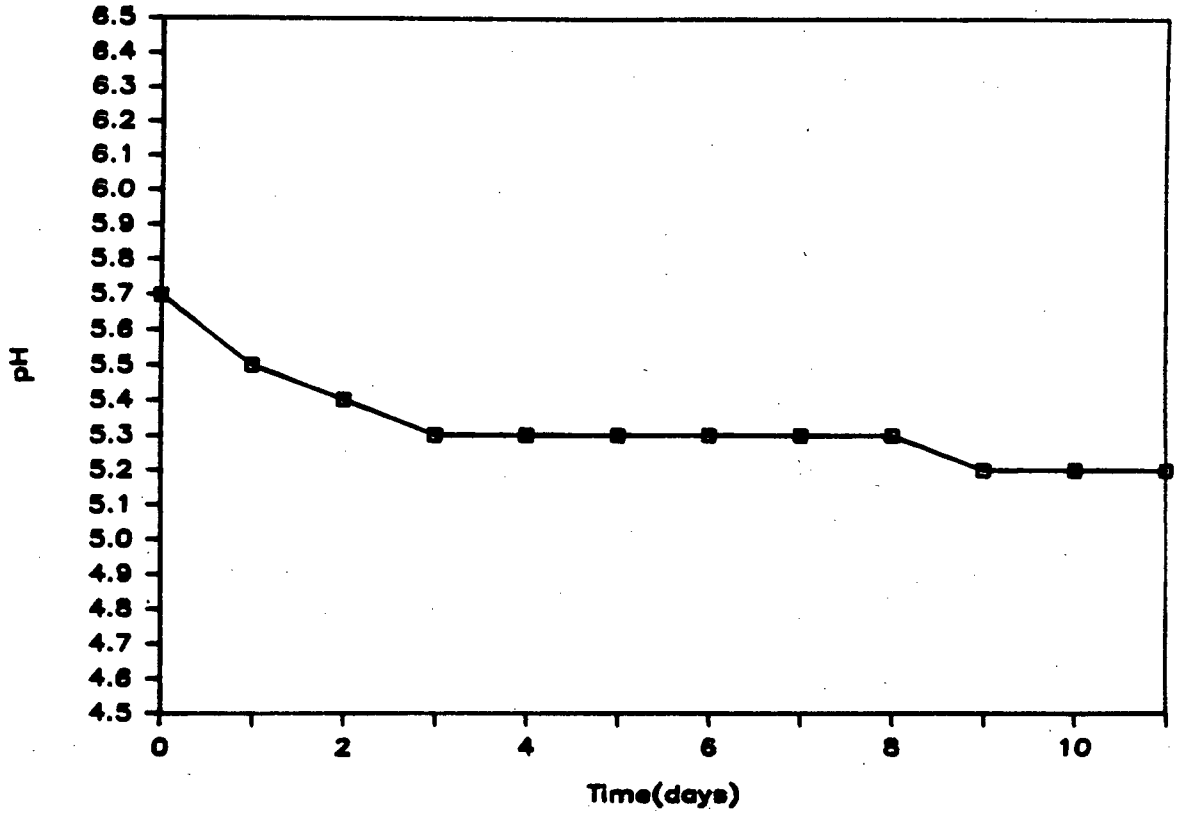

Fig B.73: pH of a batch reactor versus time – batch test 13.

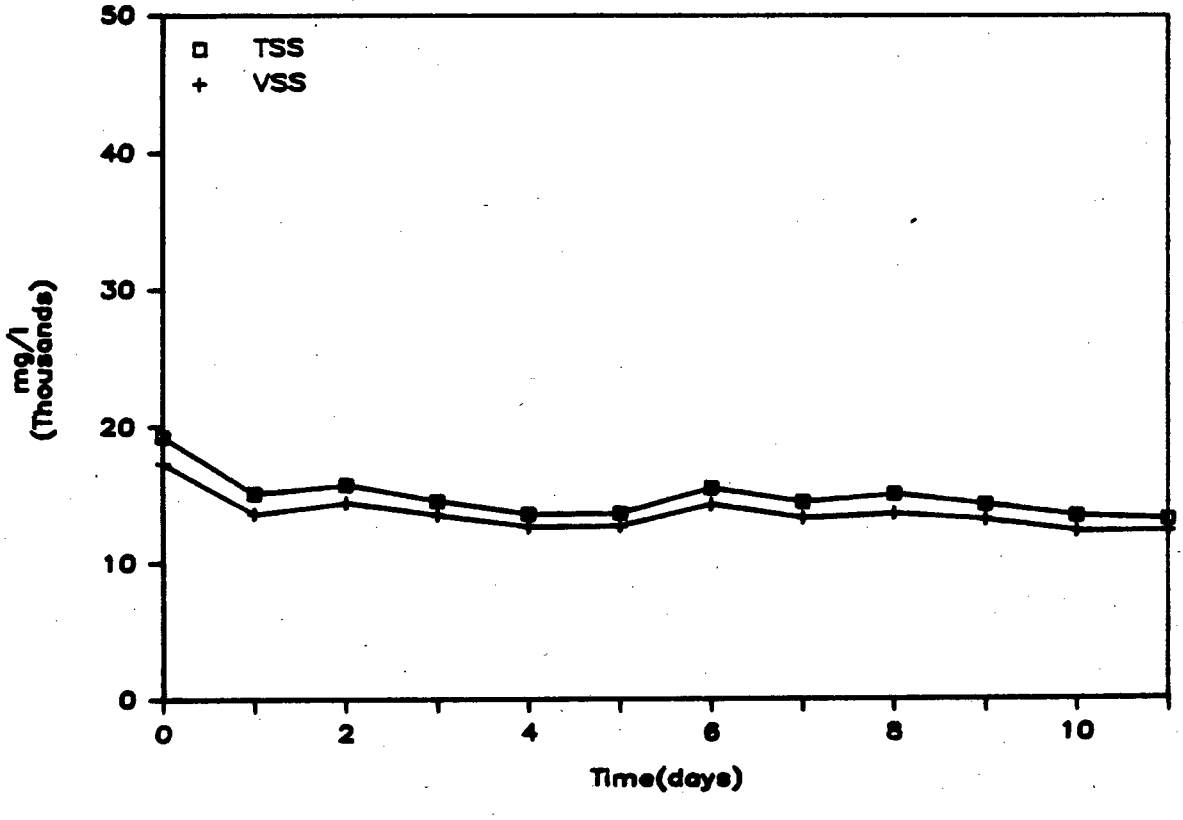

Fig B.74: TSS and VSS concentrations of a batch reactor versus time – batch test 13.

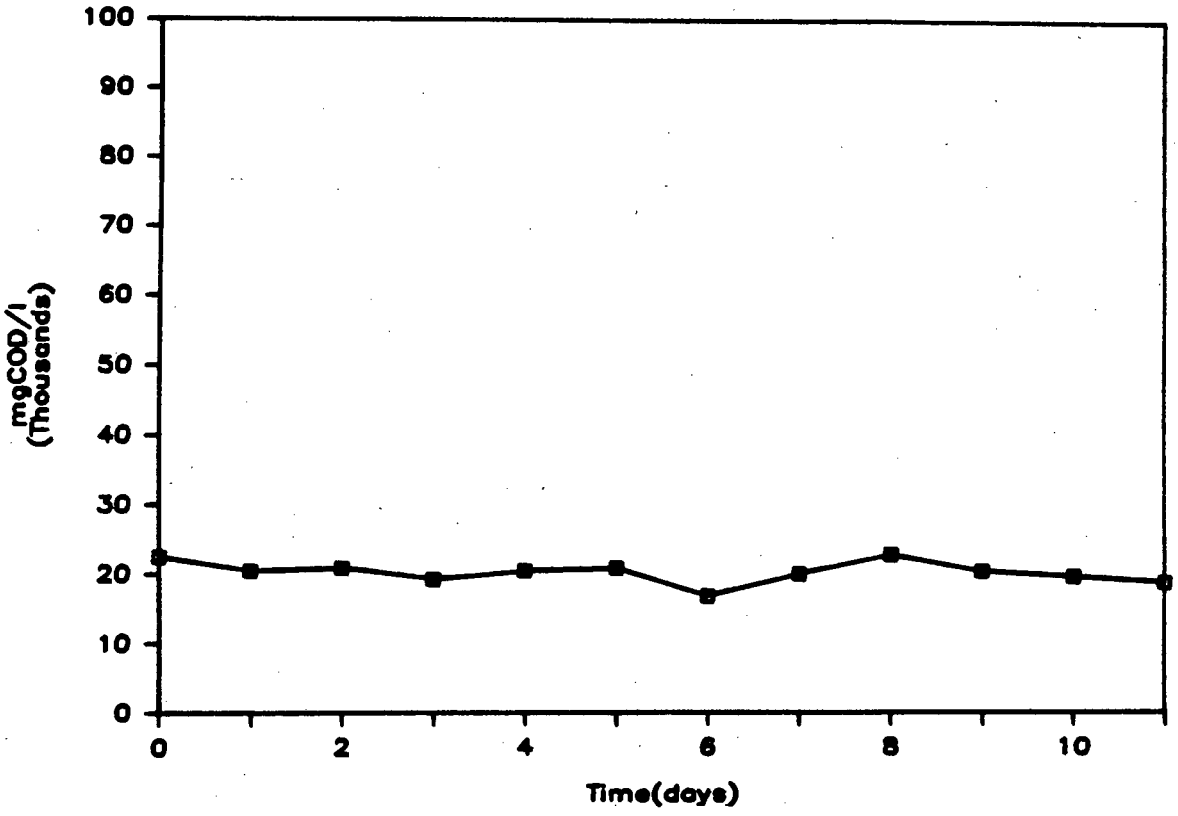

Fig B.75: COD of the VSS concentrations of a batch reactor versus time – batch test 13.

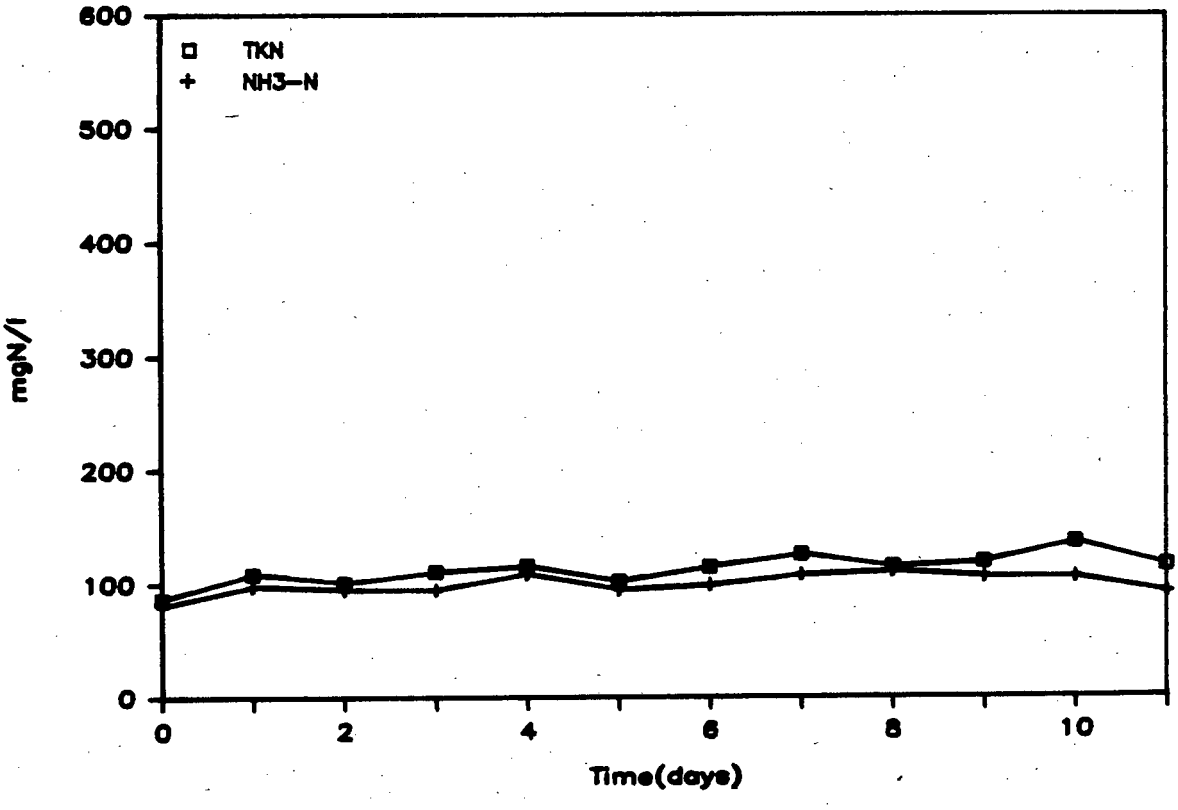

Fig B.76: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 13.

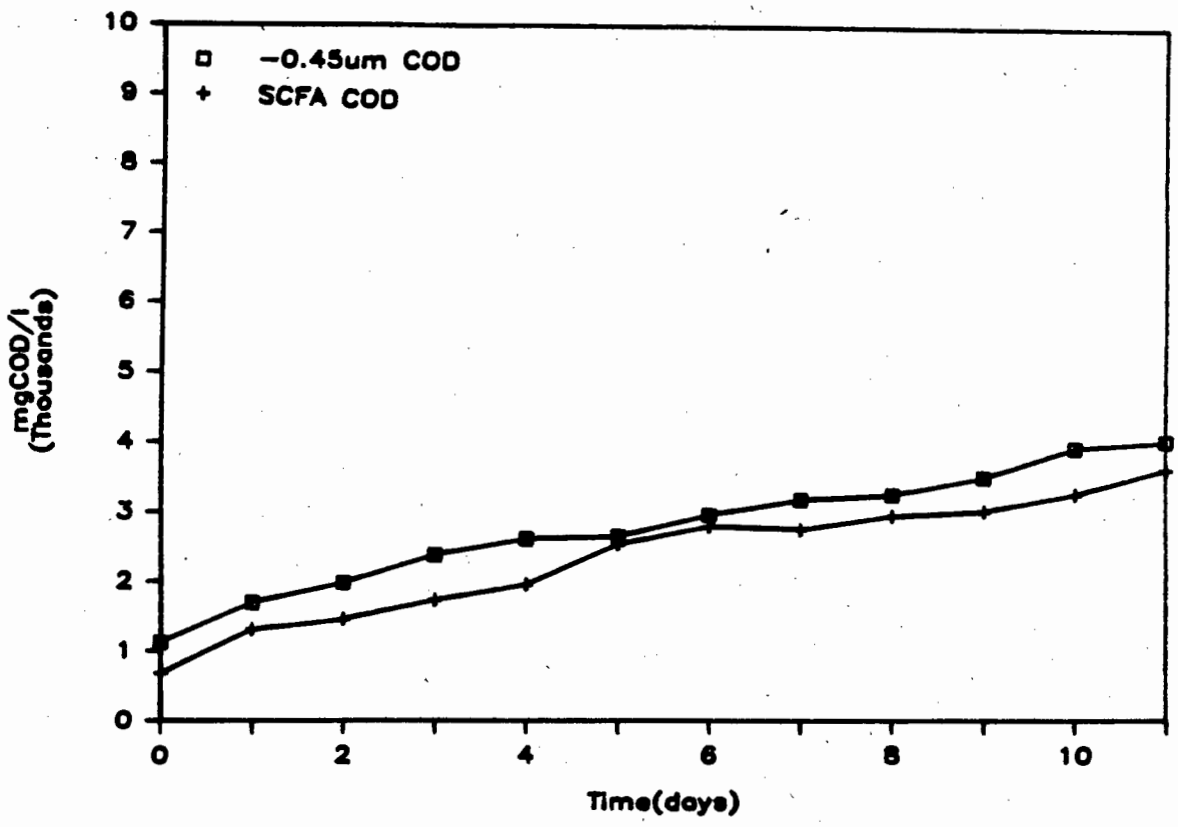

Fig B.77: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 13.

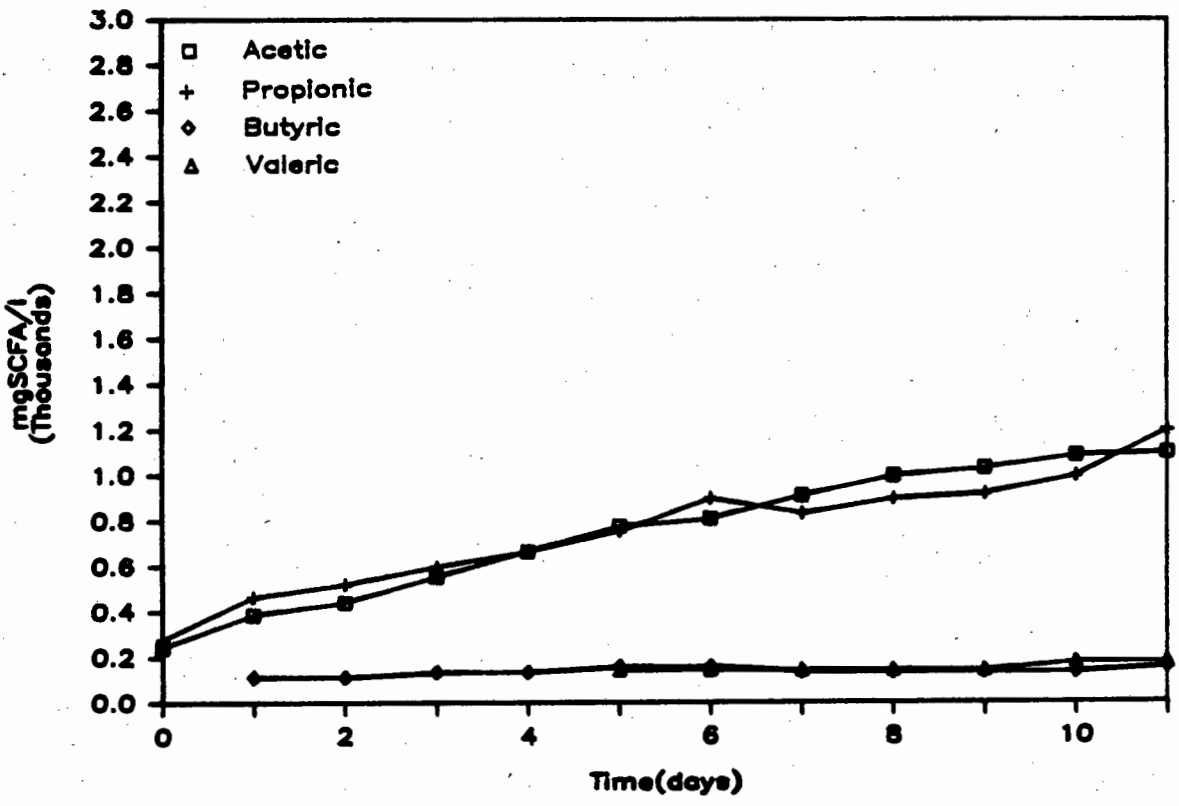

Fig B.78: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 13.

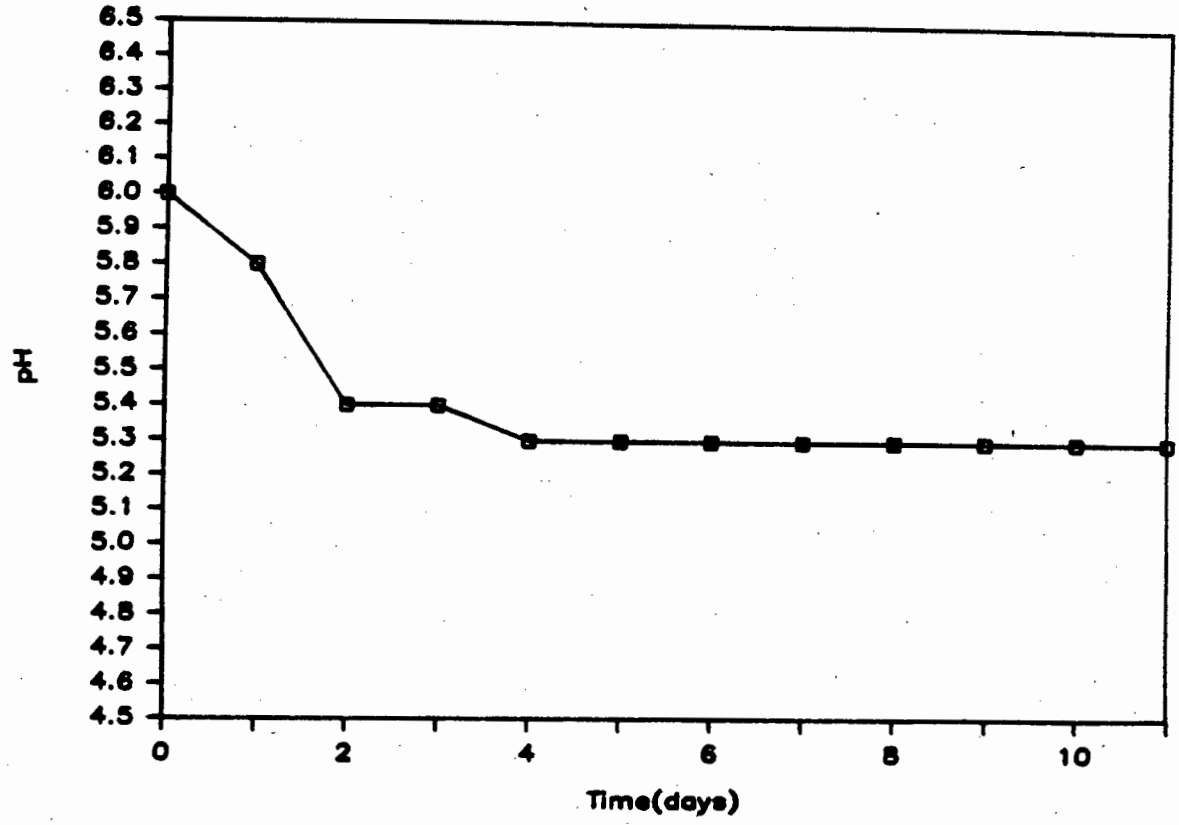

Fig B.79: pH of a batch reactor versus time – batch test 14.

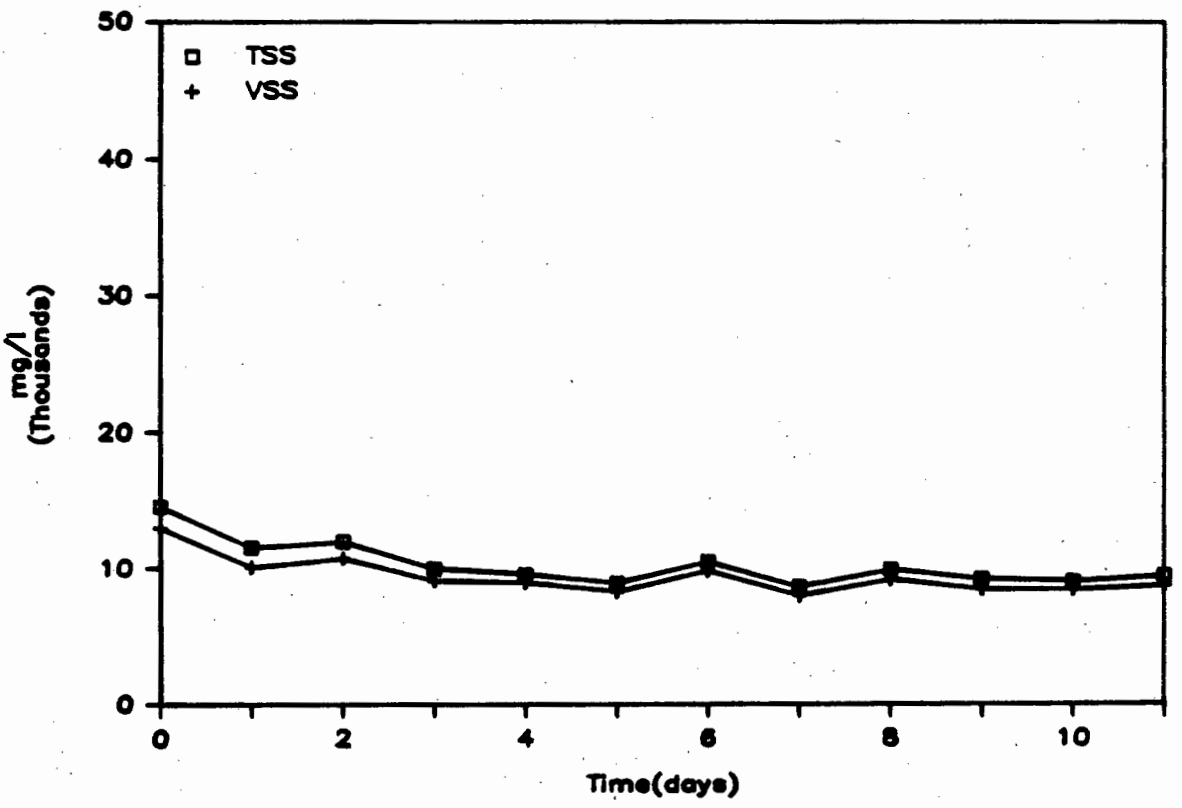

Fig B.80: TSS and VSS concentrations of a batch reactor versus time – batch test 14.

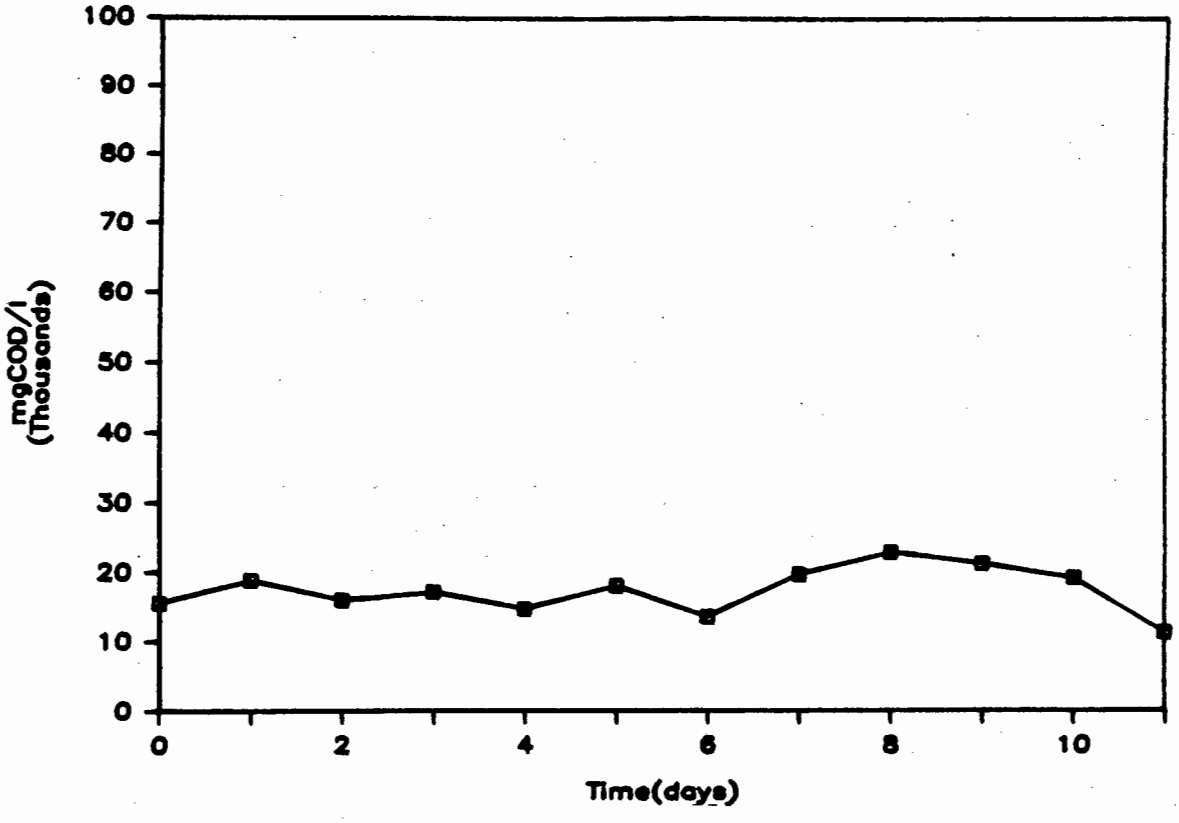

Fig B.81: COD of the VSS concentrations of a batch reactor versus time – batch test 14.

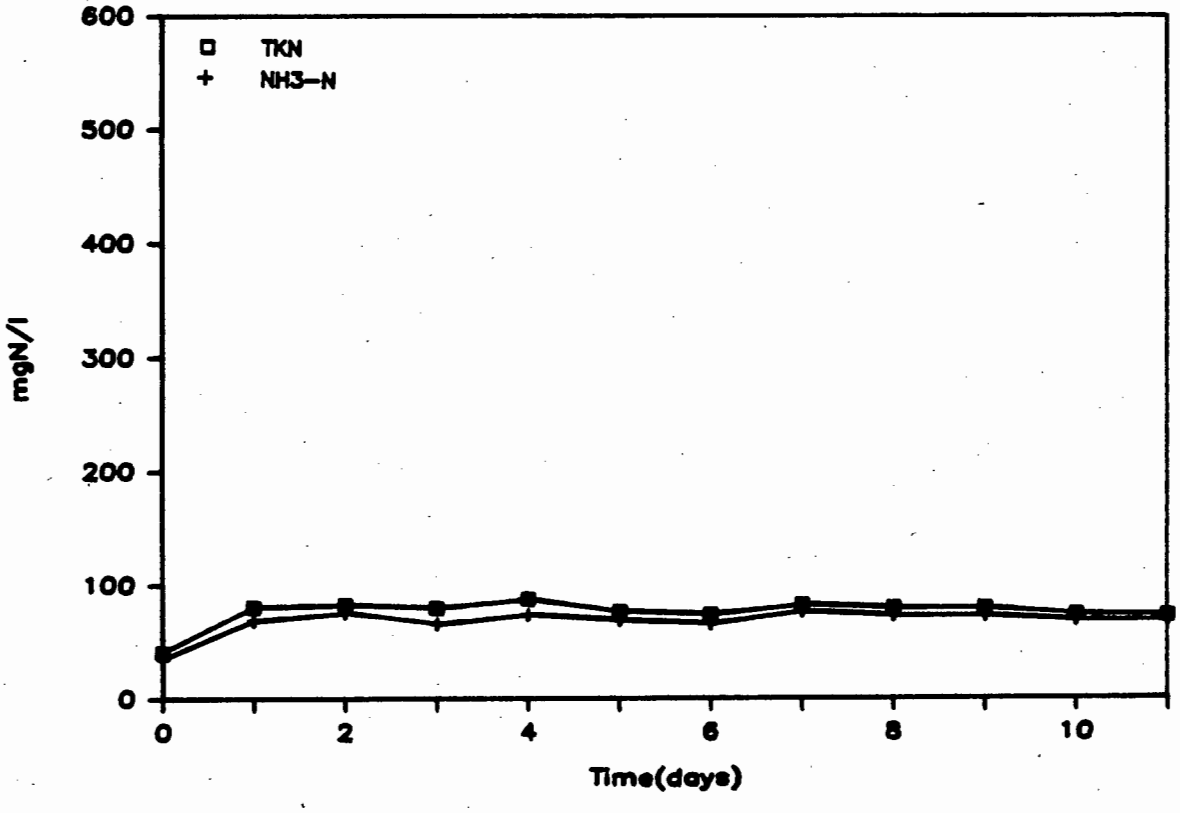

Fig B.82: TKN and NH_3-N concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 14.

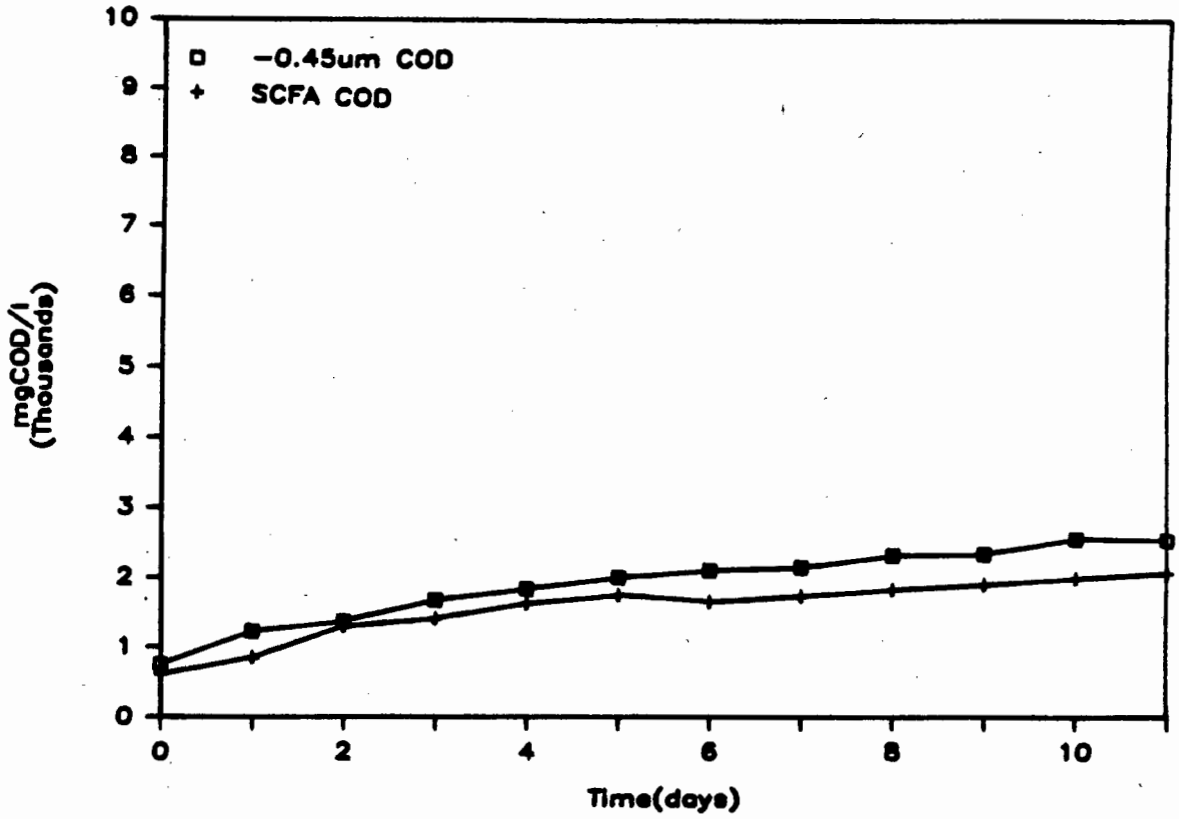

Fig B.83: COD and total SCFA COD concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 14.

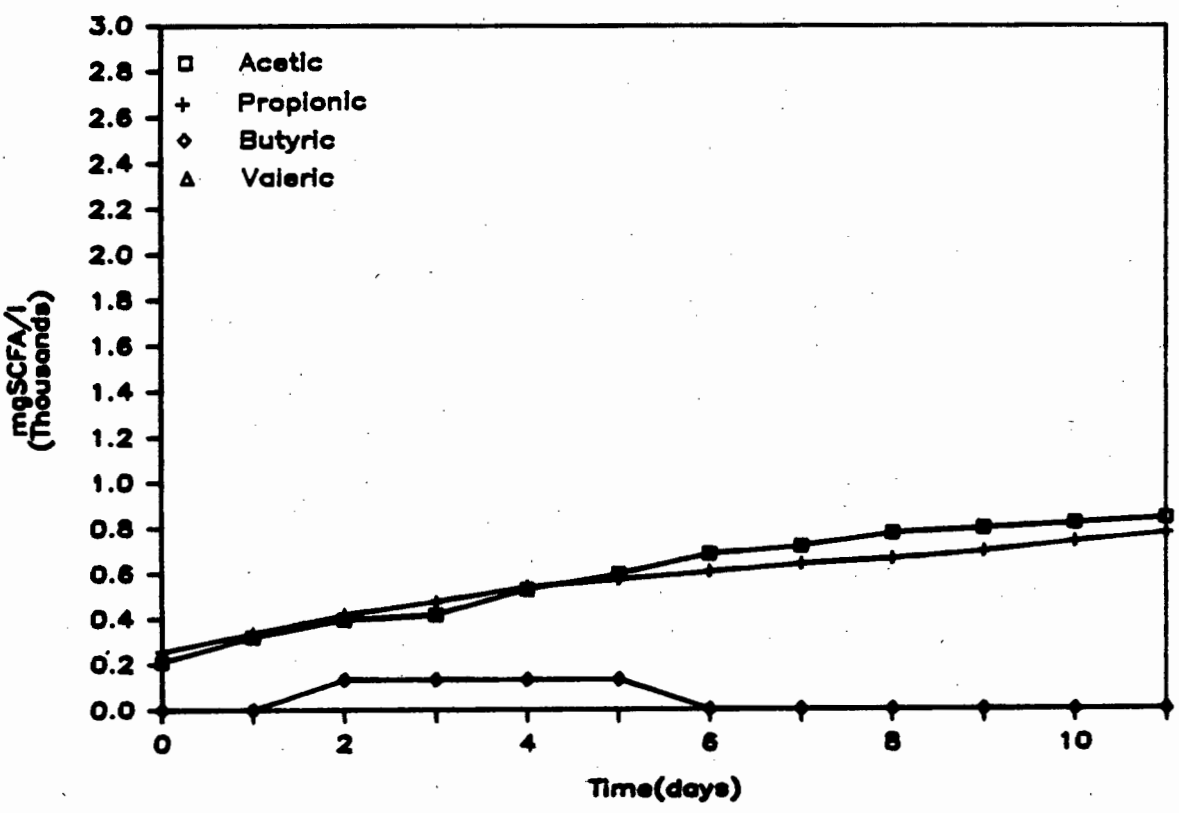

Fig B.84: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a batch reactor versus time – batch test 14.

APPENDIX C

TABLES AND PLOTS OF THE RESULTS OF THE 3 IN-SERIES, COMPLETELY MIXED REACTOR SYSTEM INVESTIGATION

Table C.1: **Results of measured parameters of the influent raw sludge in a 3 in-series, completely mixed reactor system.**

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
B1 0	5.9	188	174	46946	38912	61150	2052	56	44			126
1	6.0											
2	6.0											
3	6.0											
4	6.0											
5	6.0											
6	6.1											
7	6.1	364	218	43644	36744	65920	3708	522	611	167		1784
8	6.1											
9	6.0											
10	6.0											
11	6.0	333	216	43510	36716	50774	3488	522	611	256		1945
B3 28	5.6	389	328	75948	65306	101806	5171	722	1078	389	111	3332
29	5.7	347	280	42478	37192	56525	4608	944	1022	378	178	3601
30	5.6	442	364	46696	37256	79909	6472	333	889	467	178	2910
31	5.7	549	381	74702	64688	93798	5980	1222	1156	556	356	4785
32	5.6	465	325	49664	42368	66355	5284	911	1089	378	511	4345
33	5.7	566	409	70320	60492	97075	7291	1111	1156	689	356	4909
34	5.7	515	381	64122	55968	79053	6184	1111	1156	556	356	4667
35	5.7	504	325	68268	59590	86352	6826	1111	978	422	222	3882
36	5.7	510	403	72716	62534	100333	6620	1111	1067	444	356	4329
37												
38	5.7	543	375	66224	57274	89230	5962	733	1067	444	289	3790
39	5.7											
40	5.7											
41	5.7											
42	5.7											
43	5.7	571	386	63286		69768	6197	689	911	444	356	3643
44												
45	5.7	554	403	66738	57380	75924	6033	1111	1156	556	289	4531
46												
47	5.8		431	53368	45850	63202	5253	911	1067	444	289	3979

Table C1: continued

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
84 48												
49	5.7	302	269	52922	44534	65381	2837	689	822	133	378	2989
50												
51												
52												
53												
54												
55	5.8	442	302	55124	47362	62914	4112	622	622	200	33	2034
56												
57	5.8	431	312	53672	46466	68259	4071	622	667	200	33	2102
58	5.7	465	263	53342	45918	60446	4441	711	689	156	33	2150
59												
60												
61												
62	5.7	437	258	57966	49344	67848	4235	622	578	156	33	1888
63	5.8	398	274	55104	46936	60446	4169	622	578	156	33	1888
64												
65	5.7	420	302	52112	44704	54490	3963	622	578	156	33	1888
66	5.8	526	330	51364	44266	58618	3922	622	578	156	33	1888
67												
68												
69	5.9	448	314	51482	44118	61094	3764	622	578	156	33	1888
70	6.0	498	258	51484		50459	3846	622	578	156	33	1888
71	6.1	381	246	55096	47498	50459	4260	622	578	156	33	1888
72	6.1	336	246	52760	45638	57490	4426	489	578	156	33	1746
73												
74												
75	6.2	302	241	50070	43684	41942	3125	622	489	156	33	1753
85 76	6.2	347	241				3712	489	444	133		1434
77	6.2	286	241	46564	40640	48110	3619					
78	6.1	364	246	52132	45362	61269	3536	533	489	133		1549
79	6.2	325	258	53336	47026	62138	3679					
80												
81	6.1	364	274	50542	44142	58050	3434	533	489	133		1549
82	6.2	286	239	47848	41936	54370	3147	533	489	111	67	1646

Table C.2: Results of the measured parameters of the first reactor, of 1 day retention time, in a 3 in-series, completely mixed reactor system.

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
81 0	5.9	188	174	46946	38912	61150	2052	56	44			126
1	5.7											
2	5.7	302	283	44158	37994	64433	3591	56				60
3	5.8											
4	5.8	442	294	41960	35006	58277	4576	333	689	89	89	1740
5												
6	5.9	484	319	51206	44084	56444	5026	889	889	278	133	3068
7												
8	5.9	501	328	43078	36172	57680	5150	978	956	278	89	3174
9												
10	5.9	518	375	43182	36592	63448	5026	978	889	222	89	2971
11												
12												
83 29	5.6	577	441	66008	57370	80281	6636	1400	1356	489	267	4975
30												
31	5.5	627	431	56518	49950	65126	7045	1556	1356	378	111	4622
32												
33												
34	5.5	734	543	65492	57178	80691	8806	1800	1644	600	111	5720
35												
36	5.5	700	566	61920	53426	88408	9170	1800	1756	711	111	6091
37												
38												
39	5.5	700	554	61886	53506	79773	8676	1667	1556	600	111	5445
40												
41												
42	5.6	689	442	65496	56984	81670	8044	1578	1444	467	267	5257
43												
44	5.5	728	599	58602	50998	74693	8783	1644	1511	422	267	5347

Table C2: continued

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l
84 45												
46												
47												
48	5.5	571	448	46384	40226	61970	6731	1356	1400	378	267	4793
49												
50												
51												
52												
53												
54												
55												
56	5.5	655	493	49434	43136	56746	5716	1111	1111	333	111	3695
57												
58	5.5	510	414	46548	40872	59213	5675	1111	1133	267	111	3608
59	5.5	538	437	48518	41934	61269	5633	1111	1156	267	111	3643
60												
61												
62	5.5	543	442	46288	40248	60035	5551	1111	1156	333	111	3763
63	5.5	543	431	49254	42730	65792	5862	1178	1156	333	111	3834
64												
65	5.4	498	370	48982	42914	52426	5408	1000	1111	311	111	3537
66	5.4	582	454	50974	44038	58618	5408	1000	1111	267	111	3457
67												
68												
69	5.5	577	414	52216	45006	57379	5418	1111	1111	267	111	3575
70	5.8	515	420	51798		53768	5253	1111	1111	267	111	3575
71												
72	5.8	487	370	52054	44264	55836	5460	1111	1111	267	111	3575
73	5.8	470	375	48488	41858	65381	5140	1111	1111	333	111	3695
74												
75												
85 76	5.9	431	364				4688	933	956	333	133	3316
77	5.9	420	358	50268	44198	61269	4400					
78	5.9	476	386			59213	4605	933	867	222	89	2890
79	5.9	476	386	50724	44618	60502	4456					
80	5.9	426	386	49872	43722	60502	4579	933	867	289	89	3012
81												
82	5.9	426	390	47848	41936	54370	4456	933	933	311	89	3151

Table C.3: **Results of the measured parameters of the second reactor, of 2 days retention time, in a 3 in-series, completely mixed reactor system.**

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
B1 0	5.9	188	174	46946	38912	61150	2052	56	44			126
1												
2	5.5	347	316	42238	36670	61560	4166	56	56			153
3												
4	5.6	420	361	40560	34804	60329	4658	800	889	278	89	2883
5												
6	5.8	512	456	42402	35776	65508	5686	1144	1089	278	178	3734
7												
8	5.8	549	448	41580	35030	56032	5974	1178	1167	278	89	3706
9												
10	5.9	574		40504	34118	59328	5789	1056	1178	278	178	3774
11												
12	5.9											
B3 30												
31	5.5	666	582	53618	46802	68813	6922	1556	1444	600	111	5158
32												
33												
34	5.5	756	638	57044	49236	75366	8806	1911	1956	711	400	7101
35												
36	5.5	773	683	59924	51622	78539	9828	1911	2133	822	489	7751
37												
38												
39	5.5	801	745	59750	51534	84707	10280	2000	2133	711	400	7463
40												
41												
42	5.6	739	610	60406	51984	79207	8865	1844	1889	600	400	6726
43												
44	5.5	801	706	56098	48924	71410	9685	1844	1844	622	400	6698
45												
46												
47												

Table C3: continued

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45Sum COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
84 48	5.4	655	594	51144	43684	65254	8208	1711	1667	600	333	6112
49												
50												
51												
52												
53												
54												
55												
56	5.5	622	554	43622	38572	58802	6703	1267	1244	400	111	4184
57												
58	5.5	622	510	44944	39714	57979	6661	1267	1289	378	111	4212
59	5.5	627	498	44350	38560	67026	6497	1267	1289	378	111	4212
60												
61												
62	5.4	571	470	48164	42202	60446	6374	1267	1289	333	111	4212
63	5.4	605	470	46228	40304	60858	6770	1267	1289	333	111	4212
64												
65	5.3	588	493	46716	40424	57379	6729	1267	1289	333	111	4212
66	5.3	554	510	47906	41980	56141	6109	1267	1289	400	111	4252
67												
68												
69	5.7	666	521	52342	45076	63571	6163	1267	1289	333	111	4212
70	5.7	538	487	47964		54595	6039	1267	1244	333	111	4062
71												
72	5.7	459	431	47624	41362	55009	6287	1267	1289	333	111	4212
73	5.7	521	431	48706	41772	64147	6086	1267	1289	333	111	4212
74												
75												
76	5.8	532	414				5716	1156	1267	356	111	4021
85 77	5.8	454	409	45676	40108	57568	5510					
78	5.8	448	403	47980	41920	67026	5428	1067	1089	333	111	3615
79	5.8	459	437	52222	46286	59685	5192					
80	5.8	487	454	46568	40948	51918	5233	1133	1111	311	89	3634
81												
82	5.8	420	392	46804	39080	57232	5069	933	1089	289	111	3392

Table C.4: **Results of the measured parameters of the third reactor, of 3 days retention time, in a 3 in-series, completely mixed reactor system.**

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
B1 0	5.9	188	174	46946	38912	61150	2052	56	44			126
1												
2	5.5	358	342	41104	36618	59918	4371	389	733	167	111	2052
3												
4	5.5	423	378	40898	35470	63612	4925	1144	1022	256	111	3456
5												
6	5.7	529	479	39936	34080	60152	6036	1244	1022	322	211	3886
7												
8	5.7	529	512	39960	34294	63036	6551	1244	967	322	211	3803
9												
10	5.7	560	504	40888	34838	58092	6139	1333	1111	389	211	4237
11												
12												
13	5.7	571	504	41290	35108	58204	6757	1333	1200	389	211	4372
83 30												
31	5.6	762	683	52160	45428	70861	7701	1733	1667	644	133	5809
32												
33												
34	5.5	780	689	53848	47230	69222	9502	2000	1933	822	289	7136
35												
36	5.4	778	700	59408	50588	78128	10157	2111	2156	867	289	7673
37												
38												
39	5.4	918	790	58778	50926	75250	11555	2200	2578	1156	289	8931
40												
41												
42	5.6	767	638	54954	47600	73872	10014	1956	2044	600	289	6854
43												
44	5.5	907	784	57168	49628	70178	10342	2067	2044	600	333	7062
45												
46												
47												
48	5.4	834	655	49772	43044	69358	9521	2000	2089	600	289	6969
49												

Table C4: continued

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l
84 50												
51												
52												
53												
54												
55												
56	5.5	683	521	43450	37262	58802	7114	1356	1356	400	111	4448
57												
58	5.4	638	504	43612	38312	56746	7607	1467	1356	378	111	4527
59	5.4	610	526	43328	37686	55923	7196	1467	1378	378	111	4560
60												
61												
62	5.3	633	560	52594	44654	62091	7278	1467	1378	378	111	4560
63	5.3	616	510	46132	40358	59213	7348	1467	1378	378	111	4560
64												
65	5.2	622	560	47246	40602	57792	7265	1467	1356	378	111	4527
66	5.3	571	526	44656	38200	59030	6522	1467	1356	378	111	4527
67												
68												
69	5.4	622	571	45822	39798	63984	6700	1467	1356	378	111	4527
70	5.6	566	510	48520		50459	6576	1467	1356	378	111	4527
71												
72	5.7	538	498	48860	42106	55009	6742	1467	1356	378	111	4527
73	5.7	560	465	44642	38468	55512	6497	1467	1333	378	111	4527
74												
75												
76	5.7	554	504				6250	1333	1422	400	111	4524
85 77	5.7	465	420	48044	41628	51400	6127					
78	5.7	515	482	45554	39666	59213	6045	1022	1222	311	111	3728
79	5.7	504	448	47596	41390	58050	5805	1222	1156	333	89	3837
80	5.8	515	493	45956	40526	60502	5805	1222	1156	400	89	3958
81												
82	5.7	495	432	44658	39080	58050	5560	1244	1133	311	89	3785

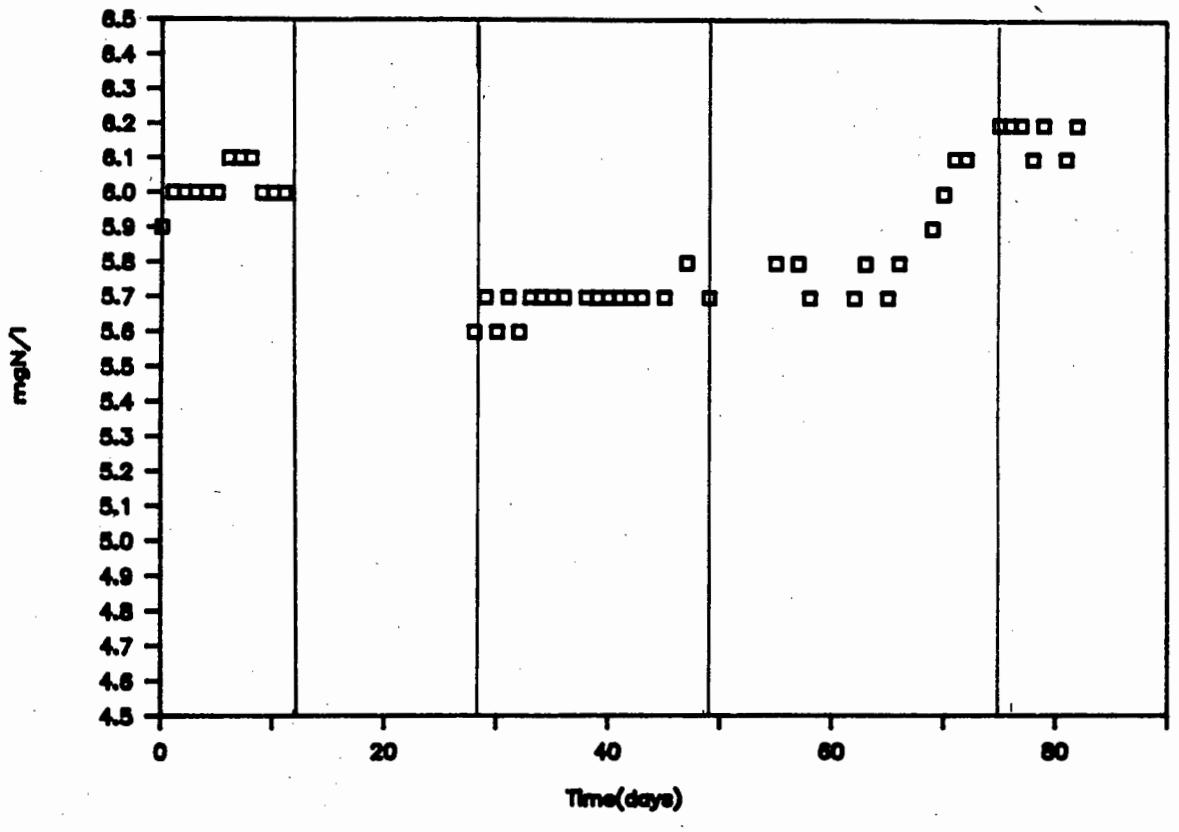

Fig C.1: Influent pH for all batches of raw sludge versus time.

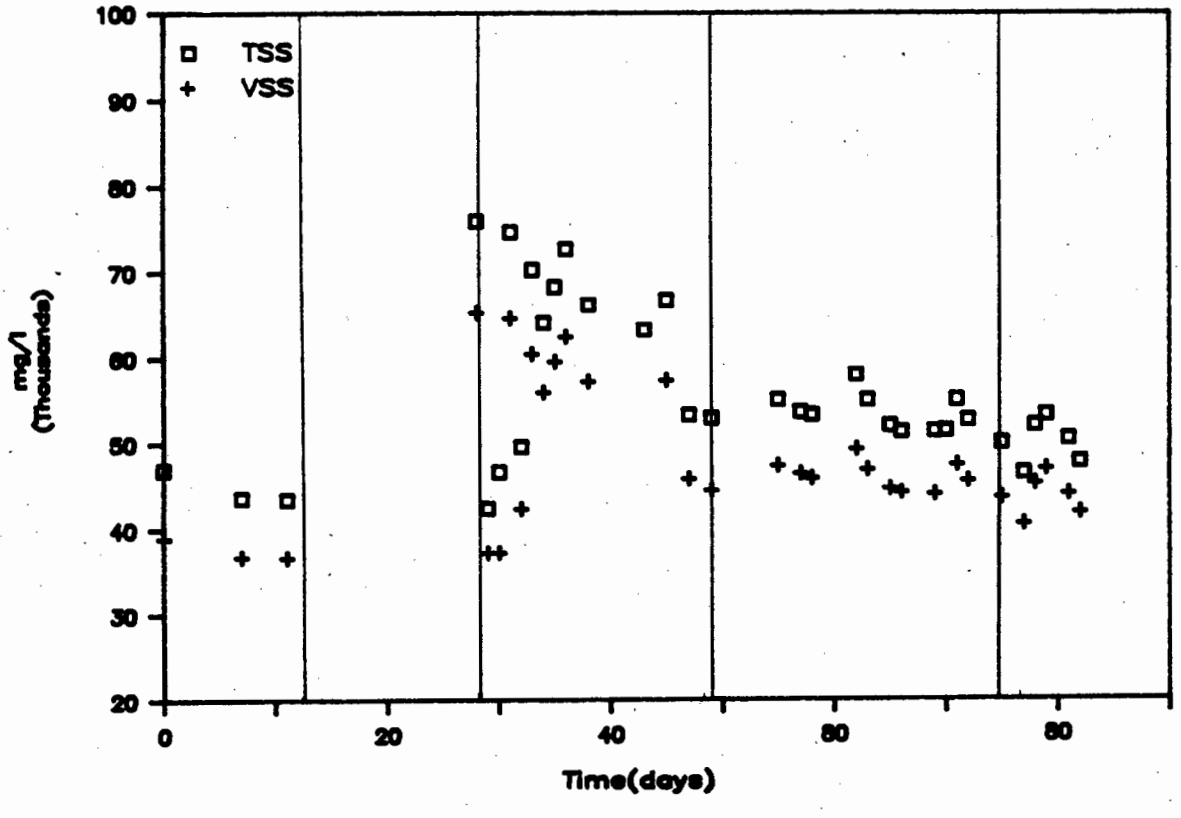

Fig C.2: Influent TSS and VSS concentrations for all batches of raw sludge versus time.

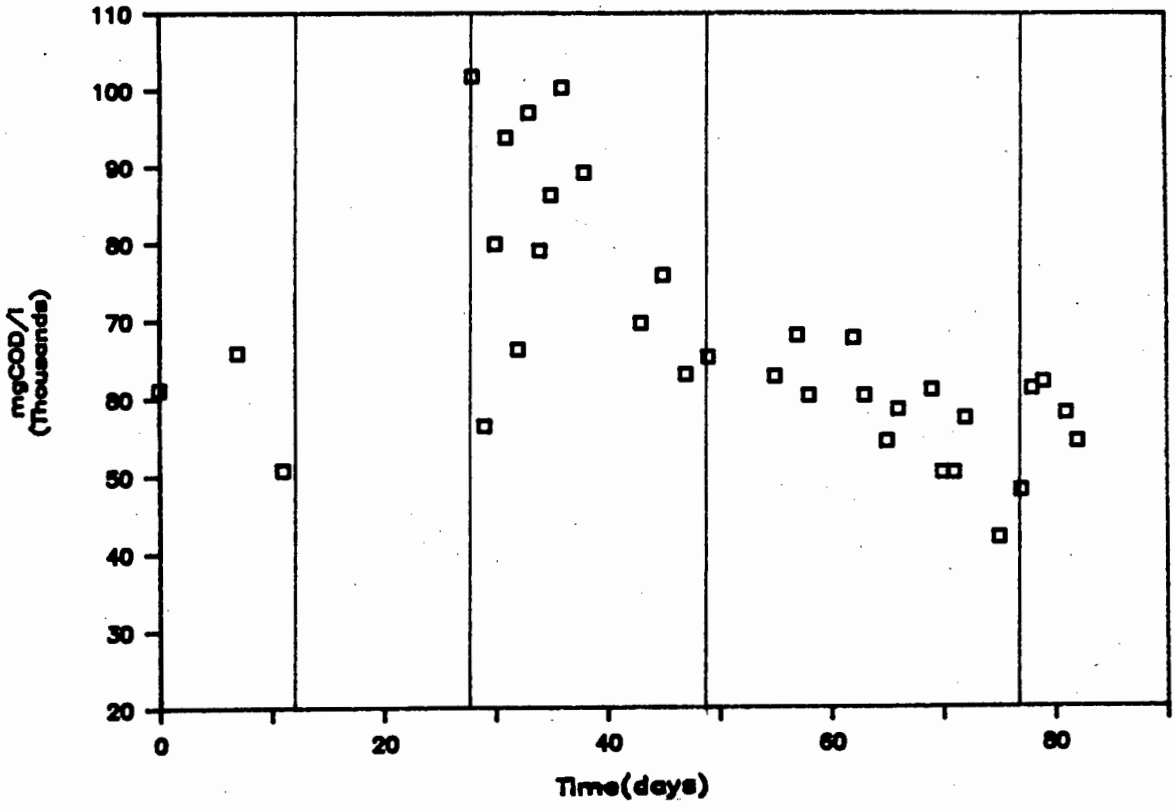

Fig C.3: Influent VSS (as COD) concentrations for all batches of raw sludge versus time.

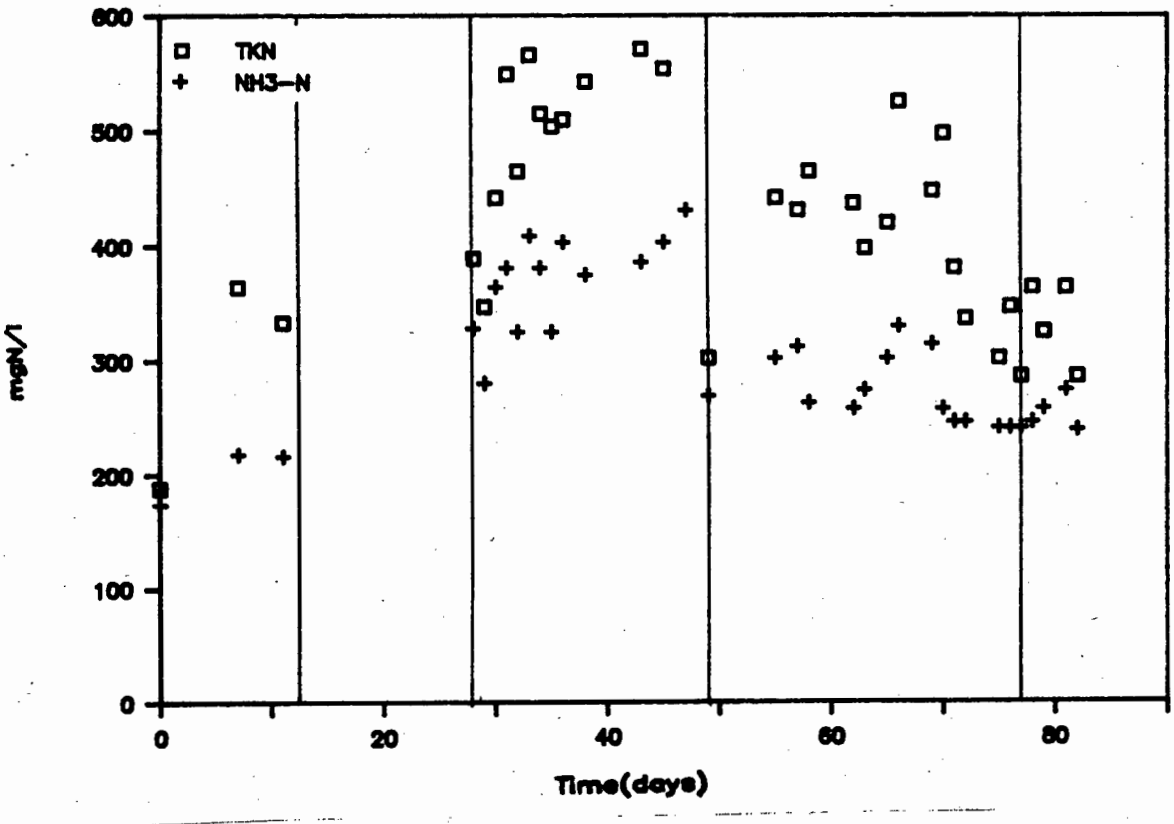

Fig C.4: Influent TKN and NH_3-N concentrations of the –0,45μm filtrate for all batches of raw sludge versus time.

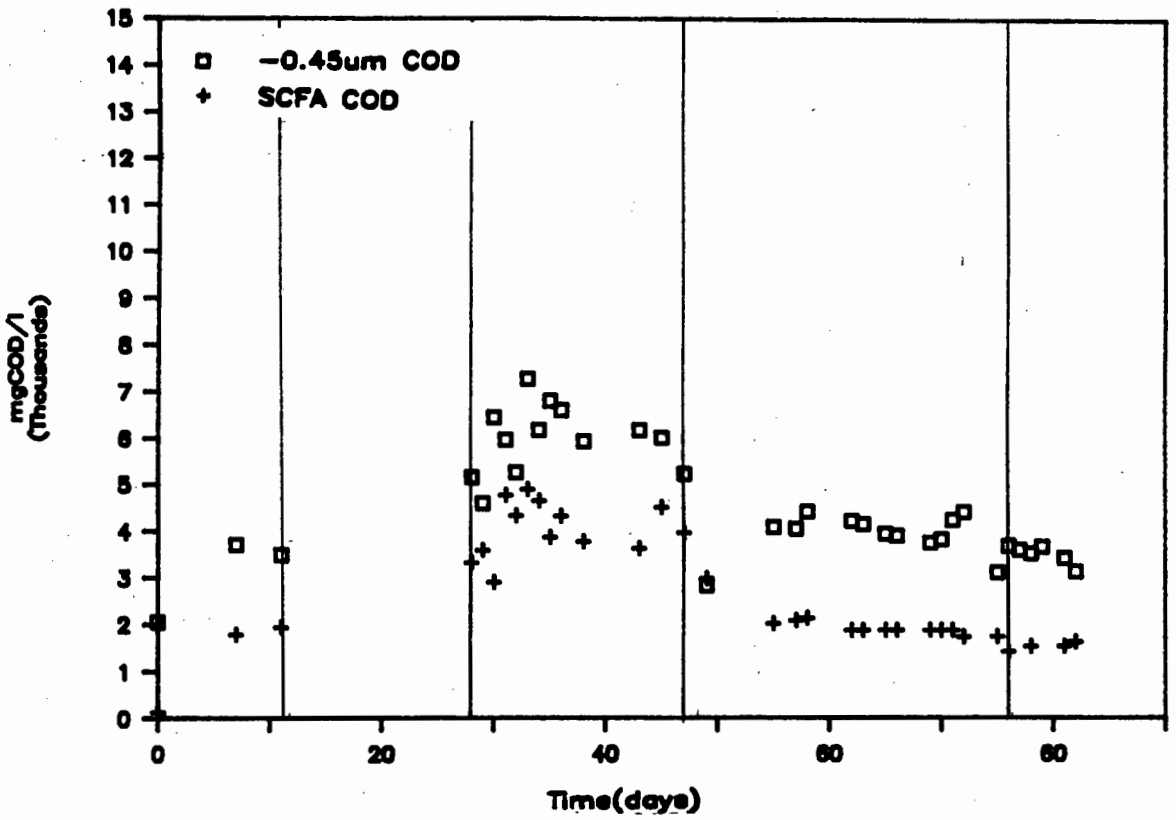

Fig C.5: Influent COD and total SCFA (COD) concentrations of the –0,45μm filtrate for all batches of raw sludge versus time.

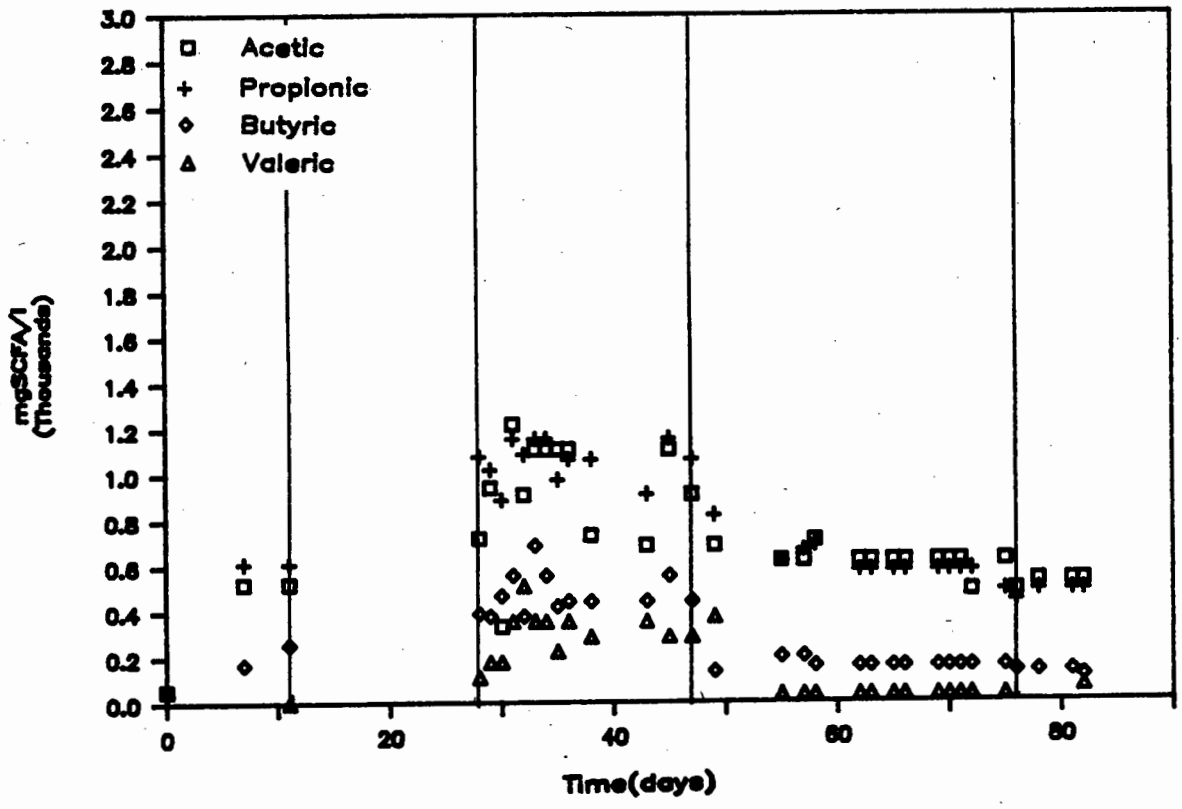

Fig C.6: Influent acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate for all batches of raw sludge versus time.

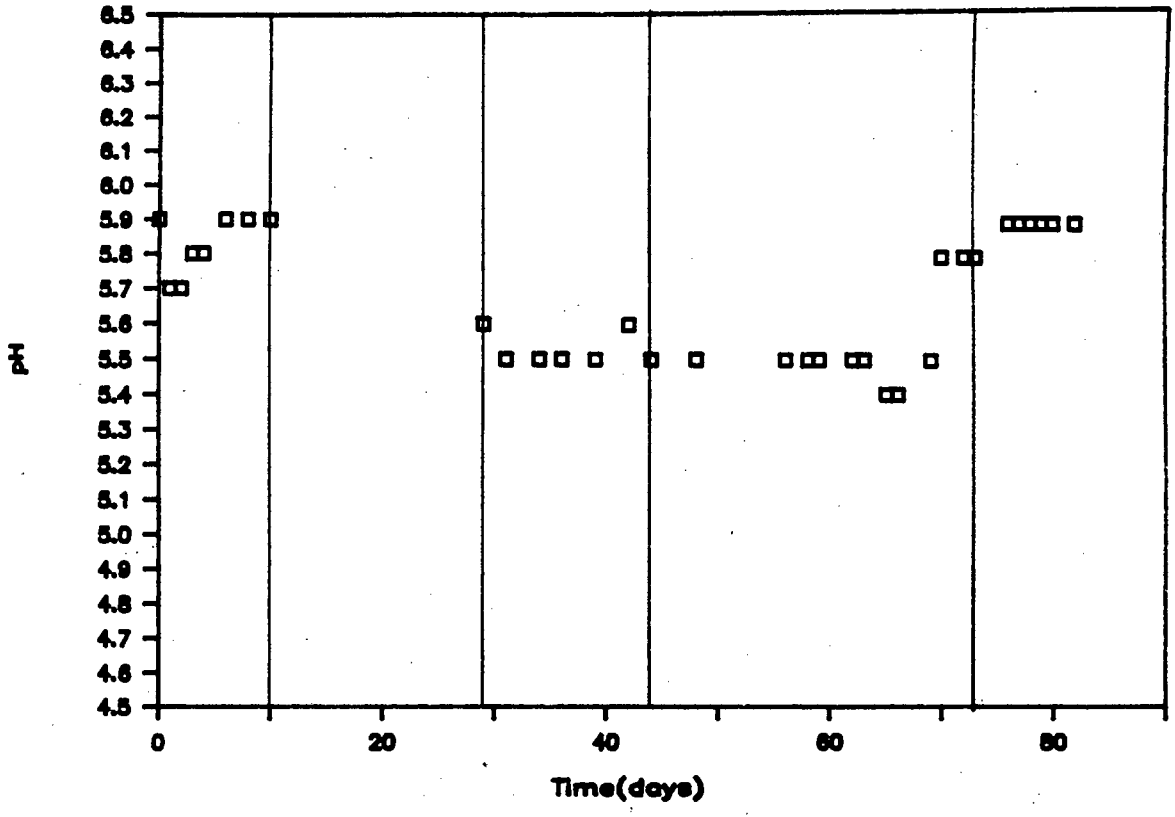

Fig C.7: pH of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 1 day versus time, for all sludge batches.

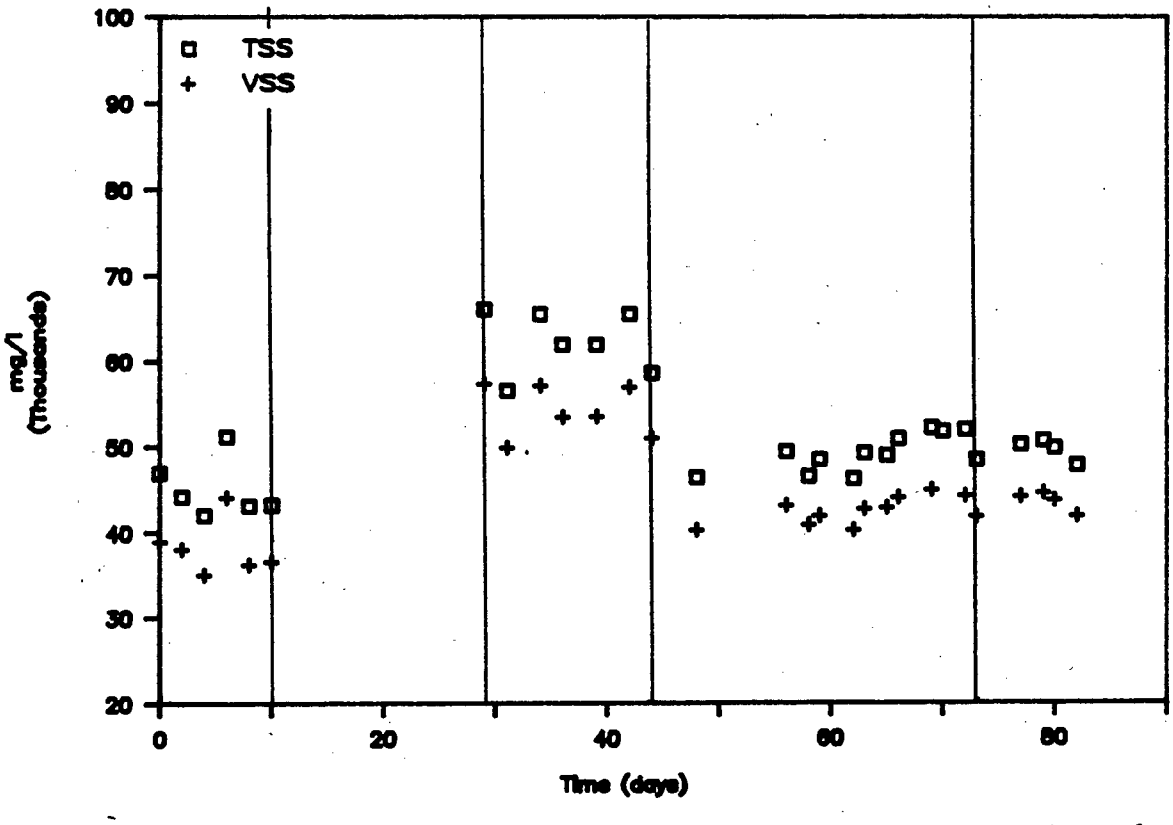

Fig C.8: TSS and VSS concentrations of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 1 day versus time, for all sludge batches.

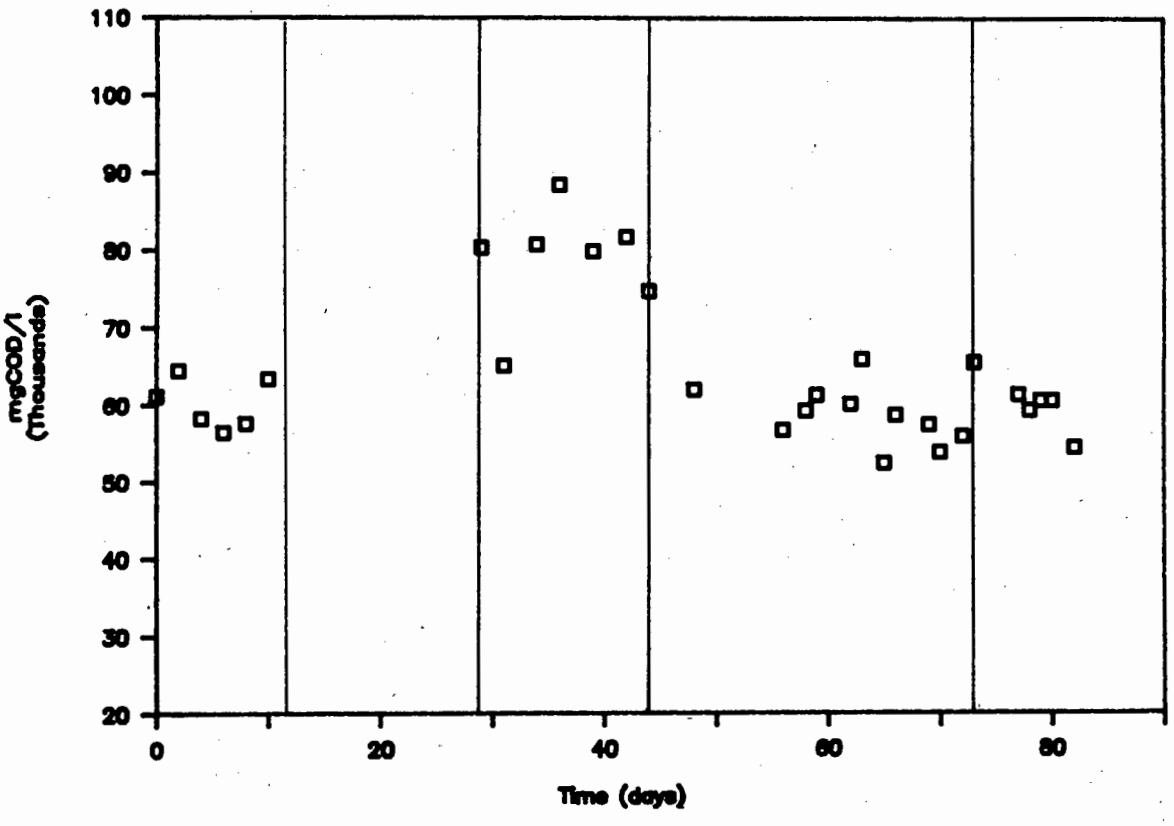

Fig C.9: COD of the VSS concentration of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 1 day versus time, for all sludge batches.

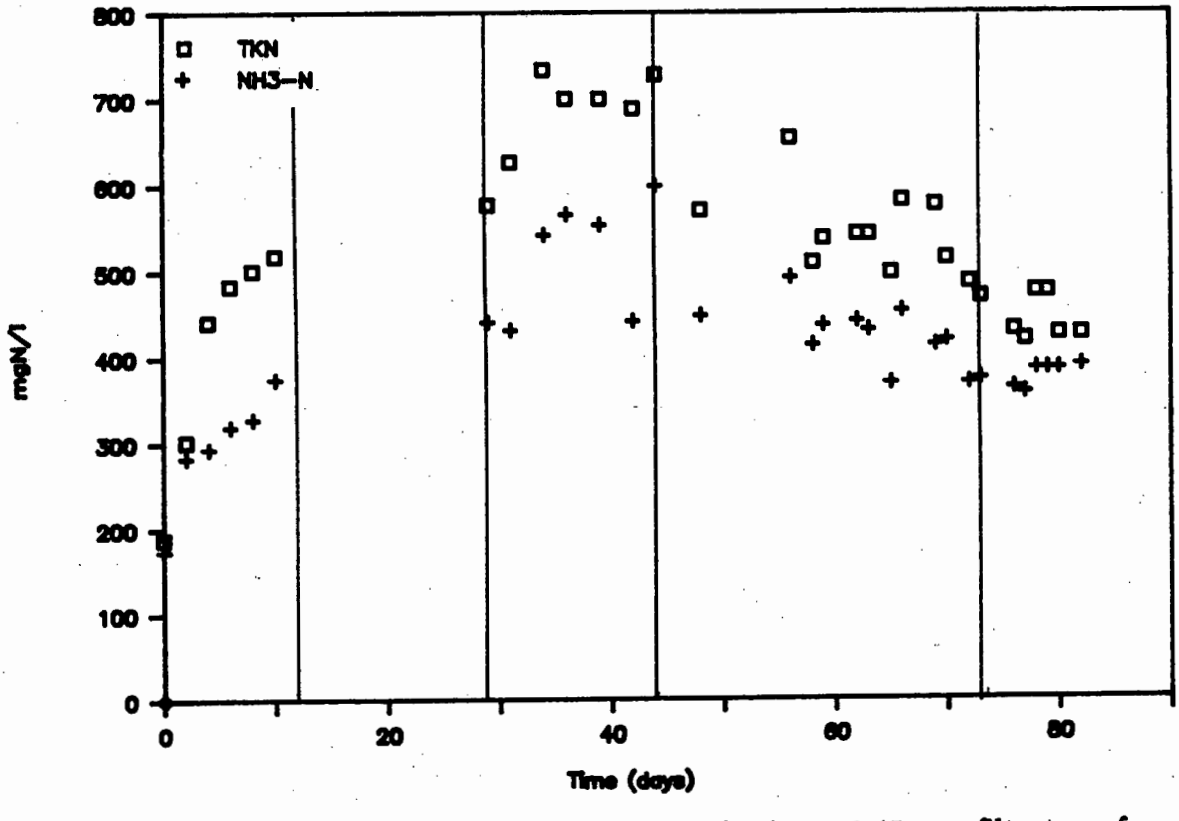

Fig C.10: TKN and NH_3-N concentrations of the $-0{,}45\mu m$ filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 1 day versus time, for all sludge batches.

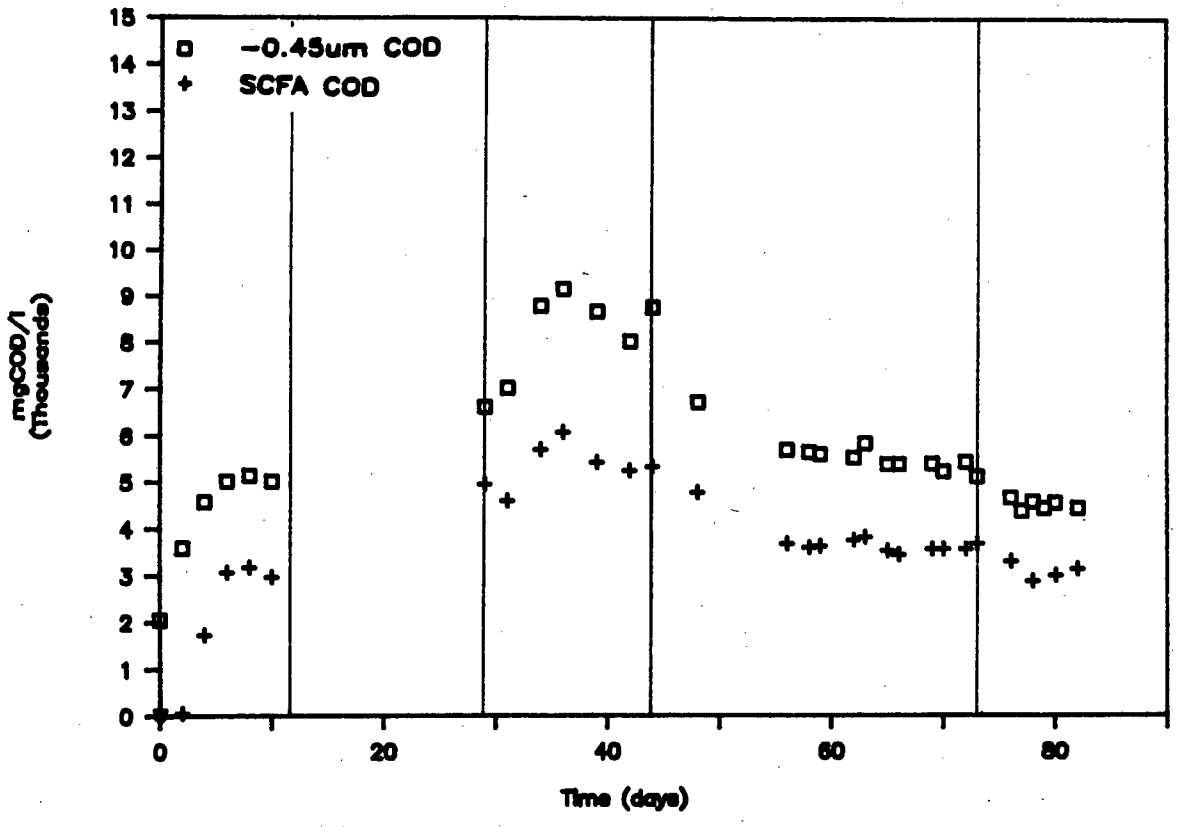

Fig C.11: COD and total SCFA COD concentrations of the −0,45μm filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 1 day versus time, for all sludge batches.

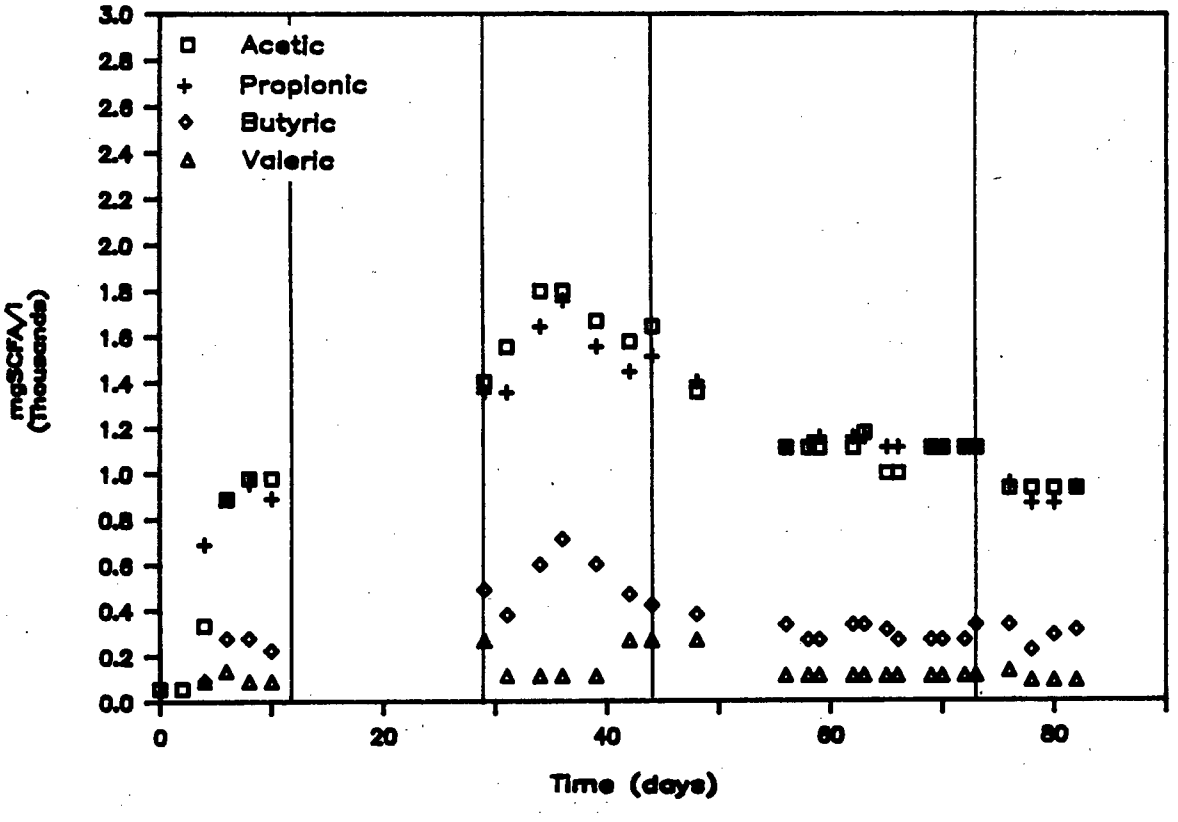

Fig C.12: Acetic, propionic, butyric and valeric acid concentrations of the −0,45μm filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 1 day versus time, for all sludge batches.

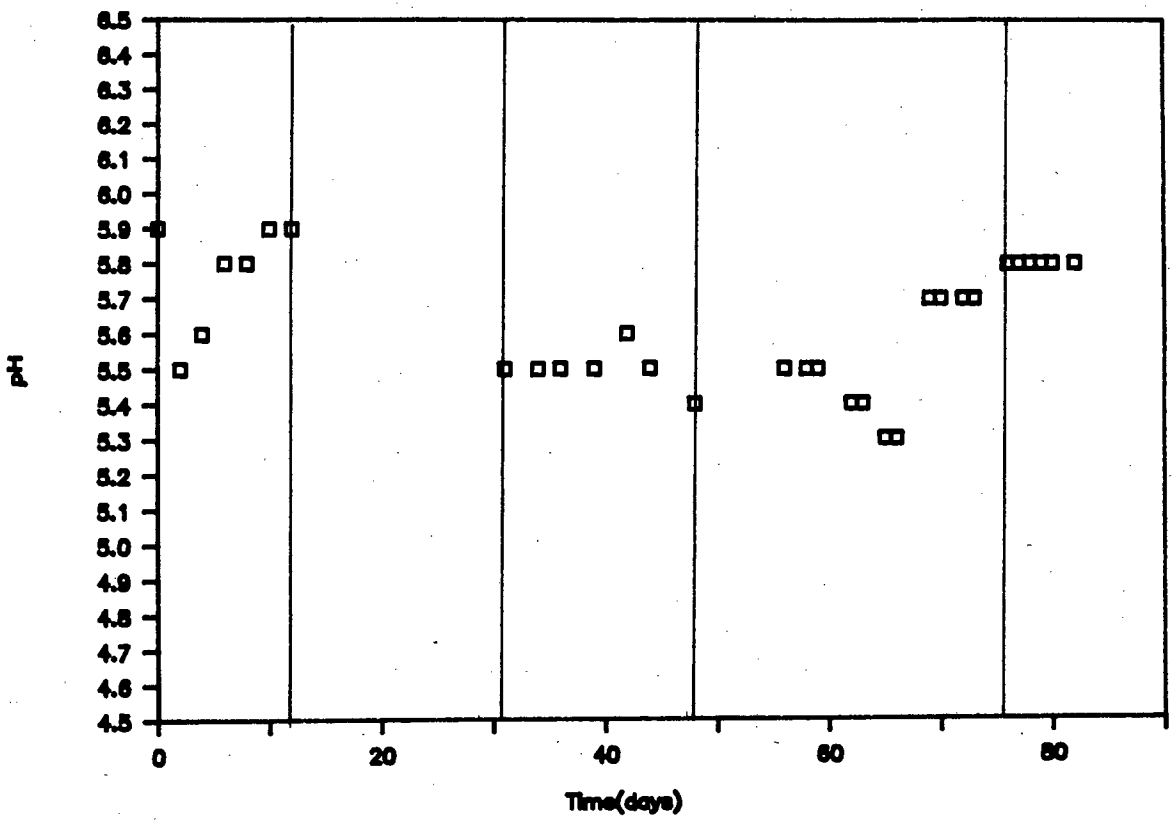

Fig C.13: pH of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 2 days versus time, for all sludge batches.

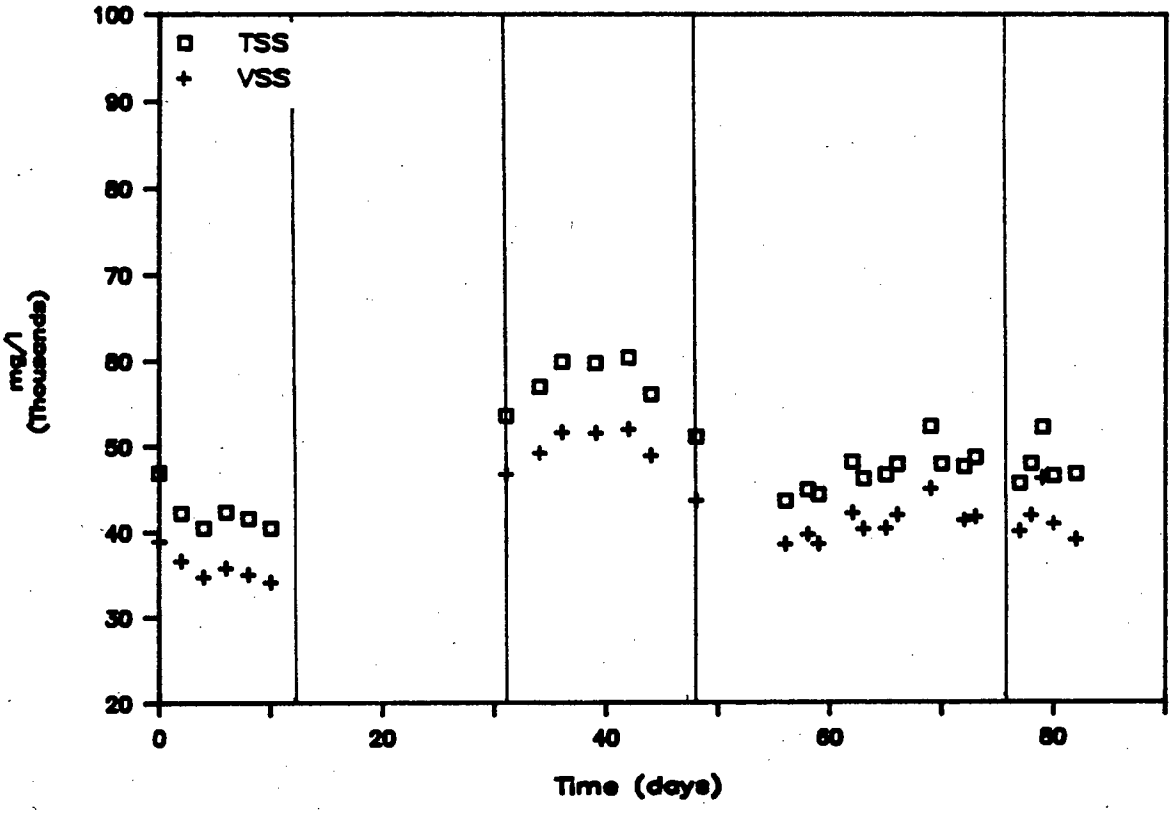

Fig C.14: TSS and VSS concentrations of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 2 days versus time, for all sludge batches.

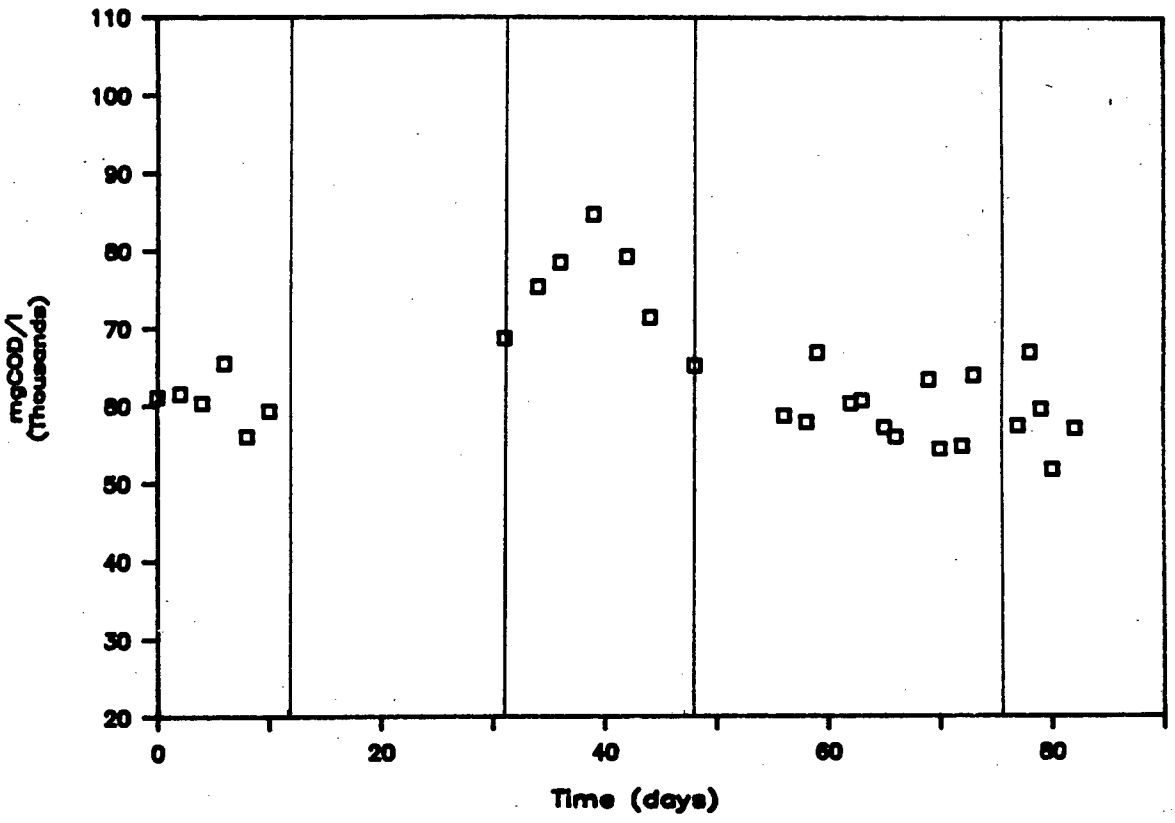

Fig C.15: COD of the VSS concentrations of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 2 days versus time, for all sludge batches.

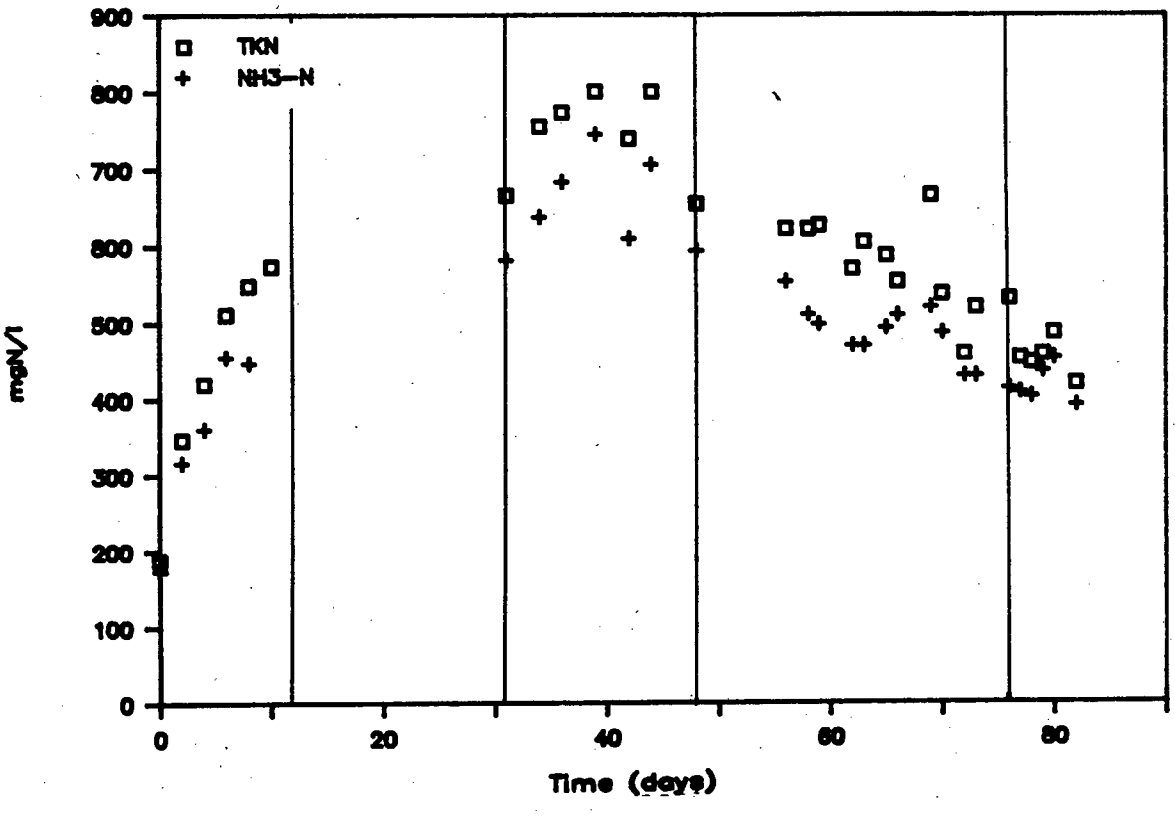

Fig C.16: TKN and NH_3-N concentration of the –0,45μm filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 2 days versus time, for all sludge batches.

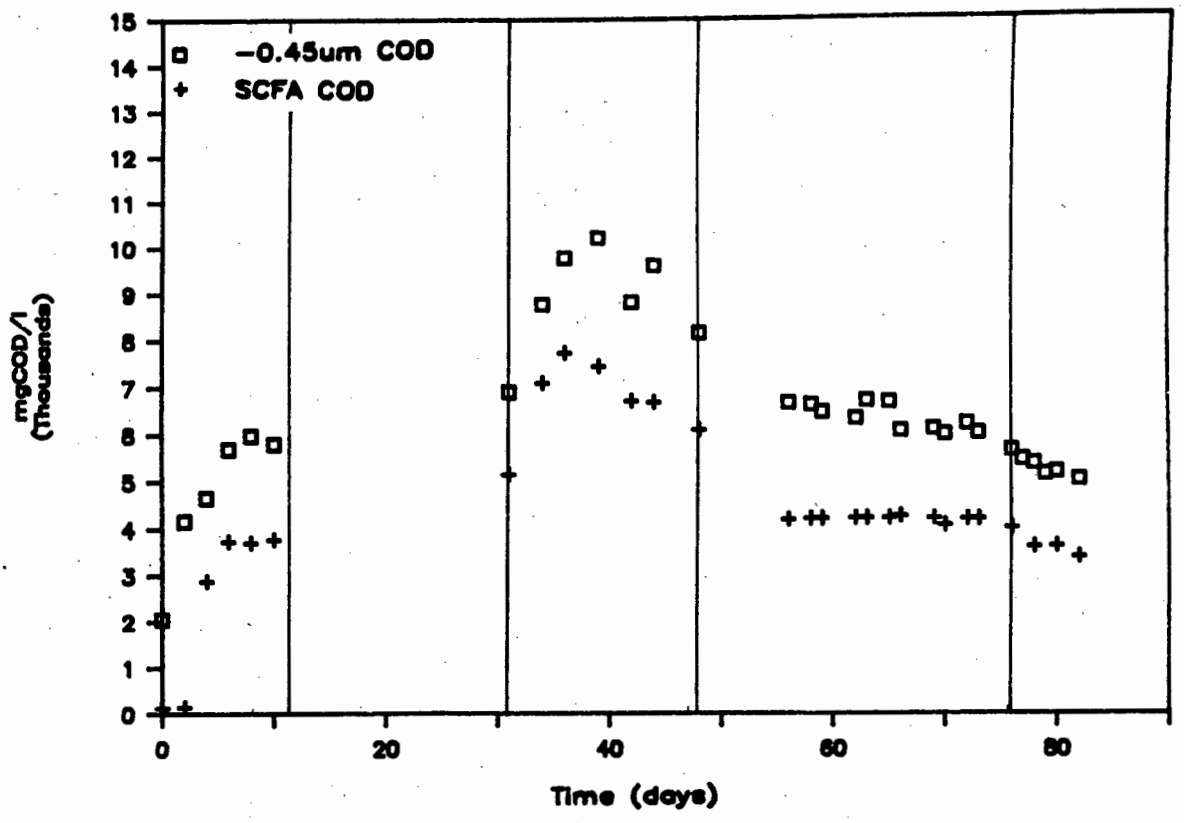

Fig C.17: COD and total SCFA COD concentrations of the −0,45μm filtrate of of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 2 days versus time, for all sludge batches.

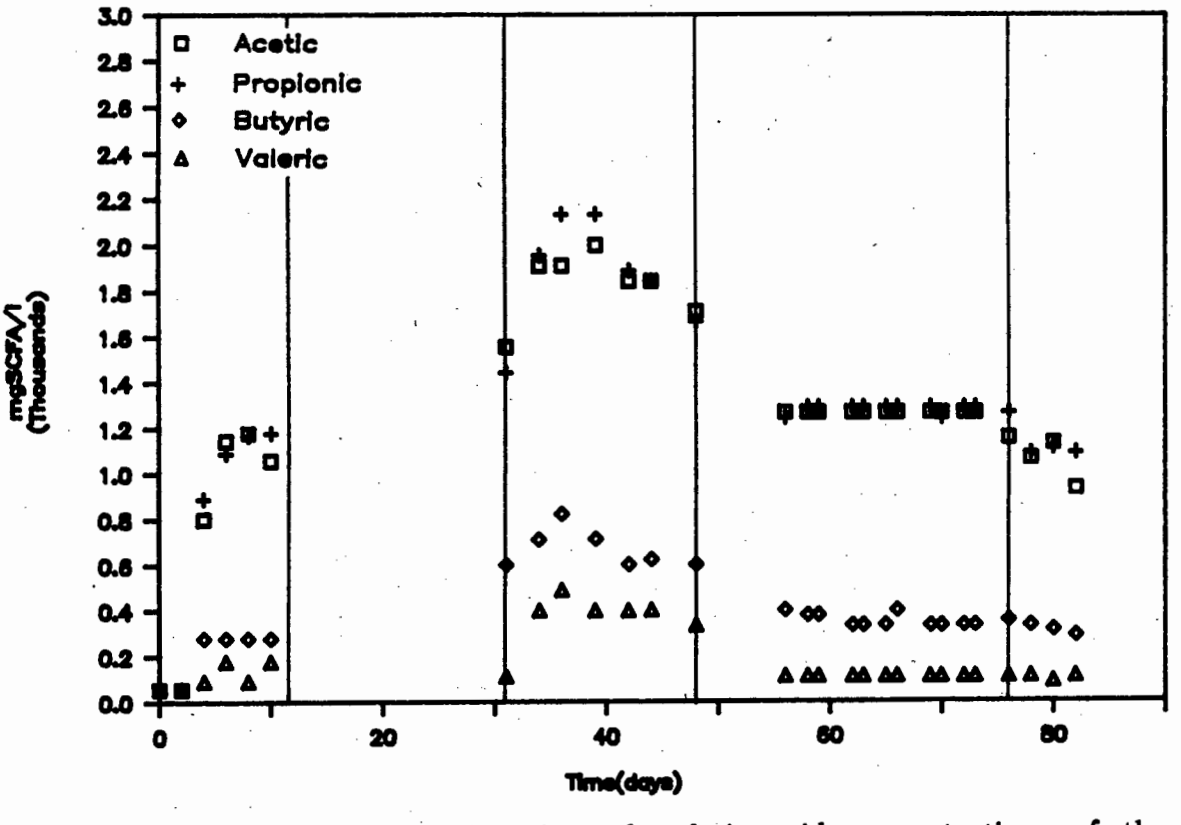

Fig C.18: Acetic, propionic, butyric and valeric acid concentrations of the −0,45μm filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 2 days versus time, for all sludge batches.

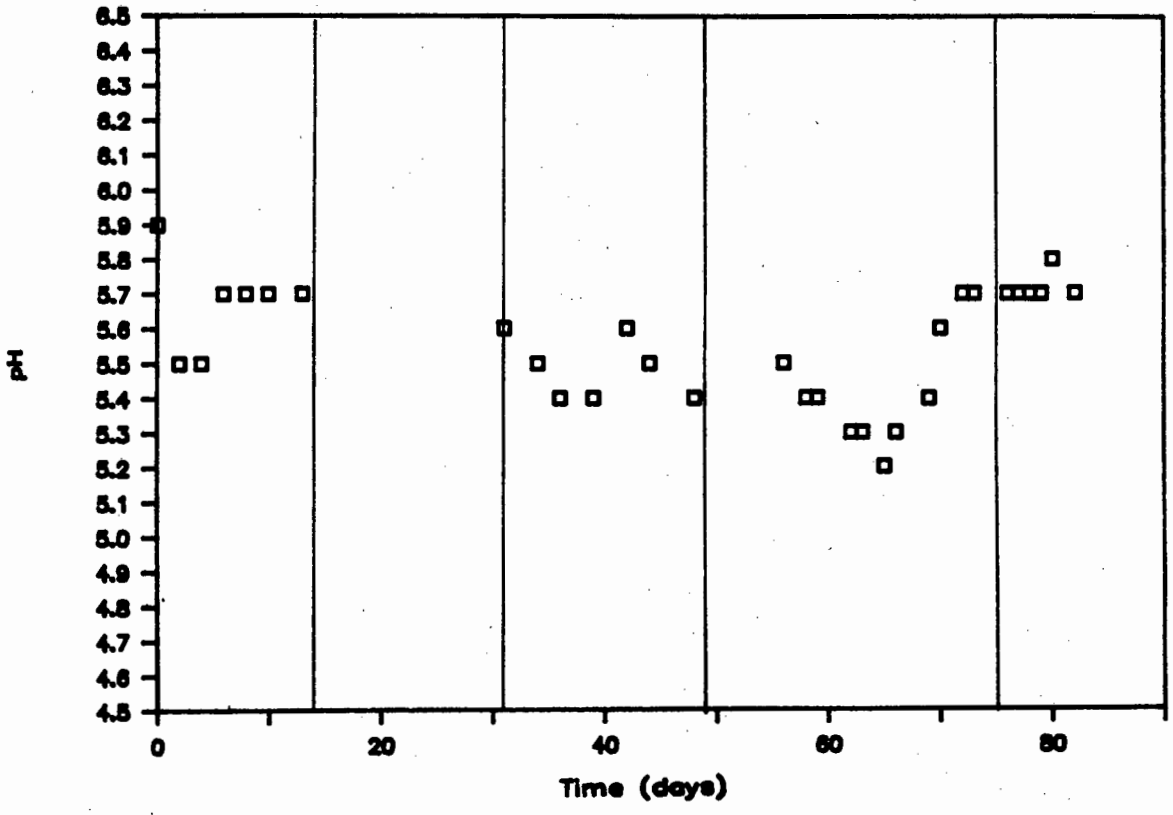

Fig C.19: pH of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 3 days versus time, for all sludge batches.

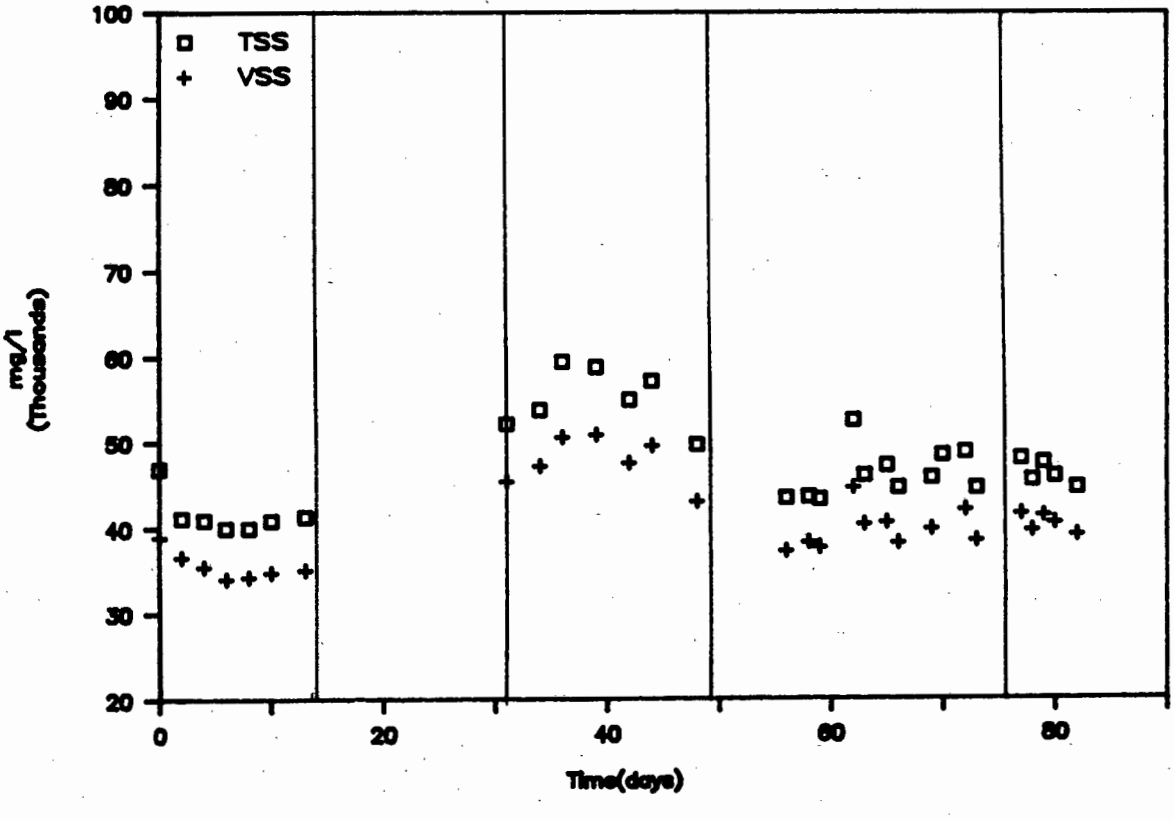

Fig C.20: TSS and VSS concentrations of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 3 days versus time, for all sludge batches.

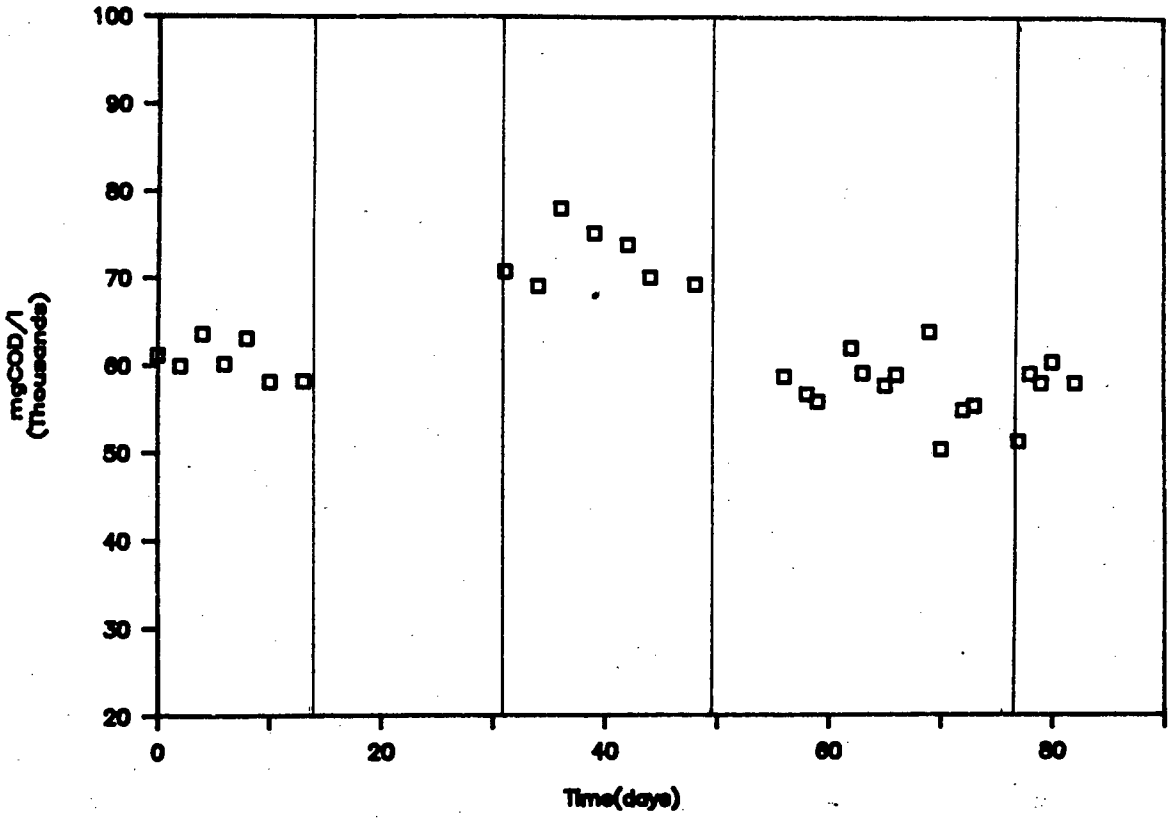

Fig C.21: COD of the VSS concentrations of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 3 days versus time, for all sludge batches.

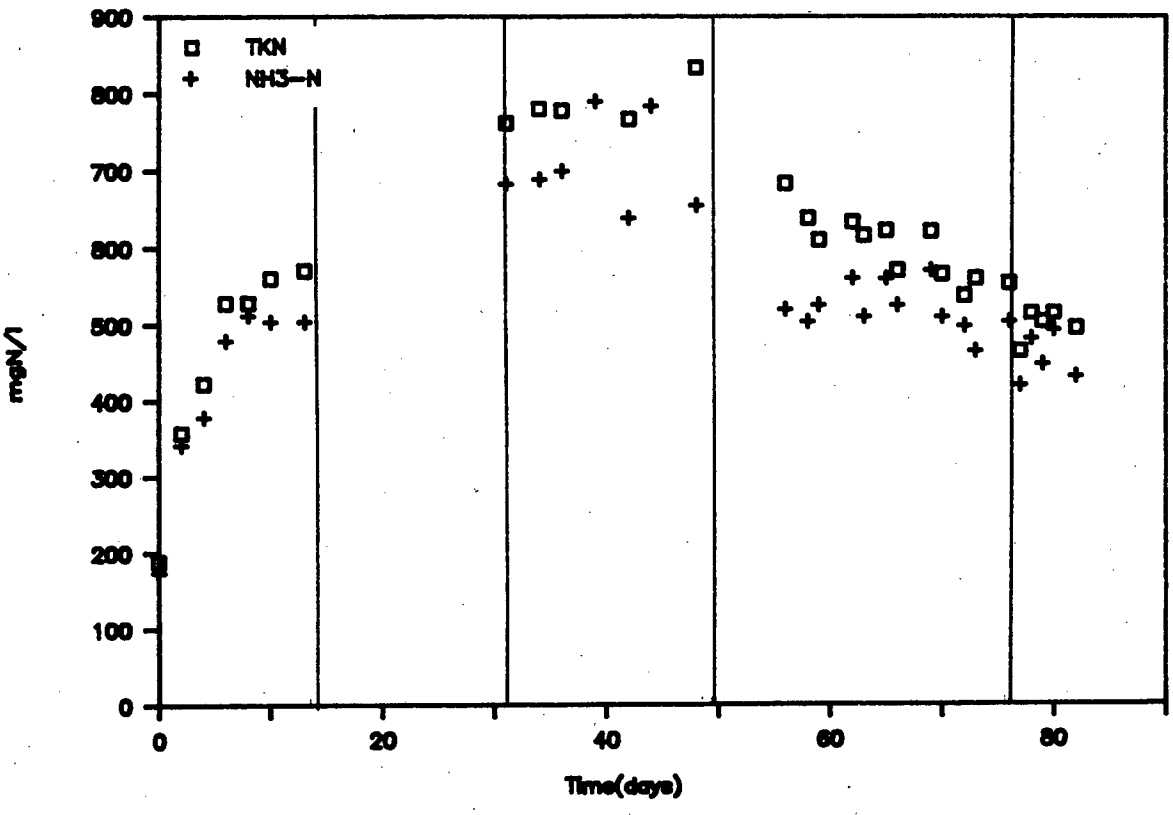

Fig C.22: TKN and NH_3-N concentrations of the –0,45μm filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 3 days versus time, for all sludge batches.

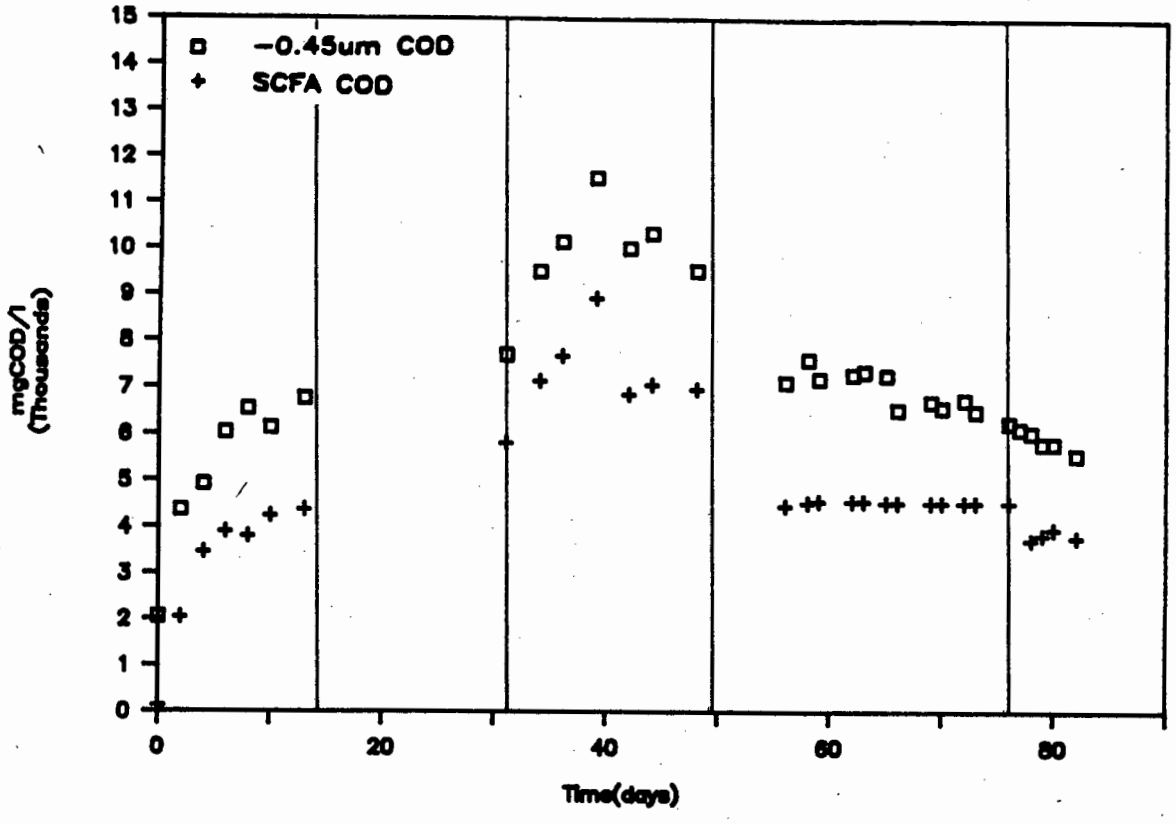

Fig C.23: COD and total SCFA COD concentrations of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 3 days versus time, for all sludge batches.

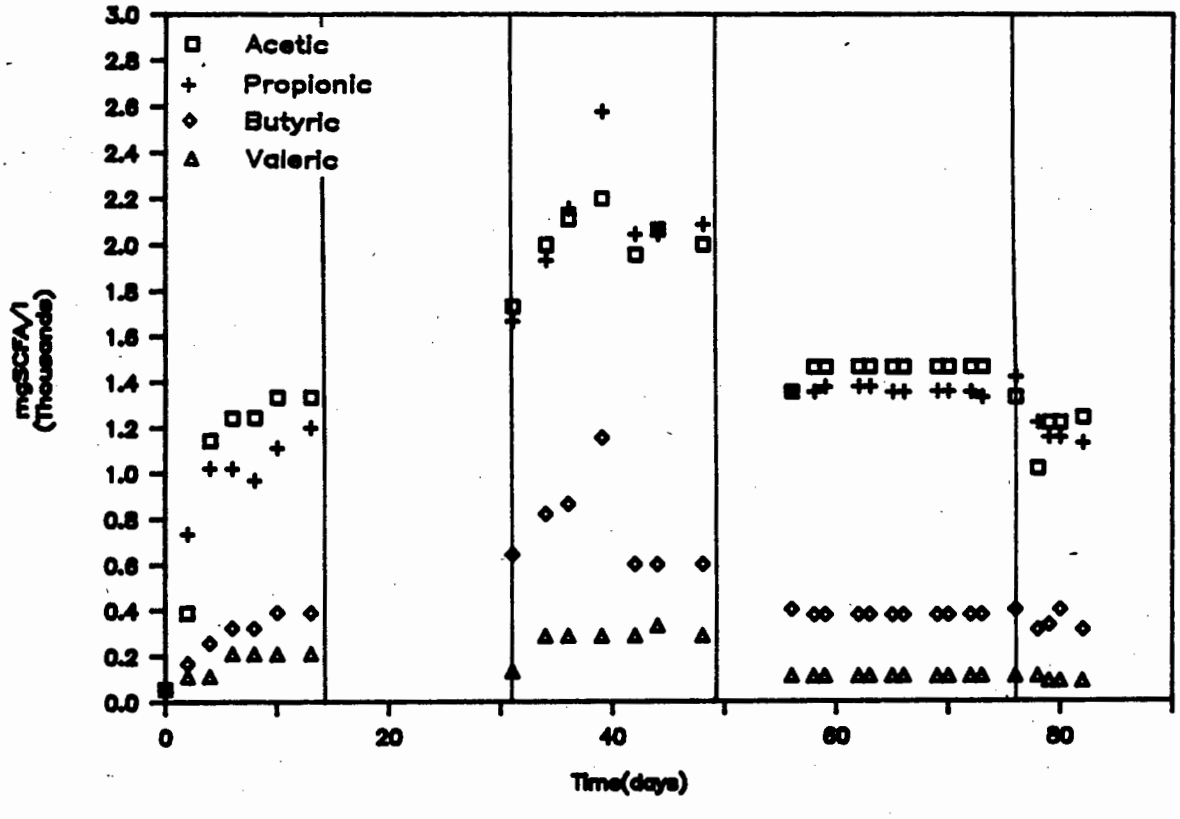

Fig C.24: Acetic, propionic, butyric and valeric acid concentrations of the −0,45μm filtrate of a completely mixed, semi-continuously fed, in-series reactor with a flow through retention time of 3 days versus time, for all sludge batches.

APPENDIX D

TABLES AND PLOTS OF THE RESULTS OF THE SINGLE, COMPLETELY MIXED REACTOR INVESTIGATION

Table D.1: **Results of measured parameters of the influent raw sludge in stage 1 of the single, completely mixed reactor system.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"SOLUBLE" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B1 0	5.7	235	148	43562	38754	56052	4048	3529	700	844	500	278	3497	
2	5.7	218	174	44516	39696	54806	4380	3944	700	828	600	278	3653	
4	5.6	272	168	47822	42514	59374	4526	3944	722	844	600	278	3702	
6	5.6	252	162	45832	40560	58752	4202	3754	722	844	600	278	3702	
8	5.6	274	174	46610	41376	56304	4406	3917	667	800	556	278	3495	58.6
10	5.6	246	185	44678	39672	54672	4243	3652	633	656	278	222	2624	60.2
12	5.6	272	179	44716	39794	56083	4186	3800	633	689	289	222	2691	60.7
14	5.6	263	182	44010	38970	60960	3968	3475	622	656	289	200	2587	53.2
16	5.6	260	151	43232	38158	58115	4064	3759	589	656	278	222	2577	62.8
B2 18	5.9	350	218	39750	34654	55270	4552	4409	589	578	456	333	3008	
20	5.7	336	224	44298	38711	62992	4552	4267	533	578	456	333	2948	
22	5.7	372	221	47602	43978	64433	4843	4412	567	578	456	278	2871	
24	5.9	361	185	48222	42050	61150	4843	4494	533	578	456	278	2835	63.0
26	6.1	344	196			57866	4802	4350	444	533	489	311	2802	
28	5.9	381	202	49118	42754	58687	4884	4617	467	533	489	311	2825	59.8
30	6.2	400	221	50894	44142	58521	4592	4267	467	533	489	311	2825	61.5
32	5.9	384	216	46802	40936	62586	4430	4308	478	533	489	311	2837	61.7
B3 34	5.9	274	188	38862	34738	52624	3927	3663	622	611	444	278	2960	
36	5.9	342	199	38676	34546	53434	3846	3621	644	556	444	278	2900	
38	5.9	286	202	39486	35306	41779	3850	3666	644	656	444	278	3051	
40	6.1	272	174	39894	35832	46285	4014	3707	644	611	444	278	2983	
42	6.2	294	174	42246	37962	53248	3850	3604	644	656	389	278	2951	56.8
44	6.1	277	176	39778	35452	46552	4007	3603	556	611	433	200	2710	58.7
46	6.1	286	190	42322	37692	51005	4169	3623	578	611	433	200	2734	64.0
48	6.1	300	190	43386	39000	50592	4529	3733	556	600	333	167	2445	57.6

Table D.2: Results of measured parameters of a single, completely mixed reactor of 2 days retention time, for all batches of sludge in stage 1.

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"SOLUBLE" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B1 0	5.4	263	227	42936	38626	55222	7619	4567	1133	1300	389	278	4446	
2	5.4	319	263	39282	35404	52730	9134	5169	1156	1267	456	333	4653	
4	5.3	356	302	41196	36614	53976	9965	5813	1033	1333	467	422	4825	
6	5.4	356	297	39208	35022	52224	9833	5630	1089	1244	422	389	4601	
8	5.4	389	308	42514	38056	55896	9180	5569	1111	1222	422	456	4727	59.3
10	5.4	389	294	40000	35424	52224	9670	5630	1144	1367	478	422	5014	62.1
12	5.3	347	319	40506	35936	51206	10119	5832	1100	1311	367	333	4500	53.5
14	5.3	378	302	39690	35472	52832	9916	5710	1200	1456	478	389	5141	57.8
16	5.3	372	316	39522	35100	52426	9794	5547	1178	1444	444	400	5060	53.3
B2 18	5.3	400	372	40894	34986	49174	10079	6015	1100	1267	411	389	4627	
20	5.4	420	339	42011	36841	56083	10282	5974	1100	1300	456	422	4826	
22	5.3	420	358	40546	39356	50479	10137	5992	1122	1267	433	400	4713	
24	5.1	448	372	42560	37492	54583	10137	6423	1178	1378	511	433	5150	63.4
26	5.2	451	378			55404	10342	6279	1244	1267	311	289	5395	
28	5.2	451	353	40020	34798	55814	10301	6341	1278	1300	333	289	4522	59.7
30	5.0	437	372	41696	36208	54051	9672	6116	1278	1211	333	278	4364	65.4
32	5.0	448	392	38564	34082	51206	9672	6035	1278	1267	356	278	4489	58.3
B3 34	5.5	364	294	39686	35124	49386	8096	5546	1244	1356	533	344	5045	
36	5.5	344	294	36236	32648	49957	8541	5485	1167	1322	478	344	4812	
38	5.5	344	305	37636	33704	40550	8110	5366	1189	1400	422	344	4851	
40	5.5	378	302	38288	34374	38502	8069	5693	1133	1378	444	344	4798	
42	5.6	353	291	37718	34092	42598	8561	5591	1167	1356	422	344	4761	50.6
44	5.6	344	294	35222	31416	45338	7934	5040	1100	1244	344	322	4334	61.9
46	5.5	322	274	38458	34246	44123	8351	5121	1056	1300	389	356	4522	58.4
48	5.5	344	300	39876	35786	40392	8282	5263	1167	1400	389	333	4746	55.2

Table D.3: **Results of measured parameters of a single, completely mixed reactor of 3 days retention time, for all batches of sludge in stage 1.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"SOLUBLE" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B1 1	5.3	298	259	39178	35472	59374	8740	5232	1311	1378	422	389	5040	
3	5.3	344	294	41142	37116	66017	10421	5875	1311	1333	422	356	4905	
5	5.2	417	358	40208	36092	62016	10608	6263	1311	1533	500	456	5552	
7	5.3	384	308	41876	37384	57936	10037	5630	1278	1433	389	444	5141	
9	5.2	358	314	41810	37198	51816	10037	5794	1278	1444	422	456	5241	
11	5.2	347	302	41462	36942	58522	10404	6035	1278	1656	444	422	5241	60.3
13	5.1	347	314	40302	35966	54458	10119	5791	1256	1489	422	344	5057	57.6
15	5.2	344	314	39516	34968	53238	10526	5730	1256	1467	422	344	5024	55.0
17	5.3	356	328	41726	37280	52832	10566	5852	1244	1278	422	389	4818	55.7
B2 19	5.2	395	356	36390	32092	54864	9916	5933	1244	1344	456	422	5047	
21	5.2	414	344	46276	40972	59334	9754	6035	1300	1378	422	456	5164	
23	5.2	417	364	43720	38446	63202	9932	6505	1322	1400	467	522	5438	
25	5.0	431	364	42752	37066	65664	10213	6649	1433	1389	422	344	5096	
27	5.1	437	367	43030	36728	58928	9347	6299	1433	1389	422	344	5096	62.9
29	5.0	428	395	41114	36224	55679	9916	6299	1433	1378	433	344	5100	58.7
31	5.0	445	400	41574	36636		10160	6679	1433	1278	367	344	4827	59.6
33	5.5	386	328	38760	34666	54243	8784	5910	1433	1322	444	344	5034	61.6
B3 35	5.5	314	297	37486	35132	47766	8582	5343	1333	1322	511	344	5049	
37	5.4	347	319	36752	33306	49971	8847	5775	1411	1356	478	344	5123	
39	5.5	344	311	37518	33280	51610	9216	5325	1333	1400	533	388	5296	
41	5.4	328	294	35876	32756	48576	8420	5505	1333	1344	444	344	4960	
43	5.4	319	260	34892	31792	51814	9189	5424	1333	1256	367	389	4780	
45	5.4	319	277	35602	32152	43718	8298	5141	1356	1222	367	267	4505	
47	5.5	330	284	38542	34674	51000	8813	5304	1300	1267	367	389	4760	
49	5.4	322	300	36972	32902	51000	8894	5304	1267	1400	444	333	4953	

Table D.4: **Results of measured parameters of a single, completely mixed reactor of 5 days retention time, for all batches of sludge in stage 1.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"SOLUBLE" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B1 1	5.3	277	267	40034	36078	57713	9155	5398	1356	1511	467	367	5324	
3	5.2	350	322	41104	36720	57713	11916	6560	1467	1700	478	389	5794	
5	5.2	350	342	37450	33666	53040	11383	6671	1467	1711	478	389	5810	
7	5.2	375	336	40094	35584	54672	12076	6814	1444	1700	478	389	5770	
9	5.2	350	311	37936	34120	53040	11872	6956	1433	1667	478	378	5685	58.6
11	5.2	378	300	38054	34076	51613	11542	6726	1611	1822	478	389	6133	54.3
13	5.3	381	330	39252	34848	52426	12192	7092	1544	1789	467	389	5991	51.2
15	5.1	389	328	40016	35820	52832	12151	6807	1544	1767	478	389	5978	59.6
17	5.1	361	339	38342	34280	52832	11379	6685	1422	1633	422	456	5680	63.8
B2 19	5.1	409	336	38628	33724	53238	12192	6893	1422	1556	444	456	5603	
21	5.3	420	372	43362	38212	58928	12233	7214	1567	1600	456	456	5845	
23	5.3	426	372	41738	34484	65254	11943	7346	1633	1700	489	456	6127	
25	5.3	414	372	41540	36180	61650	11245	7182	1744	1544	422	400	5776	
27	5.3	462	389	40590	35486	56896	10973	7376	1744	1522	444	444	5874	
29	5.3	456	392	38934	33996	58115	11623	7193	1677	1500	444	400	5667	
31	5.3	456	356	41560	35922		12104	7064	1744	1622	533	489	6277	
33	5.4	403	330	38028	33236	55053	11213	6821	1522	1700	700	578	6709	
B3 35	5.4	389	342	33712	30390	43718	11537	6720	1511	1733	700	611	6747	
37	5.4	372	333	33088	29256	45875	11305	7004	1489	1700	667	544	6477	
39	5.4	358	311	34470	30644	43418	11674	6636	1444	1656	644	578	6390	
41	5.4	381	314	32388	29512	40480	10120	6112	1444	1656	667	578	6432	55.3
43	5.5	342	300	30684	27988	38861	10565	6214	1422	1456	500	444	5531	59.8
45	5.4	336	322	34874	31250	42909	9553	6052	1400	1400	456	356	5164	53.6
47	5.4	378	319	34720		42480	9874	6038	1378	1400	456	356	5140	57.3
49	5.4	367	336	35956	31932	46512	10200	6202	1466	1611	556	422	5869	57.0

Table D.5: **Results of measured parameters of the influent raw sludge in stage 2 of the single, completely mixed reactor system.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"Soluble" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B4 0	5.9	238	202	43346	38266	46330	2967	2601	656	733	167	67	2246	
2	6.0	288	207	39968	35124	51000	3835	3325	600	667	189	67	2126	
4	6.1	283	188	42052	37048	48960	4447	3713	600	678	222	89	2249	
6	6.1	171	81	43312	37856	46920	4488	3448	600	622	200	67	2079	
8	6.3	291	196	41210	36342	53040	4243	3794	567	633	211	100	2149	
10	6.2	283	188	45922	40228	57120	4284	3815	600	611	244	122	2257	
12	6.1	311	190	41648	36504	52224	3876	3754	600	700	222	100	2305	57.6
14	6.2	288	185	40466	35590	52632	4284	3733	589	667	200	111	2226	64.3
16	6.1	286	193	39282	34650	47736	3912	3672	589	644	222	111	2233	63.6
18	6.1	300	185	38878	33942	52632	4039	3754	589	667	211	111	2246	64.3
20	6.1	297	193	41554	36422	43656	3835	3754	589	644	222	111	2233	60.2
22														
24														
B5 26	6.0	333	213	73632	63388	70584	4896	4774	600	678	244	56	2221	
28														
30														
32	5.9	384	210	61888	53638	65126	5530	4977	600	644	267	78	2257	
34														
36														
38	6.0	381	322	73704	63612	82739	6513	5386	644	578	267	100	2249	45.2
40	6.0	370	204	65384	55864	64717	5407	4915	644	667	278	122	2448	52.3
42	6.0	364	196	61464	52930	67728	6161	5365	700	733	244	122	2548	55.6
44	6.1	448	224	60600	51712	70584	6079	5345	500	600	211	67	1959	57.6
46	6.1	417	241	63738	55226	69626	6396	5303	578	667	256	89	2269	57.3
48	6.1	406	224	61208	52408	68806	6963	5728	633	678	244	89	2325	56.0
50	6.1	400	227	58190	49904	65966	6271	5579	611	667	256	89	2305	67.4

Table D.6: **Results of measured parameters of a single, completely mixed reactor of 3 days retention time, for all batches of sludge in stage 2.**

DAY	pH	TKN mgN/l	NH3-N mgN/l	TSS mgTSS/l	VSS mgVSS/l	VSS as COD mgCOD/l	"Soluble" COD mgCOD/l	-0.45um COD mgCOD/l	Acetic acid mg/l	Propionic acid mg/l	Butyric acid mg/l	Valeric acid mg/l	SCFA as COD mgCOD/l	DSVI g/l
B4 0	5.3	386	328	45482	40136	54051	10688	6828	1711	1722	522	456	6304	
2	5.3	339	291	39328	34480	51408	9547	5896	1544	1467	389	333	5249	
4	5.4	294	269	38240	33848	42840	9670	5386	1467	1278	389	322	4858	
6	5.4	182	146	37976	33094	43248	12240	5630	1522	1278	389	356	4985	
8	5.4	319	291	35876	31898	47328	9302	5569	1522	1300	444	344	5098	
10	5.4	319	305	39872	34442	50592	9466	5467	1522	1300	444	344	5098	
12	5.4	356	319	36806	32776	46920	8247	5569	1467	1300	456	344	5060	63.8
14	5.4	342	319	36632	32576	47328	8486	5630	1344	1267	400	400	4891	66.9
16	5.5	384	297	36846	32474	48552	8038	5488	1344	1222	400	367	4756	62.4
18	5.4	350	283	36548	31624	43248	7874	5447	1344	1233	400	400	4841	57.5
20	5.5	353	300	36430	32534	42480	8119	5692	1344	1222	400	400	4822	57.6
22														
24														
B5 26	5.5	392	328	43104	38160	49776	9017	6365	1444	1344	433	367	5106	
28														
30														
32	5.6	428	403	77048	66984	62669	11182	7803	1544	1667	511	444	6000	
34														
36														
38	5.6	442	395	64940	56330	56525	10936	7782	1589	1556	444	400	5668	53.0
40	5.6	462	395	65888	55678	59392	11059	7926	1589	1667	511	489	6138	49.6
42	5.6	434	344	60918	52112	59160	11057	7446	1467	1611	567	533	6115	51.1
44	5.6	487	451	57228	49696	58344	11056	7466	1500	1700	556	544	6287	52.4
46	5.6	496	395	58494	50562	62339	11011	7630	1533	1656	544	522	6190	56.1
48	5.6	496	445	56394	49406	46957	10606	7266	1556	1644	522	500	6111	60.8
50	5.6	482	428	58240	50066	57415	11198	7737	1644	1678	522	500	6257	63.4

Table D.7: **Results of measured parameters of a single, completely mixed reactor of 6 days retention time, for all batches of sludge in stage 2.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"Soluble" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B4 1	5.4	403	358	46480	40438	45696	9955	6752	1611	1744	511	511	6324	
3	5.4	395	356	39968	35124	43656	10649	6569	1611	1733	422	511	6146	
5	5.3	370	316	40632	36078	42432	11424	6691	1644	1567	378	356	5532	
7	5.4	272	227	38062	33990	46104	10649	7038	1644	1788	522	444	6313	
9	5.4	344	314	39098	34058	45288	11138	6916	1622	1700	522	444	6155	
11	5.4	344	319	37494	32620	44880	11873	6895	1644	1644	489	433	6012	
13	5.4	370	333			47736	9629	6589	1622	1711	533	444	6192	
15	5.4	364	344	34528	30936	42840	10241	6508	1744	1478	400	367	5569	59.4
17	5.5	356	314	35240	31656	44880	9874	6528	1622	1556	444	456	5818	59.7
19	5.5	347	302	35686	31362	36720	10037	6446	1711	1556	444	456	5913	56.0
21														
23														
25														
B5 27	5.5	375	330	43722	38380	49594	10644	6996	1589	1667	489	444	6007	
29														
31														
33														
35														
37	5.5	462	428	55844	49062	49971	11960	8233	1722	1944	600	589	7065	51.9
39	5.5	473	409	63062	53948	60621	11592	8192	1700	1867	600	589	6924	47.6
41	5.5	476	426	61550	53354	62016	11342	8344	1778	1867	556	533	6813	54.5
43	5.5	504	448	58310	49994	61608	11832	8017	1778	1789	578	556	6781	47.3
45	5.6	532	462	57510	49092	61530	11699	8177	1800	1756	556	533	6668	54.6
47	5.6	543	498	55524	48174	47362	11780	8136	1800	1756	544	511	6603	51.2
49	5.6	571	493	51410	45130	57886	12265	8440	1889	1844	556	556	6943	54.7
51	5.6	540	456	77394	70698	59858	11442	7716	1722	1811	522	511	6564	42.3

Table D.8: **Results of measured parameters of a single, completely mixed reactor of 9 days retention time, for all batches of sludge in stage 2.**

DAY	pH	TKN	NH3-N	TSS	VSS	VSS as COD	"Soluble" COD	-0.45um COD	Acetic acid	Propionic acid	Butyric acid	Valeric acid	SCFA as COD	DSVI
		mgN/l	mgN/l	mgTSS/l	mgVSS/l	mgCOD/l	mgCOD/l	mgCOD/l	mg/l	mg/l	mg/l	mg/l	mgCOD/l	g/l
B4 1	5.3	414	378	44130	38010	52224	12118	7630	1833	1856	511	489	6684	
3	5.3	420	353	39328	34840	48144	12322	7507	1833	1811	489	467	6531	
5	5.3	386	350	42432	36472	48552	12730	7385	1800	1789	467	467	6422	
7	5.3	260	221	38980	35314	48144	11995	7344	1722	1856	556	489	6648	
9	5.3	378	370	35072	31384	42840	12199	7201	1722	1833	533	444	6484	
11	5.3	400	364	36664	32378	45288	13219	7446	1811	1889	533	444	6662	
13	5.4	398	364	36160	32470	46104	11098	7344	1778	1822	533	444	6526	60.8
15	5.4	378	356	35456	31532	47736	11669	7181	1778	1689	489	489	6334	59.2
17	5.4	381	339	38374	33250	49368	10812	7283	1744	1733	500	500	6409	54.7
19	5.4	406	333	37678	32836	53040	11179	7385	1800	1744	522	522	6570	50.4
21														
23														
25														
B5 27	5.4	400	364	40568	35320	59674	11249	7580	1778	1667	522	433	6246	
29														
31														
33														
35														
37	5.4	493	456	44098	38908	41779	13476	9134	1944	1978	589	511	7174	52.2
39	5.4	501	431	60632	51460	48333	13476	9257	1911	2100	667	633	7713	45.4
41	5.5	504	437	64972	54010	63240	13464	9241	1867	2111	667	622	7660	46.2
43	5.5	552	482	57580	49566	49368	12893	8711	1944	2000	578	556	7278	39.2
45	5.6	588	498	50204	43312	48171	12549	8987	1867	2000	578	633	7353	48.4
47	5.6	563	512	53944	46618	51307	13030	9040	1911	2022	611	656	7540	51.1
49	5.6	599	521	68124	58206	55862	13035	9128	1800	2056	600	656	7452	44.3
51	5.5	594	510	55650	47722	50088	13112	9060	1800	2033	589	633	7353	53.4

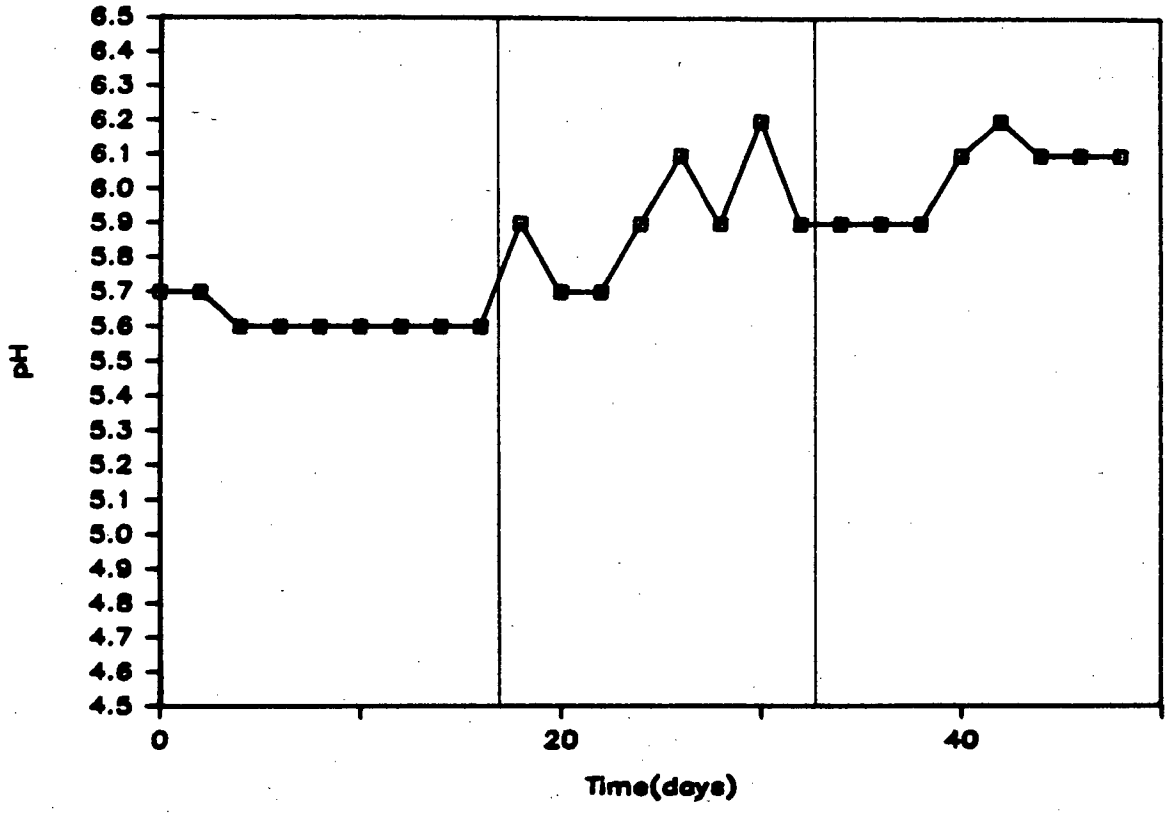

Fig D.1: Influent pH versus time, for all sludge batches in stage 1.

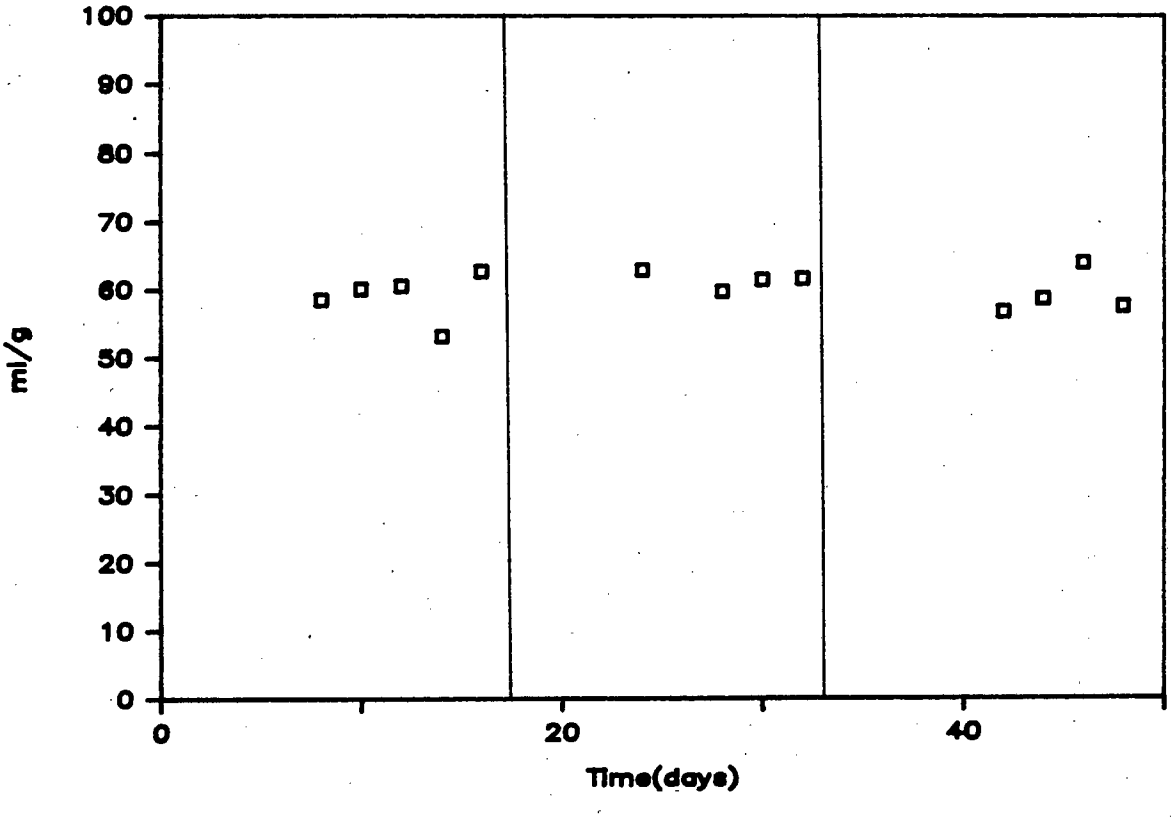

Fig D 2: Influent DSVI versus time, for all sludge batches in stage 1.

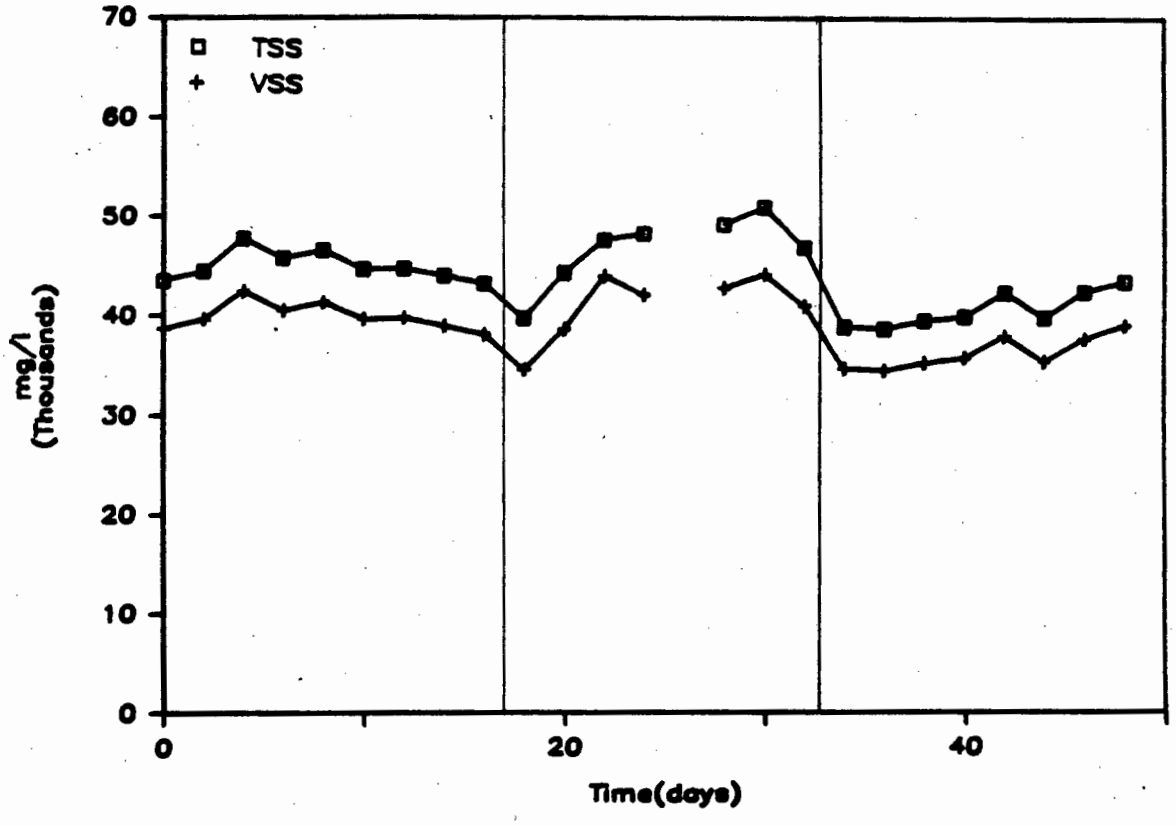

Fig D 3: Influent TSS and VSS concentrations versus time, for all sludge batches in stage 1.

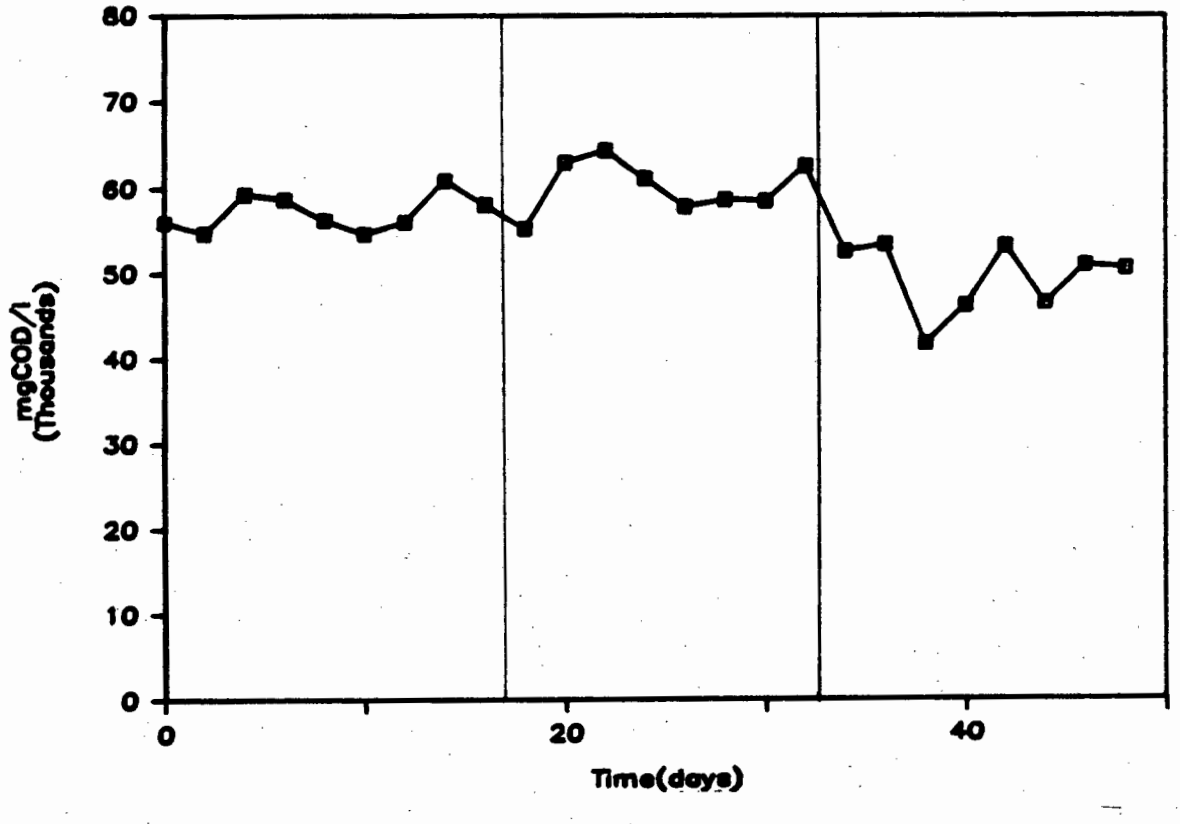

Fig D.4: Influent COD of the VSS concentrations versus time, for all sludge batches in stage 1.

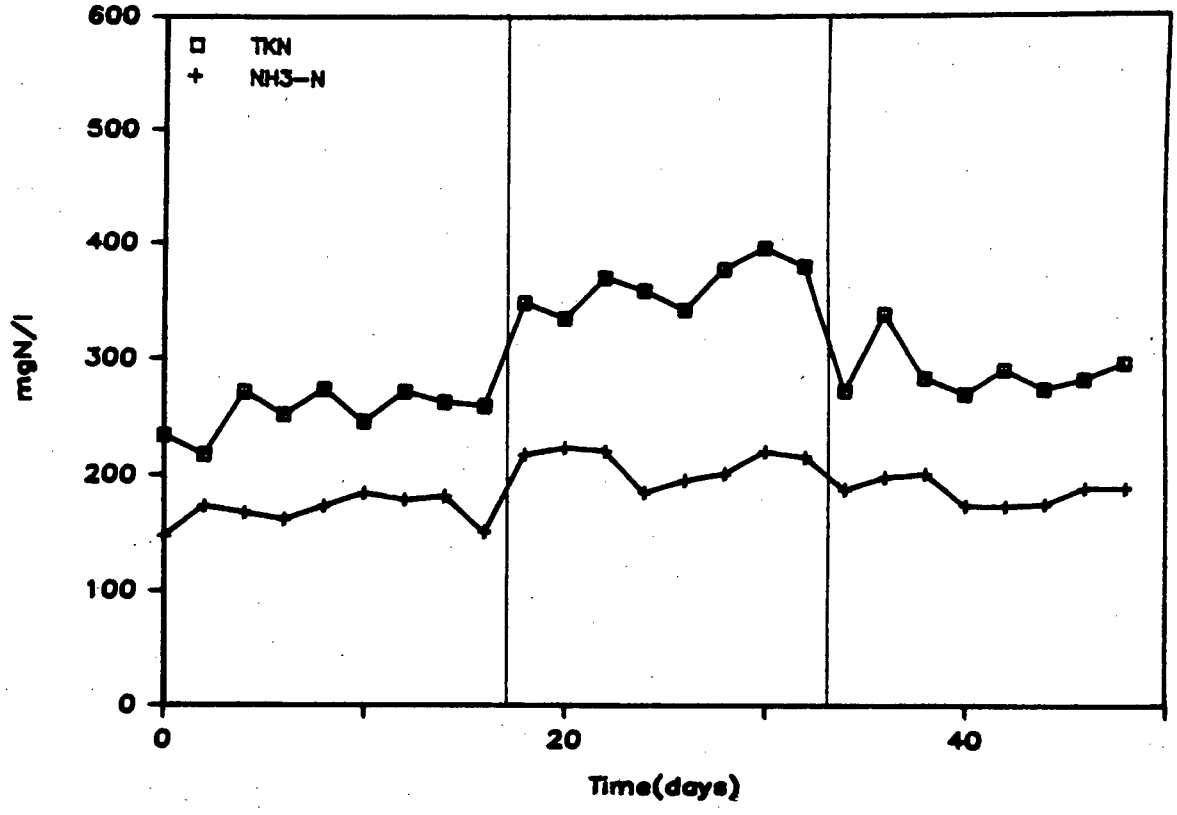

Fig D.5: Influent TKN and NH_3-N concentrations of the –0,45μm filtrate versus time, for all sludge batches in stage 1.

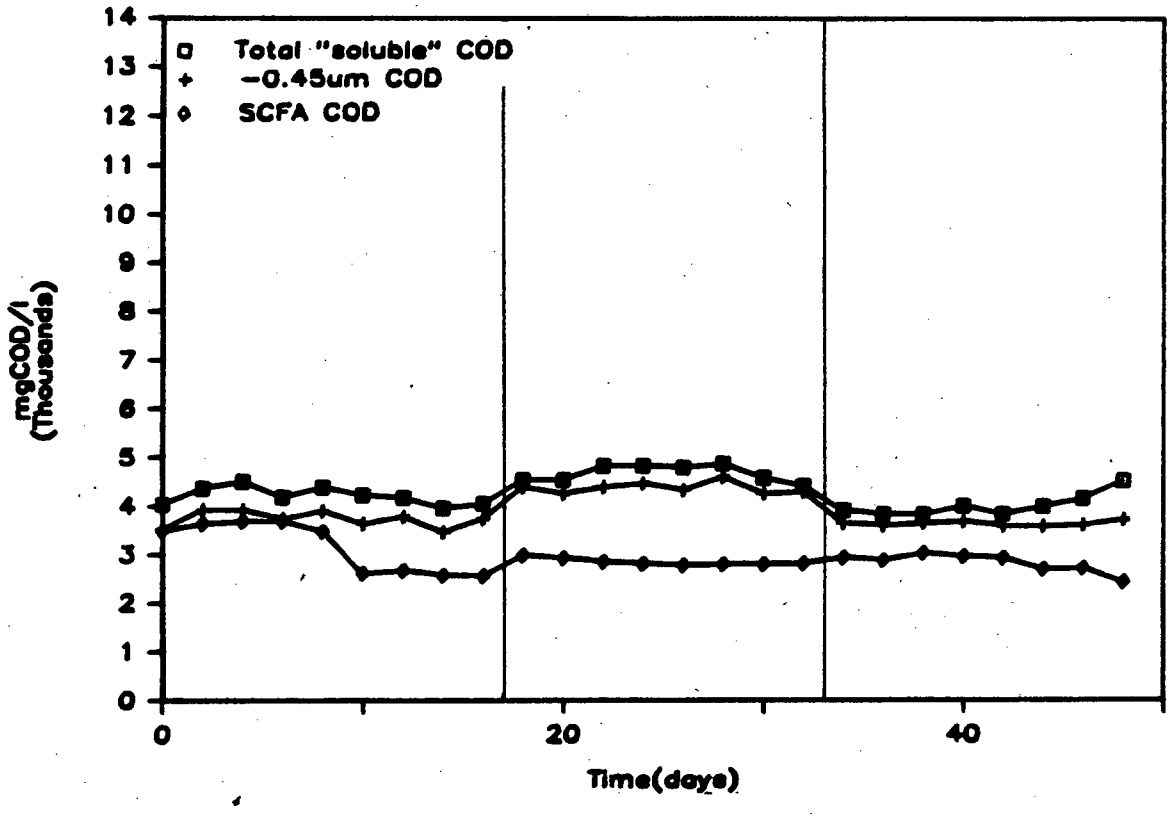

Fig D.6: Influent total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate versus time, for all sludge batches in stage 1.

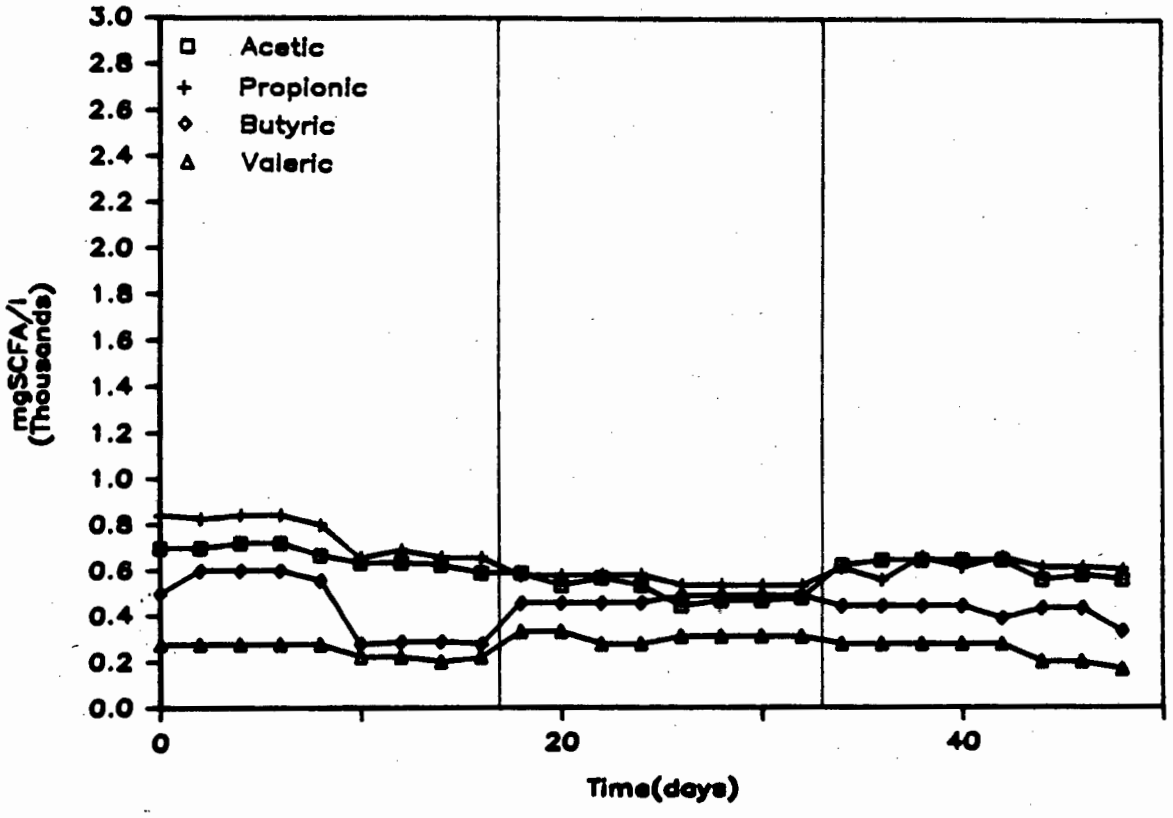

Fig D.7: Influent acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate versus time, for all sludge batches in stage 1.

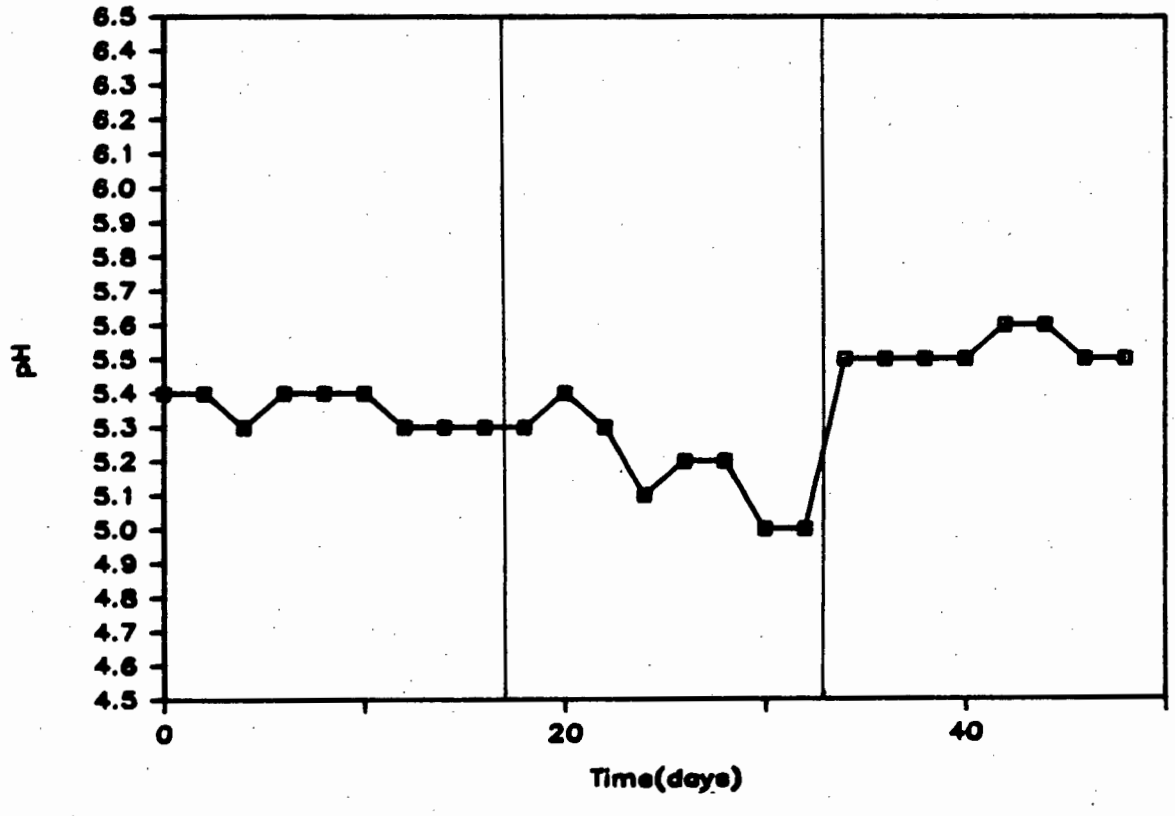

Fig D.8: pH of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

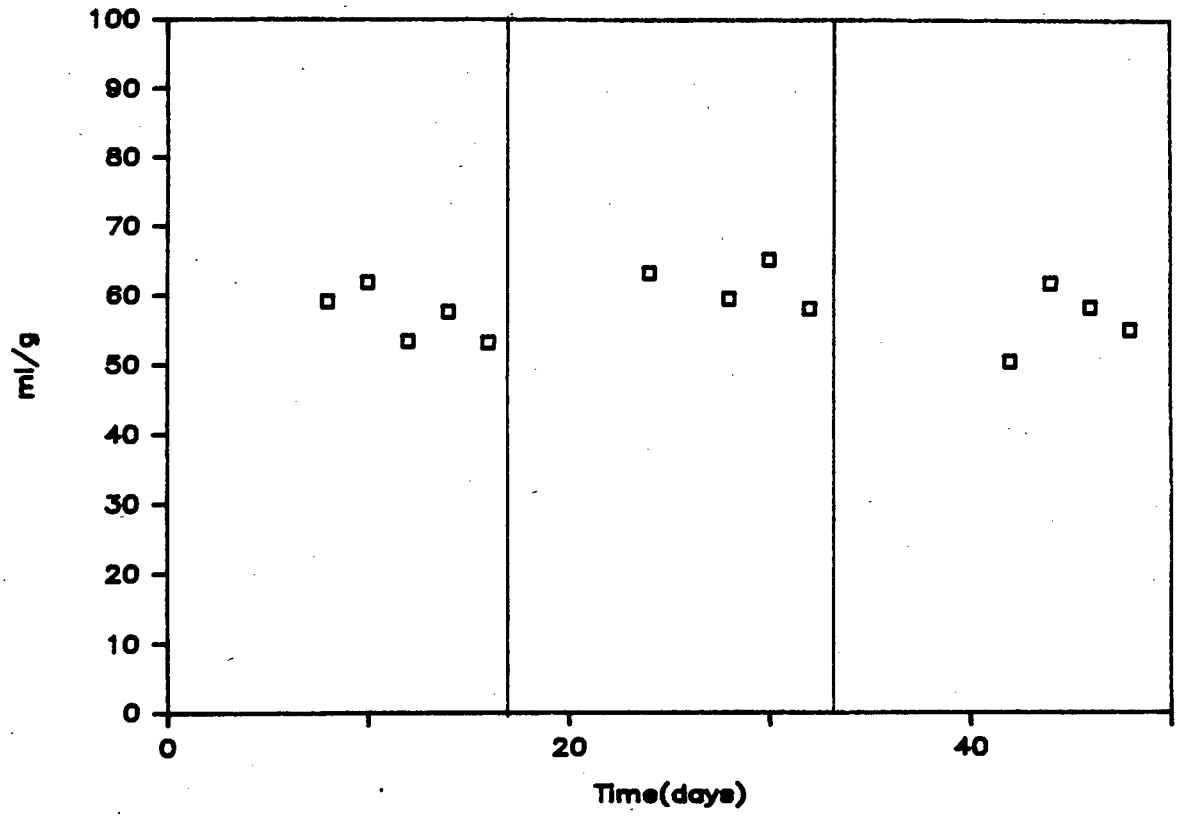

Fig D.9: DSVI of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

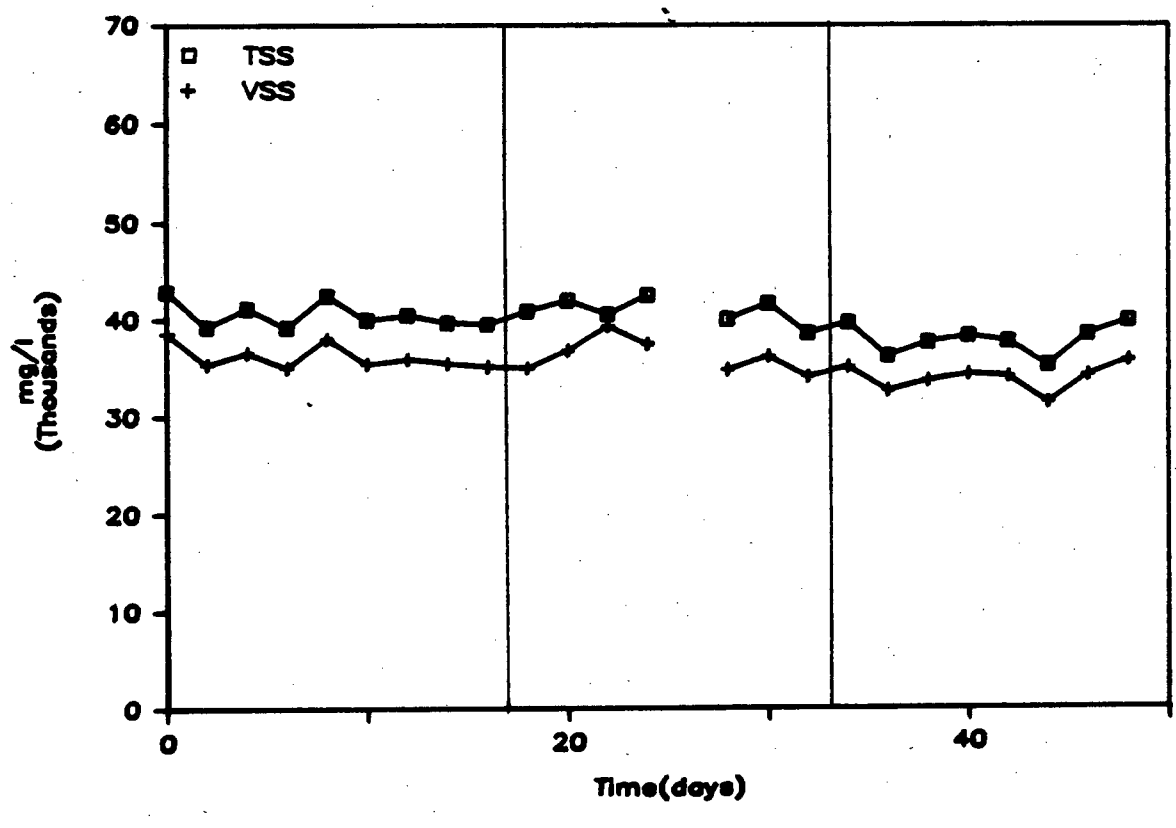

Fig D.10: TSS and VSS concentrations of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

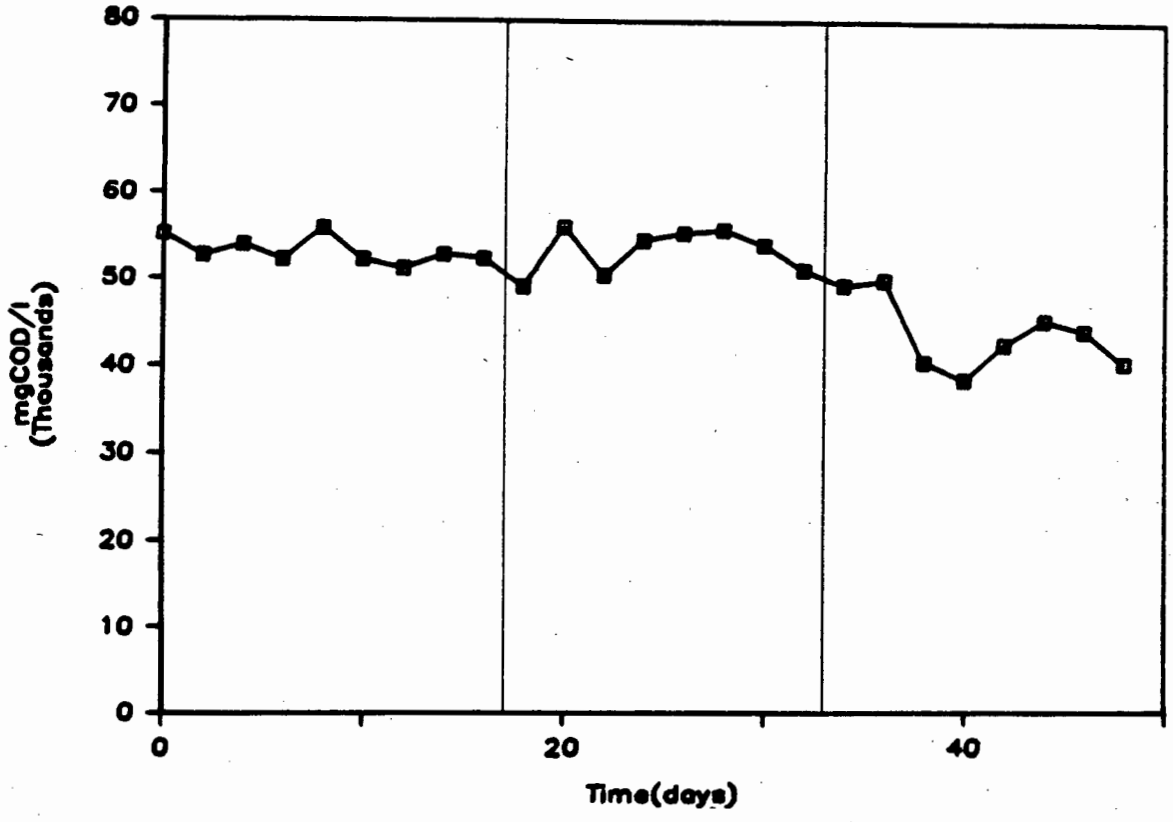

Fig D.11: COD of the VSS concentrations of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

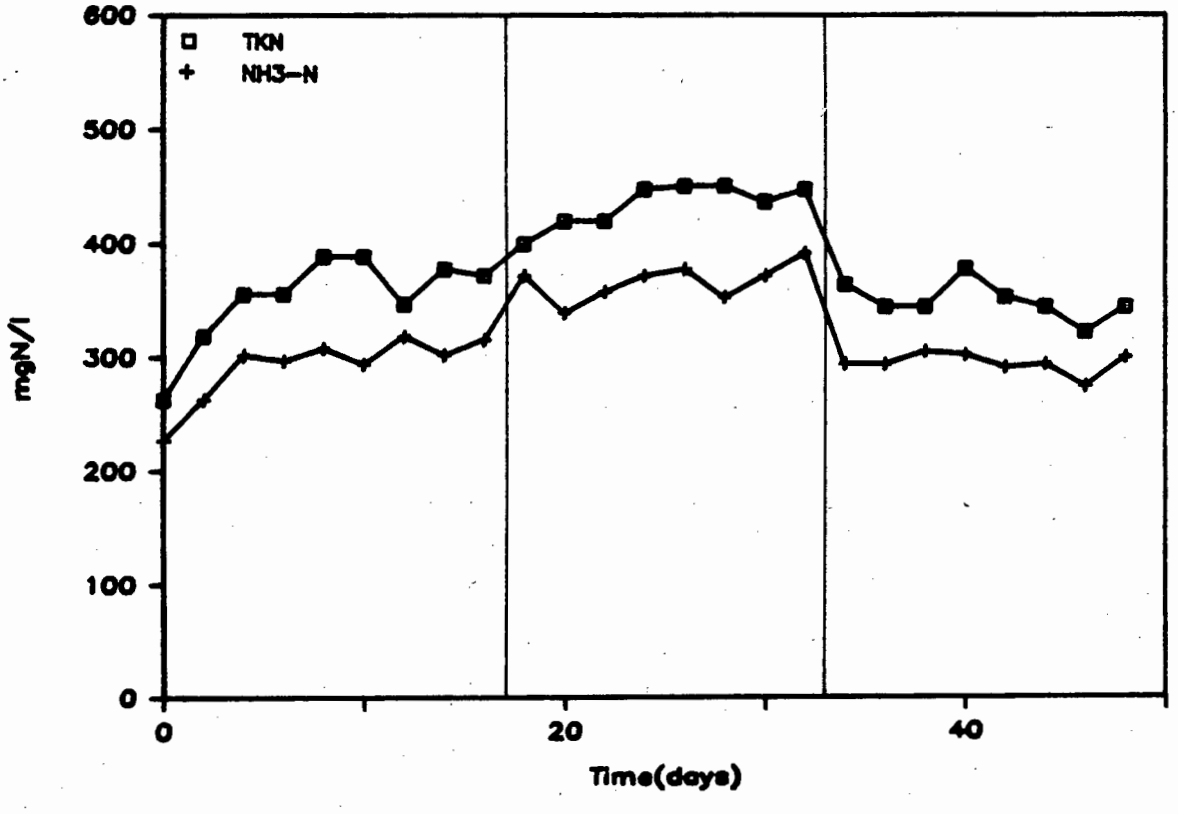

Fig D.12: TKN and NH_3-N concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

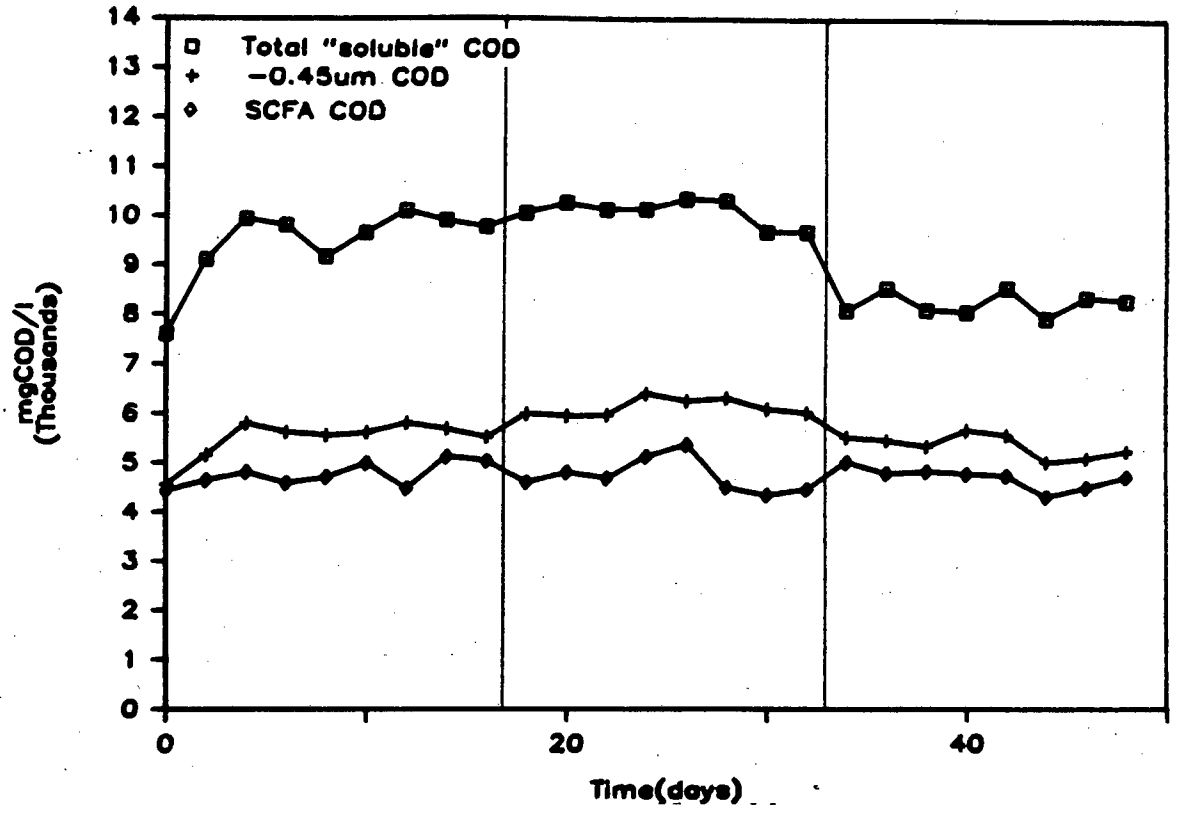

Fig D.13: Total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

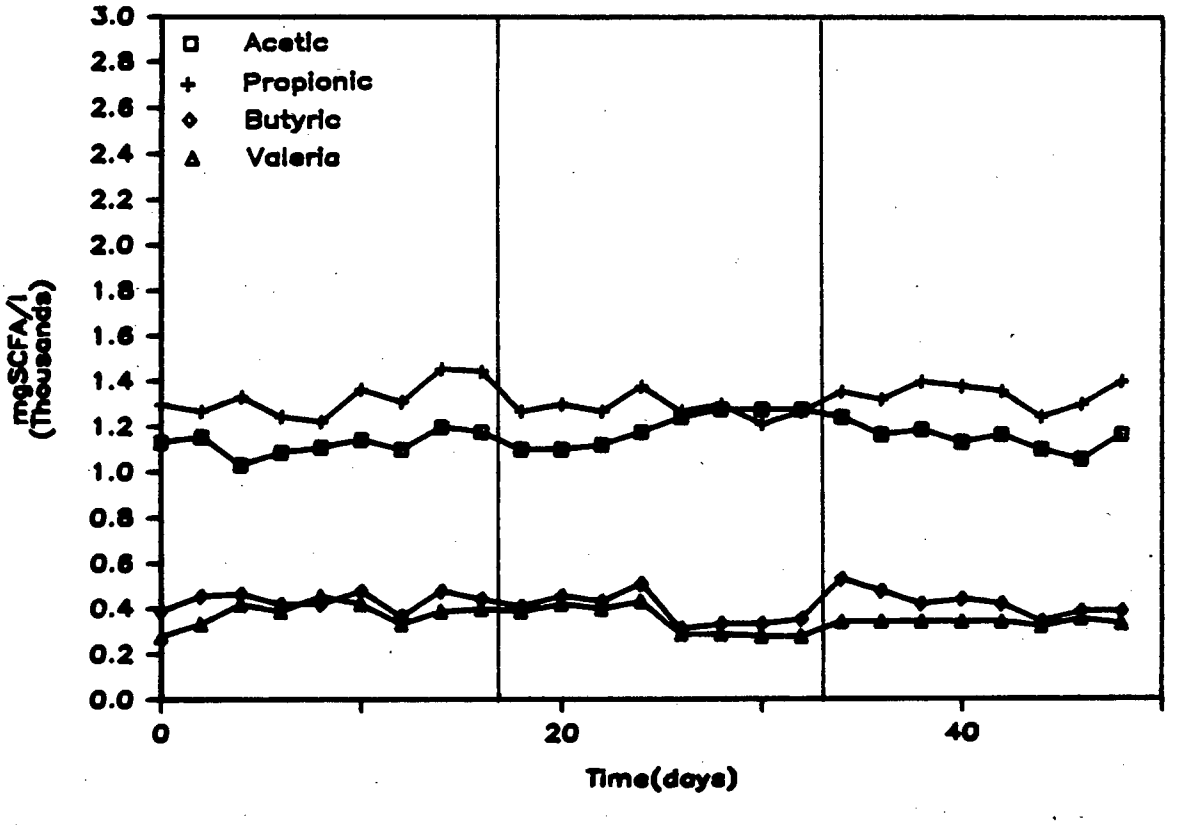

Fig D.14: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 2 days retention time versus time, for all sludge batches in stage 1.

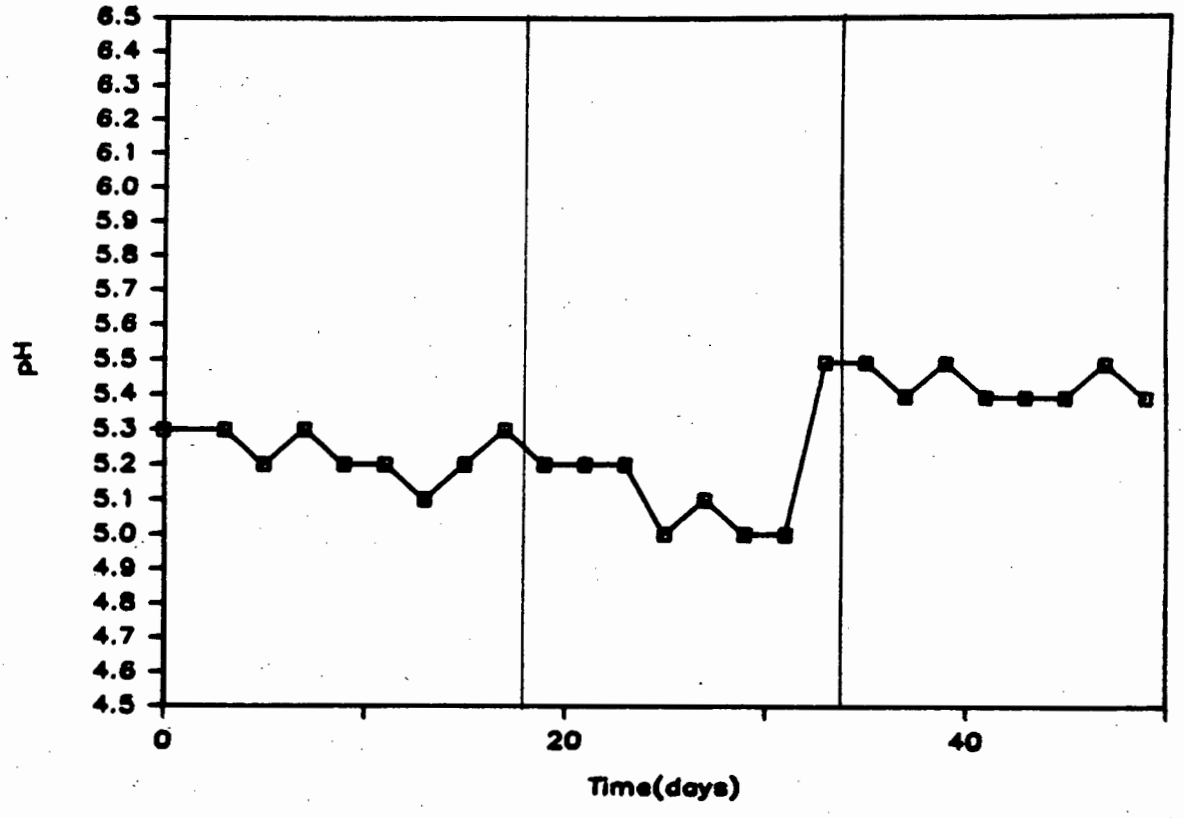

Fig D.15: pH of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

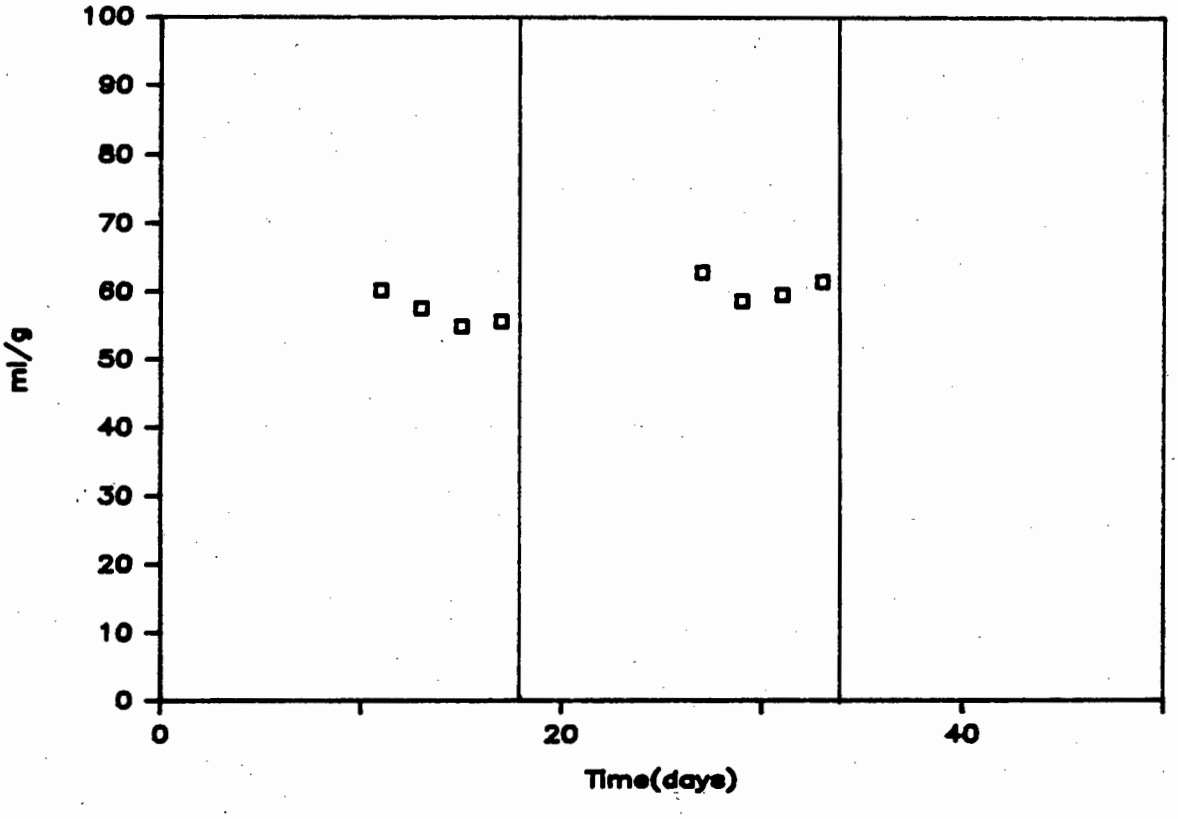

Fig D.16: DSVI of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

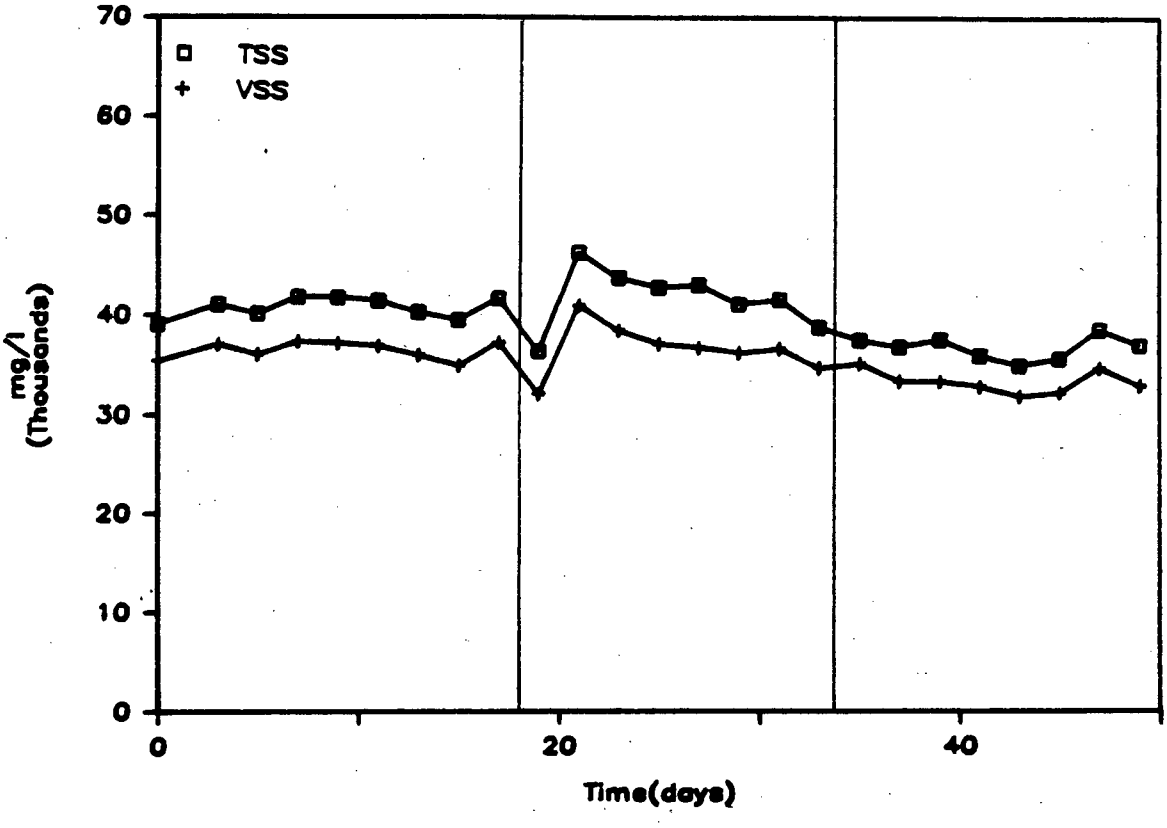

Fig D.17: TSS and VSS concentrations of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

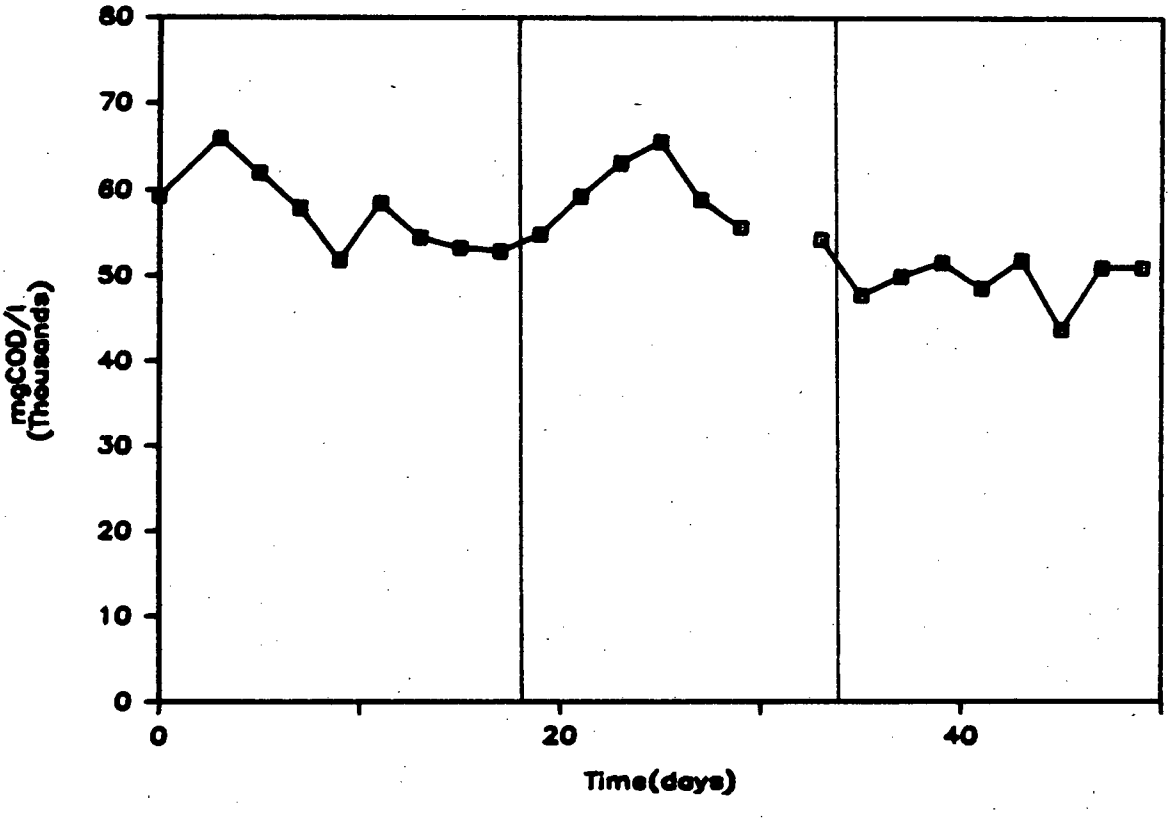

Fig D.18: COD of the VSS concentrations of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

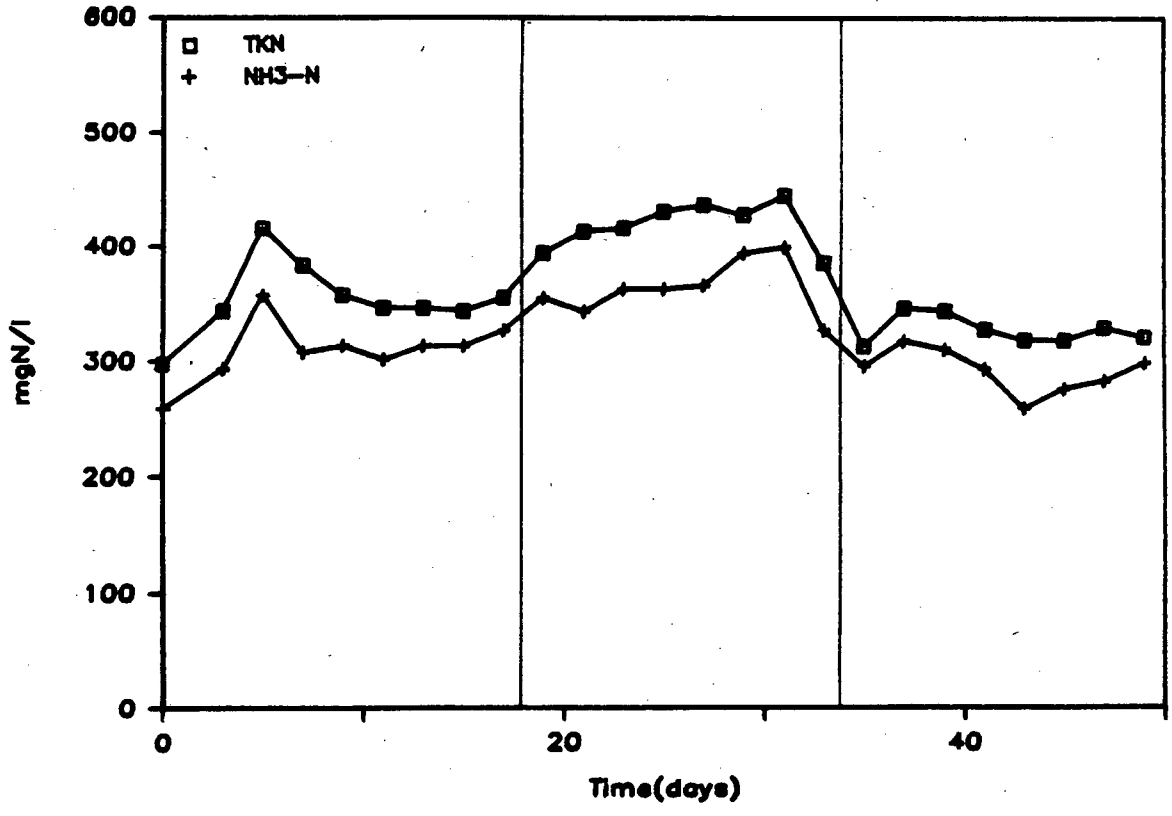

Fig D.19: TKN and NH_3-N concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

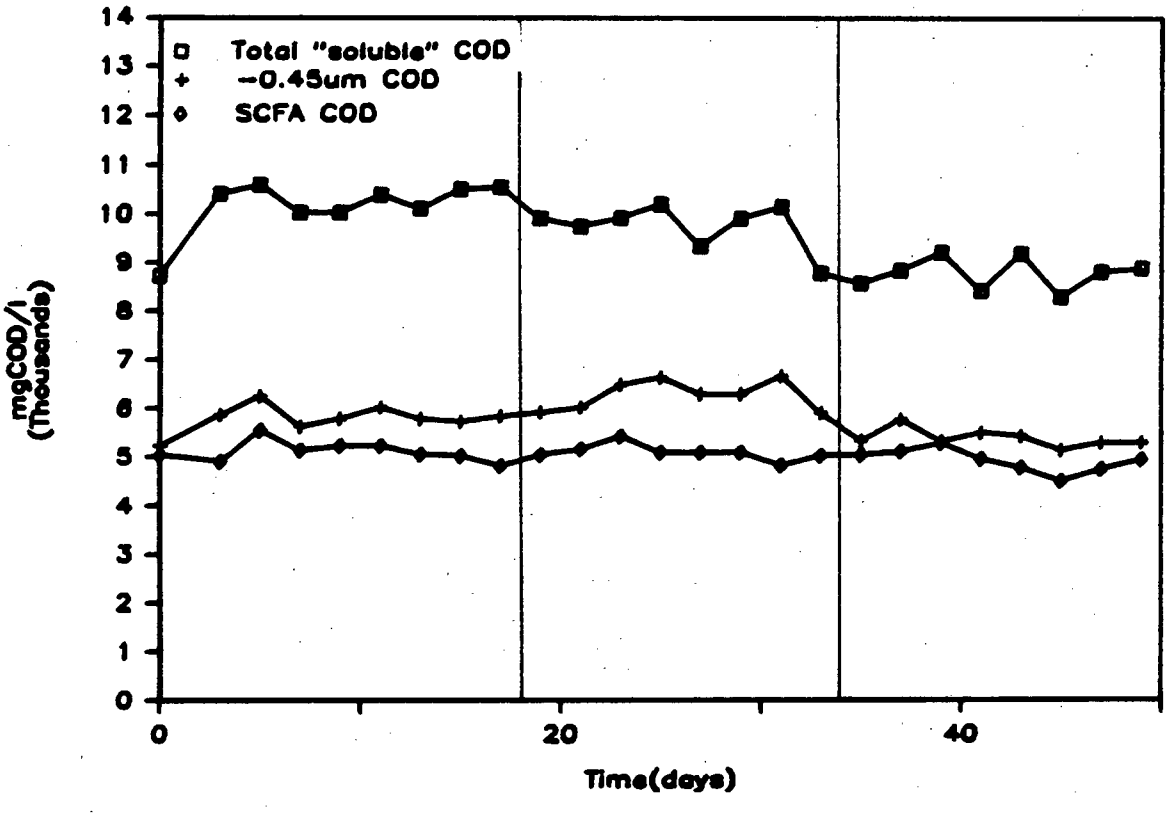

Fig D.20: Total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

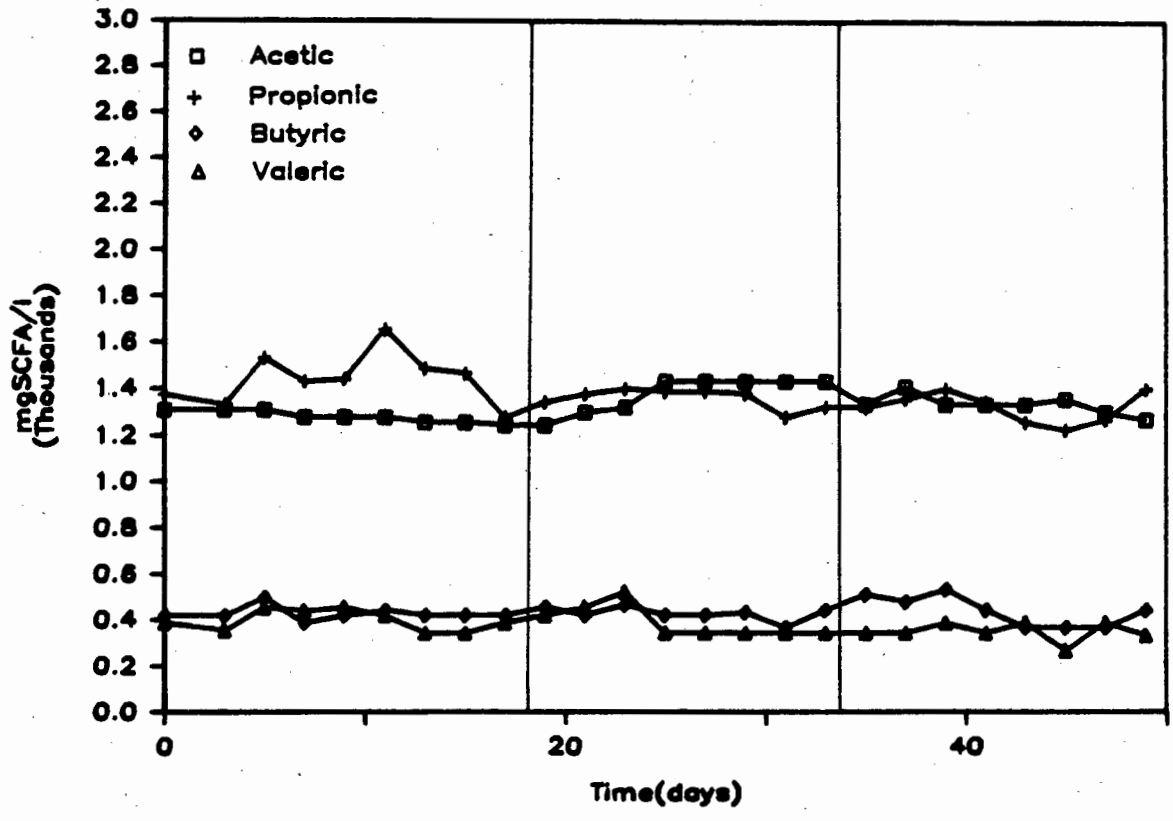

Fig D.21: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 1.

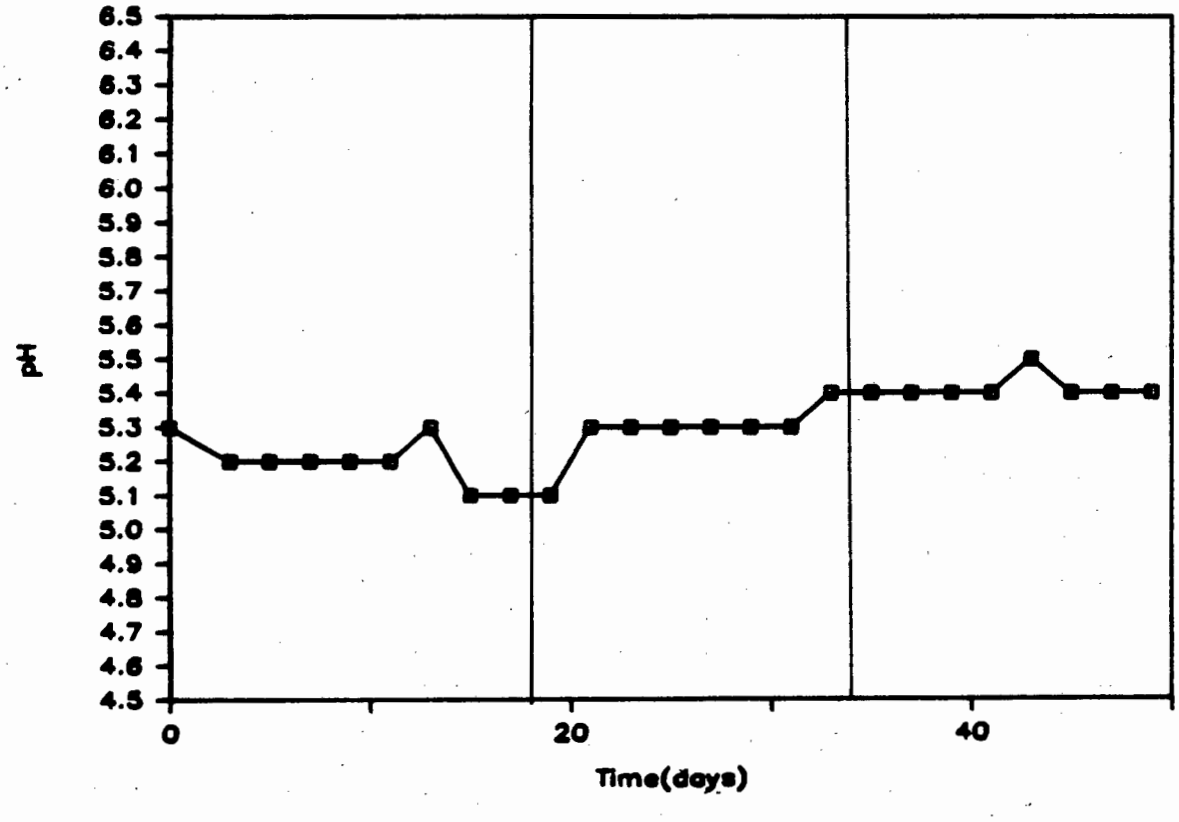

Fig D.22: pH of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

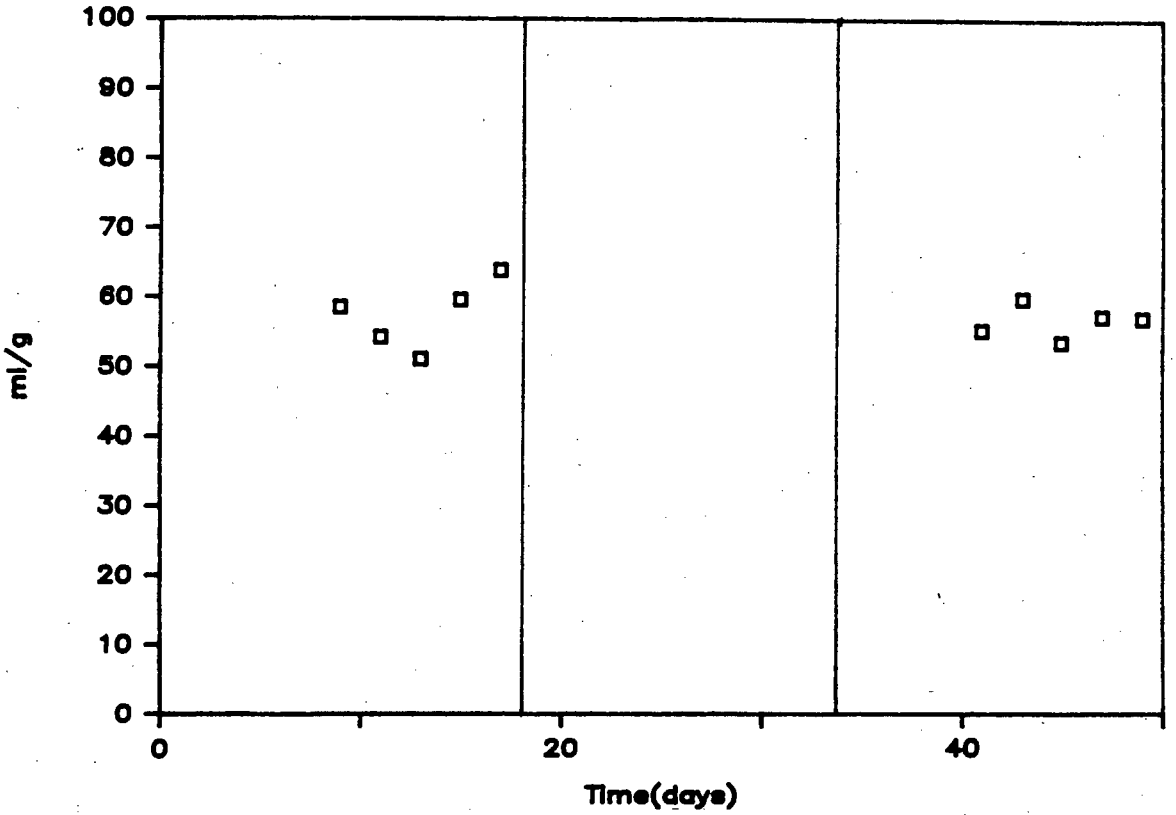

Fig D.23: DSVI of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

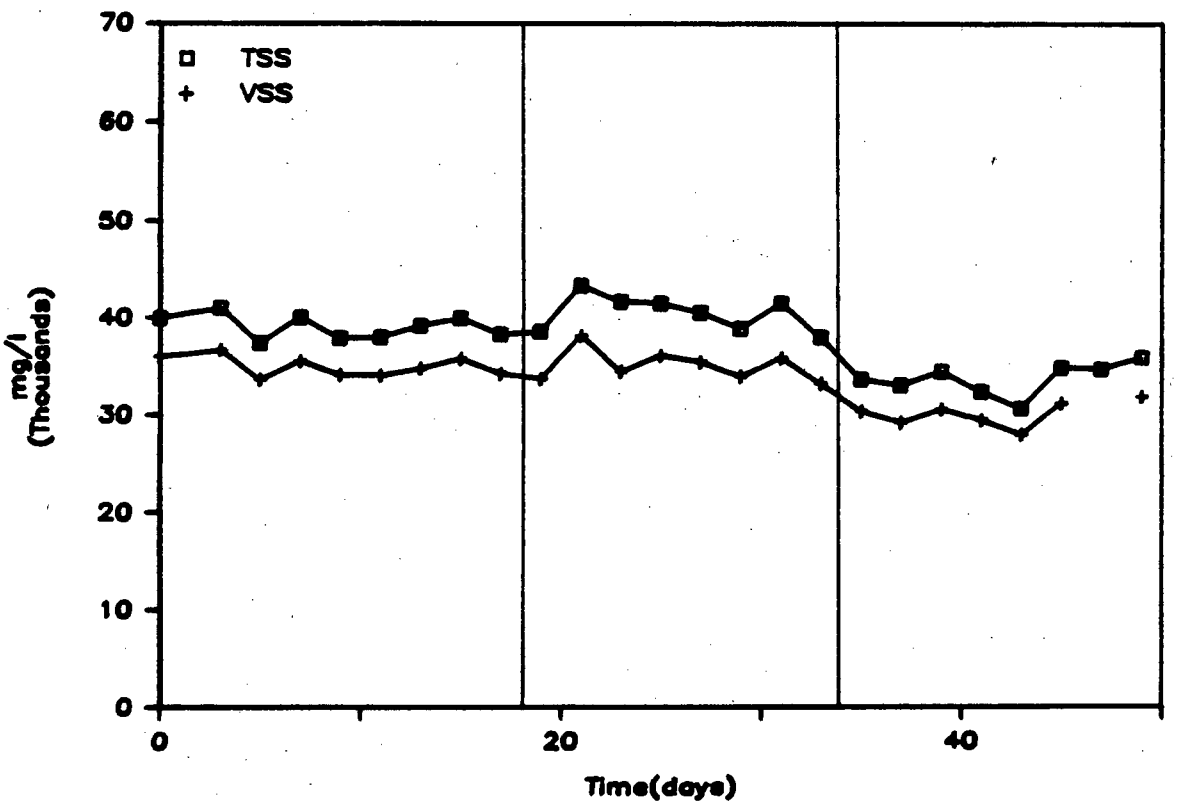

Fig D.24: TSS and VSS concentrations of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

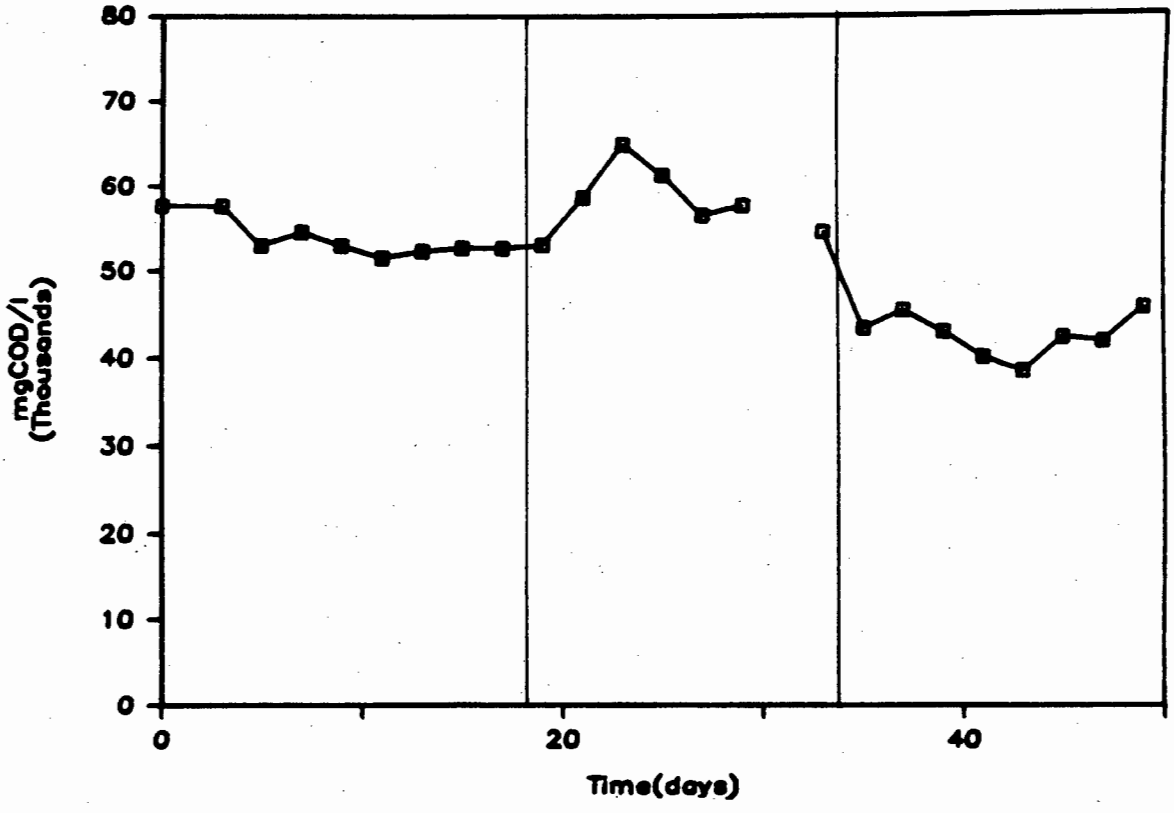

Fig D.25: COD of the VSS concentrations of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

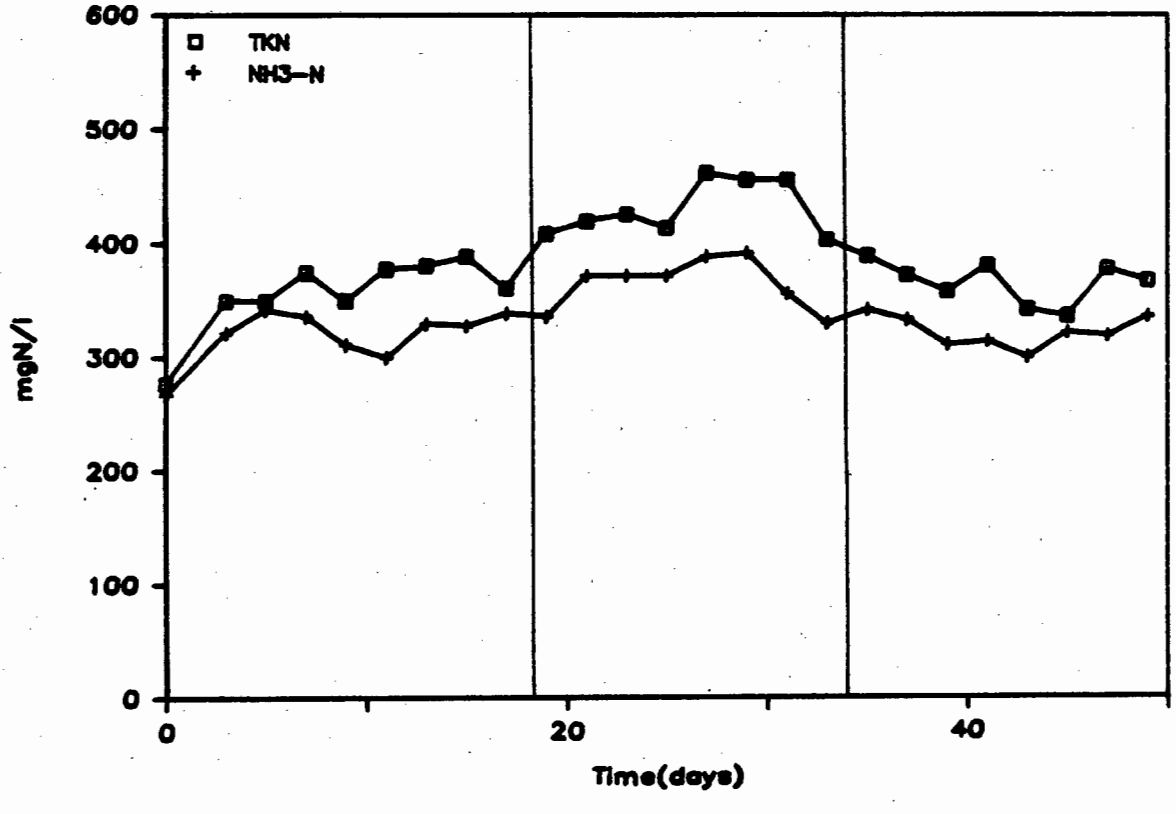

Fig D.26: TKN and NH_3-N concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

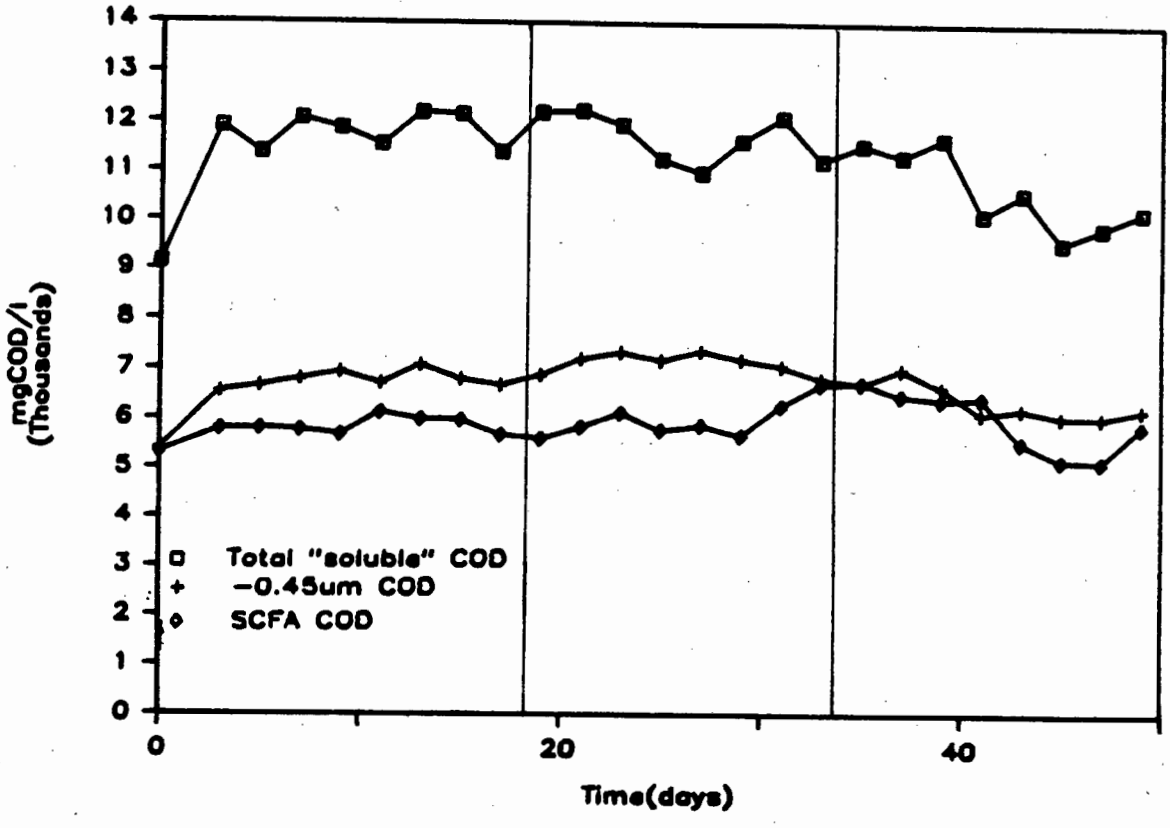

Fig D.27: Total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

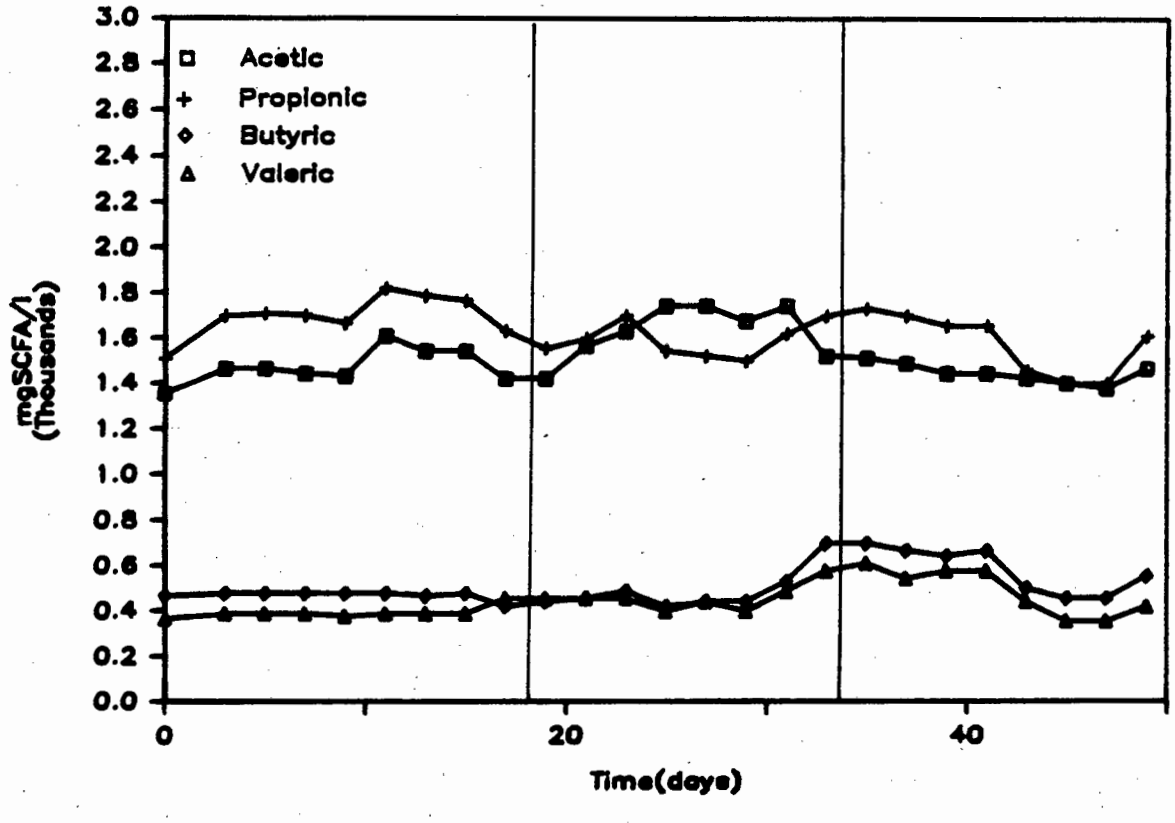

Fig D.28: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 5 days retention time versus time, for all sludge batches in stage 1.

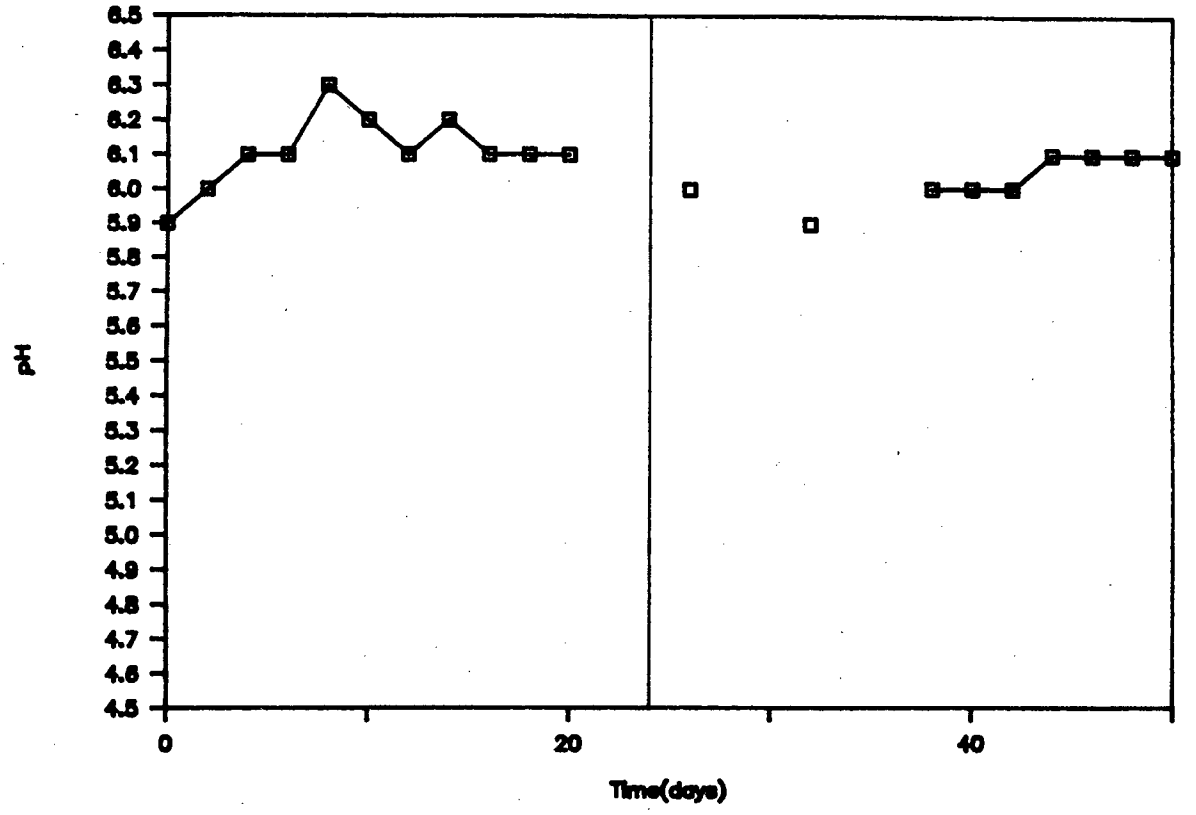

Fig D.29: Influent pH versus time, for all sludge batches in stage 2.

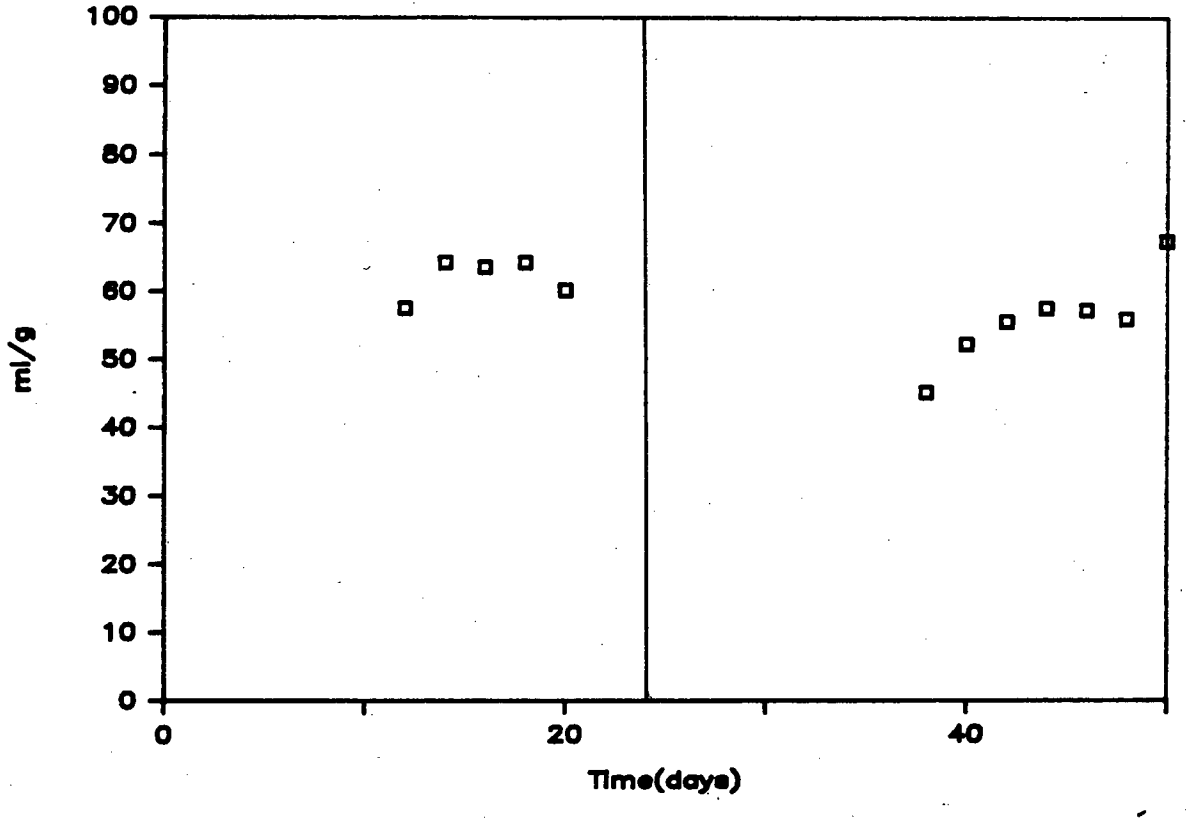

Fig D.30: Influent DSVI versus time, for all sludge batches in stage 2.

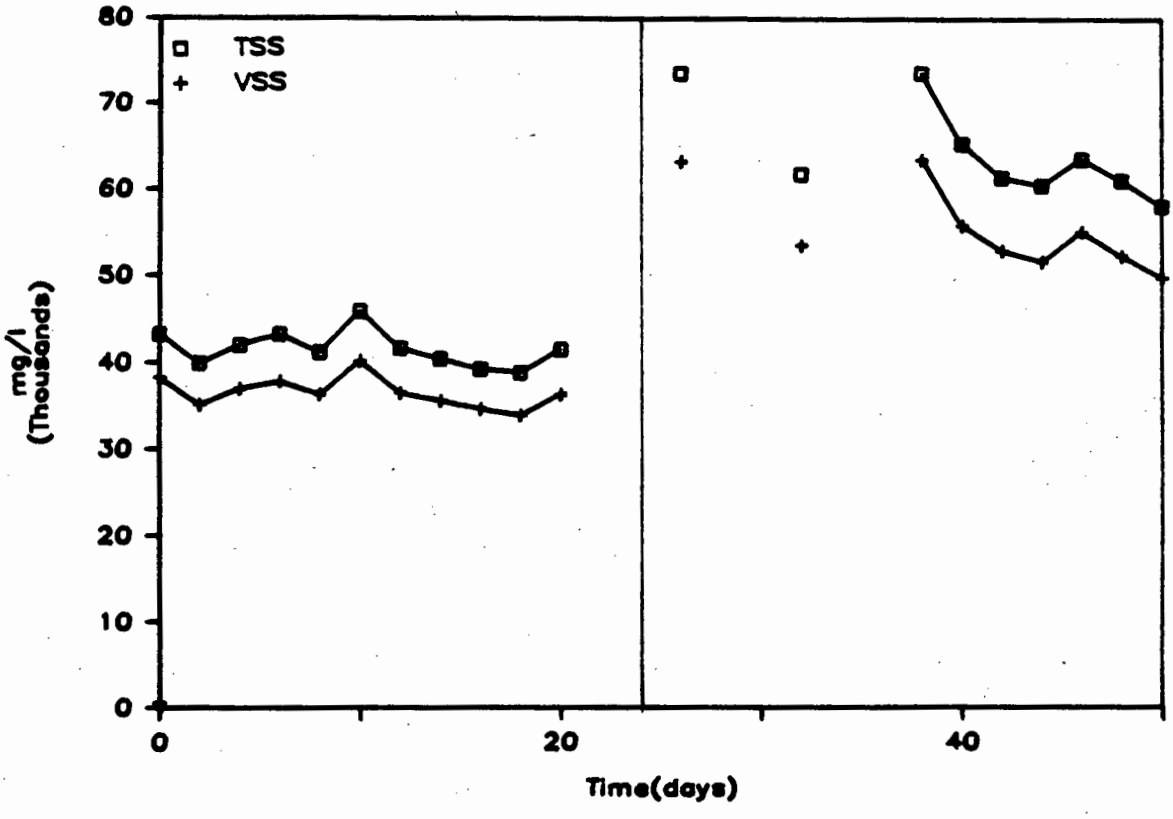

Fig D.31: Influent TSS and VSS concentrations versus time, for all sludge batches in stage 2.

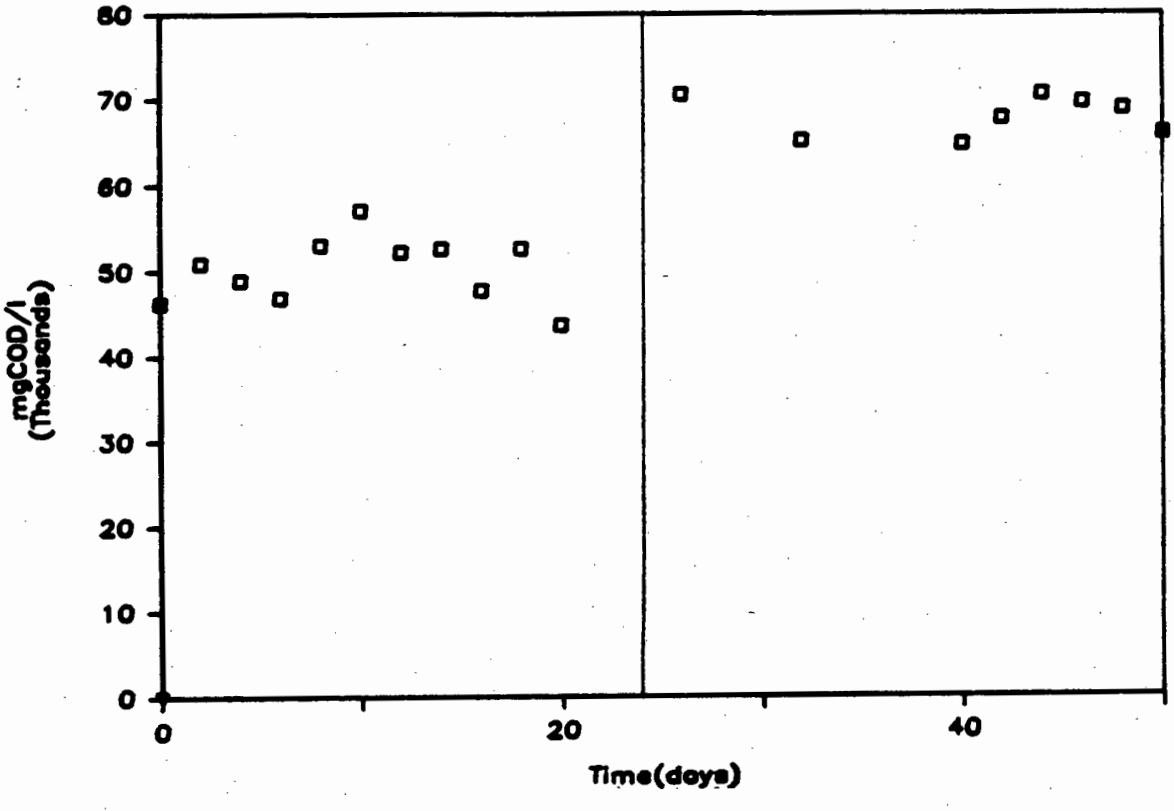

Fig D.32: Influent COD of the VSS concentrations versus time, for all sludge batches in stage 2.

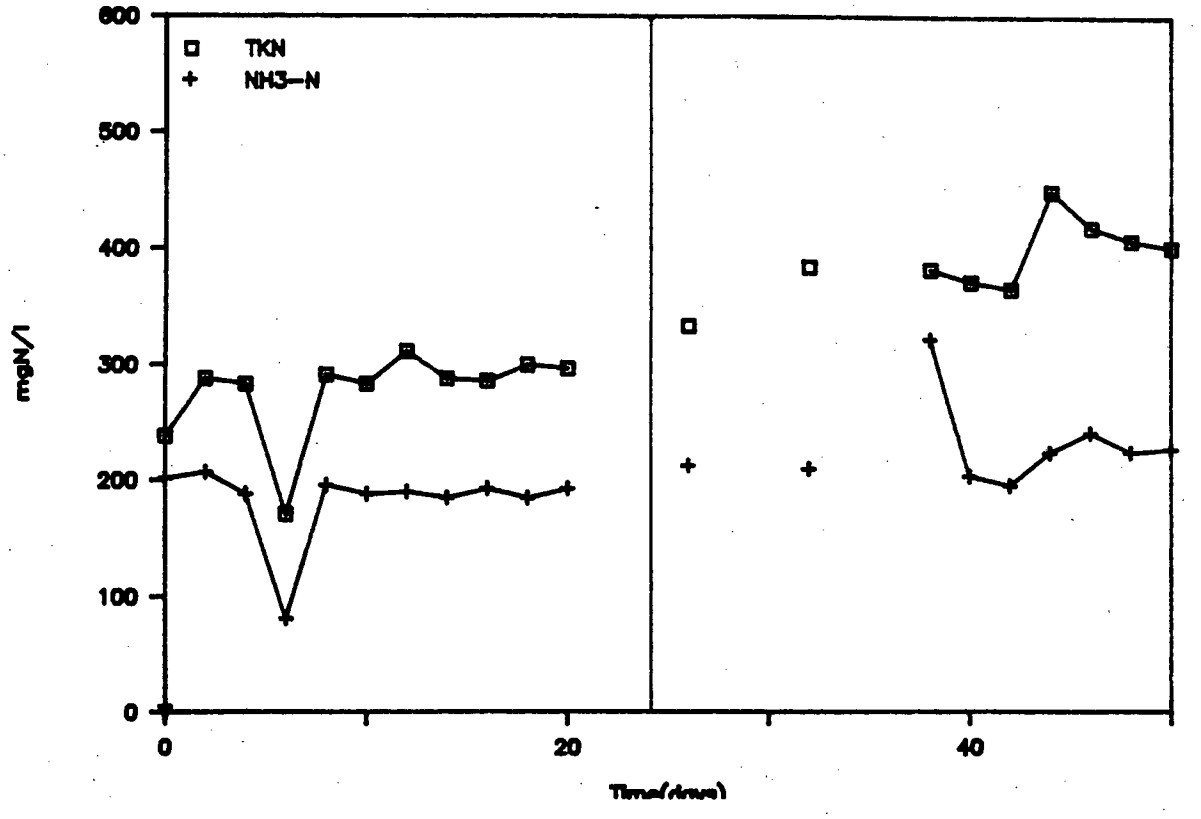

Fig D.33: Influent TKN and NH_3-N concentrations of the –0,45μm filtrate versus time, for all sludge batches in stage 2.

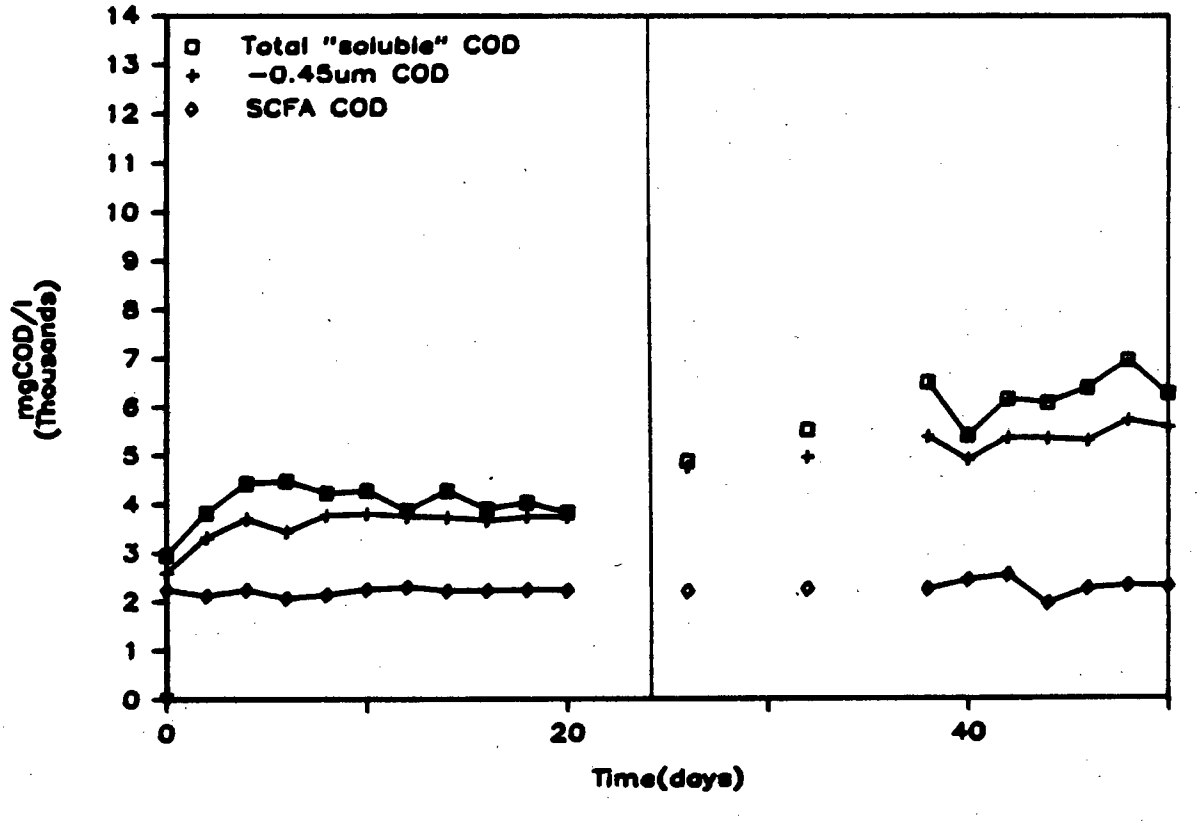

Fig D.34: Influent total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate versus time, for all sludge batches in stage 2.

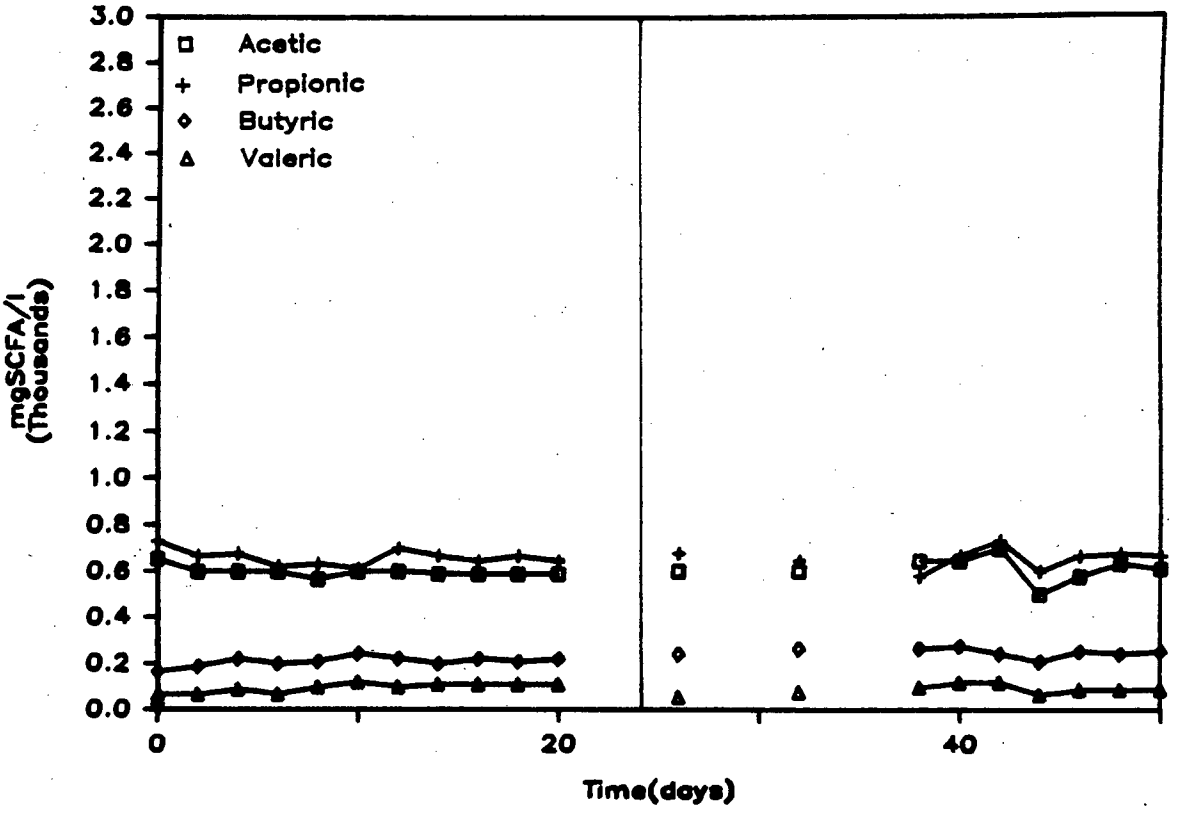

Fig D.35: Influent acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate versus time, for all sludge batches in stage 2.

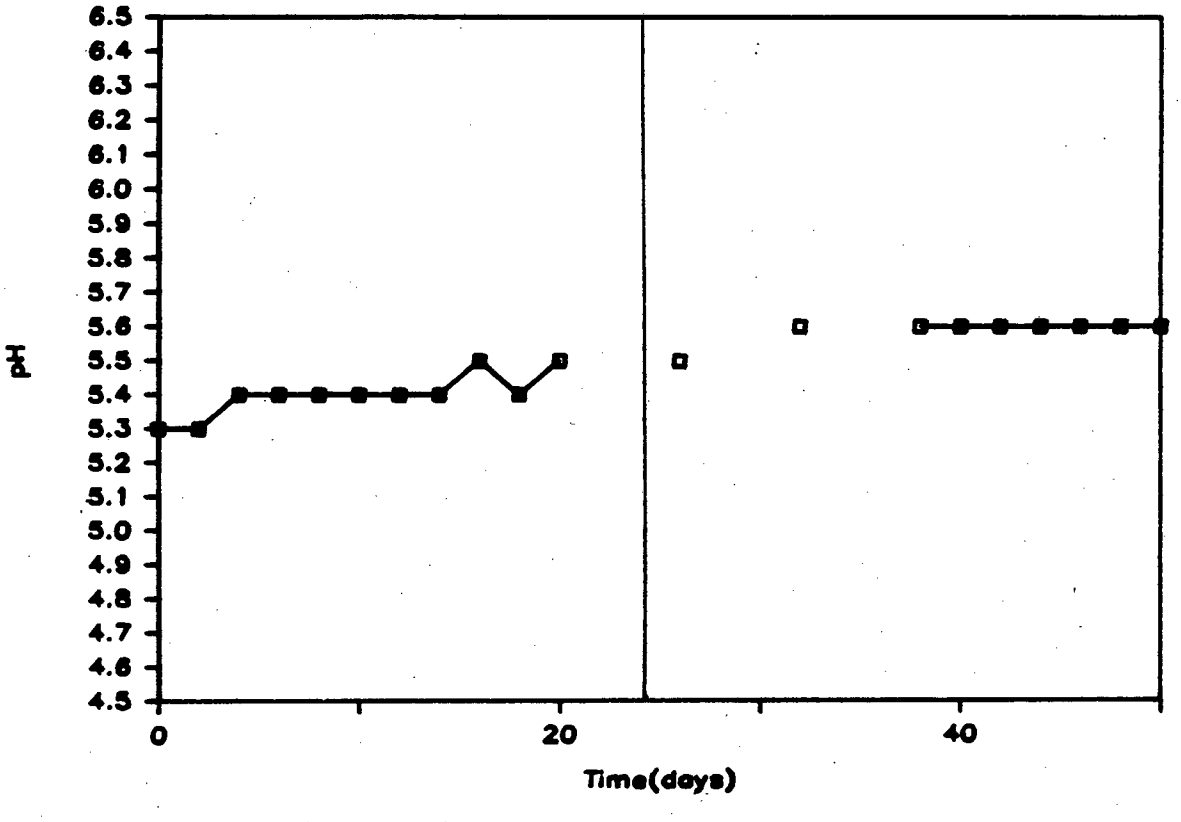

Fig D.36: pH of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

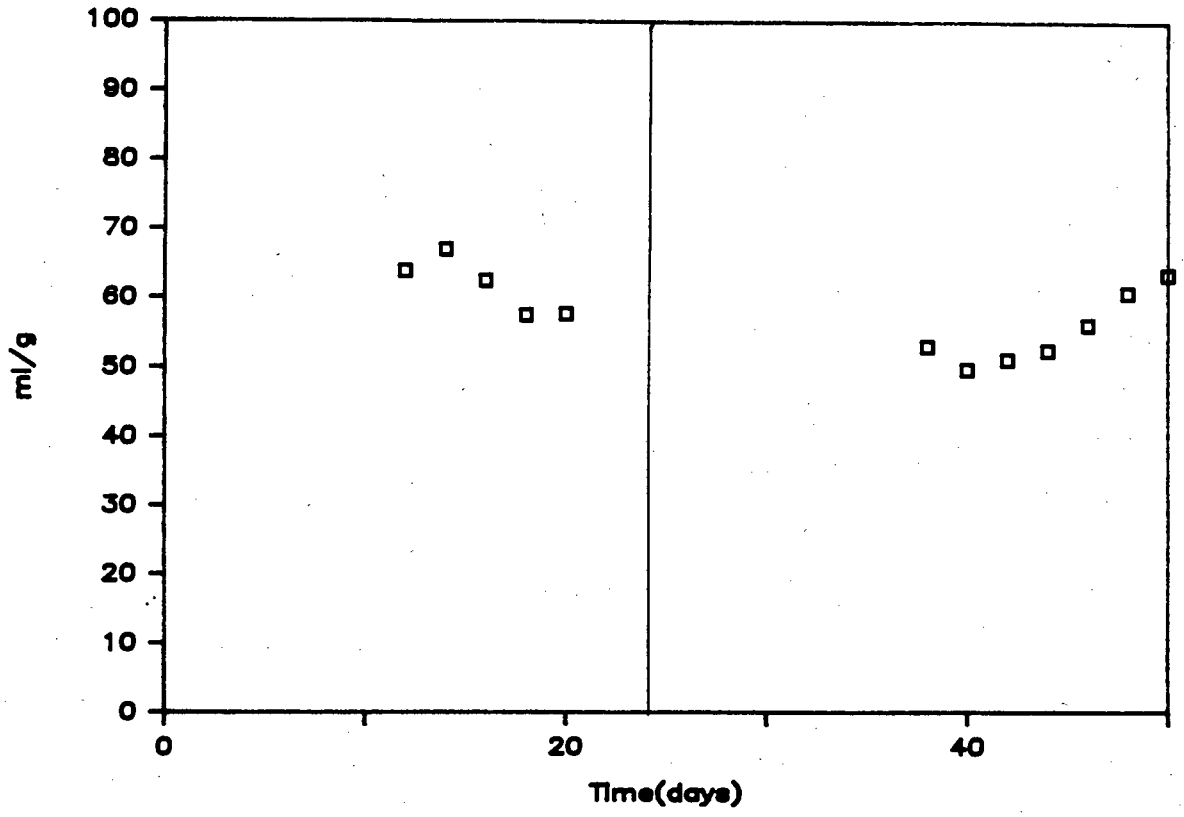

Fig D.37: DSVI of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

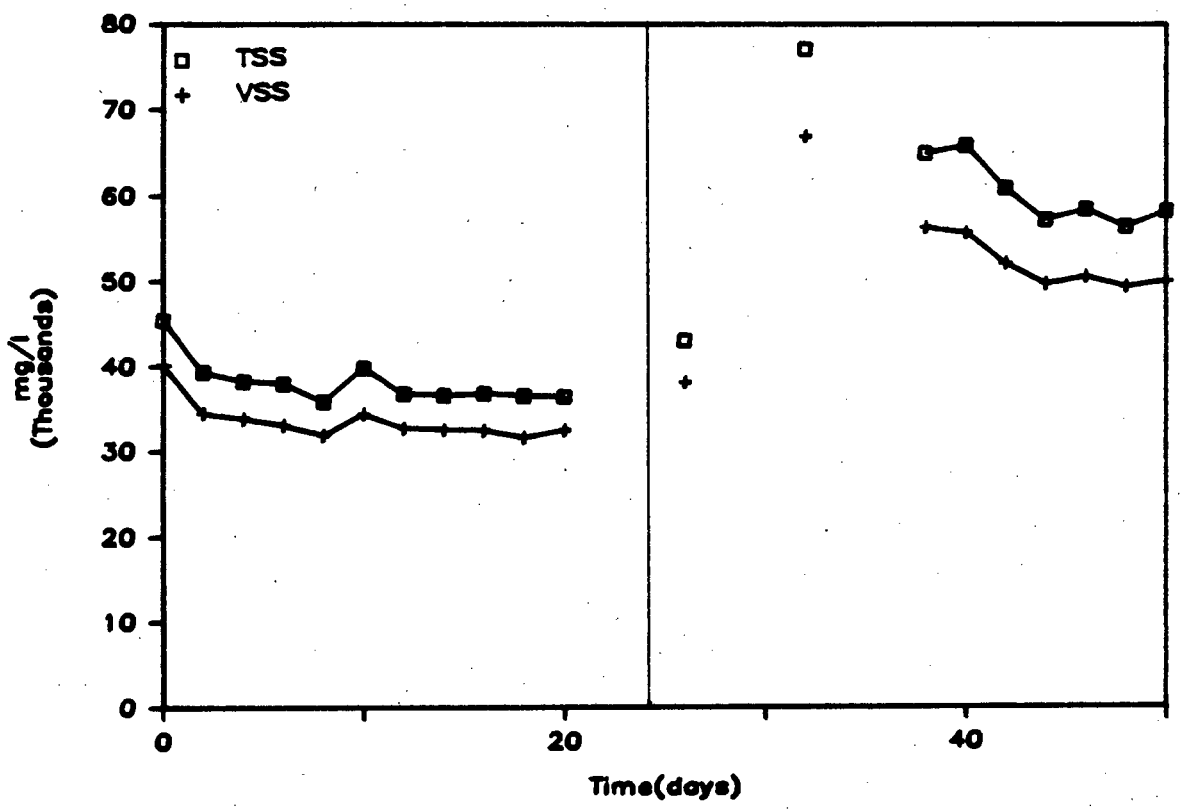

Fig D.38: TSS and VSS concentrations of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

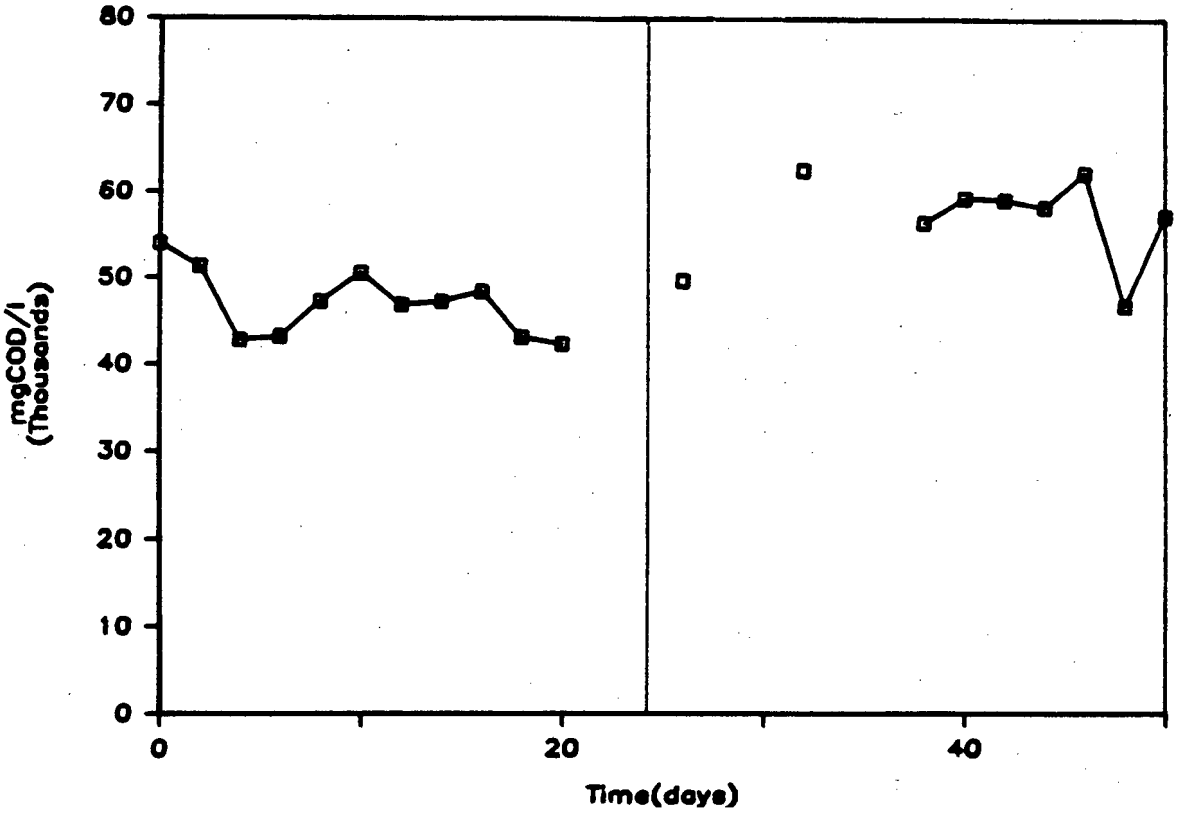

Fig D.39: COD of the VSS concentrations of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

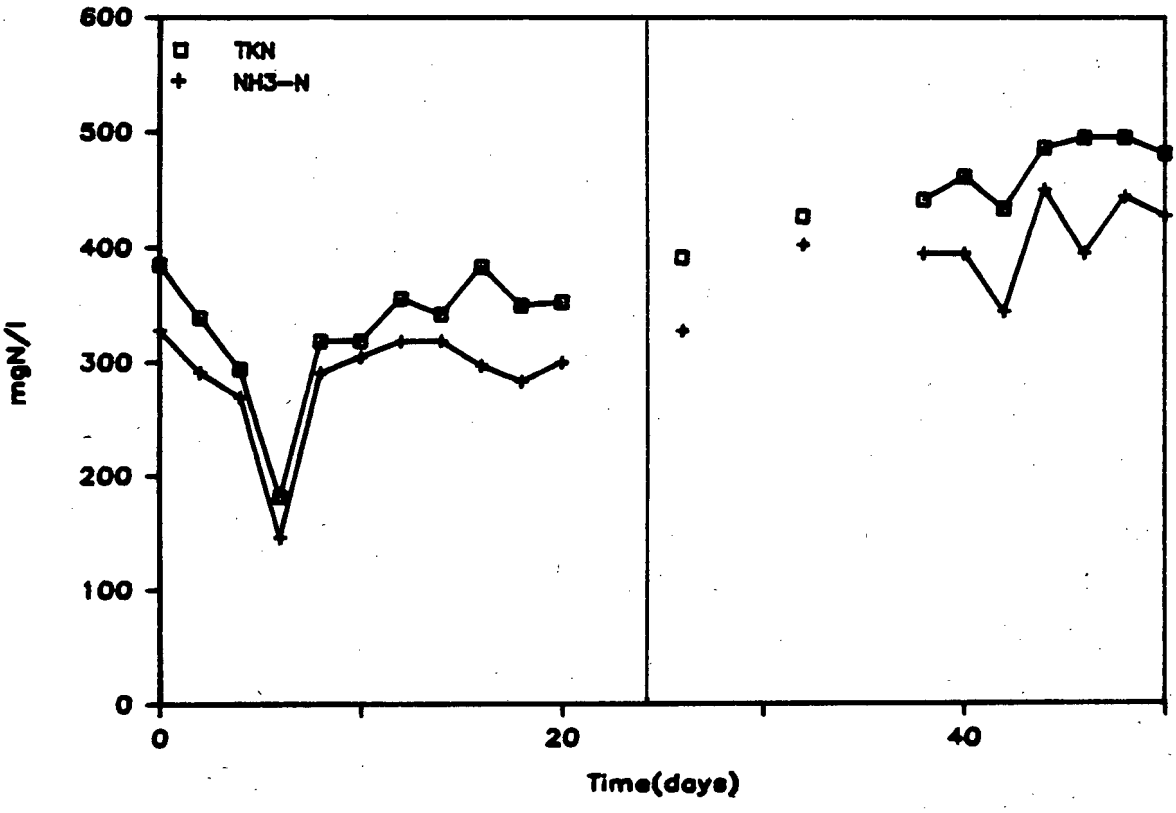

Fig D.40: TKN and NH_3-N concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

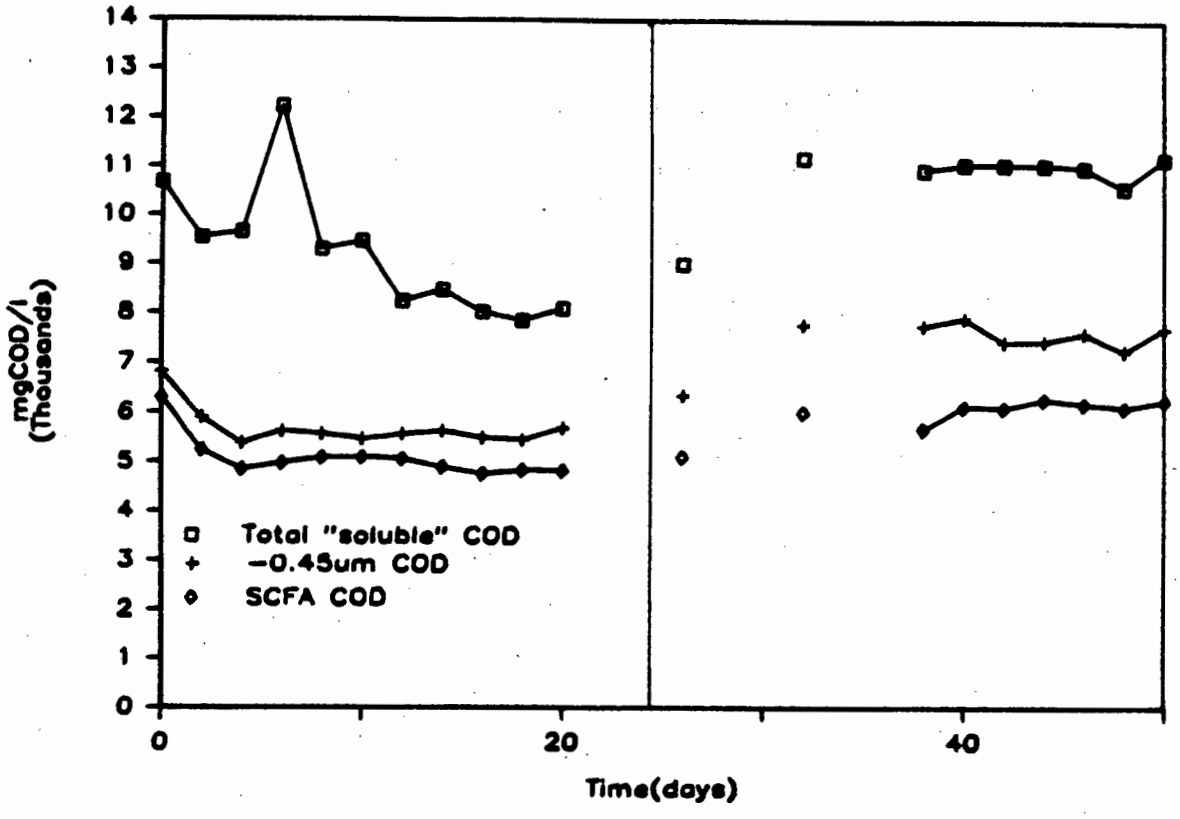

Fig D.41: Total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

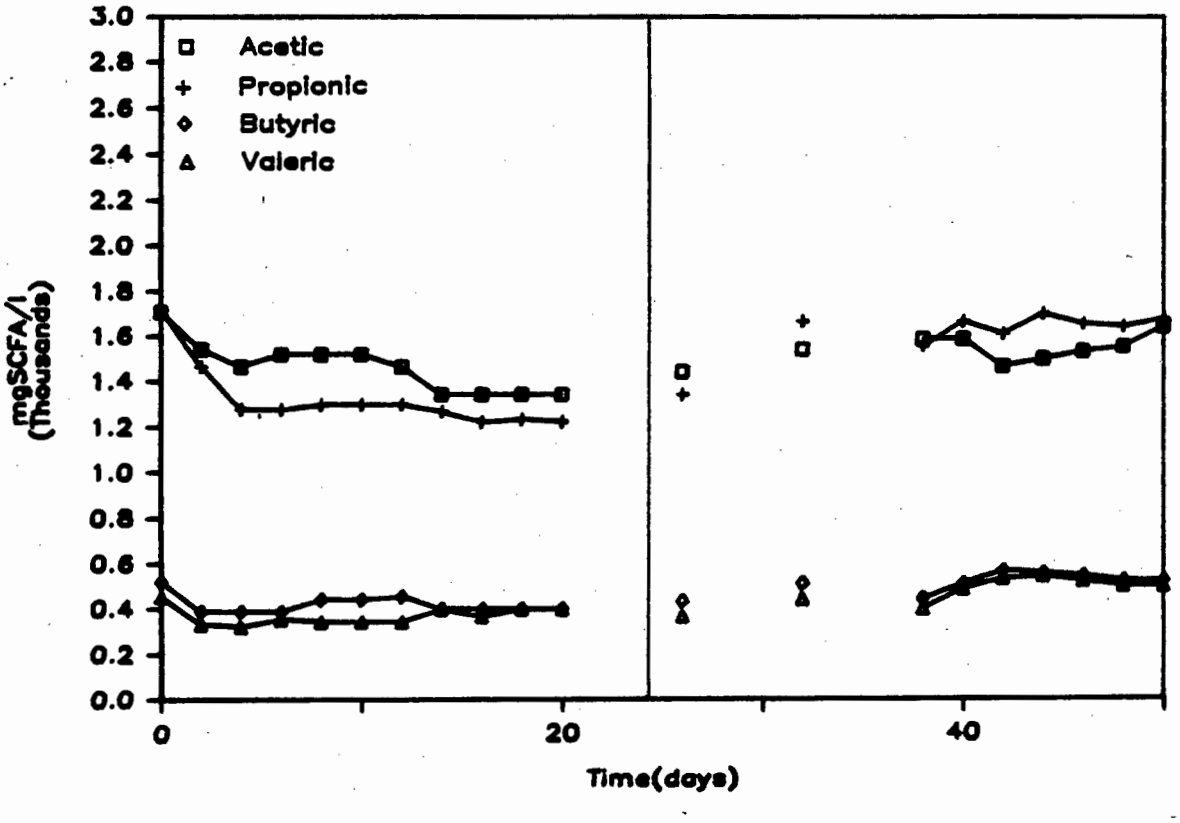

Fig D.42: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 3 days retention time versus time, for all sludge batches in stage 2.

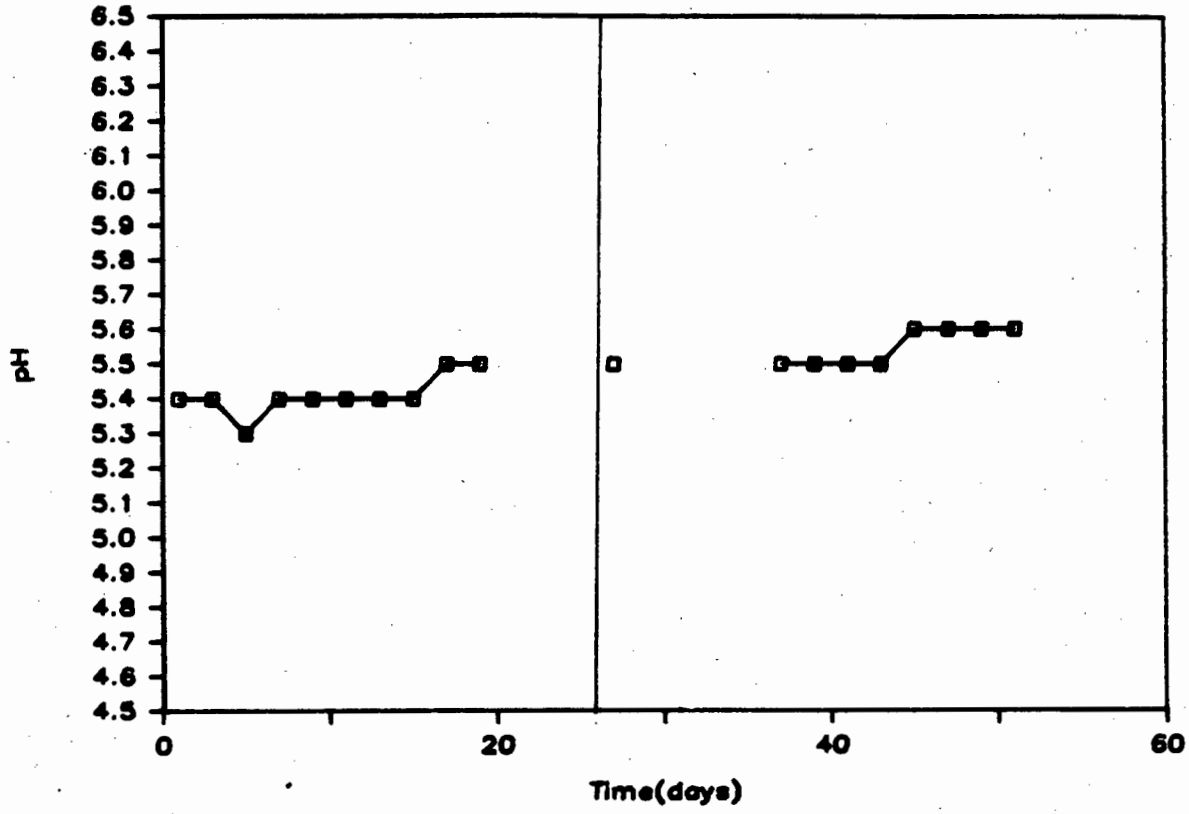

Fig D.43: pH of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

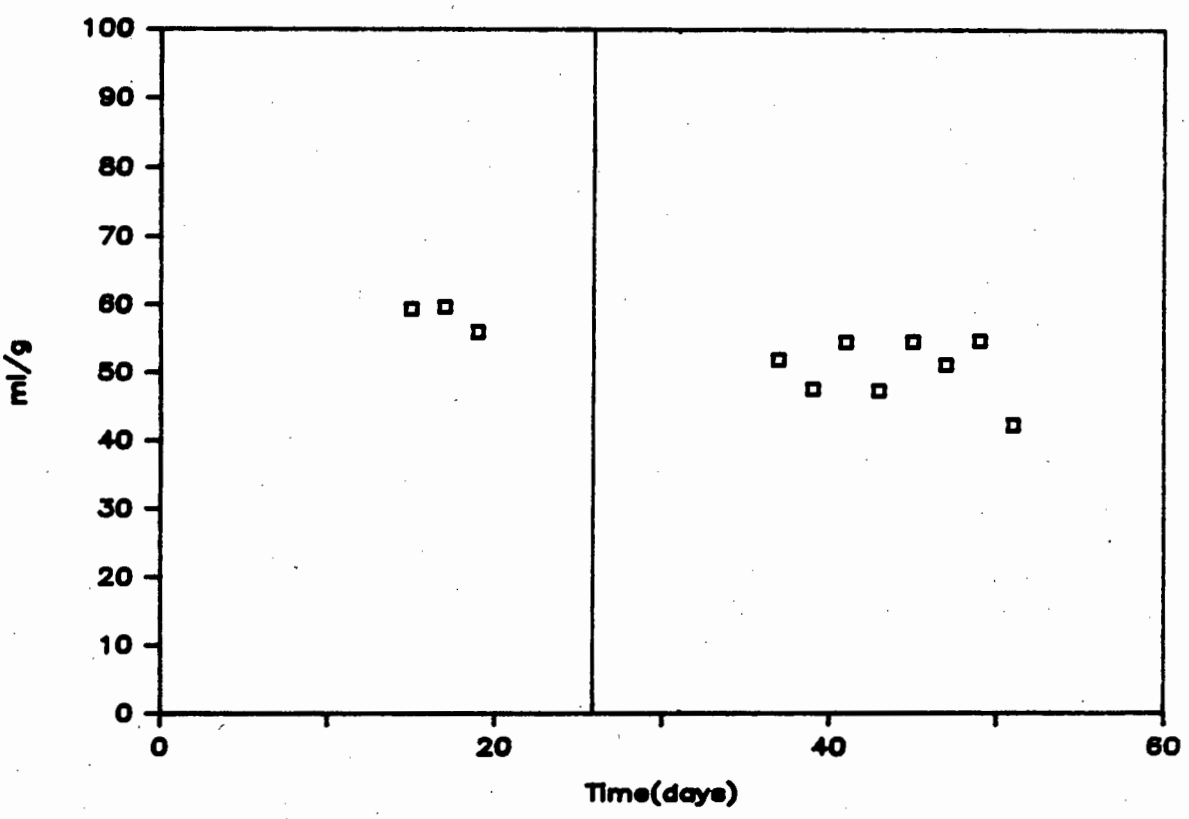

Fig D.44: DSVI of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

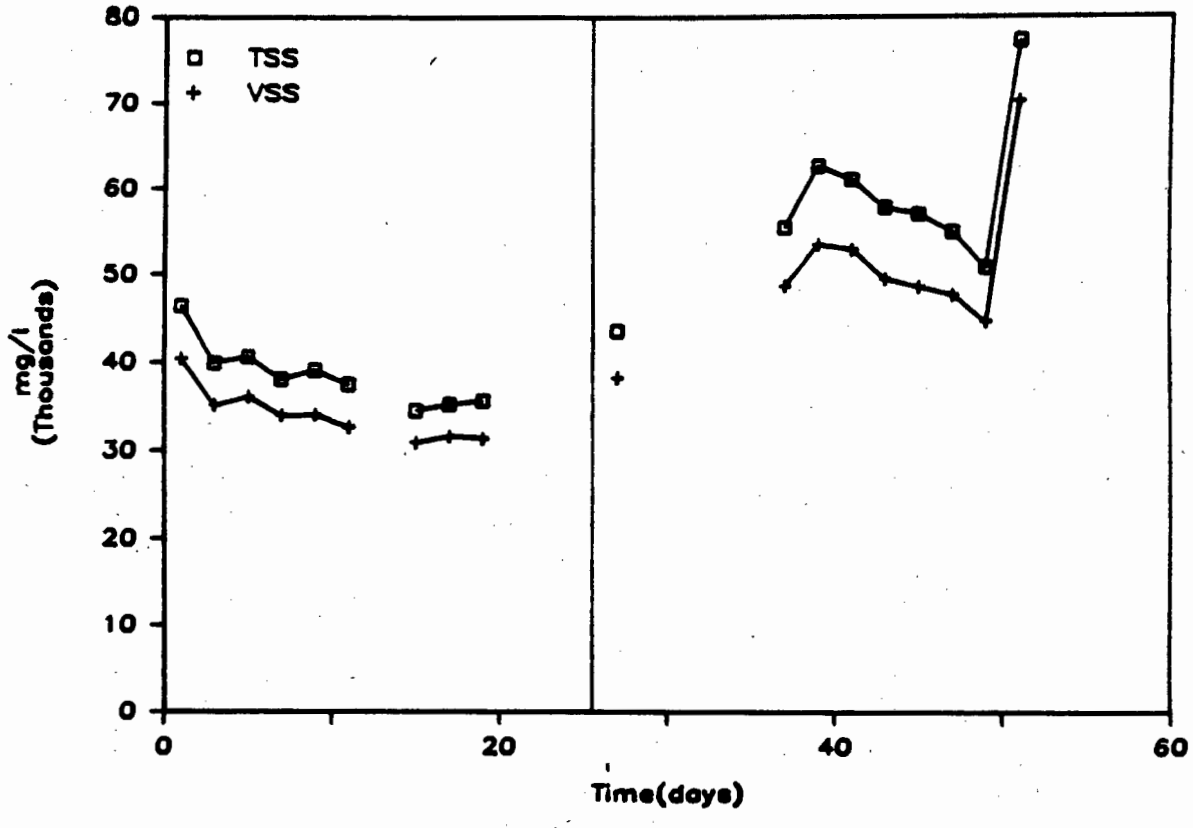

Fig D.45: TSS and VSS concentrations of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

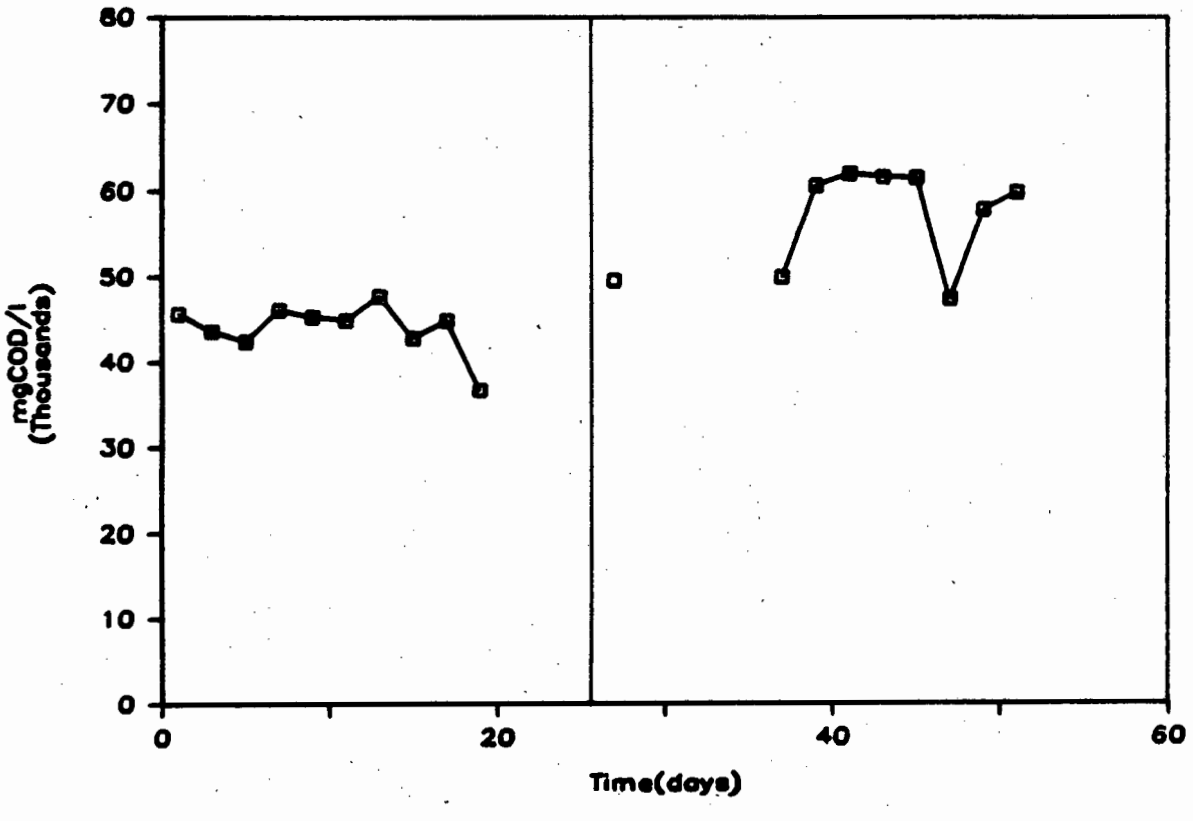

Fig D.46: COD of the VSS concentrations of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

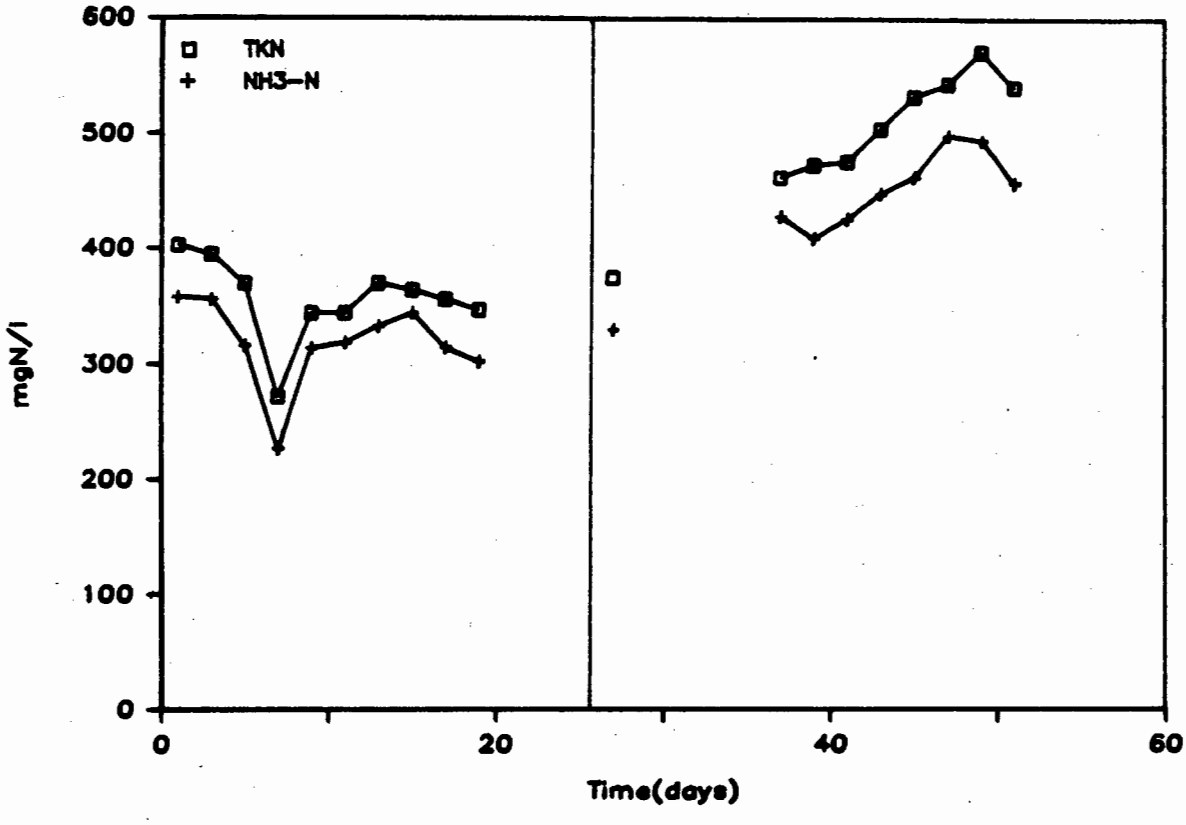

Fig D.47: TKN and NH_3-N concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

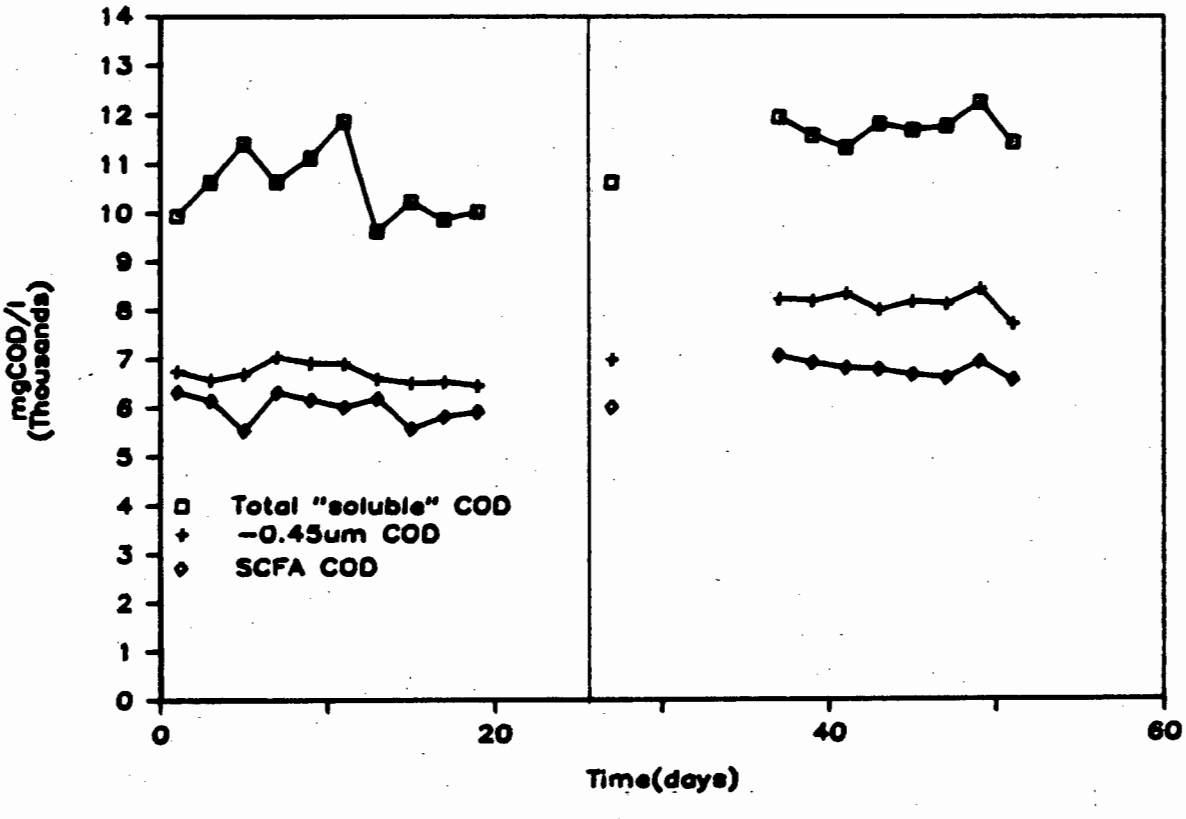

Fig D.48: Total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

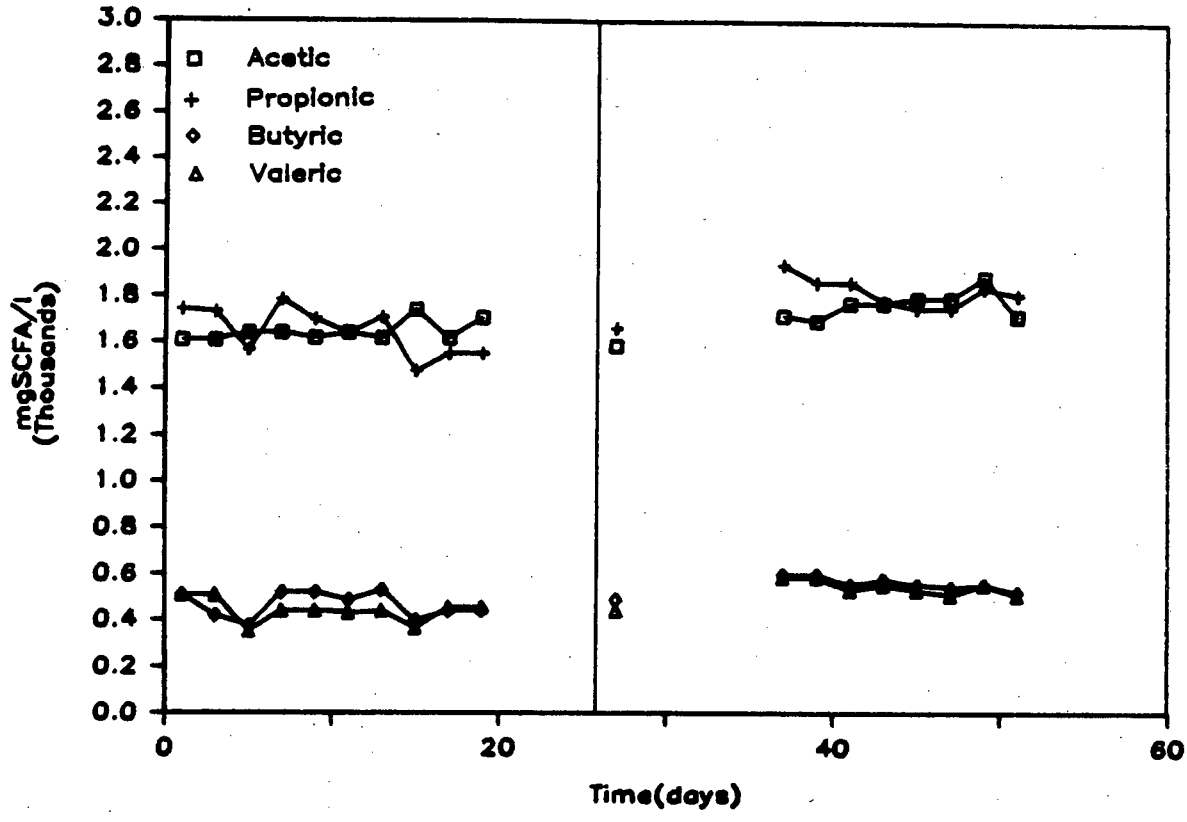

Fig D.49: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 6 days retention time versus time, for all sludge batches in stage 2.

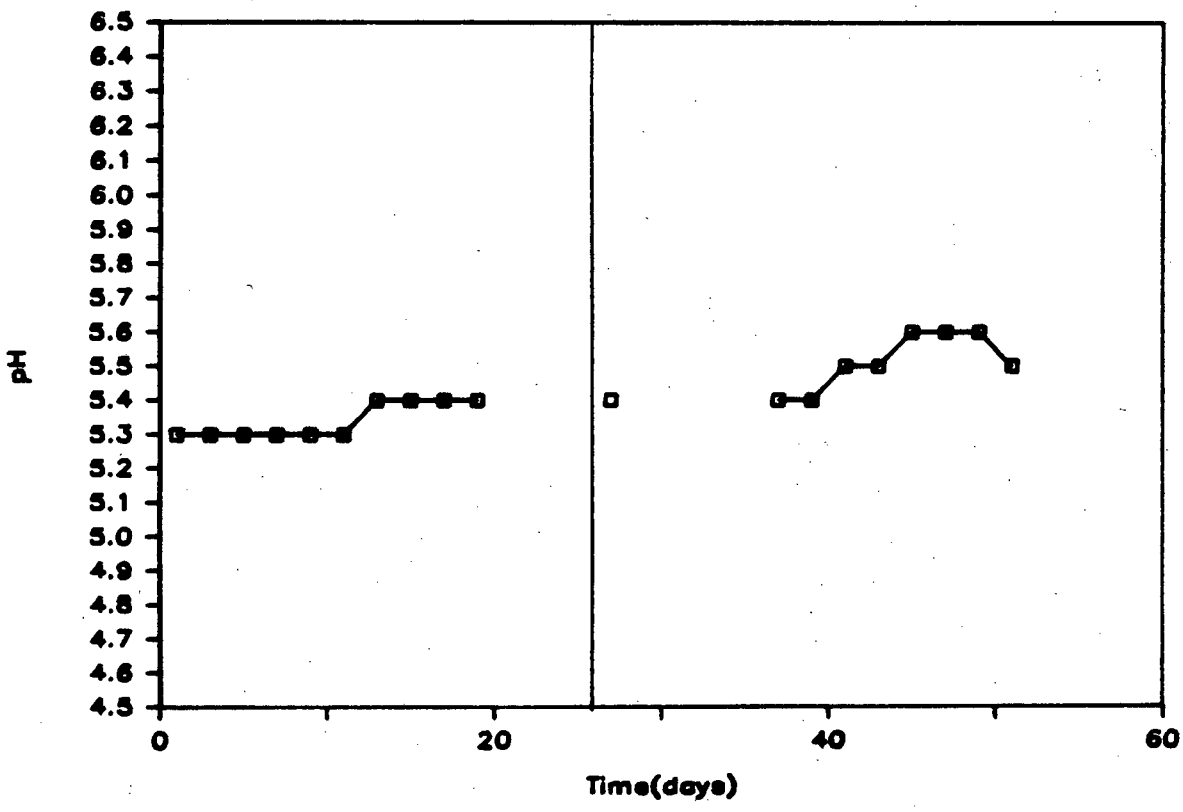

Fig D.50: pH of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.

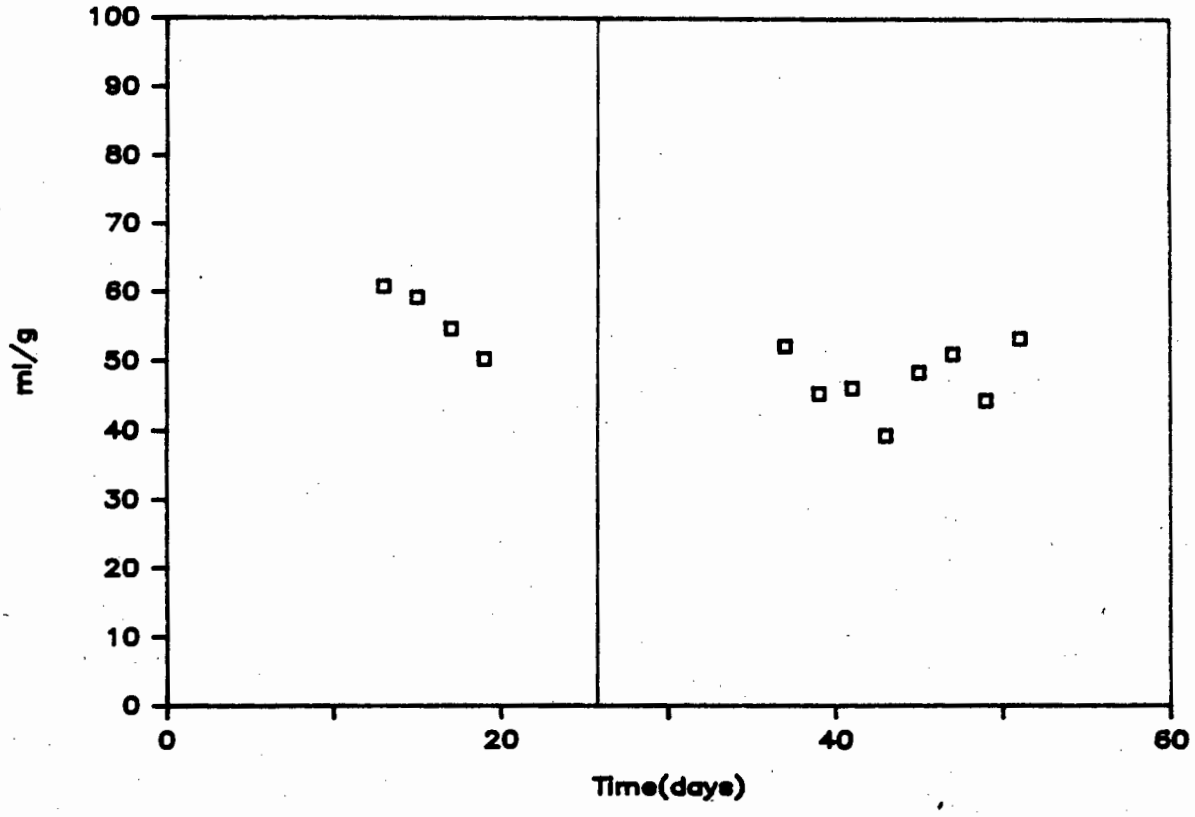

Fig D.51: DSVI of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.

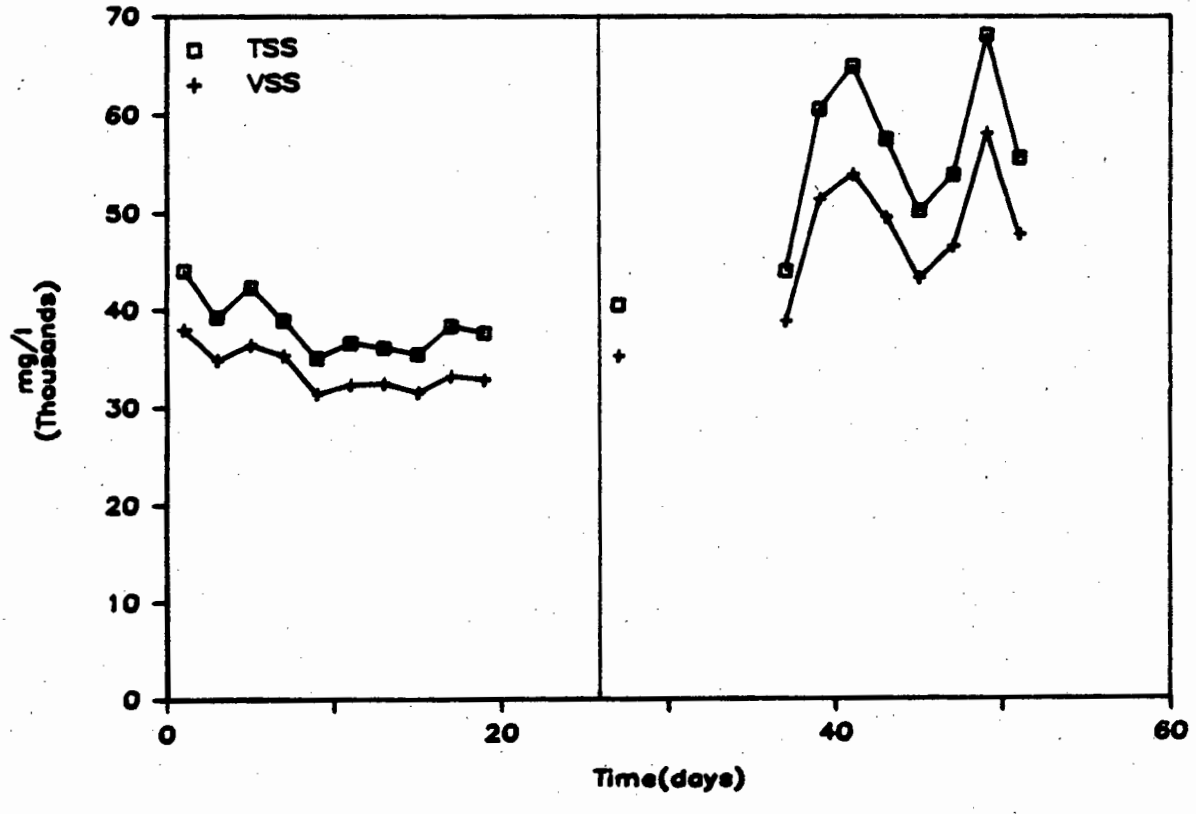

Fig D.52: TSS and VSS concentrations of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.

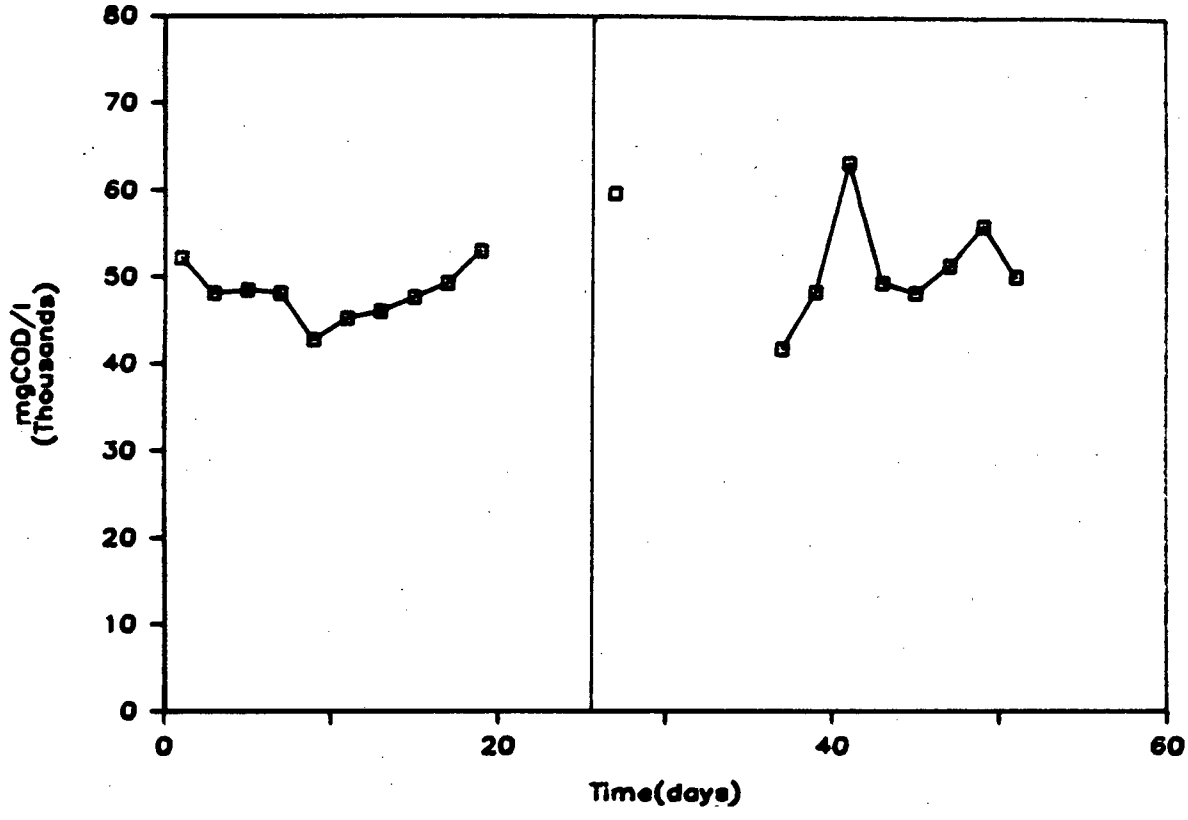

Fig D.53: COD of the VSS concentrations of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.

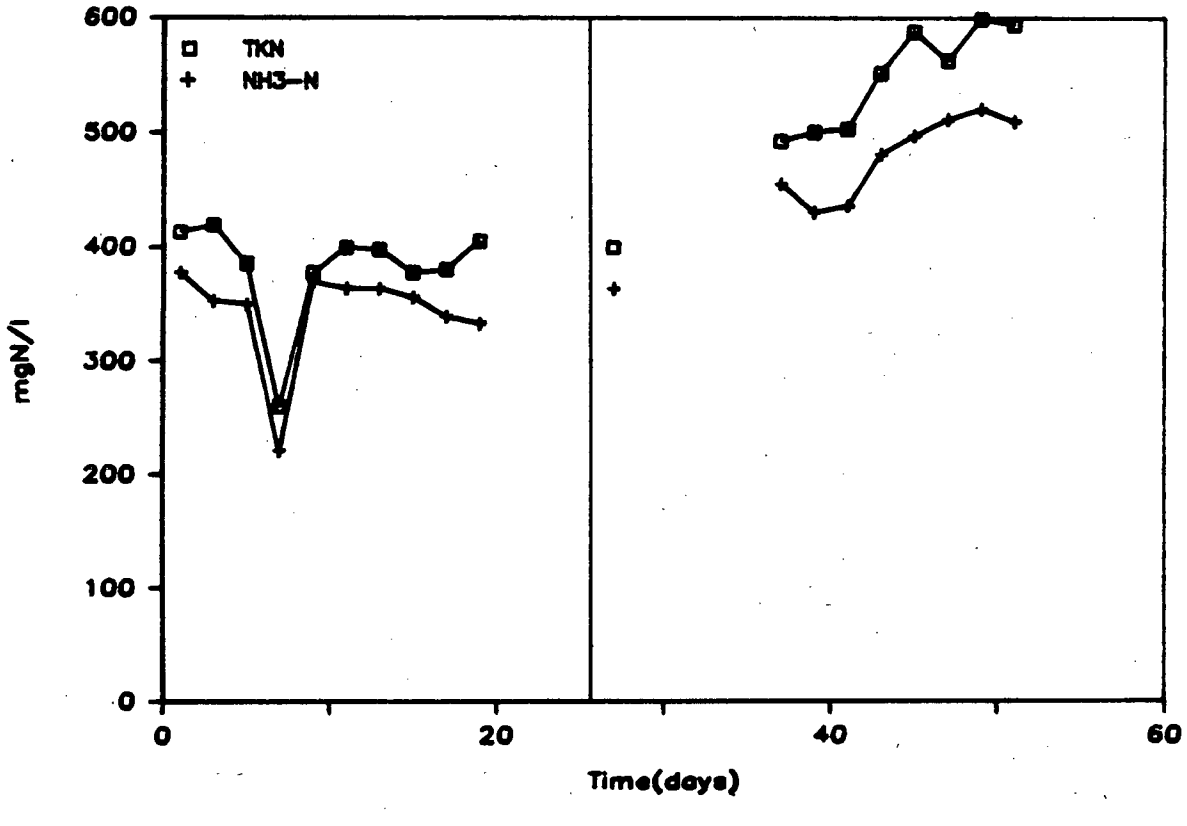

Fig D.54: TKN and NH_3-N concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.

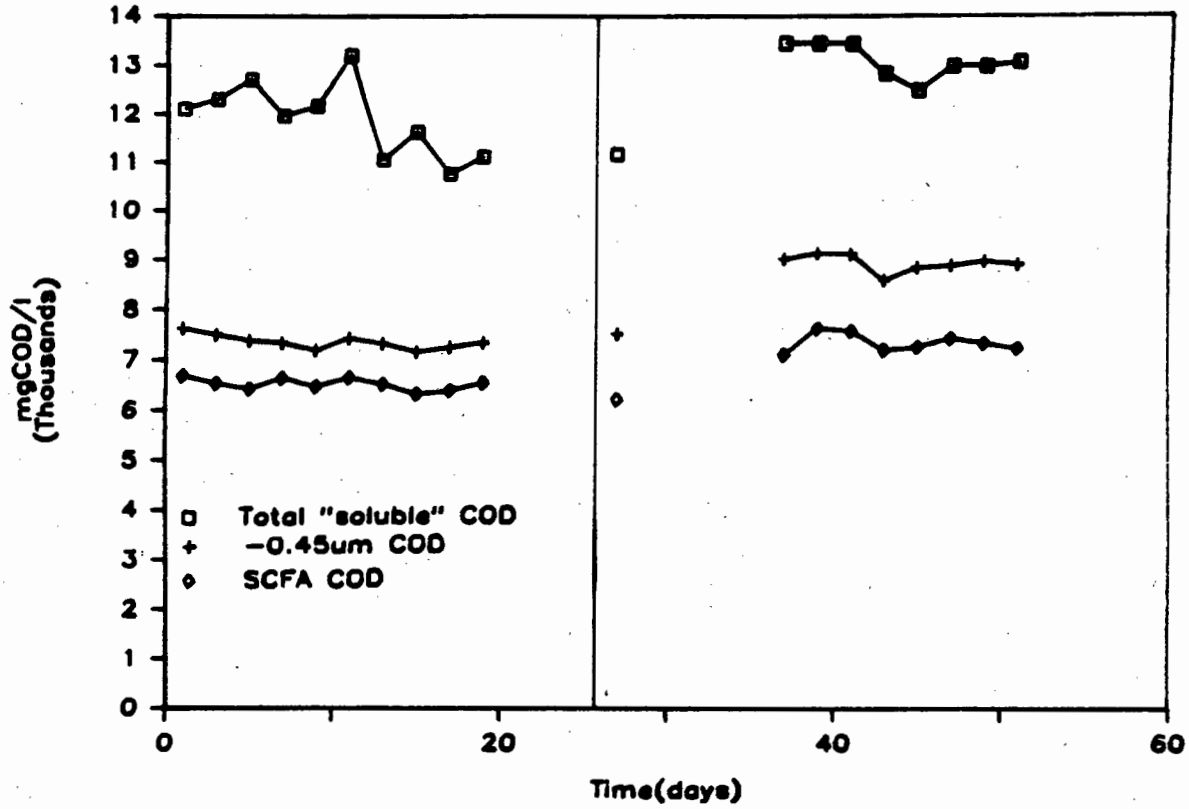

Fig D.55: Total 'soluble' COD concentration, COD and total SCFA COD concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.

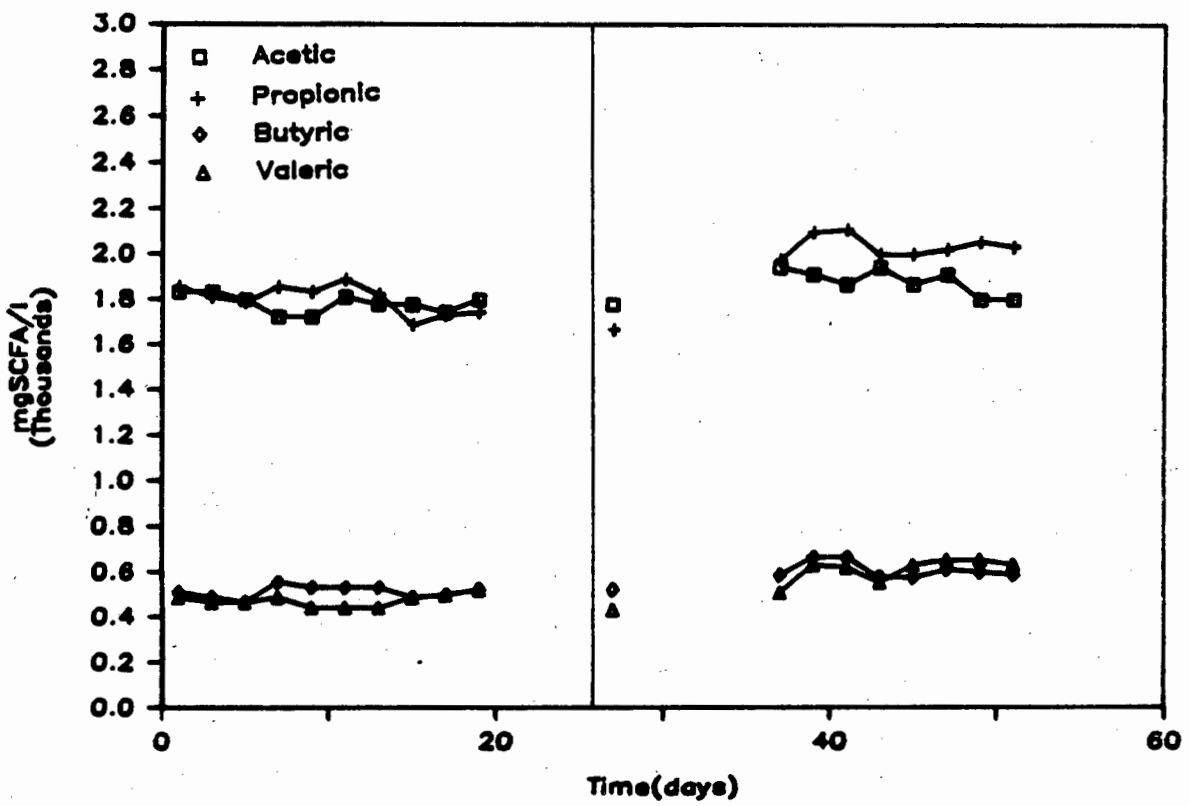

Fig D.56: Acetic, propionic, butyric and valeric acid concentrations of the –0,45μm filtrate of a single, completely mixed reactor of 9 days retention time versus time, for all sludge batches in stage 2.