



ORGANIC AND INORGANIC COMPONENTS OF ACTIVATED SLUDGE MIXED LIQUOR

by

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DECLARATION BY CANDIDATE

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

Signed

September 1997

raw (unsettled) municipal wastewater from Mitchells Plain (Cape Town, South Africa); this wastewater is principally domestic, with a minor industrial contribution (<15%). The wastewater was collected in batches, stored in stainless steel tanks at 4°C and served as feed for both the parent system and batch tests (see below) for 1 to 2 weeks. For the parent system, daily wastewater was drawn from the storage tanks after thorough mixing and diluted with tap water to give influent feed total COD ~ 500 mgCOD/l. System operational procedures detailed by Ekama *et al.* (1986) were followed. Daily monitoring included influent COD, TKN; all reactors nitrate + nitrite; aerobic reactor VSS, TSS, COD and TKN, OUR; effluent COD, TKN, nitrate + nitrite (Standard Methods, 1985). [Nitrite was <2% of nitrate and consequently could be neglected for this investigation]. Additionally, the inorganics in the influent, effluent and bioreactor were monitored (see below).

The parent system was operated for 450 days and received 28 batches of unsettled municipal wastewater from Mitchell's Plain, Cape Town. Each wastewater batch was accepted as a steady state period, and the results for each batch were averaged (after statistical analysis for outliers). From the averaged data the following were calculated:

- System COD and TKN mass balances.
- Influent wastewater unbiodegradable soluble and particulate fractions ($f_{S,us}$ and $f_{S,up}$ respectively).
- Mixed liquor VSS/COD and TKN/VSS ratios (f_{CV} and f_N respectively).
- The heterotrophic active biomass fraction of the mixed liquor organic suspended solids (f_{av}).
- The theoretical heterotrophic active biomass concentration in the steady state system bioreactor.

From the results on the parent system:

- N mass balances were variable, but generally fell in the range 90 to 110%. Sewage batches that gave mass balances falling outside this range were rejected for further analysis, unless an assignable could be found - on this basis data from five sewage batches (13, 14, 15, 16 and 21) were rejected.
- Generally COD mass balances were poor, with a number of sewage batches giving mass balances < 90%. The mixed liquor organic solids were determined by three independent tests - VSS, COD and TKN. Mean ratios for these measurements gave COD/VSS = 1.49 mgCOD/mgVSS (sample standard deviation = 0.08) and TKN/VSS = 0.106 mgN/mgVSS (sample standard deviation = 0.011). These values compare closely to the accepted standard values of 1.48 mgCOD/mgVSS and 0.10 mgN/mgVSS respectively (WRC, 1984). Accordingly it was accepted that the error in the COD mass balance did not lie in the measurement of the mixed liquor organic solids, the parameter of importance in both measurement of heterotrophic active biomass and in the inorganic materials investigation. The lower limit for the COD mass balance was set at 80%. On this basis, data from four sewage batches (2, 3, 13 and 14) were rejected for further analysis.
- The mean unbiodegradable soluble COD fraction ($f_{S,us}$) was determined to be 0.09 (sample standard deviation = 0.012).
- The mean unbiodegradable particulate COD fraction ($f_{S,up}$) was determined to be 0.12 (sample standard deviation = 0.04).

- The values for the unbiodegradable COD fractions conform closely to those recommended for a typical South African raw municipal wastewater, $f_{S,us} = 0.07$ and $f_{S,up} = 0.13$ respectively.
- Filament identifications indicated the presence of low F/M filaments, renamed anoxic aerobic (AA) filaments by Casey *et al.*, (1994a,b) and sludge settleability confirmed to the hypothesis of Casey *et al.* (1994a,b) for the proliferation of this group of filaments.

HETEROTROPHIC ACTIVE BIOMASS MEASUREMENT

From a review of the literature, it was evident that the problem in measurement of heterotrophic active biomass has been the lack of suitable experimental techniques. In the literature, principally microbiological techniques have been proposed; for example, pour plate or other culturing techniques (e.g. Gaudy and Gaudy, 1980), ATP analysis (Nelson and Lawrence, 1980), DNA analysis (Liebeskind and Dohmann, 1994), using florescent probes for ribosomal RNA (Wagner *et al.*, 1994). However, the results that these techniques provide have not yet been adequately integrated with the design and kinetic modelling theory, the culturing techniques have been widely criticized for their unreliability (e.g. Cloete and Steyn, 1988), the DNA method requires reliable quantitative DNA extraction which appears problematic (Liebeskind and Dohmann, 1994), the florescent probes are still in their infancy, and, the last-named three methods require relatively sophisticated equipment and experimental techniques that are not widely available.

In contrast, recently a simple batch test procedure has been developed to quantify the heterotrophic active biomass (Kappeler and Gujer, 1992; Wentzel *et al.*, 1995; Mbewe *et al.*, 1995). In this project, this batch test method was modified and adapted to quantify the heterotrophic active biomass of activated sludge mixed liquor. The modified method was evaluated by applying the batch test to mixed liquor samples drawn from the well defined parent laboratory-scale activated sludge system operated at sludge ages 12 and 20 d and comparing the measured values to those calculated theoretically with the models.

Two variations of the batch test procedure detailed by Wentzel *et al.* (1995) and Mbewe *et al.* (1995) were run. In one type, only unsettled municipal wastewater was added, and in the second a mixture of wastewater and mixed liquor. For both types of batch tests, wastewater was drawn from the storage tanks after thorough mixing and diluted to approximately the same COD concentration as that fed to the parent system (~ 500 mg COD/l). For the wastewater only batch tests, 3l of the diluted wastewater was preheated to 20°C and then placed in a continually stirred batch reactor, at a constant temperature of 20°C. A sample was drawn to obtain initial total COD concentration. In operating the batch test, the surface of the wastewater was covered with small plastic balls to limit surface exchange of oxygen. The OUR was monitored continually using an automated technique (Randall *et al.*, 1991). The pH was controlled to 7.5 (± 0.2). Because of the low OUR values, the walls of the reactor were thoroughly brushed (regularly during an aeration cycle) to prevent particulate matter adhering to them. At intervals, samples were drawn from the reactor, filtered (0.45 μ m) and analysed for nitrate + nitrite and nitrite (for the purpose of the batch test, nitrite concentrations were found to be negligible compared to nitrate concentrations, <1%). The batch tests were conducted for approximately 24h. At the end of the batch tests the contents of the batch reactor were homogenised, a sample drawn and total COD concentration measured.

For the mixture of wastewater and mixed liquor, a sample of mixed liquor was harvested from the aerobic reactor of the parent system and a defined volume (100 to 400 ml) placed in the batch reactor. The batch reactor volume was made up to 3ℓ with the same diluted unsettled municipal wastewater used in the wastewater only batch tests, also preheated to 20°C (see above). The batch test procedure detailed above was then followed.

As noted above for the parent system, 28 batches of wastewater served as influent. Batch tests were conducted during 7 wastewater batches with the parent system at 12d sludge age, and during 5 wastewater batches at 20d. In total 89 batch tests were conducted with wastewater only, and 115 with wastewater + mixed liquor.

From the batch tests data the following was calculated:

- COD recovery (%).
- Heterotrophic active biomass (X_H) at the start of the batch test: For the wastewater only batch tests, this gives X_H in the wastewater; for the wastewater + mixed liquor batch tests, this gives the X_H due to both the wastewater and mixed liquor.
- By difference between X_H in the two types of batch tests (taking due account of dilutions), the X_H due to the added mixed liquor was calculated - this represents the measured X_H .

Results from the batch tests indicated the following:

- For both the wastewater only and wastewater + mixed liquor batch tests, the %COD recoveries were good, with means of 96% and 102% respectively and sample standard deviations of 4% and 4% respectively. The good %COD recoveries lend credibility to the reliability of the measurements and to the batch test procedure.
- No nitrification was observed in the batch tests with wastewater only, indicating the absence of autotrophic organisms in the wastewater.
- For the batch tests with wastewater + mixed liquor, nitrification was observed since the mixed liquor added to the batch tests was drawn from a nitrifying activated sludge system. This nitrification could be closely approximated by two linear rates, a slower rate operating up to approximately the precipitous drop in OUR, followed by a second faster rate operating to the end of the batch test. This would indicate an inhibition of nitrification at the start of the batch test, possibly due to the RBCOD present in the wastewater. The OUR due to this nitrification was taken into account by subtracting it from the measured OUR, to give the OUR due to the heterotrophs only (OUR_H).
- The correlation coefficients (R^2) in linear regression of the $\ln OUR_{H(t)}$ - time plots (required to calculate X_H) generally are good; 1 and 11 batch tests for wastewater only and wastewater + mixed liquor respectively had $R^2 < 0.9$.
- For the wastewater only batch tests, the wastewater X_H ranged from 2.1 to 6.5% of total COD, with a mean of 4.5% and sample standard deviation of 1.1%. This mean agrees reasonably closely with the value measured by Mbewe *et al.* (1995) for the same wastewater (6.1%). The relatively low heterotrophic active biomass concentration for Mitchell's Plain wastewater is to be expected; this wastewater is primarily of domestic origin with a small industrial component (<15%) and the sewers are anaerobic and have a relatively short retention time (4-6 hours).

The measured X_H were compared to the theoretical values calculated for the parent system using the models:

- With the parent system at 12d sludge age the measured and theoretical mixed liquor X_H values correspond remarkably closely. With the parent system at 20d sludge age the measured and theoretical values show a close correlation; however, the values are not in agreement - the measured values are consistently lower, only about half the theoretical values. No logical explanation could be found for this inconsistency, and this aspect warrants further investigation.

MIXED LIQUOR INORGANIC COMPONENTS

From the parent laboratory-scale activated sludge system, samples were drawn from the influent, bioreactor and effluent. Part of the influent and effluent samples were filtered through $0.45\mu\text{m}$ filters, and filtered and unfiltered samples placed in preweighed crucibles. The bioreactor samples were centrifuged and the pellet transferred to preweighed crucibles. Following Standard Methods (1985), all crucibles + samples were dried in a 105°C oven for 24 hours, cooled in a desiccator and weighed. The crucibles + contents were then incinerated in a 600°C oven for at least 20 minutes, removed, cooled in a desiccator and weighed. (All organic/volatile material will burn off at 600°C within 20 minutes, and only inorganic material (ash) will remain in the crucible). The difference in weight between the crucibles and the crucibles + contents after 105°C drying gives the total solids, and the difference in weight between the crucibles + contents after 600°C incineration and after 105°C drying gives the organic/volatile solids. The difference between the total and organic/volatile solids gives the inorganic solids. Accordingly:

From the *unfiltered* influent and effluent data the following were determined:

- Total solids (TS), influent and effluent.
- Total volatile solids (TVS), influent and effluent.
- Total inorganic solids (TIS), influent and effluent.

Accepting that filtration through $0.45\mu\text{m}$ separates reasonably closely the dissolved and suspended fractions, from the *filtered* influent and effluent data the following were determined:

- Total dissolved solids (TDS), influent and effluent.
- Volatile dissolved solids (VDS), influent and effluent.
- Inorganic dissolved solids (IDS), influent and effluent.

By difference between the *unfiltered and filtered* fractions respectively above, the suspended/particulate fractions for the influent and effluent were calculated as follows:

- Total suspended solids (TSS) = TS - TDS, influent and effluent.
- Volatile suspended solids (VSS) = TVS - VDS, influent and effluent.
- Inorganic suspended solids (ISS) = TIS - IDS, influent and effluent.

For the bioreactor, the samples were centrifuged and thus are suspended/particulate. Accordingly, the bioreactor samples give directly:

- Total suspended solids (TSS), bioreactor.
- Volatile suspended solids (VSS), bioreactor.
- TSS - VSS = Inorganic suspended solids (ISS), bioreactor.

From the data the following could be concluded:

- Considering that the inorganics were determined as the difference between two measured parameters (total solids - volatile solids) and that for the filtered influent and effluent samples the inorganic weights were relatively small compared to the weights of the crucibles, the % inorganic recoveries were surprisingly good; for the 28 wastewater batches tested the mean % inorganic recovery was 94%, with sample standard deviation 5.5%.
- Of the influent inorganics, only a small fraction were incorporated into the activated sludge mixed liquor, 2.8 to 7.5%; by far the vast majority of the influent inorganics left the system with the effluent, 75 to 92%, and a relatively small amount as dissolved/soluble inorganics in the waste stream, 3 to 5.5%.
- In the influent most of the inorganics were in the dissolved form; for the 28 wastewater batches tested, mean ratio of dissolved to total inorganics was 88%, with sample standard deviation 5%.
- In the effluent the inorganics were almost exclusively in the dissolved form; for the 28 wastewater batches tested, mean ratio of dissolved to total inorganics was 98.5%, with sample standard deviation 3%.
- For all the wastewater batches tested, the influent total inorganic solids concentrations were larger than the effluent total inorganic solids concentrations. However, for 14 of the 28 wastewater batches tested, the difference was statistically insignificant at the 95% confidence interval.
- Comparing the influent and effluent dissolved inorganic solids concentrations, the ratio effluent to influent was 100% with sample standard deviation 7%. In 22 out of 28 wastewater batches tested, the differences were statistically insignificant at the 95% confidence interval. This would indicate that the influent and effluent inorganic dissolved solids were closely equal.

From the measurements, a number of approaches to model the incorporation of the inorganics into the activated sludge mixed liquor were developed and evaluated. With regard to these models the following conclusions could be drawn:

- Simple models based on the incorporation of a fraction of the influent inorganic suspended solids (ISS) or total inorganic solids (TIS) are not appropriate: The predictions with the simple TIS model are superior to those from the ISS based model, but both models cannot predict correctly the observed effect of sludge age on bioreactor ISS.
- The more fundamental model, based on the concepts incorporated in the steady state model for aerobic COD removal (WRC, 1984), provides predicted bioreactor ISS and effluent inorganic dissolved solids (IDS) concentrations that correlate reasonably closely with those measured. In particular, the model predicts correctly the observed effect of sludge age on bioreactor ISS.

CONCLUSIONS

Fundamental to the current steady state design and kinetic simulation models for activated sludge systems is the parameter heterotrophic active biomass (X_H). This mixed liquor organic suspended solids component mediates the biodegradation processes of COD removal and denitrification (and associated processes), and, in the models all relevant specific rates are expressed in terms of it. Although recently X_H has gained more acceptance than in the past, it would seem that this is due to the convenience of computer programmes based on the models, rather than substantive proof of its validity so that the parameter remains hypothetical within the structure of the models. Thus, to promote confidence in application of the models for design, operation and control of activated sludge systems, and indeed in the models themselves, it is essential that X_H is validated by experimental measurement. In this project a simple batch test procedure has been used to quantify the X_H concentration of mixed liquor drawn from a well-defined parent anoxic/aerobic activated sludge system. The results obtained are both encouraging and perplexing. With the parent system at 12d sludge age, the agreement between measured and theoretical values is remarkably good. However, with the parent system at 20d sludge age the agreement is poor, with the theoretical values being about 2 times those measured. No explanation could be found for this inconsistency. The results do indicate that the batch test method may prove to be a valuable tool that can be used to provide greater insight into the behaviour of the aerobic and anoxic/aerobic activated sludge systems. However, in systems that include biological phosphorus removal the method will not be of use. In these systems the heterotrophic organisms mediating the phosphorus removal are present also and the batch test will not be able to distinguish between the two groups of heterotrophic organisms. Furthermore, experimental evidence from such systems indicates that there are behaviours in these systems that are not recognized in the models (Ekama and Wentzel, 1997). For example, for the same wastewater there is an inconsistency in the sludge production between aerobic and anoxic/aerobic systems on one hand and anaerobic/anoxic/aerobic systems on the other; also, the sludge production in anaerobic/anoxic/aerobic systems has been found to be linked to filamentous bulking. In the current models both these observations have to be taken into account by using different influent unbiodegradable particulate COD fractions (a wastewater characteristic) which markedly affects the X_H as a fraction of the mixed liquor organic suspended solids (active fraction, f_{av}), clearly an unacceptable solution.

In developing models for the incorporation of inorganics into the activated sludge mixed liquor, it would appear that the best approach is to follow the concepts and principles used to develop the existing models for organic materials. A first simple model using this approach has been successfully developed and evaluated in this research project. The model can form the basis for further development, to focus and stimulate research into areas where knowledge is deficient; for example, the model highlights the lack of knowledge on the physical/chemical processes that lead to "entrapment" of inorganics in the activated sludge mixed liquor.

RECOMMENDATIONS

From this investigation the following recommendations can be made.

- For the activated sludge heterotrophic active biomass, the inconsistency between the results obtained at parent system sludge ages of 12d and 20d is of concern. From the data

that are available, it is not possible to determine whether this inconsistency is due to the batch test method, or due to a deficiency in the models themselves, or simply due to an aberration in the behaviour of the parent activated sludge system from which the mixed liquor was drawn. This aspect clearly requires further investigation.

- For the activated sludge mixed liquor inorganics, the more fundamental model developed can form the basis for further investigations. Specific tasks that require attention are:
 - The model was evaluated against data from the laboratory-scale system at sludge ages 12d and 20d. The model needs to be tested over a wider range of sludge ages, say at 5d and 30d.
 - The model includes incorporation of influent inorganic materials into the activated sludge matrix, to take account of processes such as inorganics entrapment, adsorption and precipitation. Two approaches to model these processes have been developed and evaluated, based on influent total inorganic solids (TIS) and inorganic suspended solids (ISS). For the laboratory-scale system operated here, the TIS approach provides better predictions than the ISS approach. However, observations on systems treating raw and settled wastewaters would suggest that the ISS approach may be superior. It was concluded that with the data available it is not possible to make a definitive judgement as to which approach is superior. This requires investigation. Also, factors influencing the relative magnitude of the incorporation of influent inorganic materials into the activated sludge matrix need to be investigated - is this closely constant for a wide range of systems, or are there a number of factors that influence it, e.g. pH, alkalinity, influent composition?

CLOSURE

The models for the single sludge activated sludge system have achieved widespread acceptance and have had a significant impact on the approach to design, operation and control of the activated sludge system, and on the research into its' behaviour. However, this acceptance should not inhibit critical evaluation of the principles on which the models are based; the danger exists that through the convenience of computer programmes incorporating the models, the models will begin to adopt a reality of their own. The models will always need to be used with great circumspection and the results obtained interpreted in terms of experience from real systems; the models are a convenient tool to aid research, design and operation of activated sludge systems and should not be regarded as a substitute for knowledge and experience.

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LIST OF SYMBOLS

AA	Anoxic-aerobic
AO	Acridine orange
AODC	Acridine orange direct count
AOE	Acridine orange epifluorescence
ATP	Adenosine triphosphate
BA	Biological activity
b_{HT}^*	Specific endogenous mass loss rate at temperature T, endogenous respiration theory (/d)
b_{H20}^*	Specific endogenous mass loss rate at 20°C, endogenous respiration theory (/d)
b_{HT}	Specific endogenous mass loss rate at temperature T, death regeneration theory (/d)
b_{H20}	Specific endogenous mass loss rate at 20°C, death regeneration theory (/d)
BEPR	Biological excess phosphorus removal
BNR	Biological nutrient removal
C	Carbon
°C	Degrees Celsius
Ca	Calcium
COD	Chemical Oxygen Demand
$COD_{t=0}$	Total unfiltered COD concentration at start of test (t=0) (mgCOD/ℓ)
$COD_{t=T}$	Total unfiltered COD concentration at end of test (t=T) (mgCOD/ℓ)
d	Day
DNA	Deoxyribonucleic acid
DO	Dissolved Oxygen (mgO/ℓ)
DSVI	Diluted sludge volume index (ℓ/gTSS)
e^-	Electron
e.g.	For example
EDTA	Ethylene diamine tetra acetic acid
f	Endogenous residue fraction
FDA	Fluoresceine diacetate
FISH	Fluorescent in situ hybridization
f_E^*	Fraction of heterotrophic active biomass that is endogenous residue
$f_{S,up}$	Unbiodegradable particulate fraction of the influent (mgCOD/mgCOD)
$f_{S,us}$	Unbiodegradable soluble fraction of the influent COD (mgCOD/mgCOD)
f_N	Nitrogen to COD ratio of mixed liquor (mgN/mgCOD)
f_{av}	Active fraction of the volatile suspended solids (mgAVSS/mgVSS)
f_{cv}	COD to VSS ratio of the mixed liquor (mgCOD/mgVSS)
h	Hour
H	Hydrogen
H^+	Hydrogen ion
H_2O	Water
i.e.	That is
IAWQ	International Association on Water Quality
IDS	Inorganic dissolved solids (mgIDS/ℓ)
INT	2- (p- codophenyl) -5- phenyl tetrazolium chloride

ISS	Inorganic suspended solids (mgISS/ℓ)
IVS	Total inorganic volatile solids (mgIVS/ℓ)
ℓ	Litre
Mg	Magnesium
$M(\text{IDS}_{\text{eff}})$	Mass of total inorganic dissolved solids in effluent (mgIDS/d)
$M(\text{ISS}_{\text{wasted}})$	Mass of total inorganic solids wasted from reactor (mgISS/d)
MLE	Modified Ludzack-Ettinger
ML	Mixed liquor
MLOSS	Mixed liquor organic suspended solids
MLSS	Mixed liquor total suspended solids concentration (mgTSS/ℓ)
MLVSS	Mixed liquor volatile suspended solids concentration (mgVSS/ℓ)
$M(\text{TIS}_{\text{inf}})$	Mass of total inorganic solids in influent (mgTIS/ℓ)
$M(X_{\text{BA}})$	Mass of autotrophic active biomass (mgVSS)
$M(X_{\text{BH}})$	Mass of heterotrophic active biomass (mgVSS)
$M(X_{\text{E}})$	Mass of endogenous material (mgVSS)
$M(X_{\text{I}})$	Mass of inert material (mgVSS)
$M(X_{\text{V}})$	Mass of volatile suspended solids (mgVSS)
NaCl	Sodium chloride
NAD	Nicotinamide adenine dinucleotide (oxidized)
NADH	Nicotinamide adenine dinucleotide (reduced)
N	Nitrogen
N_2	Nitrogen gas
NH_3	Ammonia (mgN)
NH_4^+	Ammonium (mgN)
No.	Number
NO_2^-	Nitrite (mgN)
NO_3^-	Nitrate (mgN)
$\Delta\text{NO}_3/\Delta t$	nitrification rate (mgN/ℓ/h)
O	Oxygen
OD	Optical density
OUR	Oxygen utilisation rate (mgO/ℓ/h)
$\text{OUR}_{\text{H}(t)}$	Heterotrophic active biomass oxygen utilization rate at time t (mgO/ℓ/h)
$\text{OUR}_{\text{M}(t)}$	OUR measured at time t (mgO/ℓ/h)
$\text{OUR}_{\text{N}(t)}$	Autotrophic oxygen utilization rate at time t (mgO/ℓ/h)
P	Phosphorus
polyP	Polyphosphate
PVC	Poly vinyl chloride
Q or Q_i	influent flow (ℓ/d)
RBCOD; S_{bsi}	Readily biodegradable COD (mgCOD/ℓ)
rDNA	Ribosomal deoxyribonucleic acid
R_s	Sludge age (d)
RNA	Ribonucleic acid
s	Second
SBCOD; S_{bpi}	Slowly biodegradable COD (mgCOD/ℓ)
SCFA	Short chain fatty acids
SLR	Sludge loading rate (mgCOD/mgVSS)
SSD	Sample standard deviation

S_{te}	Filtered effluent COD concentration (mgCOD/ ℓ)
S_{ti}	Unfiltered influent COD concentration (mgCOD/ ℓ)
t	Time
TDS	Total dissolved solids (mgTDS/ ℓ)
TIS	Total inorganic solids (mgTIS/ ℓ)
TKN	Total Kjeldahl Nitrogen (mgN/ ℓ)
TS	Total solids (mgTS/ ℓ)
TSS	Total suspended solids (mgTSS/ ℓ)
TVS	Total volatile solids (mgTVS/ ℓ)
UCT	University of Cape Town
USCOD	Unbiodegradable soluble COD (mgCOD/ ℓ)
μm	Micrometer
V_p	Volume of reactor (ℓ)
VDS	Volatile dissolved solids (mgVDS/ ℓ)
V_{ML}	Volume of mixed liquor added to batch test (ℓ)
V_{WW}	Volume of wastewater added to batch test (ℓ)
WRC	Water Research Commission
WW	Wastewater
X_{BA}	Autotrophic active biomass concentration (mgVSS/ ℓ)
X_{BH}	Heterotrophic active biomass concentration (mgVSS/ ℓ)
X_E	Endogenous material concentration (mgVSS/ ℓ)
X_I	Inert material concentration (mgVSS/ ℓ)
$X_t(\text{PS})$	Mixed liquor TSS concentration in parent system (mgVSS/ ℓ)
X_V	Volatile suspended solids concentration (mgVSS/ ℓ)
$X_V(\text{PS})$	Mixed liquor VSS concentration in parent system (mgVSS/ ℓ)
Y_H	Heterotrophic active biomass yield, COD units (mgCOD/mgCOD)
Y_{ZH}^*	Heterotrophic active biomass yield, VSS units (mgVSS/mgCOD)
Y_{ZA}	Autotrophic biomass yield (mgCOD/mgN)
Y_{ZH}	Heterotrophic active biomass yield (mgVSS/mgCOD)
$Z_{BH(o)}$	Heterotrophic active biomass concentration at the start of the batch test (mgCOD/ ℓ)
$Z_{BH(o)}(\text{ML})$	Heterotrophic active biomass due to added mixed liquor (mgCOD/ ℓ)
$Z_{BH(o)}(\text{WW})$	Heterotrophic active biomass in original wastewater (mgCOD/ ℓ)
$Z_{BH(o)}(\text{WW})_D$	Heterotrophic active biomass due to wastewater at the start of batch test with wastewater + mixed liquor (mgCOD/ ℓ)

CHAPTER 1

INTRODUCTION

To comply with more stringent effluent quality legislations, over the past 20 years there have been extensive developments in the activated sludge method for treating wastewater. The functions of the single sludge system have expanded from carbonaceous energy removal to include progressively nitrification, denitrification and phosphorus removal, all mediated biologically. These extensions have increased considerably the complexity of the system configuration and its operation. Concomitantly, the number of biological processes influencing the effluent quality and the number of compounds involved in these processes have increased. With such complexity, design procedures based on experience and semi-empirical methods no longer will give optimal performance; design procedures based on more fundamental behavioural patterns are required. Furthermore, it is no longer possible to make reliable quantitative predictions as to the effluent quality to be expected from a design, or to assess the effect of a system or operational modification, without some model that simulates the system behaviour accurately. To meet these requirements, increasingly sophisticated, fundamentally based steady state design procedures (e.g. Marais and Ekama, 1976; WRC, 1984) and dynamic kinetic simulation models (e.g. Dold *et al.*, 1980, 1991; Henze *et al.*, 1987, 1995; Wentzel *et al.*, 1992) have been developed. Through their successful use and application, this group of models have achieved widespread acceptance and have had a significant impact on the approach to design, operation and control of the activated sludge system, and on the research into its' behaviour.

This group of models is based, to a large degree, on a common simplified conceptualization of the mechanisms operating in the activated sludge system, which has developed particularly from an understanding of the interactions between the components making up the mixed liquor in the bioreactor of the activated sludge system, and the influent wastewater. In terms of this conceptualization, in the bioreactor of the activated sludge system the mixed liquor is made up of organic and inorganic materials.

Mixed liquor organic components

In terms of the conceptual framework of the models, in the bioreactor of the non-nitrifying aerobic activated sludge system the mixed liquor organic suspended solids is made up of three components; (1) heterotrophic active biomass, (2) endogenous residue and (3) inert material. In the nitrifying aerobic and anoxic/aerobic activated sludge systems, a fourth mixed liquor organic suspended solids component is included; (4) autotrophic active biomass. The heterotrophic active biomass arises from synthesis of living heterotrophic organisms on biodegradable organic substrates and is "lost" via endogenous respiration/death processes; in the activated sludge system this mixed liquor component performs the biodegradation processes of COD removal and denitrification. The autotrophic active biomass arises from synthesis of autotrophic organisms in the nitrification of ammonia to nitrate under aerobic conditions and is "lost" via endogenous respiration/death processes. The endogenous residue is generated from the unbiodegradable portion of the heterotrophic and autotrophic active biomasses that are lost in the endogenous respiration/death processes. The inert material arises from the influent wastewater unbiodegradable particulate organics which, on entry into the bioreactor, are enmeshed in the

mixed liquor organic suspended solids. All four mixed liquor organic suspended solid components settle out in the secondary settling tank and are returned to the bioreactor via the underflow recycle; these components leave the activated sludge system via the waste flow.

If an anaerobic reactor is included in the system to stimulate biological excess phosphorus removal (BEPR), additionally the organisms mediating the BEPR [variously termed polyP organisms (Wentzel *et al.*, 1986), bio P organisms (Comeau *et al.*, 1986), phosphate accumulating organisms (PAO, Henze *et al.*, 1995)] will contribute to the mixed liquor organic suspended solids - to avoid this complication, *only the aerobic and anoxic/aerobic systems will be considered in this research project.*

Historically, the mixed liquor organic suspended solids have been measured as a lumped parameter, via the volatile suspended solids test (Standard Methods, 1985), or, more recently, the COD test. Specific rates for the biological processes (e.g. denitrification, oxygen utilization) often were, and still are, expressed in terms of this lumped parameter. However, from the description above, in the bioreactor of the aerobic and anoxic/aerobic activated sludge systems only a part of the mixed liquor organic suspended solids is heterotrophic active biomass, the active fraction, and only this part mediates the biological processes of COD removal and denitrification. The active fraction of the mixed liquor organic suspended solids will vary depending on the influent wastewater characteristics and system design/operating parameters (WRC, 1984). Accordingly, the rates for these biological processes are directly related to the amount of heterotrophic active biomass present, and the specific rates should be expressed in terms of this parameter to allow a meaningful comparison of the rates measured in different systems. More recently, with the proliferation of kinetic simulation computer programmes that invariably include heterotrophic active biomass as a parameter, this parameter and the use of specific rates in terms of it seem to have become almost universally accepted. However, it must be remembered that this parameter exists only hypothetically within the structure of the design procedures and kinetic models: Although indirect evidence provides support for this parameter (by consistency between observations and predictions over a wide range of conditions, e.g. Dold *et al.*, 1980, 1991; Van Haandel *et al.*, 1981; Warner *et al.*, 1986), it has not been directly measured experimentally and compared to the theoretical values. This deficiency must cast a measure of uncertainty on the entire framework within which the steady state design and kinetic simulation models have been developed. The problem in measurement of the heterotrophic active biomass parameter has been the lack of suitable experimental techniques: In the literature, principally microbiological techniques have been proposed; for example, (i) pour plate or other culturing techniques (e.g. Gaudy and Gaudy, 1980), (ii) adenosine triphosphate (ATP) analysis (Nelson and Lawrence, 1980), (iii) deoxyribonucleic acid (DNA) analysis (Liebeskind and Dohmann, 1994), and (iv) fluorescent probes for ribosomal RNA (Wagner *et al.*, 1994). However, these microbiological techniques have not yet been adequately integrated with the design and kinetic modelling theory. Furthermore, the culturing techniques [(i) above] have been widely criticized for their unreliability (e.g. Cloete and Steyn, 1988), the DNA methods [(iii) above] requires reliable quantitative DNA extraction which appears problematic (Liebeskind and Dohmann, 1994), the fluorescent probes are still in their infancy, and, the last three methods [(ii), (iii) and (iv) above] require very sophisticated equipment and experimental techniques that are not widely available

In contrast, recently a simple batch test procedure has been developed to quantify heterotrophic active biomass (Kappeler and Gujer, 1992, Wentzel *et al.*, 1995, Mbewe *et al.*, 1995). In this

project, this batch test method will be modified and adapted to quantify the heterotrophic active biomass of activated sludge system mixed liquor. The modified method will be evaluated by applying the test to mixed liquor samples drawn from a well defined laboratory-scale activated sludge system and comparing these measured values to those calculated theoretically with the models: If agreement between measured and predicted heterotrophic active biomass can be obtained, this will provide powerful evidence validating both the models and the experimental method. ***Thus, measurement of heterotrophic active biomass is the first principle objective of this research.***

Mixed liquor inorganic components

In both the steady state design procedures and kinetic simulation models, the influent wastewater characteristics and biological processes that influence the bioreactor mixed liquor organic solids (as volatile suspended solids, VSS, or COD) are explicitly included. However, the mixed liquor total suspended solids (TSS, i.e. organic + inorganic solids) is calculated simply from an empirical ratio of VSS/TSS, the value for this ratio being accepted as one constant for activated sludge systems treating raw (unsettled) wastewater (VSS/TSS = 0.75 mgVSS/mgTSS, WRC, 1984) and another constant for those treating settled wastewater (VSS/TSS = 0.83 mgVSS/mgTSS, WRC, 1984). The TSS concentration (X_t) is fundamental in the design of secondary settling tanks and waste activated sludge disposal. Clearly, the empirical approach to obtaining an estimate for X_t is not satisfactory within a fundamentally based model. ***Accordingly, incorporation of the inorganic material present in the influent wastewater into the mixed liquor requires investigation - This is the second principle objectives of this research project.***

Research objectives

From the discussion above, it is evident that the organic and inorganic components making up the mixed liquor in the bioreactor of the activated sludge system are of fundamental importance in the group of design and simulation models more commonly used for the activated sludge system. Accordingly, ***the principle aim of this research project is to investigate the organic and inorganic components/materials making up the mixed liquor in the bioreactor of the activated sludge system.*** To achieve this aim, two primary objectives for this research project have been identified. These are listed below, together with specific tasks to be completed to address the objectives:

- (1) To experimentally quantify the heterotrophic active biomass concentration of activated sludge mixed liquors and compare these to the theoretical values using the steady state design and kinetic simulation models: If agreement between measured and predicted heterotrophic active biomass can be obtained, this will provide a powerful evidence validating both the models and experimental methods. Specific tasks are:
 - Review and evaluate existing methods for quantifying heterotrophic active biomass, to identify the more promising methods for further development and modification.
 - Apply the modified test to quantify the heterotrophic active biomass of mixed liquor samples drawn from a well defined activated sludge system.

- Compare the measured heterotrophic active biomass concentrations to theoretical values calculated using the steady state design and kinetic simulation models.
- (2) To investigate the incorporation of inorganic material into activated sludge system mixed liquor. Specific tasks to be completed are:
- To determine the distribution of the inorganic materials in the influent wastewater, that is, dissolved (soluble) and particulate (suspended).
 - To determine the fate of the various influent inorganic fractions in the activated sludge system bioreactor, e.g., does the particulate (suspended) material become solubilised, or *vice versa*.
 - To set up design procedures that will enable the mixed liquor inorganic material (ISS), and hence TSS, to be calculated from measurements made on the influent wastewater inorganic materials.

Research approach

The research approach adopted was to operate and monitor a well-defined and controlled parent laboratory-scale activated sludge system (Chapter 4). This parent system provided the mixed liquor samples required for measuring heterotrophic active biomass to address objective (1) above (Chapters 5 and 6). Also, the inorganics present in the influent wastewater to the parent system and in the bioreactor and effluent of the system were monitored, to address objective (2) above (Chapters 7).

CHAPTER 2

ACTIVATED SLUDGE SYSTEM MIXED LIQUOR ORGANIC AND INORGANIC FRACTIONS

2.1 INTRODUCTION

To optimize the design and operation of the single sludge activated sludge system, over the past two decades a number of steady state design models (e.g. Marais and Ekama, 1976; WRC, 1984; Wentzel *et al.*, 1990; Scheer and Seyfried, 1993; Maurer and Gujer, 1994) and kinetic simulation models (e.g. Dold *et al.*, 1980, 1991; Van Haandel *et al.*, 1981; Henze *et al.*, 1987, 1995, Wentzel *et al.*, 1992; Gujer *et al.*, 1995) have been developed, to progressively include aerobic COD removal and nitrification, anoxic denitrification and anaerobic/anoxic/aerobic biological excess phosphorus removal. These models enable system design and operational parameters to be readily identified, provide guidance in selecting values for these parameters and quantify the expected behaviour of the system.

This group of models are based, to a large degree, on a common conceptual framework which has been developed from an understanding of the mechanisms operating in the activated sludge system, particularly from an understanding of the interactions between the components making up the mixed liquor in the bioreactor and the influent wastewater. In this Chapter, this conceptual framework will be outlined briefly, to provide an overview of the current understanding of the processes that operate in the bioreactor and give rise to the various mixed liquor components, and how these processes relate to the influent wastewater. From this overview, the importance of the mixed liquor component heterotrophic active biomass and the deficiencies in the understanding of how inorganic materials are incorporated into the mixed liquor, will become evident.

2.2 FATE OF INFLUENT WASTEWATER IN ACTIVATED SLUDGE SYSTEM

The activated sludge system comprises a biological reactor and a secondary settling tank. Irrespective of whether or not biological N and/or P removal are included, many different biological and physical processes take place in the biological reactor, and the physical process sedimentation takes place in the secondary settling tank. These processes form the basis for subdividing the influent wastewater, carbon (C), nitrogen (N) and phosphorus (P) materials into subfractions (see Fig 2.1). On entry of the influent into the biological reactor, the particulate materials, which include both settleable and suspended (non-settleable or colloidal), organic and inorganic materials, are enmeshed (a biologically mediated flocculation) and become part of the activated sludge mixed liquor. The soluble materials, both organic and inorganic, remain in solution. In the biological reactor, the bacteria present will act on the biologically utilizable material, termed *biodegradable*, whether organic or inorganic, soluble or particulate, and transform these to other compounds or products, either gaseous, soluble or particulate. The gaseous products escape to the atmosphere, the particulate products become (or remain) part of the mixed liquor solids and the soluble products become (or remain) dissolved in solution. The non-biologically utilizable material, termed *unbiodegradable*, will not be transformed and will remain in either the soluble or particulate form. Following from the processes in the bioreactor,

the first major division of the influent is based on whether the material is *biodegradable* or *unbiodegradable*, see Fig 2.1.

After biological treatment the flow passes from the biological reactor to the secondary settling tank. In the secondary settling tank, the particulate materials making up the mixed liquor (whether organic or inorganic, biodegradable or unbiodegradable) settle out and are returned to the biological reactor. The particulate components of the mixed liquor entering the settling tank are thus retained in the system. All the soluble components of the mixed liquor (whether organic or inorganic, biodegradable or unbiodegradable) cannot settle out and escape with the effluent, see Fig 2.1.

The settling behaviour in the secondary settling tank therefore forms the basis for subdividing the influent *unbiodegradable* material into subfractions: The influent unbiodegradable material passes unmodified through the biological reactor to the secondary settling tank; ideally all the particulate (and colloidal) material settles out in the secondary settling tank and these constituents are therefore termed *unbiodegradable particulate*, the soluble constituents cannot settle out so that these constituents are termed *unbiodegradable soluble*, see Fig 2.1. With regard to the influent *biodegradable* material, because a substantial amount of this material has been biologically transformed in the biological reactor preceding the secondary settling tank, it cannot be subdivided into subfractions based on its behaviour in the secondary settling tank; subdivision of the biodegradable material is based on the rates of transformation/utilization by the bacteria in the biological reactor (see below).

From the above, in terms of the conceptualization of the activated sludge system behaviour, the wastewater constituents are characterized (1) biologically, i.e. as biodegradable (biologically utilizable) or unbiodegradable (non-biologically utilizable) material, and (2) physically, i.e. as soluble or particulate material. Therefore, for the models based on fundamentals of behaviour, it is necessary to divide the influent constituents into at least three components:

- biodegradable
- unbiodegradable soluble
- unbiodegradable particulate.

This general wastewater characterization structure (see Fig 2.2) conforms to the biological degradation and physical solid/liquid separation processes that take place in the activated sludge system.

From the description above:

- (1) The unbiodegradable soluble component of the influent passes unmodified through the bioreactor to the secondary settling tank, and passes out in the secondary settling tank overflow to appear in the effluent; therefore, this influent component has no influence on the mixed liquor solids, but does influence the effluent quality.
- (2) The unbiodegradable particulate component of the influent, on entry into the bioreactor is enmeshed in the mixed liquor mass and will settle out in the secondary settling tank to be retained in the system; thus this influent component has a direct influence on the mixed

liquor solids in the reactor, but no influence on the effluent quality. The unbiodegradable particulate component leaves the system with the mixed liquor wasted to maintain the sludge age.

- (3) The biodegradable component of the influent is transformed by biological action in the bioreactor to other compounds or products, either gaseous, soluble or particulate; the particulate compounds/products will settle out in the secondary settling tank to be retained in the system and will therefore influence the mixed liquor solids in the reactor; the soluble components will not settle out in the secondary settling tank and so will pass out in the effluent while the gaseous components will escape to the atmosphere - these two components will not, therefore, influence the mixed liquor solids.

Thus, the mixed liquor solids present in the bioreactor will be comprised of components arising directly from the influent and from biological transformations of the influent. This conceptualization of the fate of the influent components in the activated sludge system can be applied to any material in the influent, organic or inorganic. For aerobic and anoxic/aerobic systems it has been applied to the organic materials, both carbonaceous and nitrogenous, but has not been applied to the inorganic materials (see Section 2.5 below). Of particular interest to this discussion is the organic carbonaceous material. The carbonaceous material usually is quantified by means of the chemical oxygen demand (COD) test, which measures the electron, or equivalently energy, donating capacity of organic material, so that in effect the conceptualization of the fate of the influent is applied to the electrons (e^-) in the carbonaceous material.

2.3 BIOLOGICAL TRANSFORMATIONS OF THE ORGANIC CARBONACEOUS MATERIAL IN THE BIOREACTOR

As noted above, the biodegradable components of the influent wastewater are biologically transformed in the bioreactor to other components or products, either gaseous, soluble or particulate. In the steady state design and dynamic kinetic simulation models, the biological transformations of the organic carbonaceous materials are explicitly included, and directly influence the organic solids in the bioreactor. It is important, therefore, to gain a basic understanding of the approach adopted in the models to describe these transformations

2.3.1 Organism groups

In the bioreactor of the activated sludge system a wide diversity of organism species have been identified. However, in both the steady state design and dynamic kinetic simulation models it has been recognized that including a complete description of every organism species would be impractical. Instead microorganisms that fulfill a particular function in the activated sludge system are grouped together as a single entity which has been called a "surrogate" organism. This surrogate organism is assigned a set of unique characteristics that reflect the behaviour of the group, but may not reflect the characteristics of any individual organism or species of organisms in the group. Thus, for modelling of activated sludge systems the "organizational level" (Odum, 1971) that is followed is the mass behaviour of a population or group of selected organisms; these populations or groups are identified and selected based on identifiable functions. The principle organism groups, their functions and the zones in which these functions are performed are summarized in Table 2.1. This research project considers only the aerobic and anoxic/aerobic

activated sludge systems. Thus, two organism groups need to be taken into account; (i) heterotrophic organisms unable to accumulate polyP, termed heterotrophs and (ii) autotrophic organisms mediating nitrification, termed autotrophs or nitrifiers. The biological transformation mediated by these two organism groups are described below.

Table 2.1: Principle organism groups included in models for activated sludge systems, their functions and the zones in which these functions are performed.

ORGANISM	BIOLOGICAL PROCESS	ZONE
1. Ordinary heterotrophs (unable to accumulate polyP)	• COD removal (organic degradation; DO uptake)	Aerobic
	• Ammonification (organicN- NH_4^+)	Aerobic
	• Denitrification (organic degradation; NO_3^- - NO_2^- - N_2)	Anoxic
	• Fermentation (F-RBCOD-SCFA)	Anaerobic
2. PolyP heterotrophs (accumulate polyP)	• P release (SCFA uptake; PHA storage)	Anaerobic
	• P release (SCFA uptake; PHA storage)	Anoxic
	• P uptake (PHA degradation; denitrification?)	Anoxic
	• P uptake; P removal (PHA degradation; DO uptake)	Aerobic
3. Autotrophs (nitrifiers)	• Nitrification (NH_4^+ - NO_2^- - NO_3^- ; DO uptake)	Aerobic

2.3.2 Heterotrophic organisms

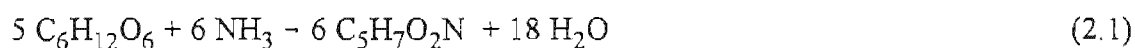
The heterotrophic organisms obtain both energy and carbon from complex organic compounds. This is a diverse group of organisms, which, given sufficient time and appropriate environmental conditions, will utilize every type of organic material. The group is ubiquitous and in any given situation those members of the group that derive maximum benefit from the specific organic material and environmental conditions will develop. As the organic source and environmental conditions change, so associated changes in the heterotrophic organism species take place.

As noted above, for the purpose of modelling the activated sludge system the heterotrophic organism species are grouped together as "surrogate" which is assigned a unique set of characteristics reflecting the behaviour of the group. This group of organisms mediates the processes of COD removal and denitrification. Conceptually, in the models this "surrogate"

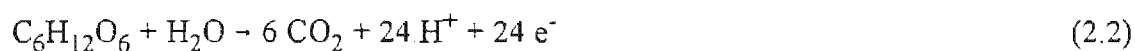
heterotroph is subject to two main biological processes; (i) synthesis or growth and (ii) endogenous mass loss/death.

(i) Synthesis/growth

For the heterotrophic organisms, the organic material in the influent serves two functions: (a) it is the supply of materials which are transformed into new cell materials, and (b) it is the supply of energy to effect these transformations. In terms of the models, on entry into the bioreactor some of the influent organic materials are transformed (via a number of biochemical pathways, collectively called anabolism) to new heterotroph cell material. Accepting the general formulation for protoplasm as $C_5H_7O_2N$ (McCarthy 1964), with glucose as an example substrate the synthesis reaction can be summarized as:



This synthesis/growth process requires energy. The energy is obtained as follows: Some of the organic molecules are split by the heterotrophs to give hydrogen ions, electrons and carbon dioxide. For example, consider the organic molecule glucose:



Because it releases electrons the organic molecule is termed an electron donor and on yielding the electrons, the molecule is said to be oxidized. The electrons (and protons) are captured by the heterotrophs, and transferred via an internal sequential set of oxidation reduction (redox) reactions eventually to a molecule which can accept them; this molecule is called the terminal electron acceptor. In this series of redox reactions, free energy is released (i.e. energy that is available to do work) which is captured by the organism (collectively this process is called catabolism). The energy captured by the organism principally is used by the organism for the transformation reactions that synthesize new cell mass, Eq. (2.1). From bioenergetics it is possible to determine the amount of glucose that must be oxidized to synthesize one mole of new cell mass (WRC, 1996).

In the oxidation of substrate, if oxygen is present (aerobic conditions) the terminal electron acceptor is oxygen (O_2) which is reduced to water (H_2O), i.e.



If oxygen is absent, but nitrate (or nitrite) is present (anoxic conditions), the nitrate (NO_3^-) (or nitrite, NO_2^-) serves as terminal electron acceptor and is reduced to nitrogen gas (N_2), giving rise to the denitrification process:



Thus, of the original biodegradable organic material present, a part is oxidized to yield free energy. This free energy is utilized by the heterotrophs to "reorganize" the remaining organic material into new cell mass, the free energy being lost as heat in the re-organization. Noting that the heterotrophic organisms use electron transfer (redox) reactions to generate the free energy,

the transformation of the biodegradable organic material can best be traced by monitoring the transformations in electrons. This has the advantage, *inter alia*, that, due to the indestructibility and hence conservation of electrons, electron mass balances can be conducted. Accordingly, of the electrons present in the biodegradable organic material (measured via the chemical oxygen demand (COD) test, see WRC, 1984), a fraction are transformed into new heterotrophic cell mass, and the remainder pass to the terminal electron acceptor, oxygen if aerobic and nitrate if anoxic.

Now, the ratio of electrons captured in new cell mass to the electrons present in the biodegradable substrate is termed the yield (Y_{ZH}), i.e

$$Y_{ZH} = \frac{e^- \text{ in synthesized material}}{e^- \text{ in biodegradable substrate}} \quad (2.5a)$$

Accepting the COD test as a measure of the electrons, then

$$Y_{ZH} = \frac{\text{COD synthesized material}}{\text{COD biodegradable substrate}} \quad (2.5b)$$

And, from a mass balance on electrons (COD)

COD of biodegradable material = COD of synthesized material + e^- to electron acceptor.

For activated sludge systems with the wide diversity of biodegradable organics in the influent and heterotrophs in the bioreactor, it has been found that the yield can be accepted to be approximately constant, at $Y_{ZH} = 0.666 \text{ mgCOD/mgCOD}$ (Dold *et al.*, 1980; 1991). In other words, for every biodegradable organic COD utilized, a constant fraction will be transformed to heterotrophic active biomass, and the balance of the e^- will pass to the electron acceptor.

A question that needs to be addressed is how much of the influent biodegradable material will be transformed in the bioreactor, within the residence time in the system. This is a problem of kinetics or rates. In considering the kinetics of biodegradable organic material transformation, it is subdivided into two components, readily biodegradable (soluble) COD (S_{bS1}) and slowly biodegradable (particulate) COD (S_{bpi}), see Fig 2.3. This division is based on observed biological responses of activated sludge mixed liquor to domestic wastewater (Dold *et al.*, 1980; Van Haandel *et al.*, 1981), that is, the division is a biokinetic one: Under dynamic loading of activated sludge (short sludge age cyclic loading, plugflow reactors, batch tests) two distinct rates of utilization of domestic wastewater biodegradable COD substrate were apparent with either oxygen (Dold *et al.*, 1980; Ekama *et al.*, 1986) or nitrate (Van Haandel *et al.*, 1981; Ekama *et al.*, 1986) as electron acceptor (aerobic or anoxic conditions respectively). A fraction (called readily biodegradable COD, RBCOD) was taken up rapidly by the sludge and metabolized, giving rise to a high oxygen or nitrate utilization rate respectively. The other fraction (called slowly biodegradable COD, SBCOD) was taken up much more slowly and metabolized, giving rise to oxygen or nitrate utilization rates about 1/10 of the rate with RBCOD. To explain these observations, the RBCOD was hypothesized to consist of simple *soluble* molecules that can be

absorbed readily by the organism and metabolized for energy and cell synthesis, whereas the SBCOD was assumed to be made up of *particulate/colloidal/complex* organic molecules that require extra cellular adsorption and enzymatic breakdown (hydrolysis) prior to absorption and utilization. The hypothesized difference in molecule size between RBCOD and SBCOD has been used to classify the RBCOD as a biodegradable soluble COD and the SBCOD as a biodegradable particulate COD. Since the RBCOD is soluble, it is exposed to biological treatment only as long as the liquid remains in the reactor, i.e. for the hydraulic retention time which is relatively short (~ 6 - 24h). However, the rate of RBCOD utilization is high and for sludge ages greater than about 3 days the concentration of RBCOD in the effluent is negligible even though the retention time is relatively short. Accordingly, for completely aerobic systems it can be safely assumed that all the RBCOD will be utilized in the system. For the SBCOD, the extracellular breakdown (hydrolysis) is slow and forms the limiting rate in the utilization of SBCOD. Although the rate of SBCOD utilization is relatively slow, the SBCOD does not appear in the effluent. This is because on entry of the influent into the bioreactor, the SBCOD becomes enmeshed in the mixed liquor, settles out in the secondary settling tank and is retained in the system. Therefore, the particulate biodegradable organics (SBCOD) are exposed to biological treatment for as long as the solid (settleable) material is retained in the system, i.e. for the sludge age. Thus, even though the utilization of the SBCOD is around 10 times slower than that for the RBCOD, because the sludge age in most activated sludge systems is usually more than 10 times longer than the hydraulic retention time, the SBCOD is completely utilized also. From simulation studies using dynamic kinetic models (Dold *et al.*, 1991) all the SBCOD is completely utilized for sludge ages greater than about 2 to 3 days and temperatures greater than about 20°C (5 to 6 days at 14°C). Accordingly, for most activated sludge systems it is sufficient to assume all the SBCOD will be utilized in the system.

Thus, for activated sludge systems at 20°C for sludge ages greater than about 3 days all the biodegradable organic material in the influent, whether soluble or particulate, will be transformed in the bioreactor by biological action mediated by the heterotrophic active biomass. The products of this transformation are:

- (1) Gaseous - carbon dioxide (only considered if the fate of the carbon is traced) and nitrogen, produced if nitrate acts as terminal electron acceptor, Eq. (2.4), i.e. anoxic conditions.
- (2) Soluble - water, produced when oxygen acts as terminal electron acceptor, Eq. (2.3), i.e. aerobic conditions
- (3) Particulate - new heterotrophic active biomass.

The particulate heterotrophic active biomass will settle out in the secondary settling to be retained in the system and thus will be another component of the mixed liquor solids. Since the influent SBCOD is virtually totally utilized for systems with sludge ages > 3d at 20°C, the SBCOD will not be a significant component of the mixed liquor solids, and hence can be neglected.

(ii) Endogenous mass loss/death

The endogenous mass loss phenomenon is the loss of active organism mass with time. The phenomenon can be observed as a reduction in organism active mass when the organism

population is aerated with no substrate added, for example, in the aerobic digestion of mixed liquor. The phenomenon also manifests itself as a decrease in specific organism yield with increase in sludge age. In the models, two conceptual approaches have been followed to describe this phenomenon; endogenous respiration and death-regeneration.

Endogenous respiration

This approach is the simpler and is followed in the steady state design models. In the approach, active organism mass is lost at a constant specific rate. Of the active organism mass that is lost, a part (about 80%) is oxidized to provide energy for maintenance of the active mass remaining and the balance (about 20%) remains as a particulate unbiodegradable organic fraction accumulating in the system, and is called endogenous residue. The oxidation of the biodegradable part of the active mass lost gives rise directly to an endogenous oxygen consumption under aerobic conditions, and indirectly to a nitrate demand (denitrification) under anoxic conditions. Whether the active mass oxidized is some “deep” storage material or from the death of individual organisms is of little practical importance in these models, but conceptually death of individual organisms would seem more likely; on organisms death the biodegradable part of the organism is oxidized by those remaining for maintenance energy, and the unbiodegradable part accumulates as a particulate endogenous residue. The simplicity of this approach allows analytical solutions to be readily determined.

Death-regeneration

This approach is followed in the dynamic kinetic simulation models. In the death-regeneration approach an attempt is made to separate out the processes which take place during the organism’s “death phase”. Disappearance of live active mass is hypothesized to be due to the net effect of death (natural or predation) and regeneration of organisms: On death the cell material is released through lysis; a part is particulate unbiodegradable endogenous residue (about 8%); the remaining part (about 92%) is biodegradable and adds to the slowly biodegradable COD (SBCOD) which passes through the path of adsorption, hydrolysis and synthesis of new cell mass (i.e. regeneration) described above. The synthesis of new cell mass gives rise to an associated aerobic oxygen or anoxic nitrate demand. Thus, in death-regeneration the oxygen or nitrate demand arises in fact from the energy requirements for resynthesis of organism active mass (regeneration) from the SBCOD liberated from organism death. The main implication of this approach is that “maintenance energy” *per se* (the oxygen/nitrate requirement for maintenance) is considered to be so small that it can be lumped with, and completely swamped by, the oxygen/nitrate demand for resynthesis of new cell mass from the lysed biodegradable substrate.

Comparing the two approaches, for the mixed cultures present in the activated sludge system predation is likely to be a significant cause for death of organisms, “liberating” substrate for synthesis of new cell mass (predator and others). Thus, conceptually the death-regeneration would appear superior. However, provided all the biodegradable COD has been depleted and a terminal electron acceptor (oxygen or nitrate) is continually available, with the appropriate selection of constants the two approaches give the same nett result, i.e. same loss of heterotrophic active biomass, utilization of oxygen/nitrate and generation of endogenous residue (Dold *et al.*, 1980, 1991). If a terminal electron acceptor is not available, then the endogenous-respiration approach is deficient and the death-regeneration approach preferable. Also, the two approaches

do deviate slightly when significant biodegradable COD is present, in for example, batch tests.

Irrespective of whether the endogenous respiration or the death-regeneration approach is followed, in both a part of the organism active mass that is lost is unbiodegradable particulate which will settle out in the secondary settling to accumulate in the system as endogenous residue. Thus, the endogenous residue will be another component of the mixed liquor solids.

2.3.3 Autotrophic organisms

In the activated sludge system, the autotrophic organisms of importance are the nitrifiers. These organisms mediate the process of nitrification, whereby free and saline ammonia is oxidized to nitrite and nitrate. It is generally accepted that the nitrification is due to two specific genera of autotrophic bacteria, the *Nitrosomonas* and *Nitrobacter*. Since these organisms are autotrophs, they obtain the carbon required to form cellular material from carbon dioxide. Their energy requirements are obtained by oxidizing ammonia to nitrite and nitrate. *Nitrosomonas* utilizes ammonium (NH_4^+) as electron donor and oxygen as electron acceptor; the ammonium is oxidized to nitrite and the oxygen reduced to water, i.e.



Nitrobacter uses nitrite as electron donor and oxygen as terminal electron acceptor; the nitrite is oxidized to nitrate and the oxygen reduced, i.e.



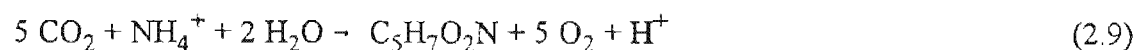
The nitrifiers can only execute these two reactions if oxygen is present, and are thus obligate aerobes.

Thus, the full nitrification process takes place in two steps. However, the rate of conversion of ammonium to nitrite by *Nitrosomonas* is very much slower than the rate of conversion of the nitrite to nitrate by *Nitrobacter*; as fast as the nitrite is formed it is nitrified to nitrate. The rate limiting step in the nitrification sequence, therefore, is that due to the *Nitrosomonas* - only the kinetics of this organism needs to be considered. As a consequence, in the models the two stage nitrification process is approximated as a single stage process with the ammonium being converted directly to nitrate, i.e.



This step is modelled as being mediated by a single nitrifying organism group, whose kinetics and characteristics closely approximate the *Nitrosomonas* (since this organism genus mediates the rate limiting step).

Part of the energy released in the single nitrification process is used for synthesis of new nitrifier organism active mass (growth), i.e. accepting $\text{C}_5\text{H}_7\text{O}_2\text{N}$ as a generalized formulation for nitrifier protoplasm (McCarty, 1964), then:



Recognizing that ammonium serves as the “substrate” for the nitrifiers, the specific yield is expressed in terms of the ammonium utilized, i.e.

$$Y_{ZA} = \frac{\text{COD of nitrifiers formed}}{\text{NH}_4^+ - \text{N utilized}} \quad (2.10)$$

The nitrifier active biomass that is formed in the activated sludge system is important in considering the mixed liquor solids because it is particulate, will settle in the secondary settling tank and so be retained in the system. The nitrifier active biomass, therefore, will be one component making up the mixed liquor solids.

As with the heterotroph active biomass, the nitrifier active biomass also is subject to endogenous mass loss/death. Although conceptually for consistency, this endogenous mass loss/death should result in the generation of an endogenous residue, compared to the other mixed liquor fractions the relative amount of endogenous residue generated by the autotrophs is so small that it is of little practical importance and can be neglected.

2.4 ACTIVATED SLUDGE MIXED LIQUOR ORGANIC COMPONENTS

From the discussion above, the mixed liquor in the bioreactor of the activated sludge system is comprised of a number of organic components (see Fig 2.4):

- (1) Inert material - derived from the unbiodegradable particulate organics present in the influent.
- (2) Heterotroph active biomass - synthesized in the bioreactor from the biodegradable organics present in the influent.
- (3) Endogenous residue - generated from the unbiodegradable portion of the heterotrophic (and autotrophic) active biomass that is lost in the endogenous respiration/death-regeneration process.
- (4) Autotrophic active biomass - synthesized in the bioreactor in the nitrification of ammonia to nitrate.

All four mixed liquor organic solids components settle out in the secondary settling tank and are returned to the bioreactor via the underflow recycle; these components leave the activated sludge system via the waste flow.

For activated sludge systems receiving “normal” municipal wastewaters (influent TKN/COD < 0.12 mgN/mgCOD) the autotrophic active biomass component of the mixed liquor organic solids is very small compared to the other three components (< 2% of the total) - the substrate source for the autotrophs (NH_4^+) is very much less than that for the heterotrophs (COD) and their specific yield is very much lower (autotrophs $Y_{ZA} = 0.15 \text{ mgCOD/mgN}$; heterotrophs $Y_{ZH} = 0.666 \text{ mgCOD/mgCOD}$, Dold *et al.*, 1980, 1991). Accordingly, in considering the components

making up the mixed liquor organic solids, with very little error the autotrophic active biomass can be neglected, so that the number of organic components reduces to three; (i) inert, (ii) endogenous residue and (iii) heterotrophic active biomass. (If the nitrification process itself is being considered, then the autotroph active biomass is of fundamental importance and must be taken into account).

Accepting that the autotroph active biomass can be neglected, a schematic diagram showing the origin of the mixed liquor organic fractions is shown in Fig 2.5. For the three mixed liquor organic solids components, two, the inert material and endogenous residue, are inactive and do not participate in any of the biological processes. The heterotrophic active biomass component, on the other hand, mediates the biodegradation processes of COD removal and denitrification. Thus, the rates for these processes are directly related to the amount of heterotrophic active biomass present. Accordingly, the specific rates should be expressed in terms of this parameter to allow a meaningful comparison of the rates measured in different systems. Although with the proliferation of computer programmes for the models, the heterotrophic active biomass seems to be almost universally accepted, it remains hypothetical within the structure of these models, because it has not been measured directly, primarily due to the lack of suitable simple measurement techniques (see Chapter 3 for a review of experimental techniques). This deficiency has cast some measure of doubt on the entire framework within which the steady state design and kinetic simulation models have been developed. *One of the main objectives of this research project is to develop a technique to measure the heterotrophic active biomass, and to compare the measured values to those calculated theoretically.*

2.5 ACTIVATED SLUDGE MIXED LIQUOR INORGANIC COMPONENTS

In the bioreactor of the activated sludge system, the mixed liquor is made up of organic and inorganic materials, the sum of these two materials making up the total solids, see Fig. 2.4. In both the steady state design procedures and dynamic kinetic simulation models, the influent wastewater characteristics and biological transformation processes that influence the bioreactor mixed liquor organic solids are explicitly included (see Sections 2.2 and 2.3 above respectively). However, the mixed liquor total solids (and hence inorganic solids) are calculated simply from an empirical ratio of organic/total solids, the value for the ratio being accepted as one constant for activated sludge systems treating raw wastewater and another constant for those treating settled wastewater (WRC, 1984; Dold *et al.*, 1980, 1991). However, the total solids concentration is fundamental to the design and operation of secondary settling tanks and of waste activated sludge treatment and disposal. Thus, more information is required on the incorporation of the inorganic material present in the influent wastewater into the mixed liquor. *This is one principle objective in this research project.*

In considering the total solids, in the influent, bioreactor and effluent these can be subdivided into components, as shown in Fig 2.6. The total solids (TS) consist of both total dissolved/soluble (TDS) and total suspended/particulate (TSS) solids. The total dissolved solids (TDS) consist of the organic/volatile (VDS) and the inorganic (IDS) dissolved solids. Similarly, the total suspended solids (TSS) consist of the organic/volatile (VSS) and the inorganic (ISS) suspended solids. The VDS + VSS gives the total organic/volatile solids (TVS) and the IDS + ISS gives the total inorganic solids (TIS). In terms of this subdivision and the conceptual framework developed for the organics, the particulate/suspended material will settle out in the secondary settling tank

to be retained in the system, and the soluble/dissolved material will pass through to the effluent. Thus, by measuring the distribution of inorganic materials in the influent, in the bioreactor and in the effluent, it will be possible to gain an initial understanding of the fate of the various influent inorganic fractions in the activated sludge system bioreactor, i.e. what transformations in the bioreactor act on the inorganics, to solubilize the particulate material and *vice versa*. With this understanding it may prove possible to set up procedures (design and simulation) that will enable the inorganic solids (and hence total solids) in the bioreactor to be calculated from measurements made on the influent. This approach will be adopted in this part of the research project.

2.6 CLOSURE

From the discussion in this Chapter, two important deficiencies can be identified in the current steady state design and dynamic simulation models:

- (1) The heterotrophic active biomass, which is the component of the bioreactor mixed liquor that mediates the biodegradation processes of COD removal and denitrification, has not been measured.
- (2) The incorporation of inorganic materials into the bioreactor mixed liquor is not explicitly included.

This research project endeavours to address these deficiencies.

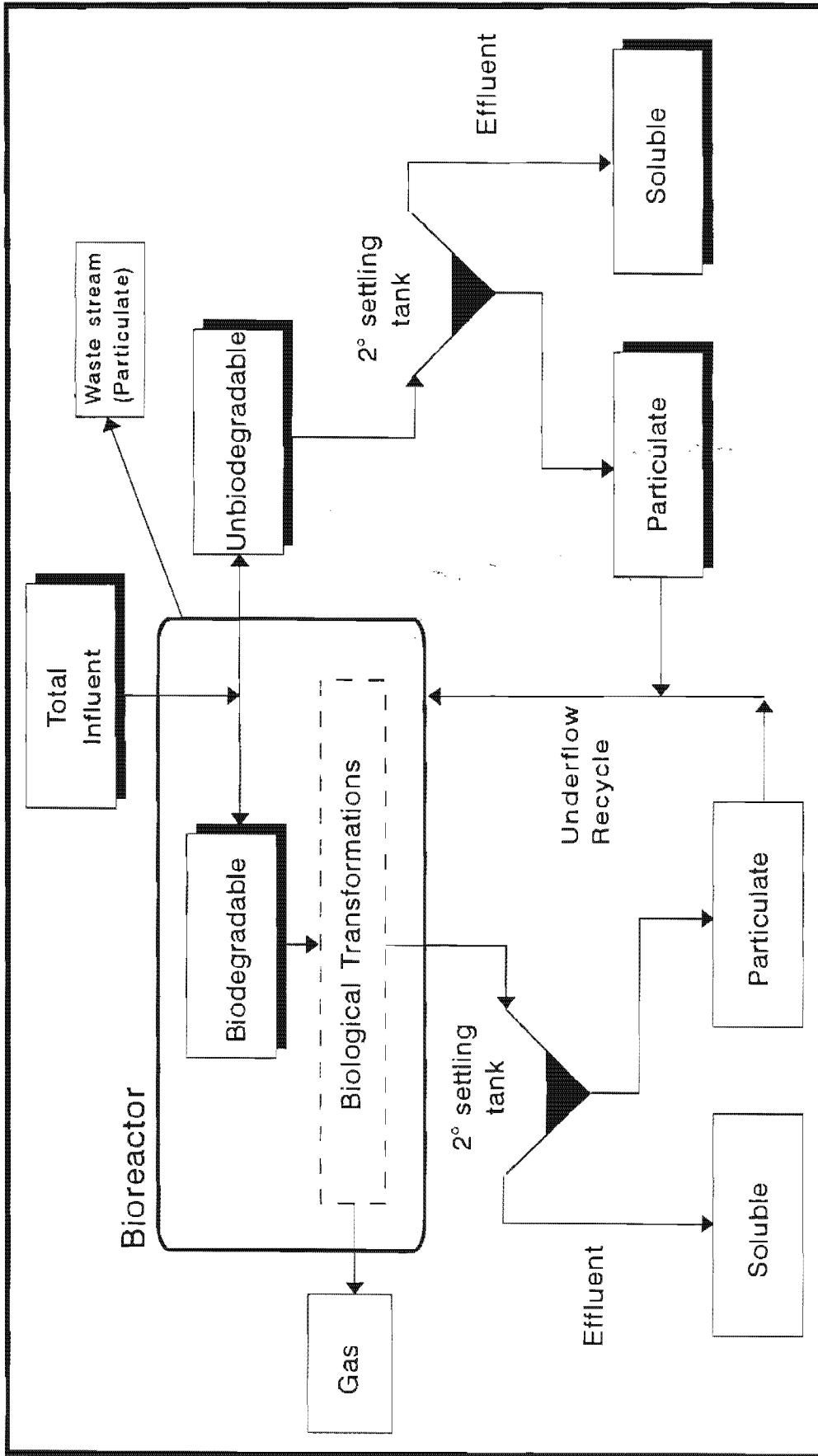


Figure 2.1: Division of influent wastewater carbon (C), nitrogen (N) and phosphorus (P) materials according to the biological and physical processes in the activated sludge system.

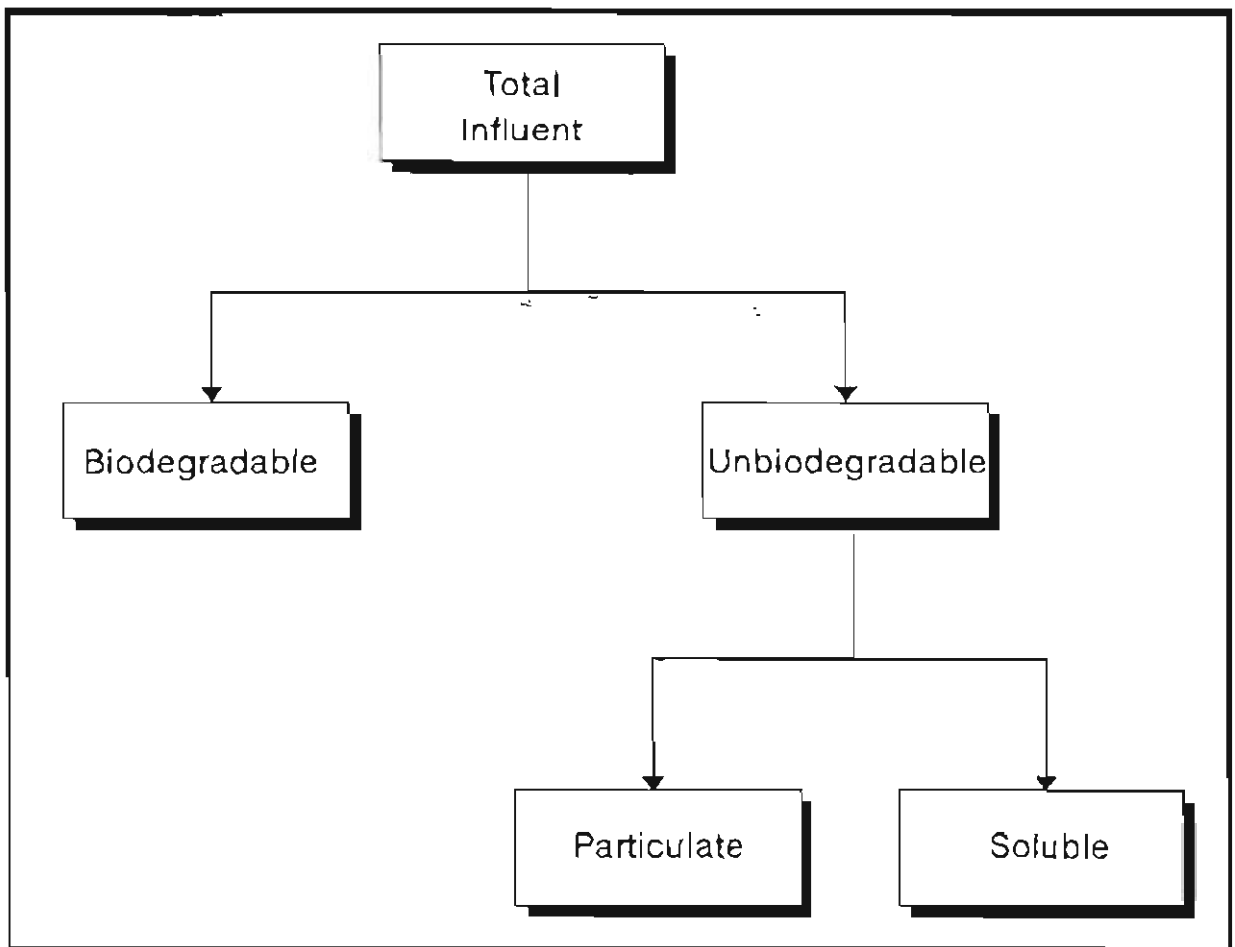


Figure 2.2: The general wastewater characterization structure for carbon (C), nitrogen (N) and phosphorus (P).

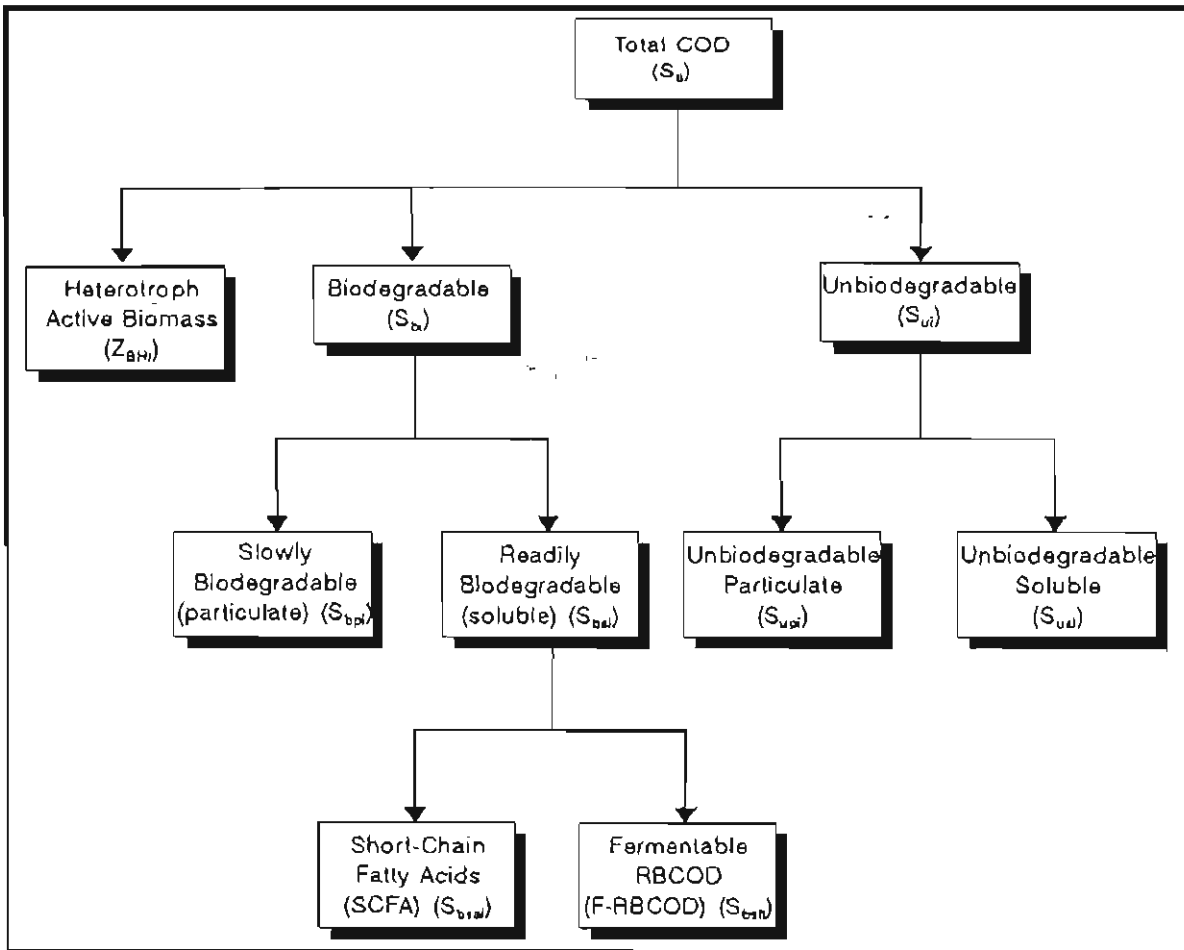


Figure 2.3: The division of COD into its different constituents.

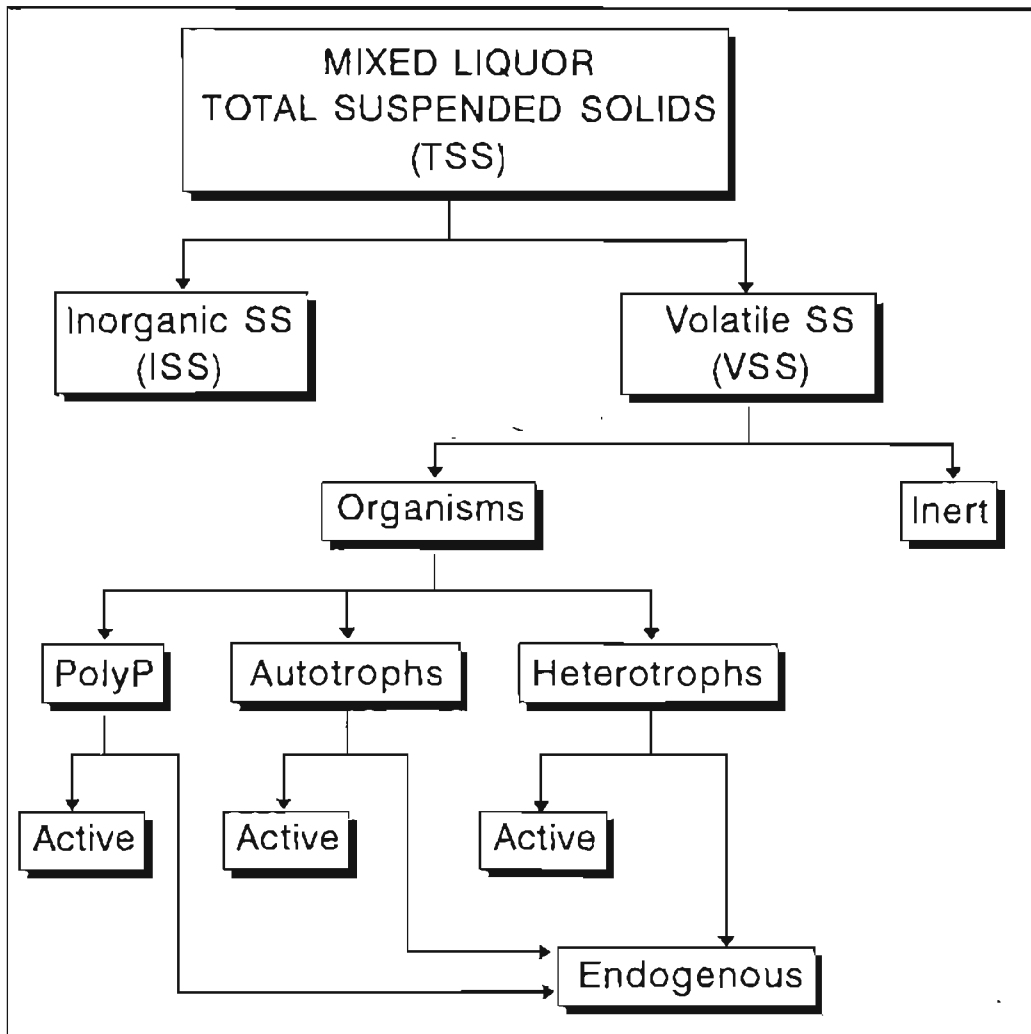


Figure 2.4: The organic and inorganic components of the mixed liquor in the bioreactor.

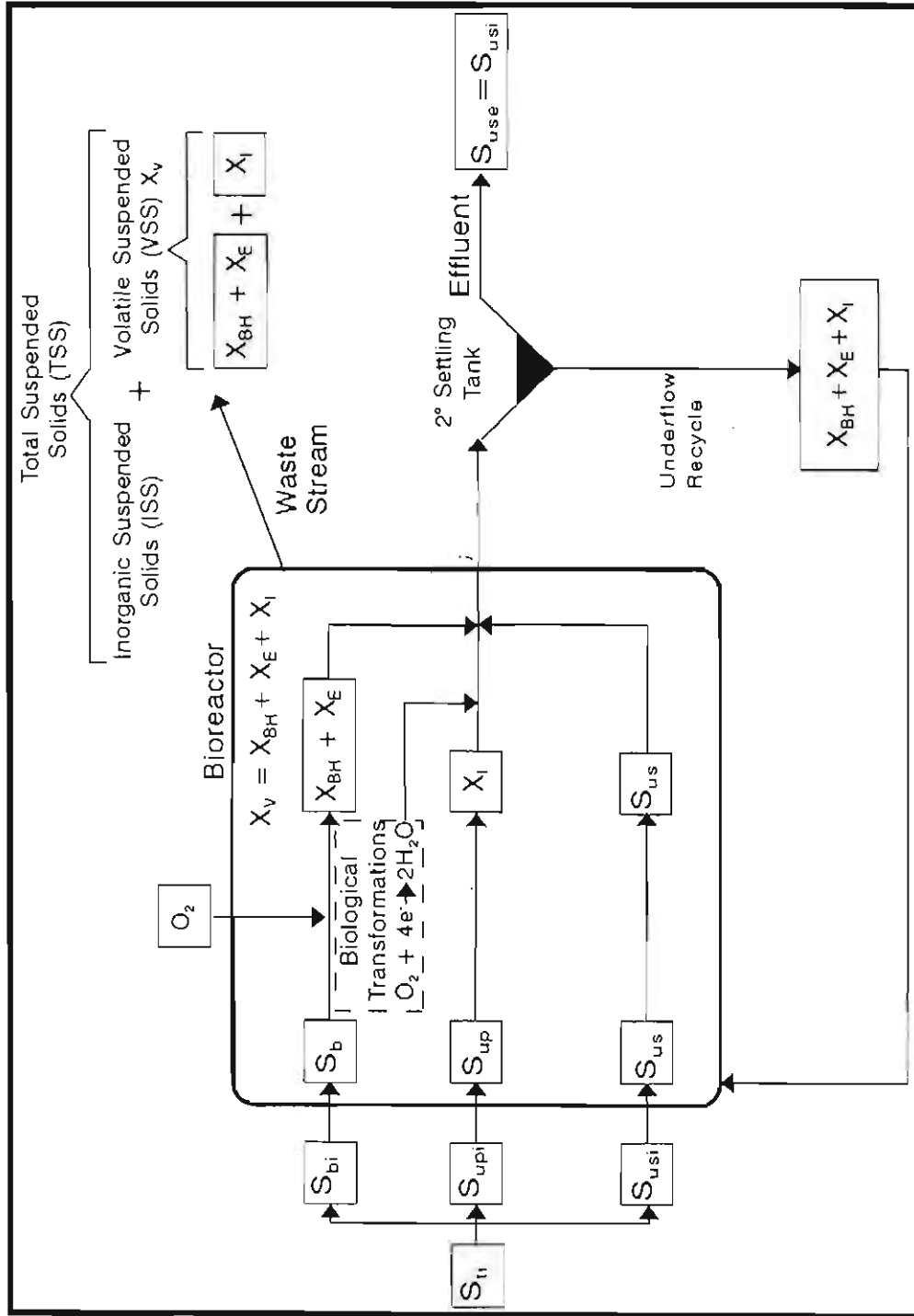


Figure 2.5: Schematic representation of the transformations of the influent COD fractions within the activated sludge system.

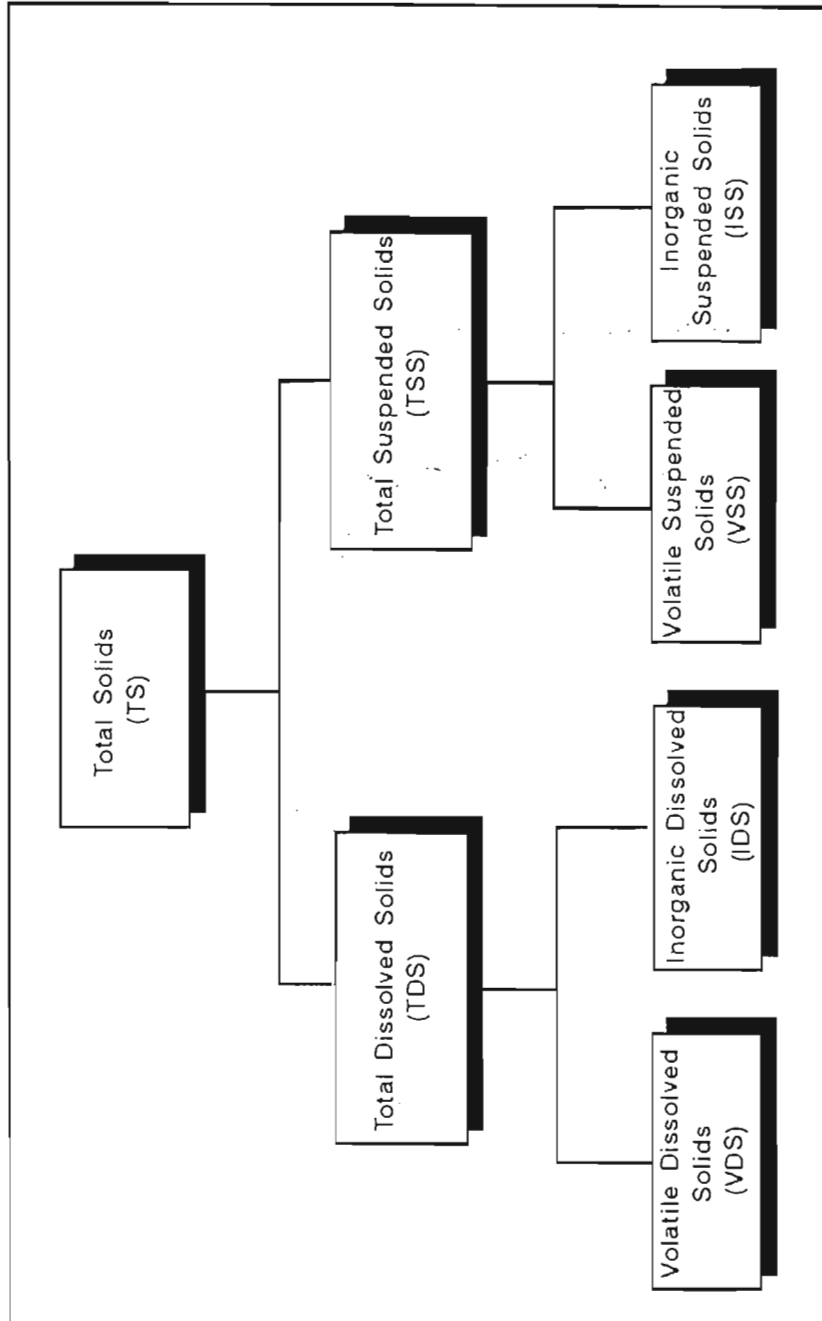


Figure 2.6: Schematic representation of the division of solids into its inorganic and organic fractions.

CHAPTER 3

EXISTING METHODS FOR QUANTIFYING HETEROTROPHIC ACTIVE BIOMASS

3.1 INTRODUCTION

In Chapter 2 the central role in the steady state design procedures and kinetic simulation models of the mixed liquor component heterotrophic active biomass has been highlighted. Further, the need for accurate quantification of this mixed liquor component has been demonstrated. In this chapter, existing methods or methods with potential to quantify the heterotrophic active biomass in activated sludge or similar systems will be reviewed, to identify their strengths and weaknesses and to select the more promising for evaluation and further development.

3.2 MEASUREMENT METHODS

A variety of methods (both direct and indirect) have been developed to attempt to experimentally quantify the parameters loosely termed "biomass". However, as will become evident in the review, the "biomass" parameter does not relate directly to the heterotrophic active biomass in the steady state design procedures and kinetic simulation models for activated sludge and similar systems. This deficiency limits possible application of a number of the methods.

3.2.1 Weight

Weight has been widely used as a measure of biomass, either by direct measurement or by the use of indirect measurements such as optical density/turbidity.

3.2.1.1 Direct measurement

The dry weight per unit of volume is readily obtained by separating the solid materials from the liquid and then drying at 105°C and weighing in a tared container; the dry weight is termed total suspended solids (TSS), Standard Methods (1985). Also, the volatile or organic solids weight can be obtained by combusting the dried sample at 600°C; the mass that combusts is termed the volatile suspended solids (VSS), Standard Methods (1985). Alternatively, the COD of the solid material can be measured (Standard Methods, 1985). These methods are widely used to quantify the mixed liquor in the activated sludge system.

3.2.1.2 Optical density (OD)

A simple technique proposed to measure biomass is to use optical density. The optical density (OD) of a growth culture is measured with a spectrophotometer at 450 nm (Jensen *et al.*, 1988; Jørgensen *et al.*, 1992). Samples of 200 ml of the growth culture are centrifuged at 4 000 rpm for 10 minutes. The sediment/pellet is dried for 24 hours at 105°C, then weighed to determine the growth culture dry weight. A calibration curve to determine the conversion of OD to dry

weight is made (a conversion factor of 250 ng/ml per absorbance unit is usually used). Absorbance of the sample to be quantified is measured and then converted to dry weight using the calibration curves. The dry weight is used as an approximation of biomass.

3.2.1.3 Summary

For activated sludge mixed liquor the weight determined with these methods will include all three organic components, i.e. active, endogenous and inert, and the dry weight (TSS) will also include the inorganic component (see Chapter 2). Thus, these types of tests will not be capable of isolating heterotrophic active biomass.

3.2.2 Total cell count

The number of cells in a population can be measured by counting under the microscope, a method called the direct microscopic count (Brock and Madigan, 1988). Two kinds of count are done, either on samples dried on slides or on samples in liquid. With liquid counts, special counting chambers are used consisting of a slide with a grid marked on the surface, the volume above each grid being precisely measured. The number of cells per grid is counted under the microscope, this giving the number of cells per chamber volume.

Direct microscopic counting has a number of limitations: (1) The method is tedious, (2) dead cells are not distinguished from living, (3) small cells are difficult to see under the microscope and probably are missed, (4) precision is difficult to achieve, and (5) with the flocs from activated sludge it is difficult to separate out individual organisms. Thus, the method is not suitable to quantify heterotrophic active biomass.

3.2.3 Viable cell count

In the total cell count described above, one limitation identified was that both living and dead cells are counted. To distinguish the living cells, viable cell counting methods have been developed. A viable cell may be defined as one that is able to divide and produce off-spring, i.e. replicate. The most usual way to perform a viable count is to determine the number of cells in the sample capable of forming colonies on a "suitable" medium. For this reason, the viable cell count also has been called the plate or colony count. Measurements of the number of cells capable of replication can be correlated to the weight of biomass. The viable count and the relation between viable numbers of cells and the weight of the biomass has been used as a basis for estimating the heterotrophic active biomass in biological wastewater treatment systems (Gaudy and Gaudy, 1980; Droste and Sanchez, 1983).

Several techniques have been used in estimating the viable count, but the most common are: (1) colony count using solid media, (2) membrane filter and (3) null-point dilution in liquid medium.

3.2.3.1 Colony count using solid media

In this method, a solid medium is used to determine the number of cells capable of forming colonies. The three main types of colony count using solid media are: (1) Pour plate, (2) spread plate and (3) spot plating. The methods differ principally in how the medium is inoculated with

the sample: In pour plating, the sample is mixed with the melted agar medium and then allowed to cool, in spread plating the sample is spread evenly over the surface of a solid agar plate, while in spot plating a micropipette is used to add a very small discrete volume to the solid agar plate. The pour plate method is perhaps the most common plating method. In all the plating methods, the number of colonies that develop on the plate must not be too large. Thus, to obtain the correct colony numbers, the sample usually must be prediluted. Several ten-fold (serial) dilutions are commonly used.

The assumption made in all the solid media methods is that each visible colony grows from a single cell. Therefore, if cells are flocculated they must be thoroughly dispersed before conducting the test. For activated sludge system mixed liquor, often it is difficult to disperse the cells without influencing their viability. Thus, to retain viability less harsh dispersal methods are used, and the counts are expressed as the number of colony forming units, not as viable cells. Spread and spot plating usually have some advantage over pour plating because (i) agar plates contaminated during the pouring of agar can be discarded, and this eliminates counting errors, (ii) in pour plating the organism must be able to withstand the temperature of the melted medium, and (iii) because all colonies will be in the same plane in spread and spot plating, counting is easier. The spread and spot plating methods also have been found to be more serviceable (Gaudy *et al.*, 1963).

In all plating techniques, the number of colonies obtained on the plate will depend not only on the inoculum sample size, but also on the suitability of the culture medium, the incubation conditions and the length of incubation. Despite these limitations, and the other listed above, these methods have been widely used; although for the activated sludge system, the plating methods have been more commonly used for organism identification than for viable cell counts.

3.2.3.2 Filter membrane

In this method a sample is poured over a membrane filter, preferably marked with grids to facilitate counting of colonies that develop. The filter paper then is placed on an absorbent pad of such thickness that the paper will take up approximately 2 ml of the nutrient solution. The nutrient in the pad diffuses to the cell on the filter. The filter paper may also be placed on an agar plate. Since large volumes can be passed through the filter, the method can be used for dilute suspensions. Although this method offers some advantages over the solid media plating methods described above (e.g. easier to apply), because it also relies on colony growth on a selected medium it experiences a number of the same limitations. Furthermore, the method has inherent increased costs associated with it (Gaudy and Gaudy, 1980).

3.2.3.3 Null-point dilution in liquid medium

The basis of this method is to determine the dilution factor for a sample that no longer will provide sufficient seed of microorganisms to permit growth in fresh liquid media, i.e. the sample is diluted serially and the presence/absence of microorganisms determined. Any convenient quantitative measurement of growth can be used to detect the presence/absence of organisms in the liquid medium, e.g. gas formation has been used in a standard test for coliform organisms (Gaudy and Gaudy, 1980). However, because the measurement method is preselected, certain organisms may be excluded. The viable count in the original sample is estimated from the dilution

and presence/absence results using the appropriate probability theory (Gaudy and Gaudy, 1980). The method usually is applied to estimate the concentration of a specific organism type, and is applicable to samples that contains very few organisms; both these factors limit possible application to determine the heterotrophic active biomass in activated sludge mixed liquor.

3.2.3.4 Summary

All the tests to detect viable cells described above rely on the ability of the organisms to replicate (plating and membrane techniques) or exhibit a specific metabolic activity (null-point dilution) in an artificial medium. This will cause the tests to be selective - only those organisms with the ability to replicate/metabolize on the artificial substrates will be included. For example, it has been estimated that less than 10% of the organisms present in activated sludge mixed liquor will be cultured on the agar plates used as a standard in the plating techniques (Cloete and Steyn, 1988). Furthermore, dispersion of the cells in the activated sludge floc (a requirement in the tests) is difficult without reducing cell viability. These factors limit possible application of this type of test to determine activated sludge mixed liquor heterotrophic active biomass.

3.2.4 Acridine orange (AO) direct count

To overcome the problems associated with culturing organisms to determine viable numbers (described above), techniques have been developed to count viable cells by microscopic examination of samples. The total cell count using microscopy has been described earlier; the principle deficiency identified with this method was that it could not distinguish living cells from dead. To get around this problem, the organisms can be stained with any one of a variety of fluorescent dyes specific for living cells, and the fluorescing cells counted under the microscope; the method is termed cell epifluorescence microscopy. Fluorescent dyes are used as they aid in microscopic counting. Acridine orange (AO) is a fluorescent dye that is commonly used; this dye stains any organism containing DNA (i.e. any living organism); cells staining green with AO are generally viable - AO binds to nucleic acids with the RNA-AO complex fluorescing orange-red while DNA-AO complex fluoresce green (Porter and Feig, 1980).

Briefly the method is: The samples are diluted with phosphate buffer to give a bacterial count of ~ 100 bacterial cells per microscopic field. A sample (0,1 ml) is placed in a filter tower, and 1 ml of 0,1% acridine orange (AO) added. The sample is incubated for 2 minutes and 3 to 5 ml of 0,1M phosphate butter added and the sample filtered. The damp filter is placed on a drop of immersion oil on a glass-slide. Immersion oil and cover slip is then added on top of the filter. The sample is examined at 1 000X (oil immersion) magnification and the number of green fluorescing bacteria counted to determine active biomass. The AO method is mainly used in water treatment (Albat *et al.*, 1986), but Bitton *et al.* (1993) have used the method for total bacterial counts in samples of non-chlorinated activated sludge effluent.

Summary

The method has a number of deficiencies for application to activated sludge mixed liquor: (i) The method yields inconsistent cell fluorescence; the fluorescence does not differentiate microbial cells on the basis of metabolic activity or viability (APHA *et al.*, 1989; ASTM, 1985), (ii) the method is tedious, (iii) with the organisms in activated sludge mixed liquor binding in flocs, counting of

individual cells is difficult - dispersion of the cells is a problem, as discussed earlier, and (iv) the colour of fluorescence depends on the moisture content of the filter paper; Bitton *et al.* (1993) found that addition of moisture to filter papers could change some cells fluorescence from orange-red to green.

3.2.5 Measurement of biochemical compounds

Due to the difficulties associated with the counting of organisms (directly via microscopy or indirectly via plating), various methods have been developed to measure quantitatively key compounds in organism's biochemical pathways and to relate these in some manner to organism mass. The two most commonly measured compounds are adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide (NAD).

3.2.5.1 Adenosine triphosphate (ATP) measurement

In this method the amount of adenosine triphosphate (ATP) is used as the indicator of microbial biomass. The ATP has the advantage of being a non-conservative constituent of the living cell which is directly related to the energy-growth process (Postage and Hunter, 1962; Holm-Hansen and Booth, 1966; Chappelle and Levin, 1968; Weddle *et al.*, 1971; Jensen *et al.*, 1988 and Jørgenses *et al.*, 1992). ATP is an energy-carrier molecule in micro-organisms, has a rapid turnover and is lost very rapidly from dead or dormant organisms. In addition, its concentration remains relatively constant and independent of the growth rate in living cells (Franzen and Binkley, 1961; Forrest, 1965; D'Eustachio and Levin, 1967; Weddle and Jenkin, 1971). Hence, the total amount of ATP measured should provide an estimate of the number of living active micro-organisms; one μg of ATP is equivalent to about 250 μg of carbon in living organisms. In the test, a sample is treated to extract ATP, and the ATP of the extract is measured. A number of sensitive methods are available for measuring ATP (Brock and Madigan, 1988). The most common method involves the measurement of light produced in the luciferin - luciferase reaction. Luciferin and luciferase are obtained from firefly lanterns and the amount of light produced when the enzyme, luciferase, acts on the substrate, luciferin, is proportional to the amount of ATP present. Thus, the ATP extracted from the sample is mixed with luciferin and luciferase and the light emission in the reaction is measured using a scintillation spectrophotometer. The light emission is proportional to the ATP present, so that from the light emission the ATP can be determined from a calibration curve. Accepting a constant ATP per unit biomass, the biomass concentration then can be calculated.

Nelson and Lawrence (1980) applied the ATP measurement method to mixed liquor drawn from a laboratory-scale completely mixed fill and draw activated sludge system receiving a synthetic wastewater. The biological solids retention time (= sludge age, R_s) in the system was varied from 0.5 to 12 days. They found that the microbial viability (measured via the ATP) of the activated sludge mixed liquor volatile suspended solids (MLVSS) exhibits a functional relationship with R_s : Expressed as % viability of the MLVSS, it is close to 100% at low values of R_s and decreases to an approximate constant value at high R_s values; this type of behaviour is typical of the activated sludge system. Nelson and Lawrence (1980), confirmed from their study that the ATP pool level for a 100% viable culture of activated sludge is in reasonable agreement with many previously reported results for pure cultures of bacteria, and that the viable percentage of MLVSS varied with the value of R_s in a manner similar to the variations described by Postage and Hunter (1962),

Weddle and Jenkins (1971) and Upadhyaya and Eckenfelder (1975). In activated sludge studies using domestic sewage as substrate, Weddle and Jenkins (1971) reported a lower viable percentage (10-20%) than found in the Nelson and Lawrence (1980) study (40-50%) at the larger values of R_s which are typical of normal process operation. Nelson and Lawrence (1980) proposed that the lower viable percentages reported in the studies treating domestic sewages are due to accumulation of non-biodegradable MLVSS which are originally present in the influent wastewater

Summary

The ATP measurement method requires sophisticated equipment and analytical techniques which are not widely available. This will cause the method to be unsuitable for general routine application. Furthermore, because ATP turns over rapidly in metabolizing cells, the levels of ATP in a single cell can vary depending upon the conditions that the cell is subjected to, e.g. concentrations of substrate, oxygen. For example, under starvation conditions the ATP levels reduce to low values (Brock and Madigan, 1988). Since the method is based on the assumption that the ATP level per unit organism remains constant (to convert ATP to biomass concentrations), the ATP may not be a good measure of biomass, but may rather be a measure of a combination of organism activity and biomass.

3.2.5.2 Nicotinamide Adenine Dinucleotide (NADH)

This test is very similar to that for ATP, with nicotinamide adenine dinucleotide (NADH) being measured instead. NADH is the electron and proton carrier molecule in organisms and its metabolism is an indicator of metabolic activity. The NADH measurement is based upon the principle that NADH, which is found in all living cells, fluoresces at 460 nm when radiated with light at 340 nm (Armiger *et al.*, 1986; 1993), the intensity of fluorescence being proportional to the NADH present. Measurement of NADH has been proposed as a method to control biological nutrient removal plant (BNR) processes (Armiger *et al.*, 1990b; 1991; Yang *et al.*, 1991). The environmental conditions of the activated sludge determine the metabolic pathways by which NADH is constantly recycled from the oxidised to the reduced form. Specifically, in BNR processes the reduction state of the activated sludge varies as the mixed culture flows from the anaerobic zone to the anoxic zone to the aerobic zone. The biological activity (BA) in each zone is defined as the reduction state of the activated sludge times the viable cell population. By constantly measuring the fluorescence from the NADH, it is possible to monitor changes in the biological activity of the activated sludge system.

Summary

NADH measurement has potential more as an indicator of biological activity than as a method to quantify heterotrophic active biomass.

3.2.6 Measurement of biochemical reactions

This group of tests involves measurement of the "activity" of key biochemical reactions, by monitoring the changes in substrates or products of the selected reaction. Two examples of this type of test are given below.

3.2.6.1 Fluorescein diacetate (FDA) hydrolysis

In this method the ability of the mixed liquor to hydrolyse fluorescein diacetate (FDA) is monitored. FDA can be quantified by measuring light adsorbance at 450 nm. Specific volumes (50 ml) of mixed liquor are centrifuged at 5 000 rpm for 5 minutes (Jensen *et al.*, 1988; Jørgensen *et al.*, 1992). The pellet is resuspended in 5 ml NaHPO buffer and homogenised for two minutes by heavy stirring (Jensen *et al.*, 1988). A 4.5 ml volume of the resuspension is placed in a 10 ml flask containing 0.1 ml EDTA and 0.4 ml of a solution of protein synthesis inhibitors. A 25 μ l volume of FDA solution is added, the flask incubated on a rotating axis for 45 minutes at room temperature. After incubation the reaction is terminated by transferring to 3 ml of acetone (Schnürer and Roswall, 1982). The mix is then vortexed and centrifuged at 5 000 rpm for 5 minutes. The absorbance of the supernatant at 450 nm is measured with a spectrophotometer, the adsorbance quantifying the FDA. Autoclaved samples are treated in the same way to serve as blanks, the difference in adsorbance between the samples and blanks quantifying the FDA that has been hydrolysed. The FDA hydrolysis results are converted, using a conversion factor of 10, to determine the biomass in the sample. Thus, this method assumes that the FDA hydrolysis per unit of viable organisms is essentially constant.

Summary

As a method for heterotrophic active biomass measurement, this technique has serious problems as the values obtained are generally higher than suspended solids measurements; the opposite is expected, as it has been found that not all bacteria are able to hydrolyse FDA (Leach, 1981; Chrzanowski *et al.*, 1984).

3.2.6.2 Dehydrogenase enzyme activity

This method measures the activity of the dehydrogenase enzyme using fluorescence microscopy. It is based on the principle that the electron transport system of respiring organisms reduce 2-(*p*-codophenyl)-5-phenyl tetrazolium chloride (TNT) to TNT-formazan (Zimmermann *et al.*, 1978; Droste and Sanchez, 1983). Respiring bacteria deposit accumulated TNT-formazan as optically dense, dark red intracellular spots which can be examined by light microscopy; the amount of TNT-formazan deposited corresponding to the intensity of the respiration. By combining formazan detection with acridine orange (AO) epifluorescence microscopy (see above), a method is then obtained which allows discrimination of bacteria from detritus, and differentiation between respiring and non-respiring cells (dehydrogenase enzyme activity) (Droste and Sanchez, 1983).

Summary

Although the method allows the determination of the total and active (cells with formazan) number of bacteria from the same sample, the method, however, fails to differentiate between heterotrophic and autotrophic active bacteria. Also, the method fails to distinguish formazan deposits in small bacteria due to interference from the structure (pore openings) of the filter paper on which the microorganisms are collected (Droste and Sanchez, 1983) and the method is thus conservative. Furthermore, since acridine orange epifluorescence is required, the problems detailed above for this method apply here also. Thus, the method cannot be used for routine

heterotrophic active biomass quantification

3.2.7 Determination of deoxyribonucleic acid (DNA) content

In this method, deoxyribonucleic acid (DNA), which constitutes the genetic material of organisms, is extracted from the activated sludge mixed liquor and the amount extracted is measured. This is used to derive an estimate for the number of active organisms present; it is assumed that each organism has a constant known amount of DNA (Weddle *et al.*, 1971).

In using measured cellular constituents (e.g. Protein, carbohydrates, ATP, DNA) to calculate active biomass, a requirement is that the quantity of the constituent per unit active biomass remains constant. However, this may not be true in activated sludge mixed liquor because, (1) some of the measured components are not exclusively found in the biomass, and (2) the nutritional conditions of the activated sludge micro-organisms are not constant; depending on the sludge loading rate (SLR) micro-organisms contain different amounts of storage polymers (Liesbekind and Dohmann, 1994). Although the nutritional condition of the activated sludge may differ, the genome size (i.e. DNA) probably does not; thus a proportionality factor between DNA and the number of micro-organisms present can be found. Micro-organism genomes contain (with some exceptions) approximately 4 to 5×10^6 base pairs (bp) (Liesbekind and Dohmann, 1994); for example *E.coli* has 4.35×10^6 bp (Schlegel, 1985). Since activated sludge does not represent a pure culture, but is a bioceonosis of several hundreds or thousands of different micro-organisms species, an average genome size of 4.5×10^6 bp per microorganism can be assumed.

The DNA method relies on reliable extraction of the DNA. However, extraction of the DNA is not without problems: Iron has a significant effect on the amount of acid extractable DNA; Hall and Axelrod (1977) showed that in pure cultures of *Asperigillus nidulans* trace quantities of cellular ferric iron (5.6 mg/l) inhibited complete DNA extraction with perchloric acid at 70°C. Iron is a common component of activated sludge, sometimes reaching concentration levels as high as 40 mg/l. Temperature and the technique of washing with EDTA solution also have a significant effect on the measured DNA content. For these and other reasons, the conventional method of biomass determination using DNA (Thomanetz, 1982, Obst and Holzatel-Pschorr, 1988), can only detect up to half the actual biomass DNA present in most activated sludge systems (Raebel and Schliert, 1980), depending on the presence/absence of substances and conditions that inhibit DNA extraction.

Despite the DNA extraction problems, in a general study on biomass characterization of activated sludge, Thomanetz (1982) described and tested 17 methods for living biomass estimation and biomass activity determination and found that the best method to determine living biomass is via the determination of the DNA content, because the method was comparatively simple, quick and reproducible.

Liesbekind and Dohmann (1994) applied the method to activated sludge mixed liquor using acid extraction of DNA, quantitative determination of the deoxyribose sugar by a colour reaction with diphenylamine, calibration of the colour reaction with standard DNA, and mathematical conversion of the measured DNA into biomass and found that the conventional DNA method is strongly affected by unknown activated sludge constituents and in particular iron. They found that washing the sludges with EDTA first improved DNA extraction, but concluded that there

still is no surety as to whether all the DNA is successfully extracted.

Summary

The method, described in detail by Liesbekind and Dohmann (1994) is complicated, tedious and requires sophisticated equipment to extract DNA. Furthermore, the extraction of all DNA is problematic and depends on the presence/absence of substances and conditions that inhibit its extraction - there is uncertainty on whether all the DNA is extracted from activated sludge mixed liquid. Also, the conversion of the measured DNA to the heterotrophic active biomass parameter used in the steady state design and kinetic simulation models is unclear. Thus this method is not practical for general routine application.

3.2.8 Molecular identification of activated sludge bacteria using rRNA/DNA

This method seeks to identify bacteria by detecting nucleic acid sequences common to the targeted bacteria. The most common nucleic acid sequences targeted are ribosomal RNA (rRNA). Ribosomal RNAs (rRNA) are selected because they possess qualities that cause them to be suitable for discerning evolutionary relationships between bacteria: rRNAs are ancient molecules, functionally constant, universally distributed and moderately well conserved across broad phylogenetic distances. They are also readily purified from organisms without the use of cloning procedures (Brock and Madigan, 1988). There are three rRNA molecules, which in procaryotes have sizes 5S, 16S and 23S. The small size of 5S rRNA (~ 120 nucleotides) limits the information contained in the molecule, and so limits its use. However, the large rRNAs, 16S and 23S (containing approximately 1 500 and 3 000 nucleotides respectively) contain several regions of highly conserved sequence useful for proper sequence alignment, yet have sufficient sequence variability in other regions to show phylogenetic diversity. Of the two large rRNAs, 16S RNA is more experimentally manageable than 23S RNA, and so has been used extensively (it has been termed small subunit, SSU, rRNA).

Exploiting the above properties of rRNA, a number of techniques have been developed for bacterial identification, and to estimate proportions of specific or functional groups of bacteria in a sample. It is not the intention here to provide an exhaustive review of these techniques, but rather to provide a very simplified overview of some of these:

(1) **rRNA sequence analysis**

This technique involves sequencing the 16S rRNA. A number of methods are used to do this. For example: The rRNA is extracted from the bacteria of interest. A small DNA oligonucleotide primer (15 - 20 nucleotides in length) complementary in base sequence to some highly conserved section of the 16S rRNA molecule, is added. The enzyme reverse transcriptase (adds to the primer nucleotides which are complimentary to the rRNA) is added with ³²P - labelled deoxyadenosine triphosphate and the other unlabelled deoxyribonucleotides. The mixture then is divided into four portions, and to each a small amount of different 2', 3' dideoxynucleotide is added. The enzyme reverse transcriptase will read the rRNA and make a DNA copy interrupted at various points by the incorporation of the dideoxynucleotide. The fragments are then sequenced by electrophoresis and autoradiography. From knowledge of the complementary DNA sequence, the sequence of the original 16S rRNA can be deduced. Once the sequence is

known, it can be compared to known sequences of known bacteria, and the sample bacteria identified or placed in the correct phylogenetic group.

(2) **rDNA gene sequencing**

The principle is the same as for the rRNA sequence analysis, except that the DNA gene coding for the 16S rRNA is sequenced. Also, instead of using the enzyme reverse transcriptase to make a complimentary copy of the nucleotide sequence, the enzyme polymerase is used to make an identical copy.

(3) **In situ hybridization**

In this technique an oligonucleotide compliment (called a probe) is manufactured for a specific bacterial 16S rRNA sequence. On being combined with the sample, the oligonucleotide probe will hybridize with its compliment rRNA sequence. On hybridization, the paired oligonucleotide can be caused to fluoresce and this fluorescence can be viewed under a microscope. The technique is known as fluorescent in situ hybridization (FISH). By careful selection of the oligonucleotide probe, the probe can be hybridized to any desired target sequence. Since some areas of the rRNA sequence are common to specific species, while others are common to genus, sub groups, groups subphyla, etc., specific bacteria or 'functional groups' can be identified. Also, by comparative tests the proportion of a specific bacteria or group relative to other groups (e.g. proportion of a species relative to a genus) can be determined.

The rRNA/DNA based methods are gaining increasing popularity for application to activated sludge mixed liquor. For example, Blackall (1994) applied rDNA gene sequencing to investigate filamentous bacteria in the stable dark viscous foam on the activated sludge aeration basin surfaces, and found that the diversity of the filamentous organisms in the foam increased with time. Similar studies were carried out on *Nocardia amarae* and *Nocardia pinensis* (now reclassified as *Gordona amarae* and *Skermania pinensis* respectively), both prominent foaming filaments in Australia. Genomine DNA was isolated from strains of *N.amarae* and *N.pinensis*. The 16S rDNA was amplified by the polymerize chain reaction and sequenced using an automated DNA sequencing machine. The sequences were compared and regions that could be exploited for oligonucleotide probes highlighted. Regions in the evolutionary conserved 16S rDNA gene were highlighted as possible contenders for an oligonucleotide probe for *in situ* identification and quantification of these bacteria in activated sludge plants. Good yields of unshered, genomic DNA were obtained with all bacterial strains studied; sequences of 16S rDNA of *N.pinensis* strains were identical, whilst those for *N.amarae* varied in a couple of positions (Blackall, 1994).

Using FISH, Wagner *et al.* (1994) compared the results from *in situ* rRNA oligonucleotide probes with those from culturing samples on nutrient rich media and found large discrepancies. They ascribed these discrepancies to the selectivity of the media and culture conditions. They successfully developed probes for *Acinetobacter*, and found that the probe results indicated that these organisms were present in BEPR systems at significantly lower levels than indicated by culturing techniques. Further, they demonstrated the application of probes to study the filamentous organism *Sphaerotilus*. They concluded that oligonucleotide probes will provide a tool that will greatly enhance knowledge of the ecology and phylogeny of wastewater organisms.

Summary

For the rRNA/DNA based methods, these are complex and analytically tedious requiring sophisticated equipment and considerable expertise. At present, the methods appear more suited for bacteria identification and the study of particular organism species or groups, than for quantification of total heterotrophic active biomass in terms of the total mass in the activated sludge system. At their current stage of development, these tests cannot be used for routine application.

3.2.9 Batch test method

Kappelar and Gujer (1992) describe a simple batch test to quantify heterotrophic active biomass in activated sludge mixed liquor; a small quantity of mixed liquor is mixed with centrifuged wastewater and the oxygen utilization rate (OUR) response is monitored with time. From the observed exponential increase in the OUR, the initial OUR in the batch test can be determined, which can be used to derive an estimate for the heterotrophic active biomass concentration. Wentzel *et al.*, (1995) and Mbewe *et al.*, (1995) modified and extended this method for application to the characterization of municipal wastewaters: The batch test was conducted on unsettled municipal wastewater *without* the addition of activated sludge mixed liquor. From the OUR-time response (for example, see Fig 3.1) and a flocculated-filtered COD measurement at the end of the test, the wastewater heterotrophic active biomass, readily biodegradable COD (RBCOD) and unbiodegradable soluble COD (USCOD) could be determined. Mbewe *et al.*, (1995) found that the RBCOD and USCOD measured in the batch test correlate closely to that measured via conventional methods, see Figs 3.2 and 3.3 respectively. However, they were not able to evaluate the results for wastewater heterotrophic active biomass, since no conventional tests were available. They did note that measurements appeared to reflect operational changes at the wastewater treatment plant where the wastewater was collected - at the treatment plant, due to operational problems with sludge handling unit processes, on occasion waste activated sludge mixed liquor was discharged into the sewer at a point upstream of where the wastewater was collected; the batch test method could correctly detect the increase in heterotrophic active biomass during these periods.

Summary

The experimental procedure for the batch test is relatively simple and does not require sophisticated equipment. It would appear that the method can be readily adapted to quantify the heterotrophic active biomass in activated sludge mixed liquor samples. Such an application will, however, have to be extensively evaluated

3.3 CLOSURE

In this Chapter a number of experimental methods to quantify heterotrophic active biomass have been reviewed. The vast majority of these methods find their origin in the microbiological/biochemical sciences, in the detailed study of pure cultures. For most of the tests, their application to activated sludge mixed liquor has been limited. For those that have been applied to activated sludge mixed liquor, or have potential for application, some possible deficiencies have been identified; in general, for the simpler tests, these give estimates that are

too approximate to provide meaningful results and for the more rigorous tests, these are too elaborate for routine use requiring sophisticated equipment and experimental techniques. Furthermore, all these methods provide estimates for active (viable) biomass that are not directly related to the heterotrophic active biomass parameter in the steady state design and kinetic simulation models; integration of the estimates from these tests with the design and modelling theory is an additional complication.

In contrast, the batch test method of Kappelar and Gujer (1992) as modified and extended by Wentzel *et al.*, (1995) and Mbewe *et al.* (1995) is relatively simple and does not require sophisticated equipment. From this method, estimates for heterotrophic active biomass are obtained that are directly related to this parameter in the modelling theory. Consequently, this test appears to hold promise for possible application - in this research project this test method will be further evaluated and developed.

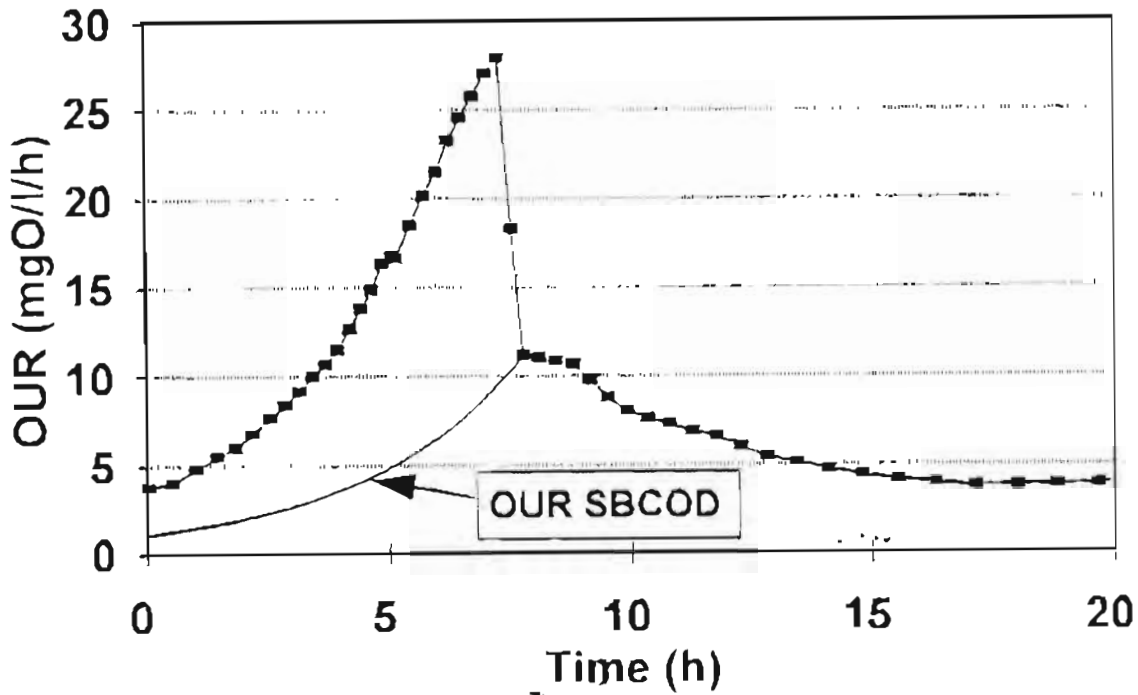


Figure 3.1: Oxygen utilization rate (OUR) response with time for aerobic batch test on raw municipal wastewater from Mitchell's Plain (Cape Town, South Africa).

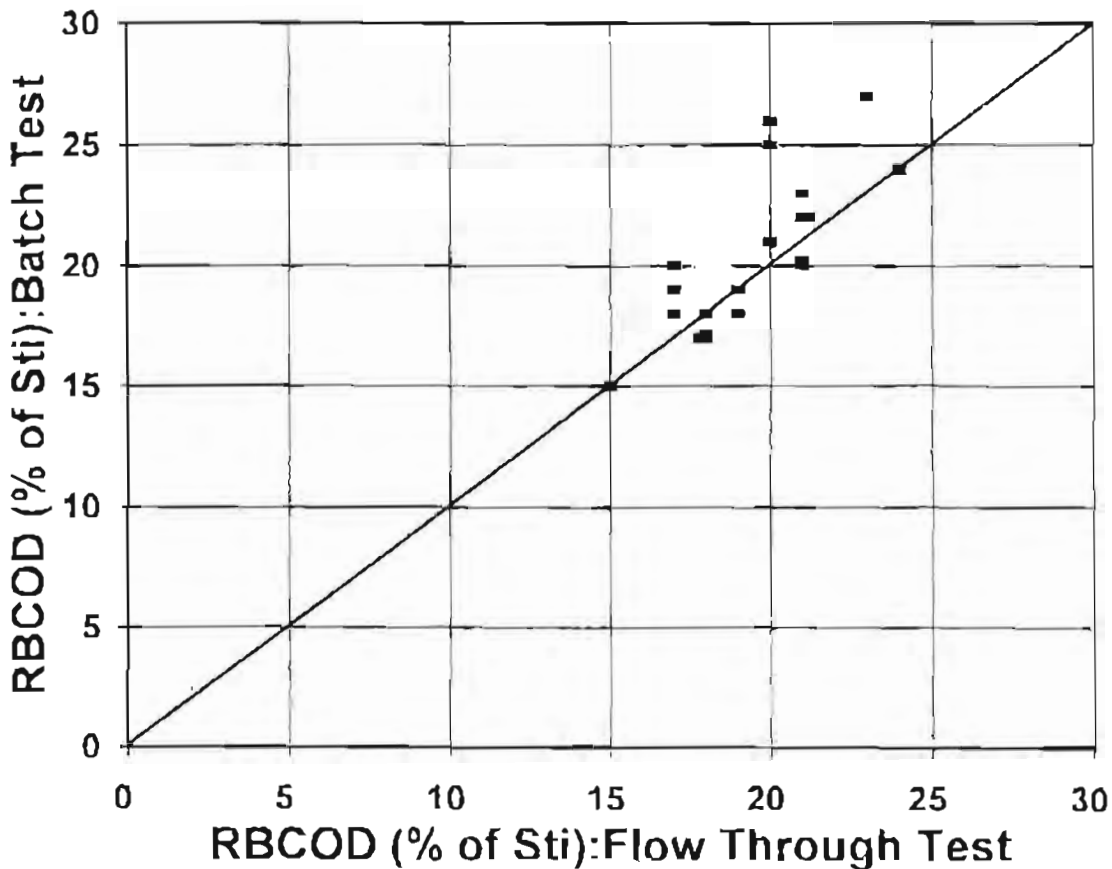


Figure 3.2: Readily biodegradable COD (RBCOD, as % of total COD) derived from the batch test versus those from the flow through square wave method. Each data point is the mean of a number of tests on one batch of sewage.

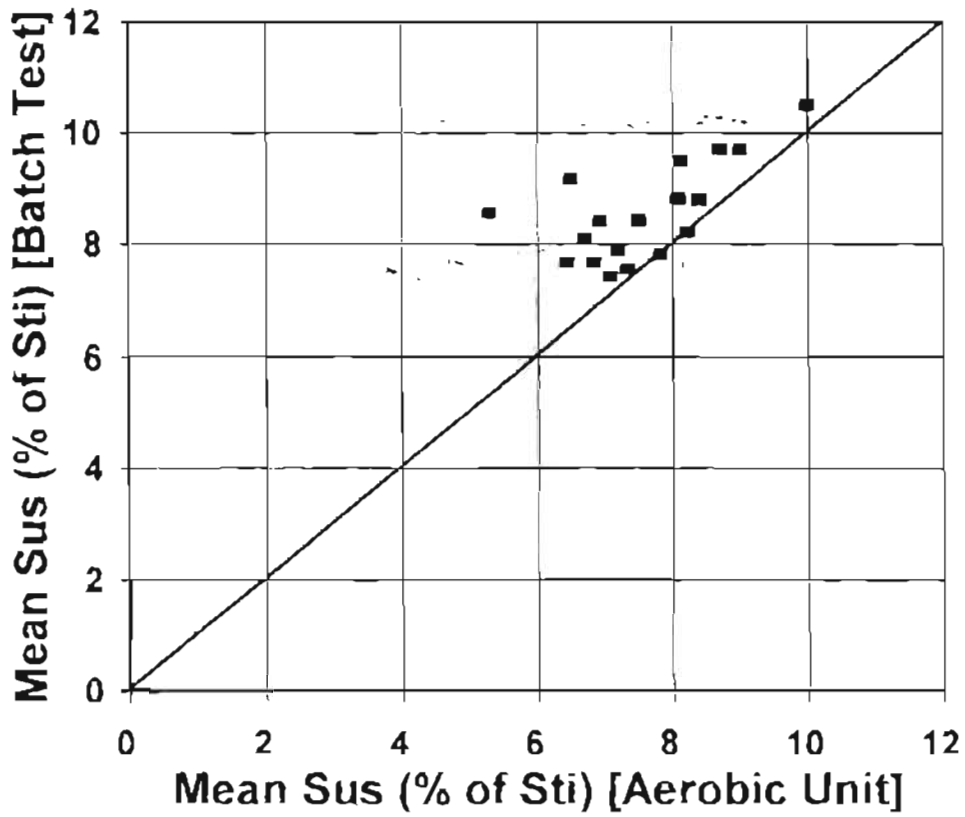


Figure 3.3: Soluble unbiodegradable COD from the batch test versus that from the aerobic unit. Each data point is the mean of a number of tests on one batch of sewage.

CHAPTER 4

THE PARENT LABORATORY-SCALE ACTIVATED SLUDGE SYSTEM

4.1 INTRODUCTION

A well defined and controlled parent laboratory-scale system was operated at steady state and closely monitored. This parent laboratory-scale system was used to:

- (1) Provide the mixed liquor samples required for measuring heterotrophic active biomass (see Chapters 5 and 6).
- (2) Investigate the incorporation of inorganic materials into activated sludge mixed liquor (see Chapter 7).

This chapter describes the layout, operation and maintenance of the parent laboratory-scale system, the tests conducted on the system and the results of these tests.

4.2 SYSTEM LAYOUT

The physical construction of the system was as described in detail by Burke *et al.* (1986) and Clayton *et al.* (1989).

4.2.1 Completely aerobic system

Initially, the system layout consisted of a single biological reactor and a secondary settling tank in series, with an underflow recycle from the settling tank to the biological reactor of 1:1 with respect to the influent flow, see Fig. 4.1.

The contents of the biological reactor were completely mixed by means of independent stirring, and aerated by passing low pressure air through a porous stone situated at the bottom of the tank. The secondary settling tank was an inclined tube at 60° to the horizontal fitted with an intermittent slow stirring (1.33 rpm) wipe blade. Pumping of influent feed and recycle flows was by means of a multiple channel peristaltic pump, with the flow rate controlled by timers switching the pump on and off. (For further details, see Burke *et al.*, 1986) Operational details for the system are shown in Fig. 4.1.

This completely aerobic system was run for three sewage batches (for details on sewage collection and feeding, see Section 4.3 and 4.5 below), whereafter severe bulking problems started [the diluted sludge volume index (DSVI) rose to 200 ml/g], and significant solids loss in the effluent was experienced. Bioreactor mixed liquor filamentous organism identification was done (Jenkins *et al.*, 1986) and it was found that the bulking was caused by the filament *Sphaerotilus natans* (*S.natans*). Several methods recommended by Gabb *et al.* (1989) to remedy bulking by the filament *S.natans* were tried;

- The reactor and all feeding and recycle tubes were cleaned using hypochlorite and the mixed liquor in the reactor was continuously aerated for three successive days,
- the aeration in the reactor was switched off for four successive days,
- two sets of influent feed tubes were set up; one set was used for feeding and the spare influent feed tubes were kept in hypochlorite diluted with water; daily fresh hypochlorite solution was made up and the two sets of tubes were swapped - this practice avoids growth of the filamentous organism *S.natans* in the feed pipes and seeding of the organism into the bioreactor.

However, none of the above conditions could successfully remedy the bulking by *S.natans*. An alternative method to control their growth is to include unaerated zones in the system layout (Gabb *et al.*, 1989). This approach was tried.

4.2.2 Modified Ludzack-Ettinger (MLE) system

To eliminate the problem of bulking by *S.natans*, an unaerated independently stirred predenitrification anoxic reactor was included in the system, that is, the system layout was changed to that of Modified Ludzack-Ettinger (MLE) configuration. The system total volume was kept constant, but the system layout now consisted of an anoxic reactor (25% of the total system volume), an aerobic reactor (75% of the total system volume) and a secondary settling tank, all in series, with an underflow recycle from the settling tank to the anoxic reactor of 1:1 and from the aerobic reactor to the anoxic reactor of 2:1, all recycle ratios with respect to the influent flow, see Fig. 4.2 for details of layout and operation. This modification essentially resolved the bulking problem, within one sludge age (R_s) the DSVI declined to 130 ml/g, and for the rest of the investigation usually was less than 150 ml/g. Accordingly, this system configuration was used for the experimental investigation.

4.3 WASTEWATER COLLECTION AND STORAGE

The influent for the parent laboratory-scale activated sludge system was raw (unsettled) wastewater from the Mitchell's Plain Treatment Plant in Cape Town (South Africa). This sewage is primarily domestic, with a small (< 25%) industrial component. The sewage was collected in batches from the head of the works, after the coarse screens, but before the grit removal and primary sedimentation tanks. The sewage batch was brought to the laboratory and stored in 400ℓ stainless steel tanks in a cold room at 4°C for 10 to 14 days, then discarded and a new batch of sewage collected; experience has shown that storage of sewage for periods longer than 3 weeks leads to hydrogen sulphide build-up in the tanks and a change in the characteristics of the sewage. On every new batch of sewage, immediately after storage in the cold room a COD test was done to determine the COD concentration required for subsequent dilution (see below) (COD ranged from 1000 to 1500 mgCOD/ℓ)

4.4 FEED PREPARATION

The total COD concentration for the feed to the parent laboratory-scale activated sludge system

was set at 500 ± 50 mgCOD/l. Knowing the total COD concentration of the sewage batch collected, volumes of sewage and tap water to dilute the sewage to the required concentration (500 mgCOD/l) could be calculated. Daily, the contents of the storage tanks were thoroughly mixed and a volume of sewage was then drawn from the tank. The sewage was drawn from a tap at the bottom of the tank, passed through a 1 mm sieve into a graduated 20 l plastic bucket. Then the appropriate volume of tap water was added to dilute the sewage to the COD concentration (500 mgCOD/l) required in the tests. To increase the alkalinity of the influent (to maintain pH in the reactors at ± 7.5), 1 or 2 teaspoons of sodium bicarbonate were added to the diluted sewage. After thorough mixing, samples were drawn for influent analysis.

4.5 FEEDING THE SYSTEM

From the diluted sewage above, daily the feed (15l) for the parent activated sludge system over the next 24 h was drawn and placed in an upright PVC bucket which had a stirrer driven at 10rpm, to keep the contents in the bucket completely mixed and limit settling of particulate matter. The surface of the bucket was covered by a floating plastic disc to minimize air entrainment from the atmosphere into the feed. The feed bucket was placed in a large chest refrigerator at a temperature of 4 - 8°C to minimise biological degradation of the sewage. The diluted sewage was pumped at a constant rate from the storage bucket to the parent activated sludge system over the 24 h period. The feed bucket was cleaned daily with boiling water.

4.6 SYSTEM MAINTENANCE AND OPERATION

The general maintenance and operational procedures set out in detail by Burke *et al.* (1986) and Clayton *et al.* (1989) were followed.

The volume of the mixed liquor in the anoxic reactor was maintained at 2.5 l and that in the aerobic reactor at 7.5 l (total volume 10 l) by controlling the level in the reactors. The sludge age (R_s) was controlled hydraulically, initially at 12 and later at 20 days, by wasting daily from the aerobic reactor 0.83 or 0.5 l of mixed liquor (including any samples drawn for analysis) respectively. When conducting batch tests, the volume of mixed liquor drawn from the reactors usually exceeded the amount to be wasted daily (depending on the volume of mixed liquor used in the batch test): To avoid over wasting, the effluent used in diluting the mixed liquor when conducting the DSVI test was decanted, and the mixed liquor rediluted to the correct volume with effluent and the appropriate volume required to avoid over wasting returned to the system. The system was operated in a temperature controlled room, kept constant at 20°C. In the bioreactor, pH was controlled at 7.5 (± 0.2). Also, the dissolved oxygen (DO) concentration was controlled to between 1.5 and 4.5 mgO/l, by using an automated DO meter (Randall *et al.*, 1991); this meter also recorded the oxygen utilization rate (OUR) automatically (see below). The DO meter and probe were recalibrated *at least* once a week.

4.7 SAMPLING AND MEASUREMENTS

Daily, the following samples were drawn for analysis:

- **Influent:** Before the influent was poured into the feed bucket, the feed was thoroughly mixed and two (later five) 200 ml samples taken in glass jars and stored at 4°C for analysis the following day.

- **Reactors:** Three (five samples when batch tests were carried out) 50 ml samples were drawn from the aerobic reactor and one from the anoxic reactor whilst the system was still feeding on the previous day's feed.
- **Effluent:** After thorough mixing a one litre sample was drawn from the effluent bucket.

The following tests were performed on the samples daily:

1. COD and TKN (Standard Methods, 1985) on influent sample.
2. COD and TKN on unfiltered effluent sample.
3. COD and TKN on filtered effluent sample (sample filtered through 0.45 μm filter paper).
4. COD and TKN on aerobic reactor mixed liquor unfiltered samples.
5. Oxygen utilization rate (OUR) in aerobic reactor (see below).
6. pH of aerobic reactor.
7. DSVI (Ekama and Marais, 1984) on aerobic reactor mixed liquor.
8. Nitrate and nitrite concentration (Technicon Auto Analyser) on effluent, aerobic and anoxic reactors, all samples filtered through 0.45 μm filter paper.
9. Total suspended solids (TSS), organic/volatile suspended solids (VSS) and inorganic suspended solids (ISS) on aerobic reactor mixed liquor (Standard Methods, 1985).

The oxygen utilization rate (OUR) in the aerobic reactor was measured continually by using an automated technique (Randall *et al.*, 1991): A DO probe (YSI) from an automatic DO meter/OUR logger (Hi Tech Microsystems) was immersed in the mixed liquor. The low and high DO set point of the meter were 1.5 and 4.5 mgO/l respectively. When the DO reached ± 4.5 mgO/l the air switched off automatically and the decrease in DO with time was monitored; when the DO reached ± 1.5 mgO/l, the air was switched on again automatically and the cycle repeated. Automatically, for each cycle the slope of the DO-time data during the air off period was determined by linear regression; this gives the OUR, which was stored by the meter (together with regression analysis and time data). The OUR results were down-loaded from the DO meter to a PC early the following day whilst the system was still feeding on the previous day's feed. OUR results with a regression correlation coefficient less than 0.99 ($R^2 = 0.99$) were rejected, and a mean OUR determined from the remaining data, the mean being used as the OUR for the day. The number of OUR readings ranged between 120 and 150 per day.

The daily tests conducted on the parent laboratory-scale system are summarized in Table 4.1

In addition a number of tests were performed to quantify the inorganic materials (for details, see Chapter 7).

10. Total solids (TS), total organic/volatile solids (TVS) and total inorganic solids (TIS) on unfiltered influent and effluent samples.
11. Total dissolved solids (TDS), organic/volatile dissolved solids (VDS) and inorganic dissolved solids (IDS) on filtered influent and effluent samples (samples filtered through 0.45 μm filter paper)

SYNOPSIS

BACKGROUND AND OBJECTIVES

To comply with more stringent effluent quality legislations, over the past 20 years there have been extensive developments in the activated sludge method for treating wastewater. The functions of the single sludge system have expanded from carbonaceous energy removal to include progressively nitrification, denitrification and phosphorus removal, all mediated biologically. These extensions have increased considerably the complexity of the system configuration and its operation. Concomitantly, the number of biological processes influencing the effluent quality and the number of compounds involved in these processes have increased. With such complexity, design procedures based on experience and semi-empirical methods no longer will give optimal performance; design procedures based on more fundamental behavioural patterns are required. Furthermore, it is no longer possible to make reliable quantitative predictions as to the effluent quality to be expected from a design, or to assess the effect of a system or operational modification, without some model that simulates the system behaviour accurately. To meet these requirements, increasingly sophisticated, fundamentally based steady state design procedures (e.g. Marais and Ekama, 1976; WRC, 1984) and dynamic kinetic simulation models (e.g. Dold *et al.*, 1980, 1991; Henze *et al.*, 1987, 1995; Wentzel *et al.*, 1992) have been developed.

This group of models is based, to a large degree, on a common simplified conceptualization of the mechanisms operating in the activated sludge system, which has developed particularly from an understanding of the interactions between the components making up the mixed liquor in the bioreactor of the activated sludge system, and the influent wastewater. In terms of this conceptualization, in the bioreactor of the activated sludge system the mixed liquor is made up of organic and inorganic materials. *The principle aim of this research project was to investigate the organic and inorganic components/materials making up the mixed liquor in the bioreactor of the activated sludge system.*

Mixed liquor organic components

In terms of the conceptual framework of the models, in the bioreactor of the non-nitrifying aerobic activated sludge system the mixed liquor organic suspended solids (MLOSS) is made up of three components; (1) heterotrophic active biomass, (2) endogenous residue and (3) inert material. In the nitrifying aerobic and anoxic/aerobic activated sludge systems, a fourth mixed liquor organic suspended solids component is included; (4) autotrophic active biomass. All four MLOSS components settle out in the secondary settling tank and are returned to the bioreactor via the underflow recycle; these components leave the system via the waste flow. If an anaerobic reactor is included to stimulate biological excess phosphorus removal (BEPR), additionally the organisms mediating BEPR will contribute to the MLOSS (Wentzel *et al.*, 1992; Henze *et al.*, 1995) - to avoid this complication, *only aerobic and anoxic/aerobic systems are considered in this research project.*

Historically the MLOSS has been measured as a lumped parameter, via the VSS or COD test (Standard Methods, 1985). Specific rates for the biological processes (e.g. denitrification; oxygen utilization) often were (and still are) expressed in terms of this lumped parameter. However, from

the above, only a part of the MLOSS is heterotrophic active biomass (X_H), the active fraction, and only this part mediates the biological processes of COD removal and denitrification. Accordingly, the specific rates for these (and associated) biological processes should be expressed in terms of X_H to allow a meaningful comparison of rates measured in different systems. More recently, with the proliferation of kinetic simulation computer programmes that invariably include X_H as a parameter, this parameter and the use of specific rates in terms of it have become much more widely accepted. However, it must be remembered that X_H exists only hypothetically within the structure of the design procedures and kinetic models. Although indirect evidence does provide support for the parameter (by consistency between observations and predictions over a wide range of conditions, e.g. Dold *et al.*, 1980, 1991; Alexander *et al.*, 1980; Van Haandel *et al.*, 1981; Warner *et al.*, 1986), it has not been directly measured experimentally and compared to theoretical values. This deficiency casts a measure of uncertainty on the entire framework within which the models have been developed. Thus, to promote confidence in application of the models for design, operation and control of activated sludge systems, and indeed in the models themselves, it is essential that the heterotrophic active biomass parameter is validated by experimental measurement. *Thus, measurement of heterotrophic active biomass was the first principle objective of this research project.*

Mixed liquor inorganic components

In both the steady state design procedures and kinetic simulation models, the influent wastewater characteristics and biological processes that influence the bioreactor mixed liquor organic solids (as volatile suspended solids, VSS, or COD) are explicitly included. However, the mixed liquor total suspended solids (TSS, i.e. organic + inorganic solids) is calculated simply from an empirical ratio of VSS/TSS, the value for this ratio being accepted as one constant for activated sludge systems treating raw (unsettled) wastewater (VSS/TSS = 0,75 mgVSS/mgTSS, WRC, 1984) and another constant for those treating settled wastewater (VSS/TSS = 0,83 mgVSS/mgTSS, WRC, 1984). The TSS concentration (X_t) is fundamental in the design of secondary settling tanks and waste activated sludge disposal. Clearly, the empirical approach to obtaining an estimate for X_t is not satisfactory within a fundamentally based model. *Accordingly, incorporation of the inorganic material present in the influent wastewater into the mixed liquor was investigated - This was the second principle objectives of this research project.*

RESEARCH APPROACH

The research approach adopted was to operate and monitor a well-defined and controlled parent laboratory-scale activated sludge system. This parent system provided the mixed liquor samples required for measuring heterotrophic active biomass to address the first principle objective above. Also, the inorganics present in the influent wastewater to the parent system and in the bioreactor and effluent of the system were monitored, to address the second principle objective above.

PARENT SYSTEM

The laboratory-scale completely mixed anoxic/aerobic parent activated sludge system was operated under carefully controlled conditions, at sludge ages of 12 and 20d. Influent feed was

Table 4.1: Daily tests conducted on parent steady state system.

Test	Influent	Anoxic reactor	Aerobic reactor	Effluent
COD	◆		◆	◆○
TKN	◆		◆	◆○
Nitrate		○	○	○
Nitrite		○	○	○
OUR			□	
TSS	◆○		×	◆○
VSS	◆○		×	◆○
ISS	◆○		×	◆○
pH			□	
DSVI			□	

- ◆ Unfiltered sample.
- Sample filtered through 0.45 μm filter paper
- Direct measurement taken.
- × centrifuged pellet.

4.8 PARENT SYSTEM CONDITIONS

As noted earlier, the parent laboratory-scale activated sludge system was operated for two reasons:

- (1) To supply mixed liquor for the batch tests, to measure heterotrophic active biomass.
- (2) To enable the incorporation of inorganic material into the mixed liquor to be studied.

This required that the conditions present in the parent system be precisely defined. The details of the parent system have been described above. The parent system operational parameters that were varied during the investigation were aerobic and anoxic/aerobic configuration (changed due to bulking problems, see Section 4.2), system sludge age 12 and 20 d (changed to vary the mixed liquor production and composition) and sewage batch (batches used to ensure steady state conditions, but changed every ± 2 weeks to prevent degradation under storage). In total 28 batches of sewage were fed to the parent system. These sewage batches and the dates they were used as feed are listed in Table 4.2, together with the system operational parameters that were varied. Also indicated are the sewage batches during which (i) mixed liquor samples were drawn from the system for batch tests, and (ii) analysis of inorganic materials were conducted.

Table 4.2: Details of the Parent laboratory-scale steady state system configurations, sludge ages, sewage feed dates, sewage batch number and batch tests conducted.

System configuration	Sludge age (R, d)	Dates of Test (1995/1996)	Sewage Batch No.	Batch Test	Inorganic Analysis
Aerobic	12	30 Mar - 12 Apr	1	No	Yes
		13 Apr - 25 Apr	2	No	
		26 Apr - 14 May	3	No	
MLE		20 Jun - 27 Jun	4	No	
		29 Jun - 20 Jul	5	No	
		21 Jul - 3 Aug	6	No	
		4 Aug - 22 Aug	7	No	
		23 Aug - 6 Sept	8	No	
		7 Sept - 20 Sept	9	No	
		21 Sept - 2 Oct	10	No	
		3 Oct - 16 Oct	11	No	
		17 Oct - 31 Oct	12	Yes	
		1 Nov - 17 Nov	13	Yes	
		18 Nov - 4 Dec	14	No	
		5 Dec - 14 Dec	15	No	
		8 Jan - 11 Jan	16	No	
		12 Jan - 25 Jan	17	Yes	
		26 Jan - 7 Feb	18	Yes	
		8 Feb - 21 Feb	19	Yes	
		22 Feb - 5 Mar	20	Yes	
6 Mar - 19 Mar	21	Yes			
20	4 Apr - 12 Apr	22	Yes		
	13 Apr - 23 Apr	23	Yes		
	24 Apr - 8 May	24	Yes		
	9 May - 19 May	25	No		
	20 May - 31 May	26	Yes		
	1 Jun - 14 Jun	27	Yes		
	15 Jun - 27 Jun	28	No		

4.9 RESULTS

4.9.1 Steady state periods

Daily results for the parent activated sludge system are listed in Appendix C, Tables C3 and C4. Each wastewater batch was accepted as a steady state period. The daily data for each wastewater batch were analysed statistically to determine outliers; data lying outside the 95% confidence interval (i.e. data lying outside the range $\text{mean} \pm 2 \cdot \text{sample standard deviation}$) were rejected (these data are shown marked in the appropriate tables). Rejection of data was checked by means of the method of Laubscher. Excluding the rejected data, for each wastewater batch (steady state period) the daily data were averaged and the sample standard deviations calculated. The averages, sample standard deviations and number of data for the different wastewater batches are listed in Table 4.3 (a and b). (Note that the data for inorganic tests on the parent laboratory-scale system are listed in Chapter 7).

4.9.2 COD and N mass balances

The reliability of the experimental measurements were checked by means of COD and N mass balances on the steady state periods (Ekama *et al.*, 1986): COD and N mass balances (%) are listed in Table 4.4, and are shown plotted in Fig 4.3 and 4.4 respectively. In Fig 4.3 and 4.4 the final destinations for the COD and N respectively in the activated sludge system also are illustrated.

In the nitrogen mass balances, experience has shown that if the nitrate concentration in the anoxic reactor is $< 0.7 \text{ mgN/l}$, the measurement is unreliable due to background colour which interferes with the Technicon Auto Analyser test for nitrate. Accordingly, for the sewage batches where this was true (10, 11, 12, 15, 18, 19), the anoxic nitrate concentration was set equal to zero. The effect of this adjustment is listed in Table 4.4 and illustrated in Fig 4.5.

Acceptability of the data is enhanced if the mass balances fall in the range 90 - 110%.

Nitrogen (N) mass balance:

For the nitrogen (N) mass balances,

- For sewage batches 5, 6, 7, 8 and 9 the N mass balances were $< 90\%$. The low N mass balances were unexpected; usually acceptable N mass balances can be achieved without undue difficulty. A number of systems operated in parallel in the UCT laboratory gave similar poor N mass balances (Lakay, 1995-1996; Mellin, 1995-1996). The error was traced to problems with the Technicon Auto Analyser, which measures nitrate and nitrite: The flow rated silicone tubing was found to be worn and partially blocked by crystals which had deposited on the inside of the tubing. The entire set of tubing on the Auto Analyser was replaced. This essentially resolved the problem, and the N mass balances showed immediate improvement ($> 90\%$ from sewage batch 10). Batch tests were not conducted during these sewage batches and so the poor N mass balances do not impact on analysis of the batch test data. However, the inorganics were monitored; since the error was traced to measurement of nitrate, it will not influence the inorganic measurements and the data was accepted for inorganic analysis.

Table 4.3(a): Parent system steady state data; for each sewage batch (steady state period, see Table 4.2) the data have been averaged and the means, sample standard deviations (SSD) and number of tests are listed.

Sew. Batch No.	TKN (mgN/l)						NITRATES (mgN/l)								
	INFLUENT		UNFILT. EFFLUENT		MIXED LIQUOR		ANOXIC		AEROBIC		EFFLUENT				
	Mean	SSD	No. of tests	Mean	SSD	No. of tests	Mean	SSD	No. of tests	Mean	SSD	No. of tests			
1	53	2	13	4.3	1.2	13	227	13	14			31.0	3.9	12	
2	51	2	10	3.2	0.8	9	217	7	6						
3	42	2	19	3.4	0.6	18	181	14	18						
4	49	6	8	3.3	0.2	8	195	9	7	3.6	1.6	8	11.4	2.1	8
5	56	2	18	3.2	0.7	19	201	17	9	2.7	0.9	20	11.3		2
6	60	4	14	1.8	1.3	14	162	29	14	11.4	3.3	13	20.7	3.5	13
7	51	3	19	3.0	1.3	19	186	26	13	1.9	0.6	16	9.8	1.1	16
8	46	2	13	2.6	1.0	13	188	22	13	0.9	0.3	13	7.2	0.6	13
9	46	1	14	6.1	1.5	13	175	8	12	5.8	2.1	14	11.4	2.3	14
10	46	3	12	4.3	0.7	12	231	18	12	0.5	0.3	10	7.5	0.9	12
11	44	1	13	3.5	0.3	13	248	16	13	0.4	0.2	12	7.0	0.3	12
12	41	3	14	3.6	0.6	15	255	13	13	0.4	0.1	14	5.3	0.6	15
13	47	3	15	3.5	0.4	13	210	16	16	1.7	0.7	13	10.9	1.2	13
14	47	2	17	3.3	0.5	16	222	14	15	5.4	3.1	17	14.7	2.5	11
15	45	2	10	2.9	0.4	9	217	26	10	0.6	0.3	9	5.4	0.5	9
16	37	1	4	3.5	0.3	4	231	5	4	3.6	0.4	4	4.7	0.4	4
17	48	1	13	3.7	0.3	13	222	11	13	1.6	0.9	14	8.7	1.0	14
18	37	1	11	3.5	0.6	13	193	15	12	0.6	0.4	11	5.3	0.3	12
19	45	2	12	3.2	0.4	12	222	9	12	0.5	0.5	12	5.9	1.3	10
20	49	1	13	3.4	0.3	12	221	20	12	6.0	0.7	13	13.1	1.2	13
21	52	4	14	3.8	0.5	13	258	21	14	1.6	0.5	10	7.9	0.6	12
22	58	1	8	3.0	0.4	9	294	11	8	9.6	0.7	8	19.7	0.5	8
23	57	4	11	3.2	0.5	11	314	24	11	6.8	1.4	11	16.0	1.1	10
24	53	2	14	3.1	0.4	15	284	24	15	3.2	2.5	14	13.0	2.7	14
25	51	6	10	3.3	0.5	11	309	12	11	4.8	1.3	11	14.1	2.3	11
26	58	3	11	3.1	0.6	11	303	14	12	12.8	1.2	11	23.4	1.4	10
27	47	4	13	3.0	0.5	13	333	15	14	2.8	1.1	9	9.8	2.4	12
28	57	7	13	3.0	0.6	13	344	32	12	6.8	1.7	13	16.5	2.2	13

Table 4.3(b): Parent system steady state data; for each sewage batch (steady state period, see Table 4.2) the data have been averaged and the means, sample standard deviations (SSD) and number of tests are listed.

Sew. Batch No.	COD (mgCOD/l)						MIXED LIQUOR			OUR (mgO/h)			VSS (mgVSS/l)		
	INFLUENT		UNFILT. EFFLUENT		MIXED LIQUOR		OUR		VSS		OUR		VSS		
	Mean	SSD	No. of tests	Mean	SSD	No. of tests	Mean	SSD	No. of tests	Mean	SSD	No. of tests	Mean	SSD	No. of tests
1	498	9	13	39	5	12	3281	117	13	28.1	3.1	14	2394	89	14
2	479	38	10	38	6	10	3294	110	6	25.5	2.9	6	2392	65	6
3	512	20	18	44	6	19	2695	114	17	25.0	2.0	17	1949	93	18
4	476	21	7	50	10	8	2718	111	8	25.2	2.7	8	1953	66	8
5	512	15	19	49	13	19	3037	227	10	29.9	2.1	10	2306	149	10
6	487	42	14	40	7	14	2876	280	13	30.6	2.2	14	1976	186	13
7	521	17	18	39	9	18	2916	237	13	27.2	2.5	13	2094	187	13
8	549	31	14	47	9	13	2925	190	13	27.1	1.9	11	1911	58	13
9	481	35	13	66	8	12	2472	181	12	26.0	1.6	13	1661	78	13
10	554	69	12	59	12	12	3372	330	12	27.6	2.1	12	2222	167	12
11	526	27	13	46	13	13	3499	195	13	27.9	1.9	12	2339	169	13
12	517	30	15	49	15	14	3433	341	13	24.6	1.7	15	2293	149	11
13	492	19	15	46	10	16	2833	301	16	23.7	0.6	10	1684	118	16
14	527	25	16	45	8	16	3125	202	17	25.3	2.0	16	1908	106	16
15	531	23	10	49	9	9	2947	280	9	24.5	0.6	9	1932	56	9
16	474	20	4	39	8	4	3160	275	4	25.7	1.4	4	2018	45	4
17	481	30	14	44	10	13	2839	185	14	25.8	0.6	14	2033	78	13
18	450	31	12	72	9	12	2513	144	12	22.7	1.6	13	1709	85	12
19	492	27	13	59	8	12	2640	153	12	23.5	0.5	12	1775	28	12
20	500	21	13	48	10	13	2958	286	13	24.3	0.9	13	2052	118	11
21	503	34	14	49	10	14	3477	185	13	25.9	1.1	13	2116	112	13
22	476	16	9	38	5	9	4284	151	8	27.4	0.3	9	2729	108	8
23	493	39	11	33	8	9	4236	246	11	27.6	0.6	8	2668	51	11
24	489	19	14	43	7	14	3659	236	15	29.3	0.3	15	2557	66	14
25	498	41	11	46	6	10	4450	188	11	28.4	2.9	11	2747	71	10
26	458	23	11	51	9	11	4297	227	11	27.9	0.5	11	2861	51	12
27	479	39	13	46	8	13	4873	266	14	23.9	1.3	13	3185	101	13
28	476	16	13	40	9	11	5103	204	13	25.9	1.3	12	3302	120	12

Table 4.4: Steady state COD and N mass balances, wastewater fractions and mixed liquor parameters for parent anoxic/aerobic activated sludge system. Data calculated from data in Table 4.3. (* indicates batches where adjustment to anoxic nitrate has an influence).

Sewage Batch No.	MASS BALANCE (%)				WASTEWATER FRACTIONS		MIXED LIQUOR	
	Anoxic NO ₃ ⁻ actual		If Anoxic NO ₃ ⁻ < 0.7 then = 0		Unbio. Soluble (f _{s,us}) (mgCOD/mgCOD)	Unbio. Particulate (f _{s,up}) (mgCOD/mgCOD)	COD/VSS (f _{CV}) (mgCOD/mgVSS)	TKN/VSS (f _N) (mgN/mgVSS)
	N	COD	N	COD				
1	90	84	90	84	0.079	0.201	1.38	0.091
2	94	79	94	79	0.078	0.180	1.37	0.095
3	92	74	92	74	0.086	0.082	1.38	0.093
4	93	88	93	88	0.105	0.120	1.39	0.100
5	87	95	87	95	0.096	0.147	1.32	0.087
6	81	91	81	91	0.082	0.114	1.46	0.082
7	88	85	88	85	0.075	0.101	1.39	0.089
8	83	86	83	86	0.086	0.056	1.53	0.098
9	85	92	85	92	0.137	0.070	1.49	0.105
10*	98	92	102	91	0.106	0.125	1.52	0.104
11*	100	97	103	96	0.087	0.165	1.50	0.106
12*	91	94	95	94	0.094	0.167	1.50	0.111
13	111	79	111	79	0.093	0.059	1.68	0.125
14	112	79	112	79	0.085	0.079	1.64	0.116
15*	77	86	83	85	0.092	0.077	1.53	0.112
16	63	105	63	105	0.082	0.151	1.57	0.114
17	93	91	93	91	0.091	0.129	1.40	0.109
18*	90	97	96	96	0.160	0.116	1.47	0.113
19*	86	88	90	87	0.120	0.081	1.49	0.125
20	92	83	92	83	0.096	0.123	1.44	0.108
21	84	97	84	97	0.097	0.161	1.64	0.123
22	92	81	92	81	0.080	0.106	1.57	0.108
23	90	80	90	80	0.067	0.081	1.59	0.118
24	98	84	98	84	0.088	0.065	1.43	0.111
25	100	87	100	87	0.092	0.099	1.62	0.112
26	96	85	96	85	0.111	0.142	1.50	0.106
27	93	87	93	87	0.096	0.168	1.53	0.105
28	99	85	99	85	0.084	0.186	1.55	0.104

- For sewage batches 13 and 14, the N mass balances were $> 110\%$. No assignable cause for these high mass balances could be identified, and these sewage batches were rejected for further analysis. Batch tests were conducted on sewage batch 13, and so this impacts both batch test and inorganic materials analysis.
- For sewage batch 15 and particularly sewage batch 16, the N mass balances were poor, 83 and 63% respectively. Here the problem appeared to be related to the sewage; the sewage was discarded and a new batch collected. These two batches were, accordingly, rejected for further analysis. This does not impact on batch test data analysis since batch tests were not conducted during this period, but it does influence analysis of inorganics.
- For sewage batch 21, the N mass balance $< 90\%$. No assignable cause for this low mass balance could be identified, and this sewage batch was rejected for further analysis. This impacts both the batch test and inorganic material analysis.

COD mass balances:

In general, the COD mass balances were poor; only 10 of 28 sewage batches (5, 6, 9, 10, 11, 12, 16, 17, 18 and 21) gave mass balances $> 90\%$ (3 of the batches, 15, 16 and 21 have already been rejected on the N mass balance). The COD mass balance contains five elements - COD of influent and effluent, oxygen utilization rate (OUR) for carbonaceous material consumption (i.e. measured OUR minus the OUR for nitrification), equivalent oxygen demand for denitrification and sludge production (i.e. the COD of the mixed liquor organic solids wasted every day, which equals the unfiltered reactor COD concentration multiplied by waste flow rate). Investigations showed that the COD measurement technique was accurate (checked with standard potassium hydrogen phthalate, Standard Methods, 1985); the COD data could be accepted. The N mass balances indicated that the problem did not lie in measurement of nitrates - to improve the COD mass balance, the nitrate generated would have to be reduced; this would reduce the N mass balance unacceptably. Thus, the problem would appear to lie in measurement of the OUR or mixed liquor organic solids. Of particular importance to this investigation is the measurement of the mixed liquor organic solids: For the batch tests, the solids measurements are used to estimate the theoretical heterotrophic active biomass active fraction (see Chapter 5), and for the inorganics the solids measurements are used directly (see Chapter 7). Three independent measurements were made on the mixed liquor organic solids, volatile suspended solids (VSS), COD and TKN. To check the reliability of these measurements, the ratios of COD/VSS and TKN/VSS for the parent system mixed liquor were calculated for each sewage batch, see Table 4.4. Statistical plots for these ratios were constructed, see Figs 4.6 and 4.7 respectively. (See Appendix D for interpretation of statistical plots). From the statistical plots it is evident that the data are normally distributed; this indicates that no single factor has had a dominating influence on the measurements. The means for COD/VSS and TKN/VSS were 1.49 mgCOD/mgVSS and 0.106 mgN/mgVSS respectively, with sample standard deviations 0.08 and 0.011 respectively. These values compare very favourably with the accepted standard values of 1.48 mgCOD/mgVSS and 0.10 mgN/mgVSS respectively (WRC, 1984). Accordingly, it can be accepted that the errors in the COD mass balances do not lie in the measurement of the mixed liquor organic solids. For this reason, the lower limit for the COD mass balance was set at 80%. With this limit, sewage batches 2, 3, 13 and 14 were rejected for further analysis. Batch tests were only conducted during sewage batch 13.

Batches rejected for further analysis:

From the above, sewage batches 2, 3, 13, 14, 15, 16 and 21 were rejected for analysis. The data collected on these sewage batches (batch tests and inorganics) will be included where appropriate, and will be analysed, but it will be noted that the data should be rejected and the data will not be used to draw conclusions. This will be done to determine the influence of poor mass balances on the test and analytical procedures.

4.9.3 Determination of unbiodegradable soluble and particulate fractions

The unbiodegradable soluble and particulate fractions of the influent COD ($f_{S,us}$ and $f_{S,up}$ respectively) were determined using the methods of Ekama *et al.* (1986).

Unbiodegradable soluble COD fraction ($f_{S,us}$)

According to Ekama *et al.* (1986), the unbiodegradable soluble COD is given by the COD of the filtered effluent of the activated sludge system. Hence:

$$f_{S,us} = S_{te}/S_{ti} \quad (4.1)$$

where

$$\begin{aligned} S_{te} &= \text{filtered effluent COD concentration (mgCOD/l)} \\ S_{ti} &= \text{unfiltered influent COD concentration (mgCOD/l)} \end{aligned}$$

For the averaged data on each sewage batch (Table 4.3), the $f_{S,us}$ was calculated using Eq. (4.1), and the values are listed in Table 4.4. The $f_{S,us}$ data from all the sewage batches were analysed using a statistical plot, see Fig. 4.8. (For interpretation of the statistical plot, see Appendix D). Two outliers were identified, $f_{S,us} = 0.16$ and 0.137 , see Figure 4.8. Rejecting these points, the data are shown plotted in Fig. 4.9. The data are normally distributed, giving for Mitchell's Plain raw wastewater a mean $f_{S,us} = 0.09$ and sample standard deviation of 0.012.

Unbiodegradable particulate COD fraction ($f_{S,up}$):

Following the method of Ekama *et al.* (1986), the mixed liquor volatile suspended solids (MLVSS) was used to determine $f_{S,up}$. From the averaged data on each sewage batch (Table 4.3) and the calculated $f_{S,us}$ (Table 4.4), the $f_{S,up}$ was calculated using the following equation (Ekama *et al.*, 1986):

$$MX_v = \frac{MS_{ti}(1 - f_{S,us} - f_{S,up})Y_H R_s}{(1 + b_H R_s)} + f_{S,up} MS_{ti} R_s / f_{cv} \quad (4.2)$$

where

$$\begin{aligned} MX_v &= \text{total volatile solids mass (mgVSS)} \\ &= X_v \cdot V_p \\ X_v &= \text{MLVSS concentration (mgVSS/l)} \\ &= \text{measured value (Table 4.3)} \end{aligned}$$

V_p	= system volume = 10ℓ
Y_H^*	= heterotrophic active biomass yield (VSS units) = 0.45 mgVSS/mgCOD
R_s	= sludge age (d) = 12d
b_H^*	= net specific endogenous mass loss rate = 0.24/d
f	= endogenous residue fraction = 0.20
f_{cv}	= COD/VSS ratio of mixed liquor (mgCOD/mgVSS) = measured value (Table 4.4)
MS_{Li}	= total influent COD mass fed per day (mgCOD/d) = $Q_i \cdot S_{Li}$
Q_i	= influent flow rate = 15ℓ/d
S_{Li}	= influent COD concentration (mgCOD/ℓ) = measured value (Table 4.3)

For each batch of wastewater tested, successive values for $f_{S,up}$ were substituted into Eq.(4.2); the $f_{S,up}$ value that gave a theoretical MLVSS mass (MX_V) equal to the measured value was accepted. The $f_{S,up}$ values for the different wastewater batches are listed in Table 4.4.

The $f_{S,up}$ data for all the wastewater batches were analysed using a statistical plot, see Fig. 4.10. The data are normally distributed and no outliers were identified. The data gives for Mitchell's Plain raw wastewater, a mean $f_{S,up} = 0.12$ with sample standard deviation of 0.04. This mean is in close agreement with values recommended for the design of N removal activated sludge systems receiving South African unsettled municipal waste waters, $f_{S,up} = 0.13$ (WRC, 1984). This indicates the data obtained for $f_{S,up}$ are acceptable.

4.9.4 Sludge settleability

Although not explicitly part of this research project, the sludge settleability of the system was monitored daily by means of the Diluted Sludge Volume Index (DSVI); DSVI versus day of operation are shown plotted in Figure 4.11. During operation of the completely aerobic system (Day 0-46) the increase in DSVI to values above 180 ml/g TSS is evident. Filament identifications indicated the filament *S. natans* as the causative agent for the high DSVI. Attempts to control the proliferation of this filament by implementing the strategies recommended by Gabb *et al.* (1989) did not prove successful, and the system eventually failed due to solids loss in the effluent. Introduction of the anoxic reactor (MLE system, see Section 4.2.2 above) caused the DSVI to decrease rapidly, to less than 120 ml/gTSS within one sludge age (12d). Thereafter the DSVI varied, from a minimum of 80 ml/gTSS to a maximum of 210 ml/gTSS. In seeking an explanation for this variation, the filaments in the mixed liquor were identified after Jenkins *et al.* (1986) on four occasions: 3 March 1996 (Day 334), 2 April 1996 (Day 364), 7 May 1996 (Day 399) and 7 June 1996 (Day 430). The filament identifications indicated 0092 as dominant, *Microthrix parvicella* as secondary and variously Types 0041, 1851, 0803 as other. These filaments belong to the low F/M group (Jenkins *et al.*, 1986), subsequently renamed the anoxic

aerobic (AA) group (Casey *et al.*, 1994a,b). According to the hypothesis of Casey *et al.* (1994a,b) which explains the proliferation of AA filaments, the nitrate/nitrite concentration in the primary anoxic reactor preceding the aerobic reactor is of fundamental importance. If the nitrate/nitrite concentration is high, the growth of AA filaments is stimulated and *visa versa* (for details, see Casey *et al.*, 1994 a,b). The primary anoxic reactor nitrate concentration is shown plotted on the same graph as the DSVI versus day of operation, Figure 4.11. In general, the DSVI and anoxic nitrate concentration behaviour tends to conform to hypothesis of Casey *et al.*. There is a general trend for the anoxic nitrate concentration and DSVI to increase and decrease concomitantly, and for the DSVI to be high when the anoxic nitrate concentration is high, and *vice versa*.

4.9.6 Operational problems

When the parent laboratory-scale system was receiving sewage batch No.24, the coldroom refrigerator where the sewage was stored at 4°C broke down, and the temperature of the stored sewage increased to 20°C. From the data in Table 4.3 (a and b) and 4.4 it would appear that this operational problem influenced the parent system steady state behaviour:

- With sewage batch No.24 the mixed liquor organic suspended solids measured with the COD, VSS and TKN tests are all lower compared to the sewage batches immediately preceding and following. In contrast, the OUR for sewage batch No.24 is higher.
- The lower mixed liquor organic suspended solids concentration for sewage batch No.24 causes the calculated wastewater unbiodegradable COD fraction ($f_{S,up}$, Table 4.4) to be lower. This, in turn, will cause the theoretical active fraction for sewage batch No.24 to be higher.
- The COD and N mass balances for sewage batch No.24 do not vary significantly from the batches immediately preceding and following.

The above would indicate that although the data for sewage batch No.24 is consistent (COD and N mass balances), the increased storage temperature for the sewage had an impact on the parent system steady state behaviour. Cognisance must be taken of this observation in evaluating results from tests conducted during the period.

4.10 CLOSURE

In this Chapter the layout, operation and maintenance of the parent laboratory-scale activated sludge system has been described. This parent system will be used to:

- (1) Provide mixed liquor samples for measuring heterotrophic active biomass, see Chapters 5 and 6, and,
- (2) Investigate the inorganic materials into activated sludge mixed liquor, see Chapter 7

The parent system was operated for 450 days and received 28 batches of unsettled municipal wastewater from Mitchell's Plain, Cape Town. From the results obtained from the system:

4.15

- N mass balances were variable, but generally fell in the range 90 to 110%. Sewage batches that gave mass balances falling outside this range were rejected for further analysis, unless an assignable could be found - on this basis sewage batches 13, 14, 15, 16 and 21 were rejected.
- Generally COD mass balances were poor, with a number of sewage batches giving mass balances < 90%. The mixed liquor organic solids were determined by three independent tests - VSS, COD and TKN. Mean ratios for these measurements gave COD/VSS = 1.49 mgCOD/mgVSS (sample standard deviation = 0.08) and TKN/VSS = 0.106 mgN/mgVSS (sample standard deviation = 0.011). These values compare closely to the accepted standard values of 1.48 mgCOD/mgVSS and 0.10 mgN/mgVSS respectively (WRC, 1984). Accordingly it was accepted that the error in the COD mass balance did not lie in the measurement of the mixed liquor organic solids, the parameter of importance in both measurement of heterotrophic active biomass and in the inorganic materials investigation. The lower limit for the COD mass balance was set at 80%. On this basis, sewage batches 2, 3, 13 and 14 were rejected for further analysis.
- The mean unbiodegradable soluble COD fraction ($f_{S,us}$) was determined to be 0.09 (sample standard deviation = 0.012).
- The mean unbiodegradable particulate COD fraction ($f_{S,up}$) was determined to be 0.12 (sample standard deviation = 0.04).
- The values for the unbiodegradable COD fractions conform closely to those recommended for a typical South African raw municipal wastewater, $f_{S,us} = 0.07$ and $f_{S,up} = 0.13$ respectively.
- Filament identifications indicated the presence of low F/M filaments, renamed anoxic aerobic (AA) filaments by Casey *et al.*, (1994a,b) and sludge settleability conformed to the hypothesis of Casey *et al.* (1994a,b) for the proliferation of this group of filaments.
- Operational problems were experienced when the parent system was receiving sewage batch No.24; the coldroom refrigerator where the sewage was stored at 4°C broke down and the temperature increased to 20°C. This influenced the steady state behaviour of the system (decreased sludge production), and this must be taken into account in evaluating batch tests results during this period.

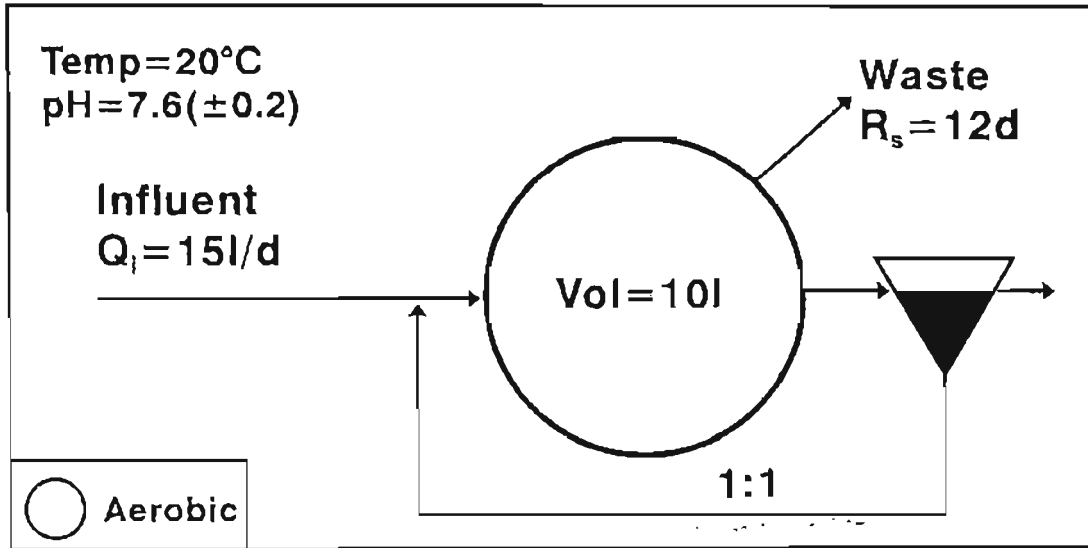


Figure 4.1: Schematic layout and operational data for parent laboratory-scale aerobic activated sludge system.

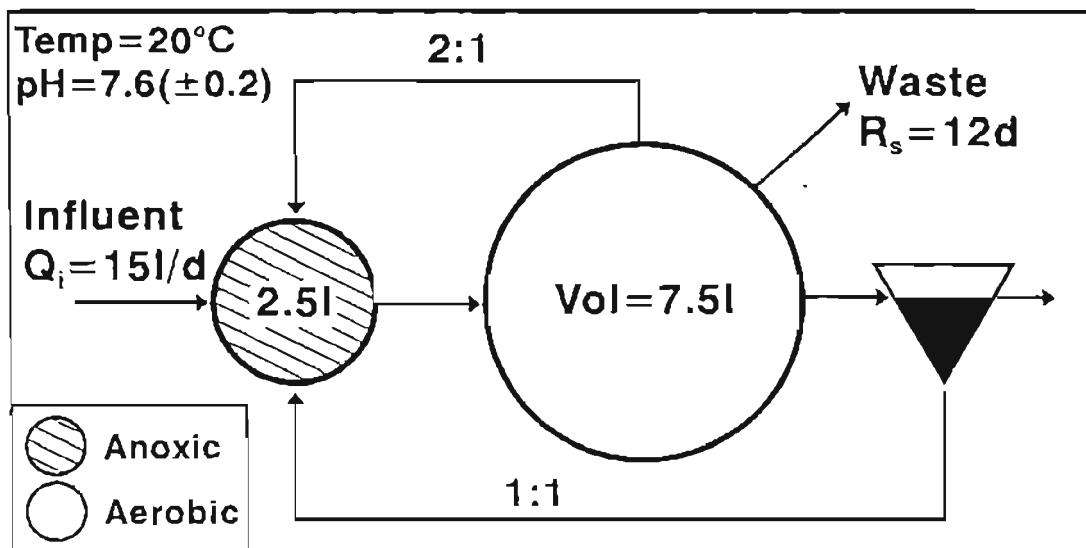


Figure 4.2: Schematic layout and operational data for parent laboratory-scale Modified Ludzack-Ettinger (MLE) anoxic/aerobic activated sludge system.

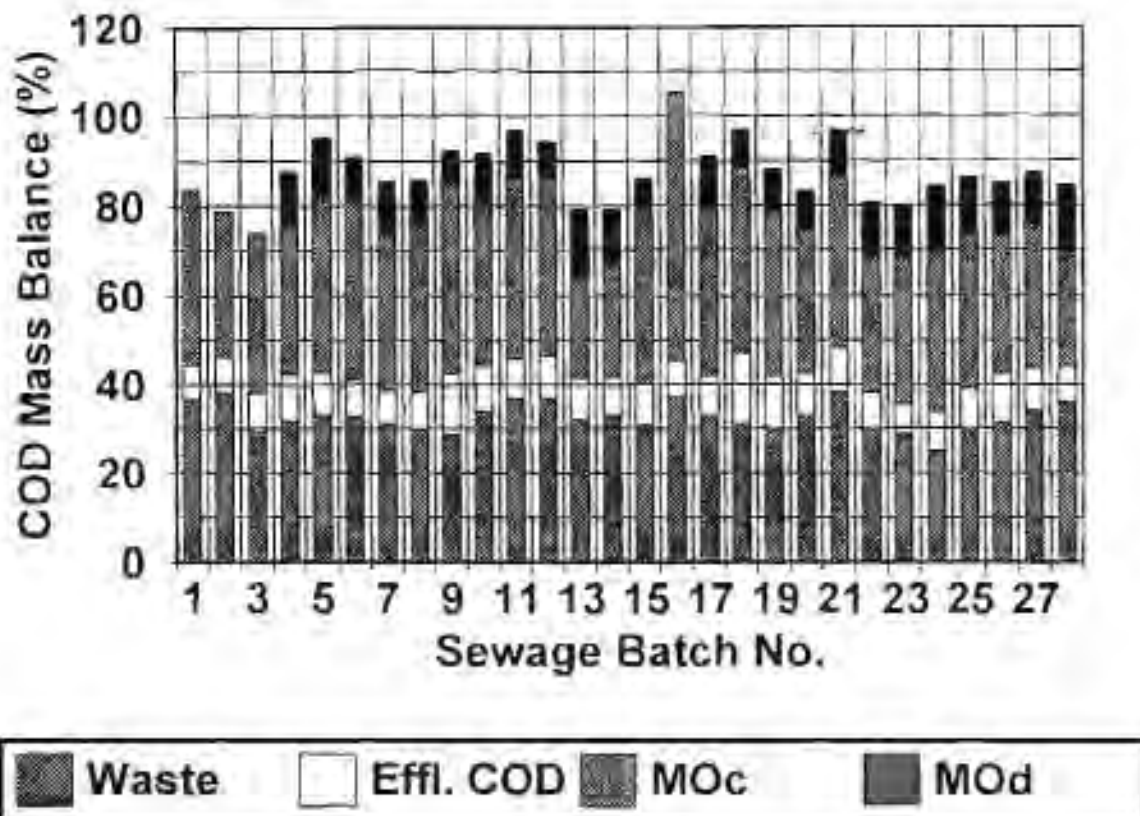


Figure 4.3. Graphical representation of the percentage COD mass balance for the various wastewater batches. Percentages are also shown for waste sludge COD, unfiltered effluent COD, carbonaceous oxygen demand and oxygen demand for nitrification.

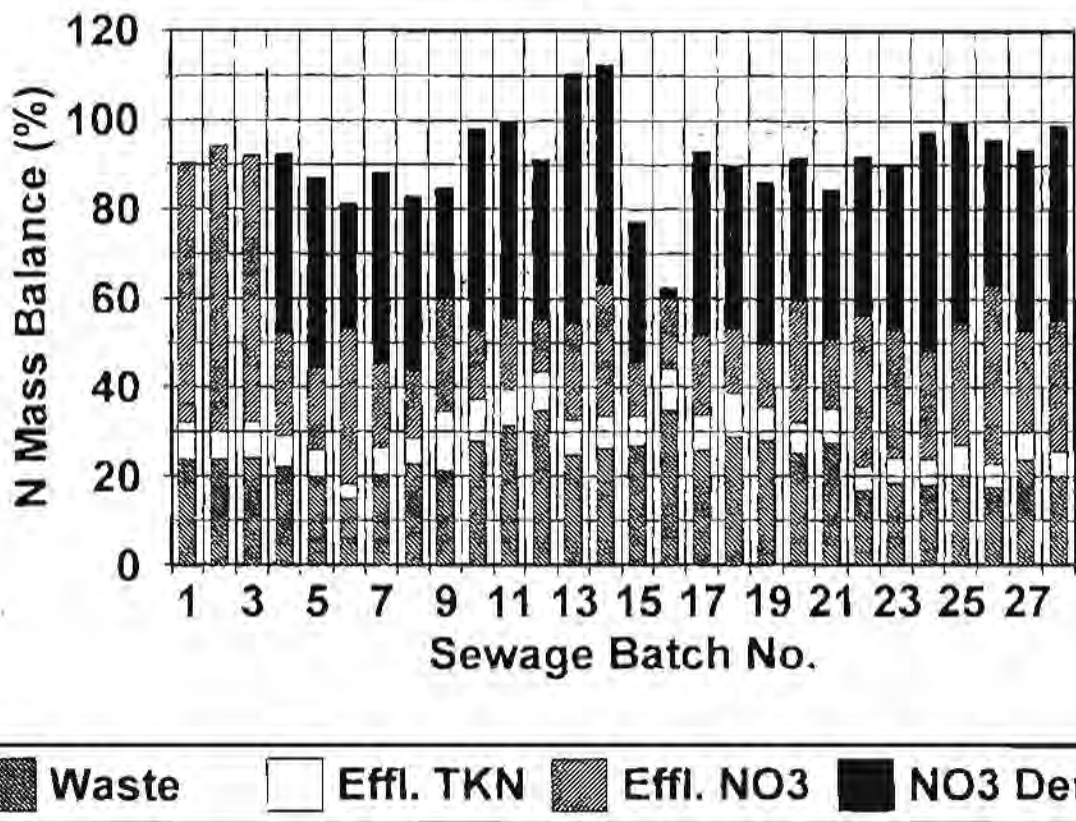


Figure 4.4: Graphical representation of the percentage Nitrogen (N) mass balance for the various wastewater batches. Percentages are also shown for: nitrogen for sludge production (waste), effluent TKN, effluent nitrate and nitrate for denitrification.

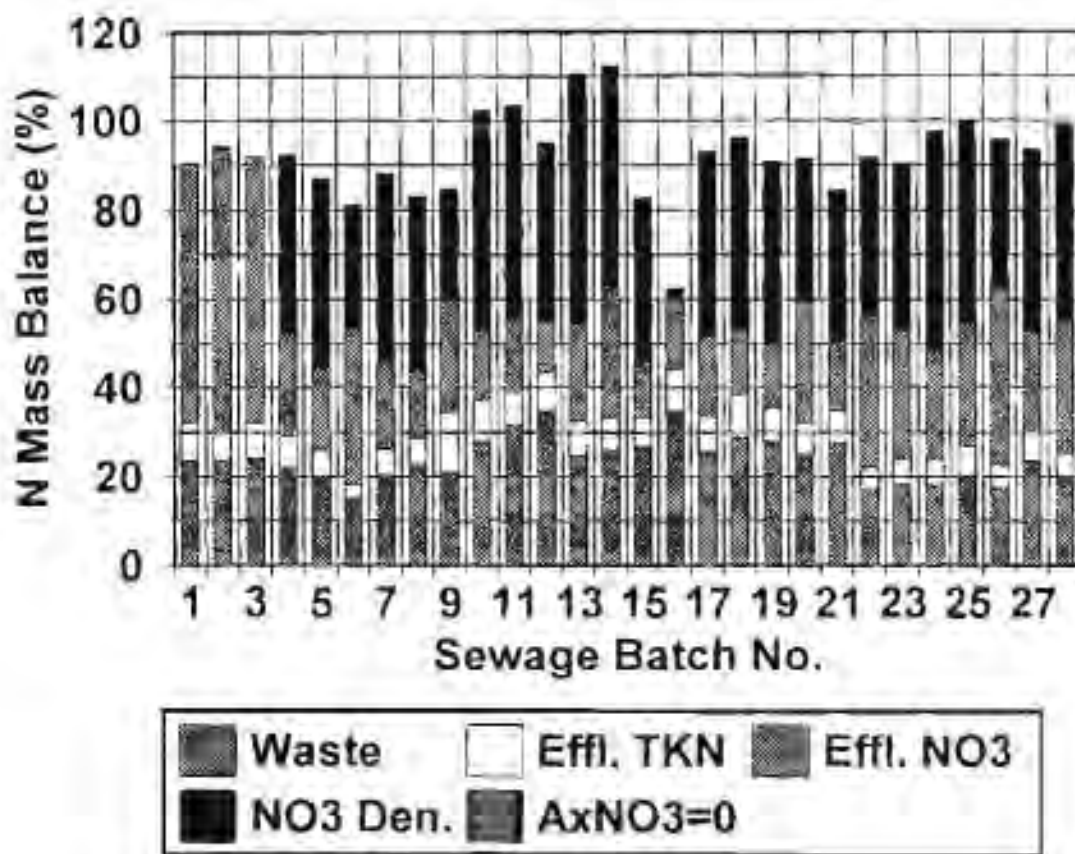


Figure 4.5. Graphical representation of the percentage Nitrogen (N) mass balance for the various wastewater batches. Percentages are also shown for: nitrogen for sludge production (waste), effluent TKN, effluent nitrate and nitrate for denitrification when the nitrate in the anoxic reactor is assumed zero.

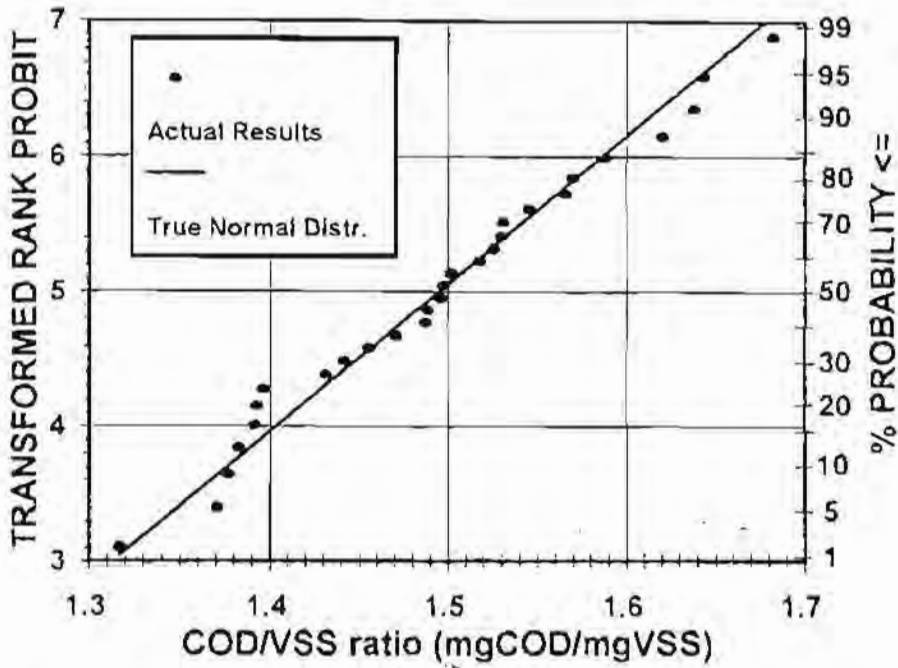


Figure 4.6: Statistical plot for COD/VSS ratio for the parent laboratory-scale activated sludge system mixed liquor.

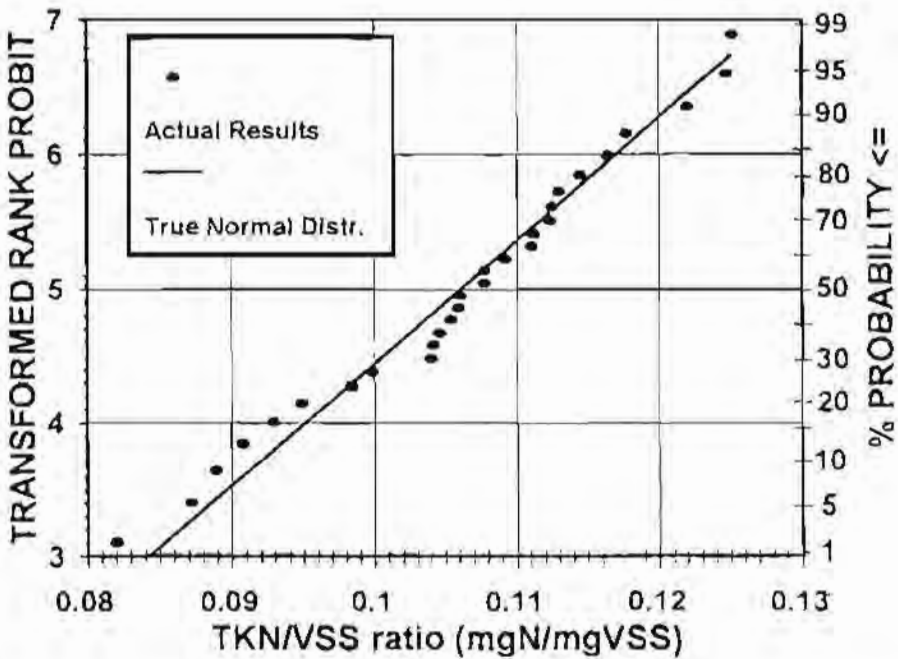


Figure 4.7: Statistical plot for TKN/VSS ratio for the parent laboratory-scale activated sludge system mixed liquor

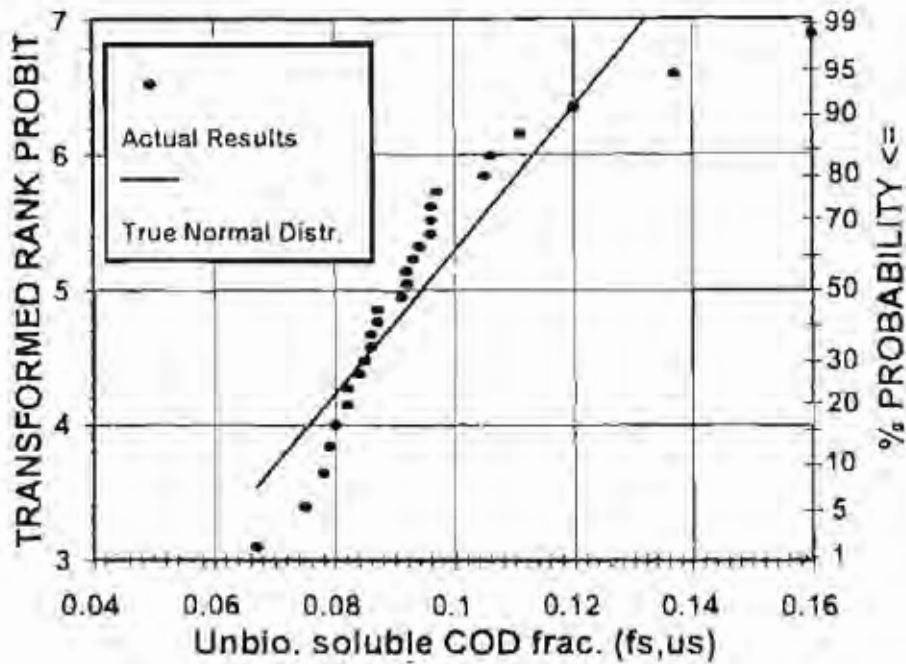


Figure 4.8: Statistical plot for unbiodegradable soluble COD fractions ($f_{s,u}$) for the parent laboratory-scale activated sludge system fed with municipal wastewater from Mitchell's Plain (Cape Town, South Africa).

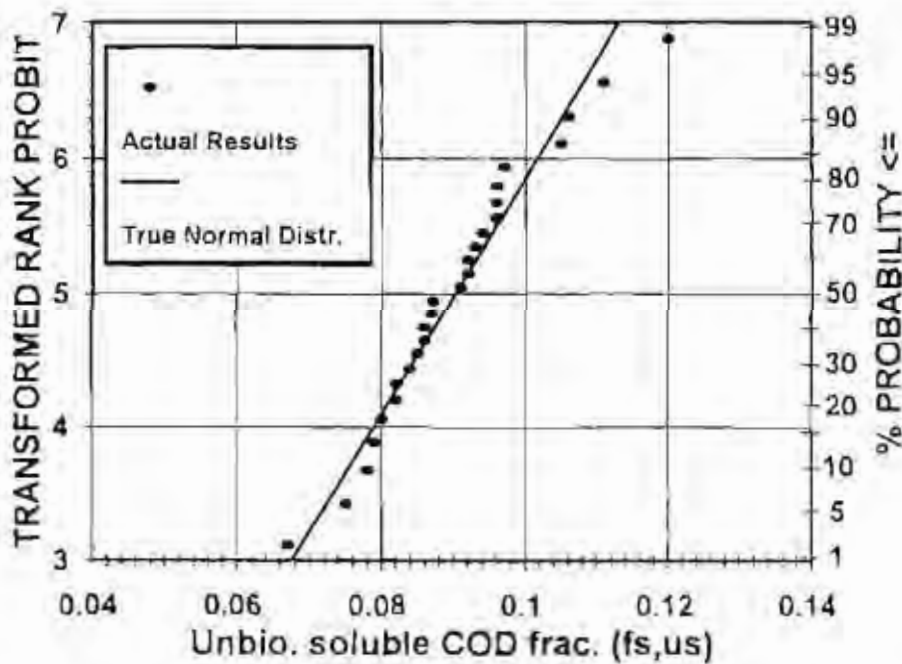


Figure 4.9: Statistical plot for unbiodegradable soluble COD fractions ($f_{s,u}$) for the parent laboratory-scale activated sludge system fed with municipal wastewater from Mitchell's Plain (Cape Town, South Africa).

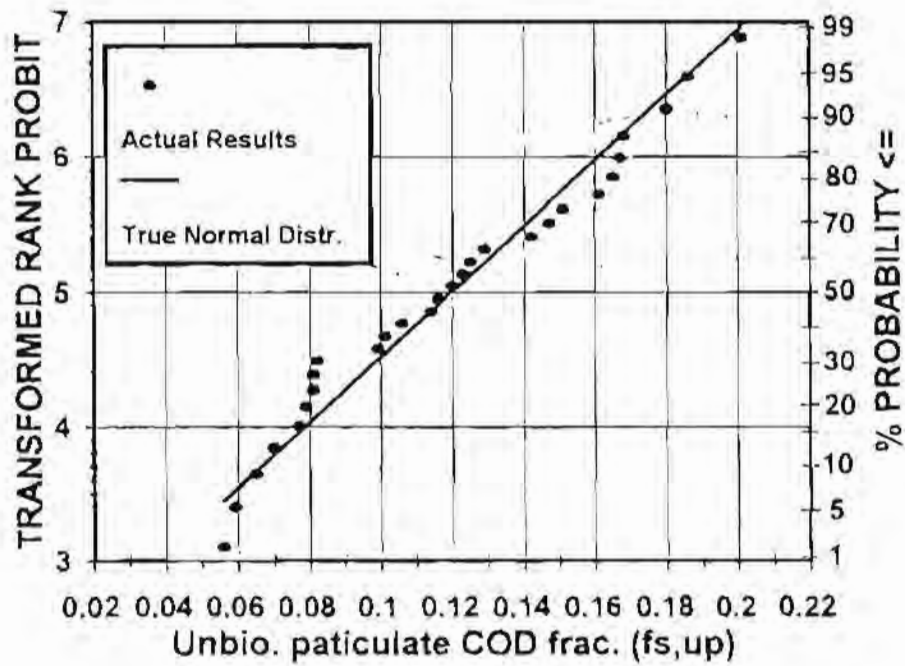


Figure 4.10: Statistical plot for unbiodegradable particulate COD fractions ($f_{s,up}$) for the parent laboratory-scale activated sludge system fed with municipal wastewater from Mitchell's Plain (Cape Town, South Africa).

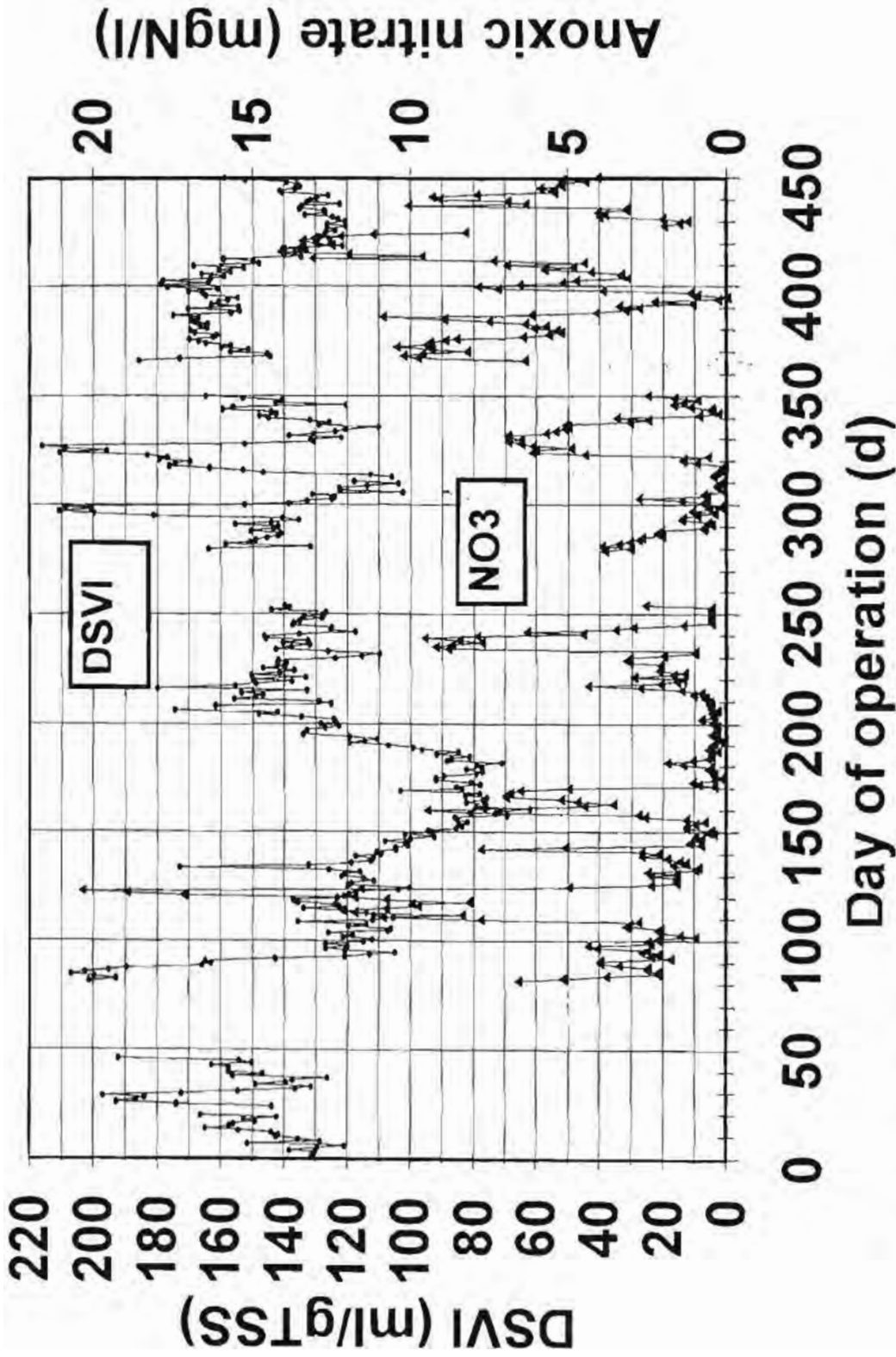


Figure 4.11: Graphical representation of the daily Diluted Sludge Volume Index (DSVI) and nitrate concentration (NO_3) for the parent laboratory-scale activated sludge system.



CHAPTER 5

DEVELOPMENT OF BATCH TEST TO QUANTIFY HETEROTROPHIC ACTIVE BIOMASS

5.1 INTRODUCTION

In the current steady state design and kinetic simulation models for activated sludge systems, the heterotrophic active biomass is a key parameter (see Chapter 2). However, this parameter remains hypothetical within the structure of the models; it has not been measured directly, primarily due to the lack of suitable experimental techniques (see Chapter 3). From the review in Chapter 3 of experimental techniques that possibly could be used to measure heterotrophic active biomass in activated sludge mixed liquor, the batch test method of Kappeler and Gujer (1992), as extended by Wentzel *et al.* (1995) and Mbewe *et al.* (1995), was identified to hold the most promise for further development. In this Chapter, this method will be modified and extended to quantify the heterotrophic active biomass of activated sludge mixed liquor. One set of batch tests will be used as an example to illustrate the experimental techniques and calculation procedures; the set of batch tests are those on sewage batch No. 12, see Tables 4.2 and 4.3, Chapter 4. Having developed the batch tests procedure, in the next Chapter (Chapter 6) heterotrophic active biomass measurements from the batch tests will be compared to theoretical values, to evaluate the batch test method.

5.2 EXPERIMENTAL PROCEDURE

5.2.1 Experimental approach

A well defined and controlled parent laboratory-scale anoxic/aerobic nitrification/ denitrification system was operated and monitored, see Chapter 4. Mixed liquor samples were harvested from the parent system and various quantities combined with unsettled municipal wastewater in batch reactors under aerobic conditions. The oxygen utilization rate (OUR) response in the batch tests were monitored with time and used to derive estimates for heterotrophic active biomass. Parallel batch tests were run without addition of mixed liquor to quantify the heterotrophic active biomass present in the wastewater itself. The difference in heterotrophic active biomass between the batch tests with and without mixed liquor addition gives the heterotrophic active biomass due to the mixed liquor addition.

5.2.2 Parent system

The parent laboratory-scale system and its operation have been described in detail in Chapter 4; however, some of the relevant details for sewage Batch No. 12 are repeated here. The system was operated in the Modified Ludzack Ettinger (MLE) configuration; system layout is shown in Fig 5.1. Sludge age was 12d, maintained by wasting mixed liquor from the aerobic reactor (hydraulic control) taking due account of any samples drawn from the reactors for analysis; temperature was controlled at 20°C, pH at 7.6 (± 0.2); influent flow rate was constant, set at 150/d. Influent feed was raw (unsettled) municipal wastewater from Mitchell's Plain Treatment

Plant (Cape Town, South Africa); the sewer retention time for this treatment plant is relatively short (± 4 hours) and the conditions are anaerobic and therefore it was expected that the heterotrophic active biomass concentration in this wastewater would be low. The wastewater was collected in batches from the treatment works, stored in stainless steel tanks at 4°C and served as feed for both the parent system and batch tests for a period of 1-2 weeks (see Chapter 4 for details). For the parent system, a sample of the wastewater was drawn from the storage tanks after thorough mixing and diluted with tap water to give influent feed total COD ~ 500 mgCOD/l. System operational procedures detailed by Ekama *et al.* (1986) were followed. Daily monitoring included influent COD, TKN; all reactors nitrate + nitrite; aerobic reactor VSS, TSS, COD and TKN of the VSS, oxygen utilization rate (OUR); effluent COD, TKN, nitrate + nitrite (Standard Methods, 1985). (Individual nitrite measurements indicated that nitrite concentrations were very low compared to nitrate concentrations and consequently could be neglected for this investigation). To ensure steady state, the parent system was operated for more than 10 sludge ages before the batch tests were commenced, on sewage batch number 12 (see Table 4.3, Chapter 4). Detailed data on the parent system have been described in Chapter 4; here, to illustrate the batch test procedure, the data from the period with sewage batch number 12 (Table 4.3, Chapter 4) will be used. The reliability of the experimental measurements were checked by means of mass balances on COD and N (Ekama *et al.*, 1986).

5.2.3 Batch Tests

In the batch test procedure detailed by Wentzel *et al.* (1995) and Mbewe *et al.* (1995), unsettled municipal wastewater without the addition of activated sludge mixed liquor was placed in a batch reactor and the oxygen utilization rate response monitored with time. From the OUR-time response, the heterotrophic active biomass concentration in the wastewater could be determined. Two variations of this batch test procedure were run. In one type, only unsettled municipal wastewater was added to the batch test and in the second, a mixture of wastewater and mixed liquor was added. For both types of batch tests, a sample of the wastewater was drawn from the storage tanks after thorough mixing and diluted to approximately the same COD concentration as that fed to the parent system (~ 500 mg COD/l).

For the wastewater only batch tests, a 3l volume of the diluted wastewater was preheated to 20°C and then placed in a continually stirred batch reactor maintained at a constant temperature of 20°C . A sample was drawn to obtain the initial total COD concentration (Standard Methods, 1985). In operating the batch test, the surface of the wastewater was covered by small plastic balls to limit surface exchange of oxygen. The oxygen utilization rate (OUR) was monitored continually using an automated technique (Randall *et al.*, 1991) - the DO was raised to ± 6 mgO/l, the air switched off and the decrease in DO monitored, the rate of decrease giving the OUR; when the DO reached ± 4 mgO/l, the air was switched on again and the cycle repeated. (The exact values for the high and low DO set points were varied depending on the OUR - if the OUR was low the high and low DO set points were moved closer together and *visa versa*). The pH of the reactor was monitored continually and controlled to pH 7.5 (± 0.2). Because of the low OUR values, the walls of the reactor were thoroughly brushed (regularly during an aeration cycle) to prevent particulate matter adhering to them. At intervals, samples were drawn from the reactor, filtered ($0.45\mu\text{m}$) and analysed for nitrate + nitrite and nitrite (for the purpose of the batch test, nitrite concentrations were found to be negligible compared to nitrate concentrations). The batch tests were conducted for approximately 24h. At the end of the batch tests, the contents of

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the batch reactor were homogenised in a liquidiser, a sample drawn and total COD concentration measured.

For the batch tests with a mixture of wastewater and mixed liquor, a sample of mixed liquor was harvested from the aerobic reactor of the parent system and a defined volume (variously 100, 200, 300 or 400 ml) placed in the batch reactor. The batch reactor volume was made up to 3ℓ with the same diluted unsettled municipal wastewater used in the wastewater only batch tests, also preheated to 20°C (see above). The batch test procedure detailed above was then followed

To illustrate the batch test procedure, batch tests with sewage batch number 12 will be used (Table 4.3, Chapter 4).

5.3 RESULTS AND DATA INTERPRETATION

5.3.1 Parent system

For the batches of wastewater fed to the parent system, detailed results have been presented in Appendix C; the daily results were averaged and the averages have been shown listed in Table 4.3 together with standard deviations. To illustrate the batch test calculation procedure, the data from sewage batch No 12 will be used; the averaged data for this sewage batch are listed in Table 5.1 together with the averaged data from the preceding two sewage batches (No.10 and 11). Following the procedures set out by Ekama *et al.* (1986), and set out in Chapter 4, the following were determined: The influent wastewater unbiodegradable soluble and particulate COD fractions ($f_{S,us}$ and $f_{S,up}$ respectively); system COD and N mass balances; the COD and TKN to VSS ratios of the mixed liquor (f_{cv} and f_N respectively). These are listed in Table 5.2. Referring to Table 5.2, acceptable COD and N mass balances were obtained; thus, the steady state data for the parent system can be considered acceptable.

Table 5.1: Steady state results for parent laboratory-scale anoxic/aerobic sludge system (Fig. 5.1). For each of the four wastewater batches tested, the daily results have been averaged and the averages are listed with sample standard deviations in brackets.

ANOXIC/AEROBIC STEADY STATE SYSTEM													
WW Batch	No of tests	COD (mg/l)		TKN (mg/l)		Nitrate+Nitrite (mgN/l)			Aerobic OUR (mgO ₂ /l/h)	Mixed liquor (mg/l)			Aerobic pH
		Inf	Eff	Inf	Eff	Anoxic	Aerobic	Eff		VSS	COD	TKN	
10	12	554 (69)	59 (12)	45.7 (3.3)	4.3 (0.7)	0.5 (0.3)	7.5 (0.9)	7.2 (0.8)	27.8 (2.1)	2222 (167)	3372 (330)	231 (18)	7.89 (0.25)
11	13	526 (27)	46 (13)	44.0 (1.5)	3.5 (0.3)	0.4 (0.2)	7.0 (0.3)	7.1 (0.4)	27.9 (1.9)	2339 (169)	3499 (195)	248 (16)	7.73 (0.14)
12	15	517 (30)	49 (15)	41.5 (2.5)	3.6 (0.6)	0.4 (0.1)	5.3 (0.6)	4.9 (0.7)	24.6 (1.7)	2293 (149)	3433 (341)	255 (13)	7.68 (0.17)

Table 5.2: Steady state COD and N mass balances, wastewater fractions and mixed liquor parameters for parent laboratory-scale anoxic/aerobic activated sludge system (Fig. 5.1). Data calculated from data Table 1, either directly or using the steady state (SS) design (WRC, 1984) or kinetic simulation (sim.) models (Dold *et al.*, 1991)

ANOXIC/AEROBIC STEADY STATE SYSTEM										
WW Batch	No of tests	Mass Balance (%)		Wastewater fractions			Mixed liquor			
		COD	N	Unbiol Soluble COD (fs.us)	Unbio. Particulate COD (fs.up)		COD/VSS ratio (mgCOD/mgVSS) (fcv)	TKN/VSS ratio (mgN/mgVSS) (fn)	Active Fraction (fav)	
					SS Design	Kinetic Sim.			SS Design	Kinetic Sim.
10	12	91	102	0.106	0.125	0.115	1.52	0.104	0.400	0.395
11	13	96	103	0.087	0.165	0.153	1.50	0.106	0.351	0.351
12	11	94	95	0.094	0.167	0.154	1.50	0.111	0.348	0.349

From the parent system steady state data, the theoretical heterotrophic active biomass of the mixed liquor drawn from the parent system and added to the batch tests was calculated. To do this two approaches could be followed - either the steady state design or the kinetic simulation models could be used. In the kinetic simulation models (Dold *et al.*, 1980, 1991; Henze *et al.*, 1987), at 20°C (the temperature for all experiments) for sludge ages > about 3d, virtually all the influent biodegradable COD is depleted. Certainly this will be the case for the parent system at 12d sludge age with the small anoxic mass fraction (25%) present (Fig 5.1). Under these conditions the steady design equations (WRC, 1984) and the kinetic simulation models should give near identical values for heterotrophic active biomass, provided equivalent values for the constants are used; to verify this, both the steady state and kinetic approaches were used.

Steady state model: From WRC (1984), the heterotrophic active biomass fraction of the mixed liquor volatile suspended solids (VSS) (f_{av}) can be determined from:

$$f_{av} = \frac{MX_{BH}}{MX_V} \quad (5.1)$$

$$= \frac{MX_{BH}}{MX_{BH} + MX_E + MX_I + MX_{BA}}$$

where

MX_{BH} = mass of heterotrophic active biomass, VSS units (mgVSS)

$$= V \cdot X_{BH}$$

MX_E = mass of endogenous material, VSS units (mgVSS)

$$= V \cdot X_E$$

MX_I = mass of inert material, VSS units (mgVSS)

$$= V \cdot X_{BA}$$

V = system volume (ℓ)

X_{BH} = heterotrophic active biomass concentration, VSS units (mgVSS/ℓ)

X_E = endogenous material concentration, VSS units (mgVSS/ℓ)

X_I = inert material concentration, VSS units (mgVSS/ℓ)

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- X_{BA} = autotrophic active biomass concentration, VSS units (mgVSS/l)
 MX_V = mass of volatile suspended solids, VSS units (mgVSS)
 = $V \cdot X_V$
 X_V = volatile suspended solids concentration, VSS units (mgVSS/l)

In Eq (5.1), for activated sludge systems receiving "normal" municipal wastewaters (influent TKN/COD ratio < 0.12 mgN/mgCOD) the autotrophic active biomass (MX_{BA}) component of the mixed liquor organic suspended solids is very small compared to the other three components (< 2% of the total for the parent system here). Thus, with very little error, the autotrophic active biomass can be neglected when calculating the mixed liquor VSS. Accordingly, from WRC (1984), substituting in Eq (5.1) for MX_{BH} and $MX_V = (MX_{BH} + MX_E + MX_I)$:

$$\frac{1}{f_{av}} = 1 + f_E^* b_{HT}^* R_S + \frac{f_{S,up} (1 + b_{HT}^* R_S)}{f_{cv} Y_H^* (1 - f_{S,us} - f_{S,up})} \quad (5.2)$$

where

- f_E^* = fraction of heterotrophic active biomass that is endogenous residue
 = 0.2 (endogenous respiration theory, Dold *et al.*, 1980).
 b_{HT}^* = specific endogenous mass loss rate at temperature T (/d)
 = $b_{H20}^* 1.029^{(T-20)}$
 b_{H20}^* = specific endogenous mass loss rate at 20°C
 = 0.24/d @ 20°C (endogenous respiration theory, Dold *et al.*, 1980)
 R_S = system sludge age (d)
 = 12 d
 $f_{S,up}$ = fraction of influent substrate that is unbiodegradable particulate
 $f_{S,us}$ = fraction of influent substrate that is unbiodegradable soluble
 f_{cv} = COD to VSS ratio of mixed liquor organic suspended solids
 (mgCOD/mgVSS)
 Y_H^* = heterotrophic active biomass yield, VSS units (mgVSS/mgCOD)
 = 0.45 mgVSS/mgCOD (WRC, 1984)

Using Eq (5.2) and the data in Table 5.1, values for f_{av} were calculated and are listed in Table 5.2.

Kinetic simulation: For the kinetic simulation models, using the UCTOLD computer programme (Dold *et al.*, 1991), values for f_{av} were determined from simulations of the parent system steady state periods - for each steady state period the values for the influent wastewater unbiodegradable particulate COD fraction ($f_{S,up}$) were adjusted until the simulated and measured reactor mixed liquor organic suspended solids concentrations (COD units) were near equal and the f_{av} calculated from the simulated results. These values for $f_{S,up}$ and f_{av} are also listed in Table 5.2. Comparing the values for f_{av} from the steady state design procedure and the kinetic simulations, near identical values were obtained for the wastewater batch. The small differences arise principally because (i) with the steady state design models the $f_{S,up}$ and f_{av} were determined from the measured mixed liquor organic suspended solids (MLOSS) VSS concentration whereas with the kinetic simulation models these were determined from the MLOSS COD concentration, and (ii) the kinetic simulation models include autotrophic active biomass and non-utilised slowly biodegradable COD in the MLOSS whereas these are ignored in the steady state design models.

5.6

Due to their near equality, the f_{av} from either the steady state design or the kinetic simulation models could be used, but the steady state design model is probably preferable for the simpler more direct analytical calculation procedure.

Now, knowing f_{av} and the concentration of the mixed liquor VSS that was drawn from the parent system [X_V (PS)] to be added to the batch tests (available from the averaged steady state VSS concentration measured in the parent system, Table 5.1), the theoretical heterotrophic active biomass concentration in the batch reactor due to the added mixed liquor [Z_{BH} (theo)_{BT}, COD units] is given by

$$Z_{BH} \text{ (theo)}_{BT} = [X_V \text{ (PS)} \cdot f_{av} \cdot f_{cv} \cdot V_{ML}] / (V_{ML} + V_{WW}) \quad (5.3)$$

where

- $Z_{BH} \text{ (theo)}_{BT}$
= theoretical heterotrophic active biomass concentration in batch test reactor due to added mixed liquor, COD units (mgCOD/ℓ batch reactor)
- $X_V \text{ (PS)}$ = mixed liquor VSS concentration measured in parent system, Table 5.1 (mgVSS/ℓ)
- V_{ML} = volume of mixed liquor from parent system added to batch test (ℓ)
- V_{WW} = volume of wastewater added to batch test (ℓ).

Theoretical values for the heterotrophic active biomass concentration in the batch reactor due to the added mixed liquor are listed in Table 5.4.

Note that in Eq (5.3) the parent system mixed liquor organic suspended solids are expressed in VSS units [$X_V \text{ (PS)}$], whereas the heterotrophic active biomass is expressed in COD units. This is done because conventionally the mixed liquor organic suspended solids in activated sludge systems are measured via the VSS test, whereas the kinetic models used to develop the batch test are in terms of the COD parameter (see later). However, the two units of measure are directly related through the COD/VSS ratio of the mixed liquor organic suspended solids (f_{cv}) which was measured, see Table 5.2. If a value for f_{cv} is not available from measurement, the standard value of 1.48 mgCOD/mgVSS (WRC, 1984) can be accepted.

Table 5.3: Batch tests with wastewater (WW) only. COD recovery, regression data from \ln OUR versus time plots and heterotrophic active biomass at the start of the batch test [$Z_{BH(O)}$ (WW)].

BATCH TEST: WASTEWATER (WW) ONLY							
WW Batch	Batch Test No	COD Recovery (%)	Regression			$Z_{BH(O)}$ WW	
			Y-intcpt	Slope	R^2	Concentration (mgCOD/l)	Fraction of Total COD (%)
12	W1	92	1.344	0.287	0.992	25	5
	W2	98	1.059	0.276	0.961	19	4.6
	W3	91	0.544	0.194	0.998	16	3.9
	W4	94	0.521	0.198	0.999	15	3.6
	Ave.	93.8				18.8 (SD = 4.5)	

Table 5.4: Batch tests with mixture of wastewater (WW) and mixed liquor (ML) drawn from parent laboratory-scale system: Volumes added, COD recoveries, regression data from \ln OUR_H versus time plots and heterotrophic active biomass present in the batch test ($Z_{BH(O)}$) due to mixed liquor+wastewater (ML+WW), wastewater (WW_D , taking due account of dilution) and mixed liquor (ML). Also shown are the theoretical heterotrophic active biomasses due to the mixed liquor addition.

BATCH TEST: WASTEWATER (WW) + MIXED LIQUOR (ML)											
WW Batch	Batch Test No	Volume (l)		COD Recov. (%)	Regression			$Z_{BH(O)}$ (mgCOD/l)			
		ML	WW		Y-intcpt	Slope	R^2	Measured			Theoretical ML
								ML+WW	WW_D	ML	
12	M1	0.1	2.9	95	1.409	0.137	0.987	50	18.0	32	40
	M2	0.2	2.8	102	2.209	0.143	0.972	108	17.5	90	80
	M3	0.2	2.8	99	2.199	0.160	0.990	97	17.5	80	80
	M4	0.3	2.7	100	2.267	0.113	0.907	139	16.9	122	119
	M5	0.3	2.7	101	2.310	0.113	0.962	145	16.9	128	119
	M6	0.3	2.7	97	2.266	0.136	0.969	119	16.9	102	119
	M7	0.4	2.6	96	2.399	0.092	0.960	185	16.3	168	159
	M8	0.4	2.6	96	2.262	0.076	0.993	188	16.3	172	159

5.3.2 Batch tests

Batch tests conducted using sewage batch No. 12 (Table 4.2 and 4.3) are used here to illustrate the calculation procedures. As noted above, two types of batch tests were conducted, one type with wastewater only and the other type with wastewater and mixed liquor.

Wastewater only

Four batch tests on wastewater Batch No. 12 were conducted with wastewater only, see Table 5.3. The data for the batch tests are set out in detail in Appendix A. As an example, the OUR (mgO/ℓ·h) versus time (h) responses for a batch test with wastewater only (Batch test No. W3, Table 5.3) is shown plotted in Fig 5.2. No nitrate or nitrite was detected in this series of batch tests indicating the absence of nitrification, that is, no autotrophic biomass was present in the wastewater. (Should nitrification take place, it can be taken into account by following the procedures set out below).

Referring to the OUR time plot (Fig 5.2), the profile conforms to that described by Wentzel *et al.* (1995): During the first period of the batch test (<8.5h) the OUR exhibits an exponential increase due to heterotrophic active biomass growth. After ± 8.5h, the OUR drops precipitously due to depletion of the wastewater readily biodegradable COD (RBCOD). For the remainder of the batch test, the OUR exhibits an inverted S pattern typical of saturation kinetics, due to slowly biodegradable COD (SBCOD) utilization.

Following the procedures set out by Wentzel *et al.* (1995) and Mbewe *et al.* (1995), the batch tests were analysed to determine:

- COD recovery (%)
- wastewater heterotrophic active biomass, $Z_{BH(t)}$ (mgCOD/ℓ)

A detailed derivation of equations for the above two parameters is given in the references cited, and accordingly is not repeated here.

For COD recovery (Wentzel *et al.*, 1995)

$$\% \text{ COD recovery} = \frac{\text{COD}_{t=T} + \int_{t=0}^{t=T} \text{OUR}_{H(t)} \cdot dt}{\text{COD}_{t=0}} \cdot 100 \quad (5.4)$$

where

- | | |
|---|---|
| t | = time (h) |
| $\text{COD}_{t=0}$ | = total unfiltered COD concentration at start of test ($t = 0$) (mgCOD/ℓ). |
| $\text{COD}_{t=T}$ | = total unfiltered COD concentration at end of test ($t = T$) (mgCOD/ℓ). |
| $\text{OUR}_{H(t)}$ | = heterotrophic active biomass oxygen utilization rate at time t (mgO/ℓ/h). |
| $\int_{t=0}^{t=T} \text{OUR}_{H(t)} \cdot dt$ | = integral (area) under the heterotrophic OUR versus time plot between start and end of test (mgO/ℓ). |
| | = oxygen consumed over the test by heterotrophic active biomass. |

In Eq (5.4), since in this series of batch tests no nitrification was observed, the measured OUR at time t ($OUR_{M(t)}$) is due to heterotrophic growth only and equals $OUR_{H(t)}$. Integrating the area under measured OUR time profile and substituting into Eq (5.4), the COD recoveries for the different batch tests with wastewater only were calculated and are listed in Table 5.3; all COD recoveries were $> 90\%$, providing support for the reliability of the measurements.

To determine heterotrophic active biomass at the start of the batch test ($Z_{BH(o)}$), the OUR values for the data up to the precipitous drop in OUR were plotted \ln OUR versus time (h) (for example, the OUR data in Fig 5.2 are shown plotted in Fig 5.3; data for the other batch tests are listed in Appendix A), and linear regression applied to determine the y-intercept, slope and correlation coefficient; these are listed in Table 5.3 for the different batch tests on wastewater only. From the slopes and y-intercepts, $Z_{BH(o)}$ can be determined (Wentzel *et al.*, 1995):

$$Z_{BH(o)} = \frac{e^{y\text{-intercept} \cdot 24}}{\frac{1 - Y_{ZH}}{Y_{ZH}} \cdot (\text{slope} \cdot 24 + b_{HT})} \quad (5.5)$$

where

- $Z_{BH(o)}$ = heterotrophic active biomass concentration at the start of the batch test
(mgCOD/l batch reactor)
- Y_{ZH} = Heterotrophic active biomass yield, COD units (mgCOD/mgCOD)
= 0.666 mgCOD/mgCOD (Dold *et al.*, 1980, 1991; Wentzel *et al.*, 1995)
- b_{HT} = heterotroph specific death rate at temperature T (/d)
= $b_{H20} \cdot 1.029^{(T-20)}$
- b_{H20} = heterotrophic specific death rate at 20°C
= 0.62/d (death/regeneration theory, Dold *et al.*, 1980; Wentzel *et al.*, 1995).

Note that in Eq (5.5) for the batch tests, the death regeneration theory (Dold *et al.*, 1980) is used (with $b_{H20} = 0.62/d$), whereas in Eq (5.2) for the steady state system, the endogenous respiration theory (Dold *et al.*, 1980; WRC, 1984) is used (with $b_{H20}^* = 0.24/d$). In the death regeneration theory, the heterotrophic active biomass dies at a certain rate; of the biomass lost, the biodegradable portion adds to the slowly biodegradable COD which passes through the various stages to be utilized for heterotrophic active biomass synthesis with associated oxygen utilization [i.e the oxygen demand arises, in fact, from the energy requirements for resynthesis of heterotrophic active biomass (regeneration) from the slowly biodegradable substrate liberated from organism death]; the unbiodegradable portion adds to the endogenous residue. In the endogenous respiration theory, the heterotrophic active biomass dies at a certain rate; of the biomass lost, the biodegradable portion gives rise *directly* to oxygen utilization (there is no slowly biodegradable substrate intermediate) and the unbiodegradable portion adds to endogenous residue. For the steady state parent system where all the biodegradable COD has been depleted, with the appropriate selection of constants the two approaches give the same nett result, i.e same loss of heterotrophic active biomass, utilization of oxygen and generation of endogenous residue (Dold *et al.*, 1980). However, the endogenous respiration approach allows a simple analytical procedure to be developed to provide a solution for the steady state system (WRC, 1984); accordingly, the endogenous respiration approach is followed here for the steady state parent

system. For the batch tests, the conditions are transient (e.g. the wastewater biodegradable COD has not been depleted, and is utilized over the course of the batch tests). Thus, to interpret the batch test results, a full kinetic model should be used (e.g. UCTOLD, Dold *et al.*, 1991). In the kinetic models the death regeneration approach has been adopted (for reasons see Dold *et al.*, 1980), and thus this approach is followed here for analysis of the batch tests. However, the endogenous respiration theory can be used to derive an equation that is numerically identical to Eq (5.5). Thus, the choice of using the death regeneration theory over the endogenous respiration theory does not influence the results.

Accepting Eq (5.5) and substituting into the equation the regression data listed in Table 5.3 for the batch tests, values for $Z_{BH(o)}$ for the various batch tests with wastewater (WW) only were calculated and are listed in Table 5.3 as concentrations and percentages of the total wastewater COD: As reported by Mbewe *et al.* (1995) and Wentzel *et al.* (1995), for Mitchell's Plain wastewater, heterotrophic active biomass was found to be present at low concentrations, 3.5 - 5% of total COD.

Wastewater + mixed liquor

Eight batch tests were conducted on mixtures of various quantities of mixed liquor and wastewater for Batch No. 12, see Table 5.4. The data for the batch tests are set out in detail in Appendix B. As an example, the OUR (mgO/ℓ · h) versus time (h) response for a batch test with 100 ml mixed liquor added to 2.9 ℓ diluted wastewater (Batch test No. M1, Table 5.4) is shown plotted in Fig 5.4. Referring to Fig 5.4, the general shape of the OUR time profile is the same as that for wastewater only (see Fig 5.2). However, due to the larger concentration of heterotrophic active biomass present (added with the mixed liquor) the OURs are higher and the time to the precipitous drop in OUR shorter. Further, since mixed liquor was drawn from a nitrifying activated sludge system and added to the batch test, nitrification can be expected and indeed was observed, see Fig 5.5. The OUR due to this nitrification must be taken into account in deriving estimates for % COD recovery and $Z_{BH(o)}$, since both these parameters are determined from the OUR for heterotrophs only. This can be done by noting that the measured OUR at any time t ($OUR_{M(t)}$) is made up of the OUR due to heterotrophic growth ($OUR_{H(t)}$) and due to nitrification ($OUR_{N(t)}$), i.e.

$$OUR_{M(t)} = OUR_{H(t)} + OUR_{N(t)} \quad (\text{mgO}/\ell/\text{h}) \quad (5.6a)$$

[Note that for the batch tests with wastewater only, no nitrification was observed, i.e. in Eq (5.6a) $OUR_{N(t)} = 0$ and $OUR_{M(t)} = OUR_{H(t)}$.]

Rearranging Eq (5.6a)

$$OUR_{H(t)} = OUR_{M(t)} - OUR_{N(t)} \quad (\text{mgO}/\ell/\text{h}) \quad (5.6b)$$

Accordingly, to determine $OUR_{H(t)}$, an estimate for $OUR_{N(t)}$ is essential. The $OUR_{N(t)}$ can be readily determined from the nitrate concentration time profile (see Appendix B; for Batch test No. M1, see Fig 5.5). For the batch tests with nitrification, ammonia - N is available in excess and nitrification proceeds at the maximum rate. Further, since the yield and maximum specific growth rate of the autotrophs are relatively low, the nitrification rate can be assumed constant within the time scale of the batch test - this assumption is confirmed by the linearity of the nitrate

concentration-time profiles. Accepting a constant nitrification rate, the slope of a "best-fit" linear line to the nitrate (mgN/l) time (h) profile is the nitrification rate ($\Delta\text{NO}_3^-/\Delta t$, mgN/l/h), and the OUR_N is given by

$$\text{OUR}_{N(t)} = 4.57 \cdot \Delta\text{NO}_3^-/\Delta t \quad (\text{mgO/l/h}) \quad (5.7)$$

Linear regression was applied to the batch tests nitrate time profiles to determine the y-intercept, slope and correlation co-efficient, see Table 5.5. From the slopes, the OUR_N 's for the different batch tests were calculated using Eq (5.7), and also are listed in Table 5.5. The OUR_N is assumed constant over the batch test (see above) so that $\text{OUR}_N = \text{OUR}_{N(t)}$, and hence $\text{OUR}_{H(t)}$ can be calculated via Eq (5.6b), i.e. from each measured OUR value ($\text{OUR}_{M(t)}$), a constant nitrification OUR value (OUR_N , Table 5.5) is subtracted to give the OUR due to the heterotrophs only ($\text{OUR}_{H(t)}$).

Having determined the $\text{OUR}_{H(t)}$ for the batch tests, the % COD recoveries were calculated using Eq (5.4) and are listed in Table 5.4. Referring to Table 5.4, for batch tests M1-M8 COD recoveries range from 95-102%. The good mass balances provide support for the reliability of the measurements.

To determine the heterotrophic active biomass present at the start of the batch tests, the $\text{OUR}_{H(t)}$ (i.e. $\text{OUR}_{M(t)} - \text{OUR}_N$) up to the precipitous drop in OUR were plotted (i.e. $\text{OUR}_{H(t)}$ versus time (h), for example see Fig. 5.6. Linear regression was used to determine the y-intercept, slope and correlation coefficients of the (i.e. $\text{OUR}_{H(t)}$ versus time plots, see Table 5.4. From the y-intercept and slope data, values for $Z_{B_{H(t)}}$ (ML+WW) (the heterotrophic active biomass present at the start of the batch tests, due to that added with the mixed liquor (ML) and that present in the original wastewater (WW)) were calculated using Eq. (5.4) and also are listed in Table 5.4.

Table 5.5: Batch tests with mixture of wastewater (WW) and mixed liquor drawn from parent laboratory-scale system. Regression data from nitrate versus time plots, nitrification rates ($\Delta\text{NO}_3^-/\Delta t$) and OUR for nitrification (OUR_N).

BATCH TEST: WASTEWATER (WW) + MIXED LIQUOR (ML)						
WW Batch	Batch Test No	Regression			$\Delta\text{NO}_3^-/\Delta t$ (mgN/l.h)	OUR_N (mgO/l.h)
		Y-intcpt	Slope	R^2		
3	M1	0.343	0.075	0.989	0.075	0.343
	M2	0.547	0.129	0.983	0.129	0.590
	M3	0.557	0.211	0.882	0.211	0.964
	M4	0.426	0.506	0.923	0.506	2.312
	M5	0.541	0.296	0.987	0.296	1.352
	M6	0.645	0.191	0.913	0.191	0.873
	M7	0.572	0.257	0.962	0.257	1.174
	M8	0.739	0.326	0.965	0.326	1.490

5.3.3 Comparison

In the batch tests with both wastewater (WW) and mixed liquor (ML) present, heterotrophic active biomass at the start of the test [$Z_{BH(o)}$] is due to the heterotrophic active biomass present in the original wastewater (WW) and that added with the mixed liquor (ML); therefore, the $Z_{BH(o)}$ due to the wastewater [$Z_{BH(o)}(WW)$] must be subtracted from the $Z_{BH(o)}$ due to both the wastewater and mixed liquor [$Z_{BH(o)}(WW+ML)$] to determine $Z_{BH(o)}$ due to the mixed liquor only [$Z_{BH(o)}(ML)$]. Now, $Z_{BH(o)}(WW)$ is available from the batch tests with wastewater only; for a particular wastewater batch these were averaged (see Table 5.3) and then the dilution in $Z_{BH(o)}(WW)$ caused by the addition of mixed liquor to the batch tests with wastewater and mixed liquor was taken into account, as follows:

$$Z_{BH(o)}(WW)_D = Z_{BH(o)}(WW) \cdot V_{WW} / (V_{ML} + V_{WW}) \quad (5.8)$$

where

$Z_{BH(o)}(WW)_D$	=	heterotrophic active biomass due to wastewater at start of batch test with WW + ML, taking due account of dilution (mgCOD/l)
$Z_{BH(o)}(WW)$	=	heterotrophic active biomass present in the original wastewater, Table 5.3 (mgCOD/l)
V_{WW}	=	volume of wastewater added to batch test (l)
V_{ML}	=	volume of mixed liquor added to batch test (l)

From the data in Table 5.3, the heterotrophic active biomass *concentration* in the batch tests due to the added wastewater [$Z_{BH(o)}(WW)_D$] were calculated using Eq. (5.8); values are listed in Table 5.4.

Now,

$$Z_{BH(o)}(ML) = Z_{BH(o)}(ML + WW) - Z_{BH(o)}(WW)_D \quad (5.9)$$

Using Eq. (5.9), the heterotrophic active biomass *concentrations* in the total batch test volumes (WW + ML) due to the added mixed liquor [$Z_{BH(o)}(ML)$] were calculated; values are listed in Table 5.4. These values represent the measured mixed liquor heterotrophic active biomass concentration in the total batch test volume. The theoretical values were calculated using Eq. (5.3) and are listed in Table 5.4 also.

To compare the measured and theoretical mixed liquor $Z_{BH(o)}(ML)$, the values are plotted against each other in Fig. 5.7: For wastewater batch No 12, very good agreement was obtained between the theoretical and measured heterotrophic active mass

5.4 CLOSURE

In the current steady state design and kinetic simulation models for activated sludge systems, the mixed liquor organic suspended solids is made up of a number of components. One key component is the heterotrophic active biomass, as this component mediates the biodegradation processes of COD removal and denitrification. Thus, the rates for these processes are directly related to the heterotrophic active biomass present, and the specific rates should be expressed in

terms of this parameter (e.g. Dold *et al.*, 1980; Van Haandel *et al.*, 1981; WRC, 1984; Ekama *et al.*, 1986) to allow a meaningful comparison of the rates measured in different systems (e.g. Clayton *et al.*, 1991). Although the heterotrophic active biomass parameter seems to have become almost universally accepted, it remains hypothetical within the structure of these models; it has not been measured directly, primarily due to the lack of suitable simple measurement techniques. This deficiency has cast some measure of doubt on the entire framework within which the steady state design and kinetic simulation models have been developed. In this Chapter a simple batch test procedure has been developed to quantify the heterotrophic active biomass concentration of mixed liquor drawn from a well defined anoxic/aerobic activated sludge system. For the wastewater batch (No. 12) used to illustrate the procedure and calculations, the measured heterotrophic active biomass concentrations are in close agreement with those calculated theoretically. This agreement provides evidence supporting both the models and the experimental method and indicates that there is merit in pursuing this investigation further. A more detailed investigation is required to comprehensively evaluate the results from the batch test procedure; this evaluation will be undertaken in Chapter 6.

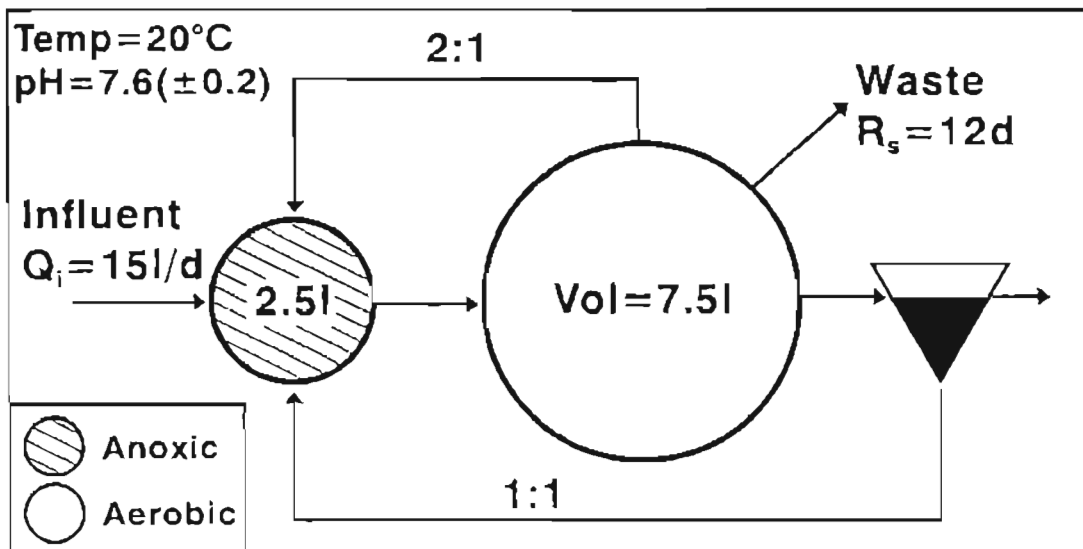


Figure 5.1: Schematic layout and operational data for parent laboratory-scale anoxic/aerobic activated sludge system.

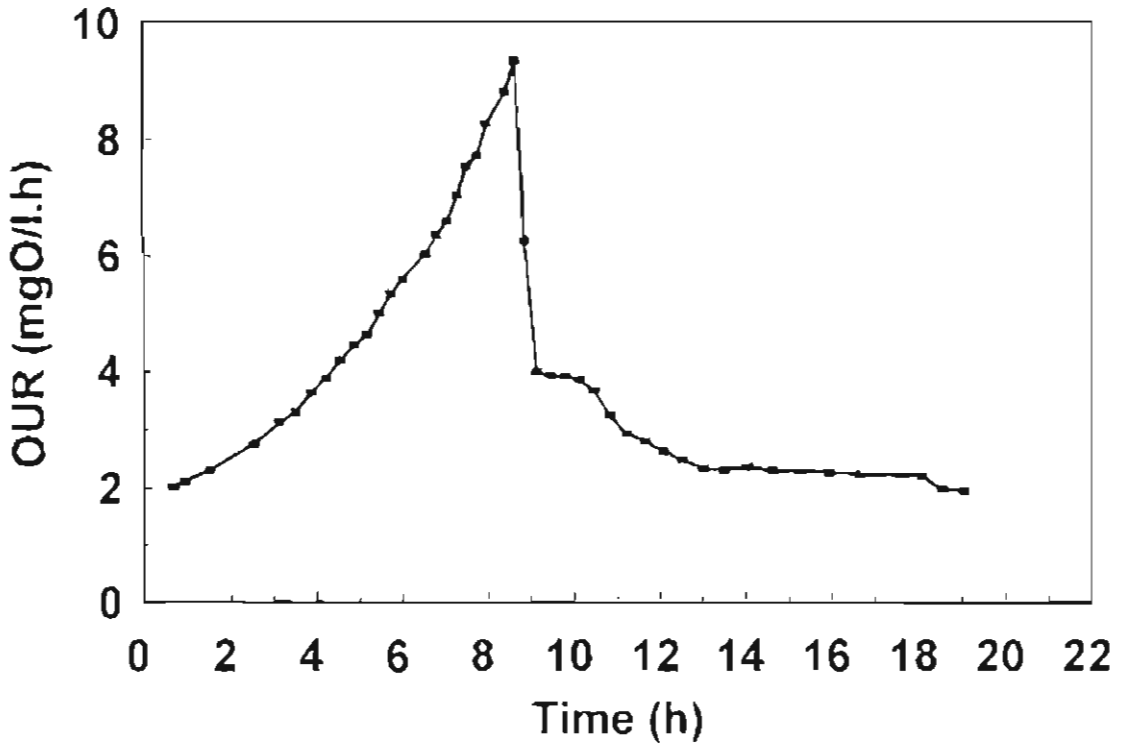


Figure 5.2: Oxygen utilization rate (OUR) response with time for aerobic batch test on raw municipal wastewater from Mitchell's Plain (Cape Town, South Africa). (Batch test No. W3, Table 5.3).

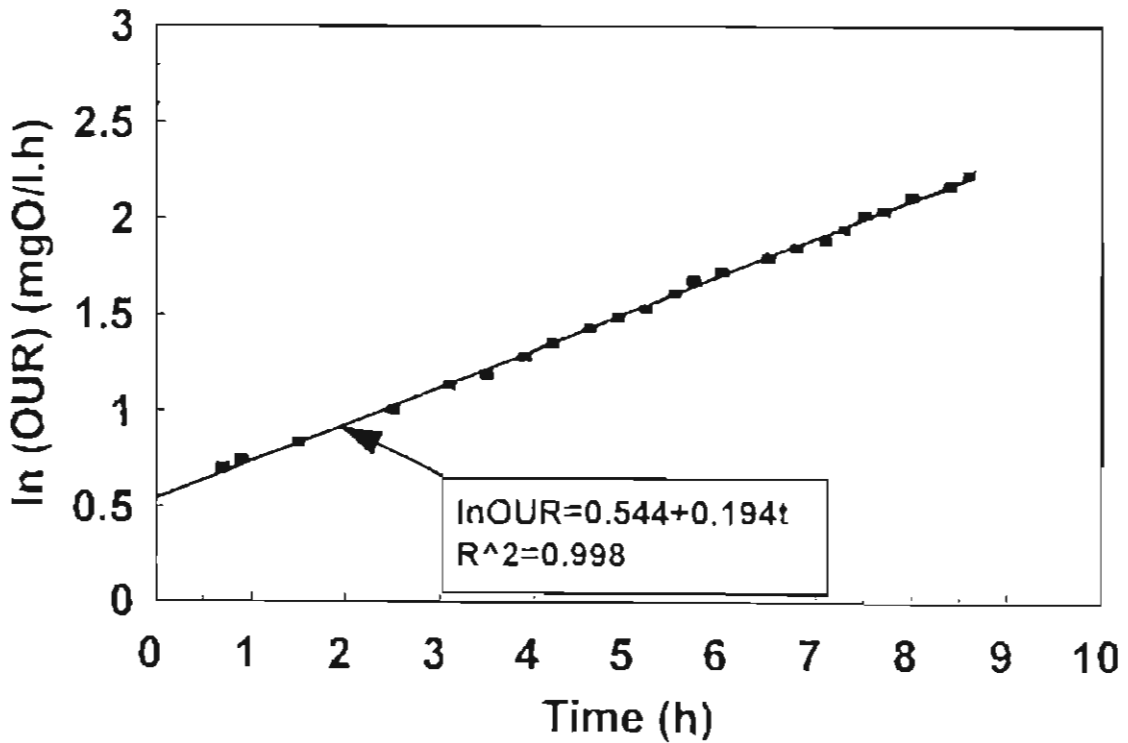


Figure 5.3: \ln oxygen utilization rate (OUR) versus time for the OUR data in Fig. 5.2, up to the precipitous drop in OUR.

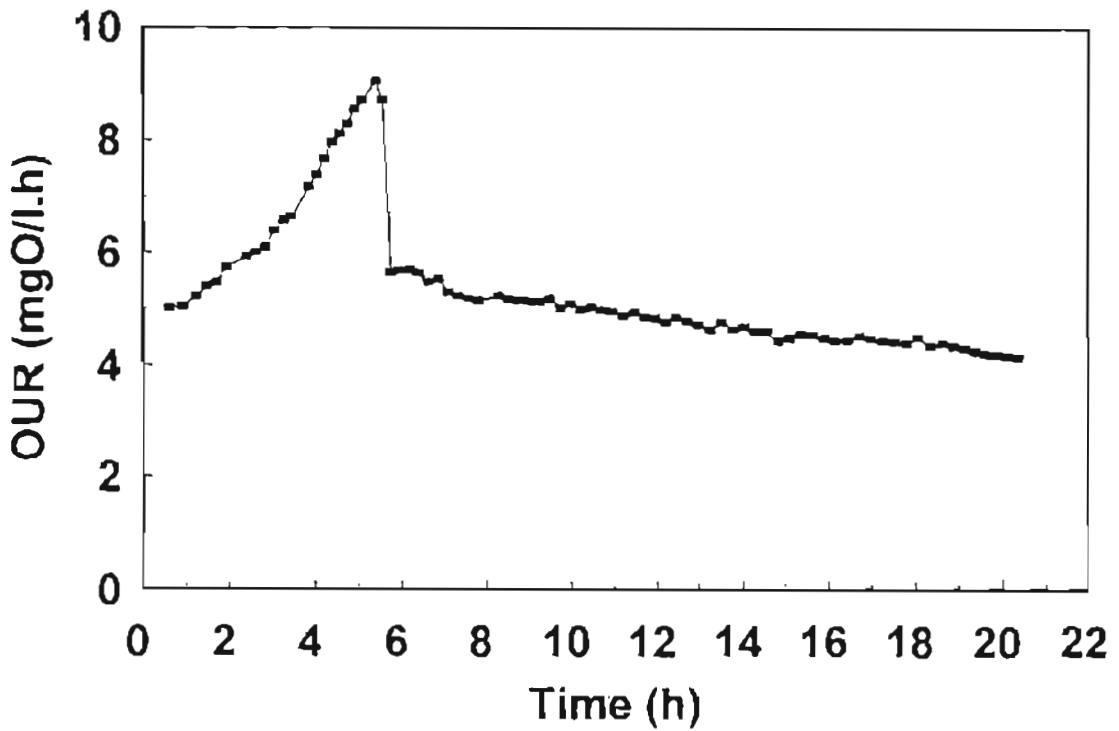


Figure 5.4: Oxygen utilization rate (OUR) response with time for aerobic batch test on a mixture of raw municipal wastewater (2.9ℓ) from Mitchell's Plain (Cape Town, South Africa) and mixed liquor (0.1ℓ) drawn from the aerobic reactor of the parent laboratory-scale system (fig. 5.1). (Batch test No. M1, Table 5.4).

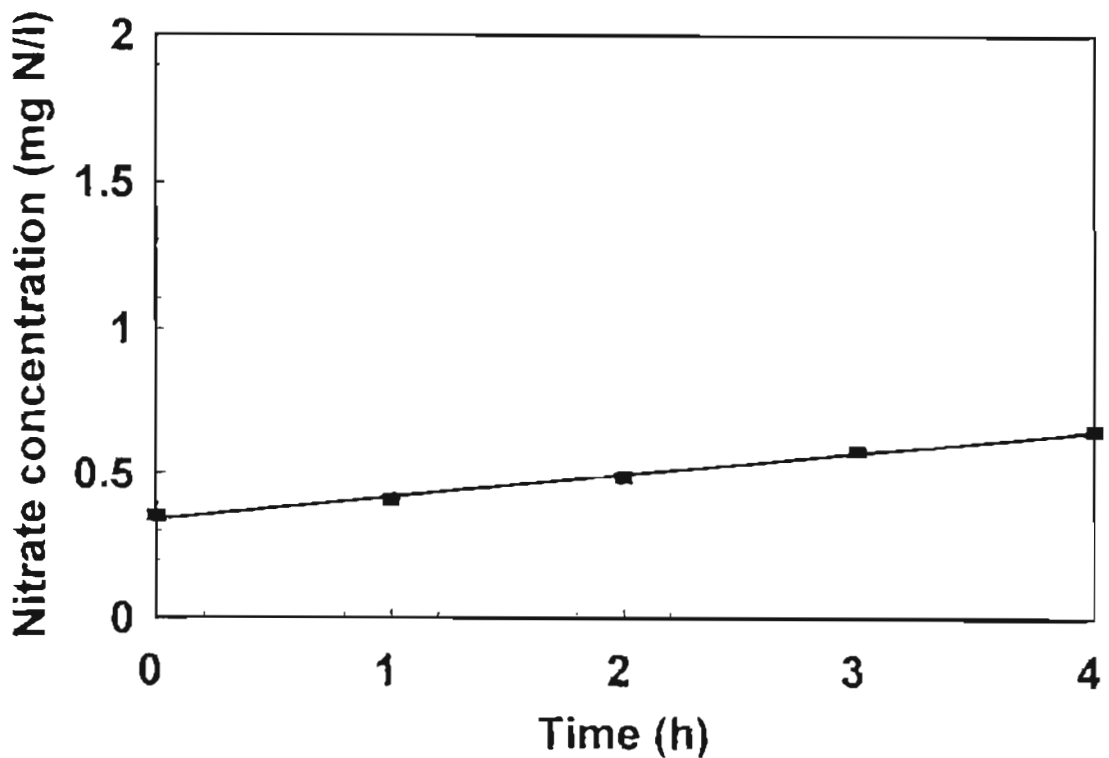


Figure 5.5: Nitrate concentration with time for aerobic batch test in Fig. 5.4.

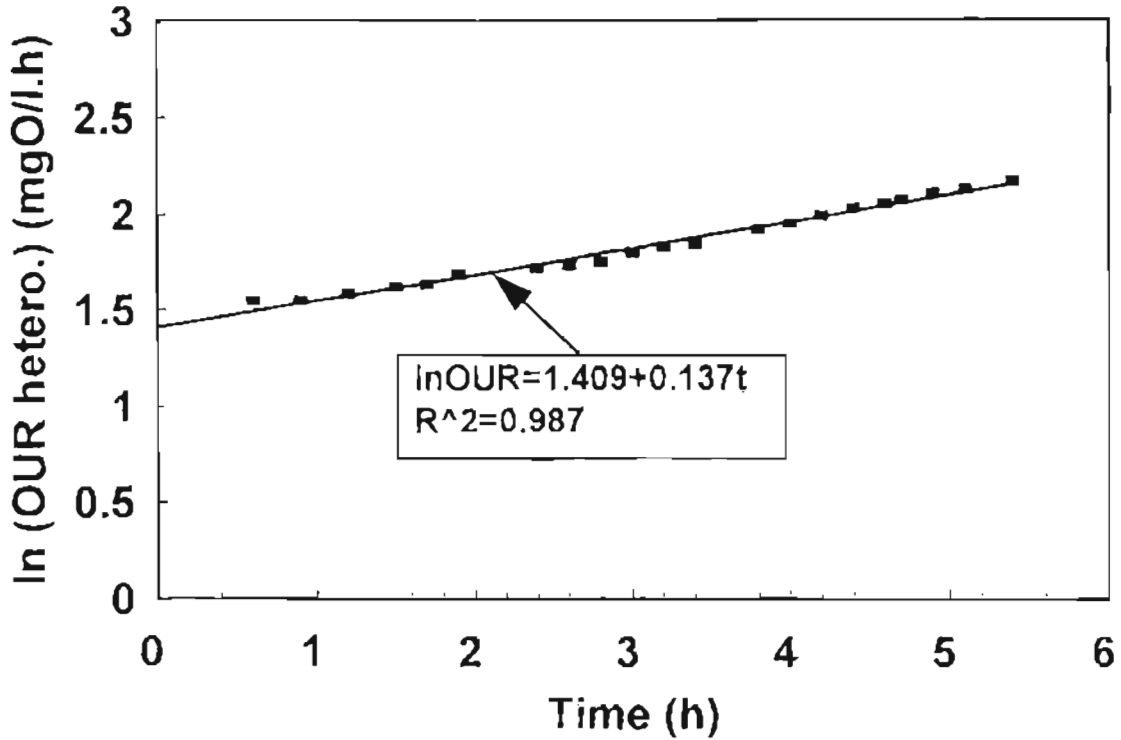


Figure 5.6: \ln oxygen utilization rate (OUR) due to heterotrophic active biomass versus time for the OUR data in Fig. 5.4 up to the precipitous drop in OUR [i.e. OUR due to nitrification ($0.343 \text{ mgO}/\ell$, Table 5.5, Batch test No. M1) subtracted from measured OUR data in Fig. 5.4 and then plotted].

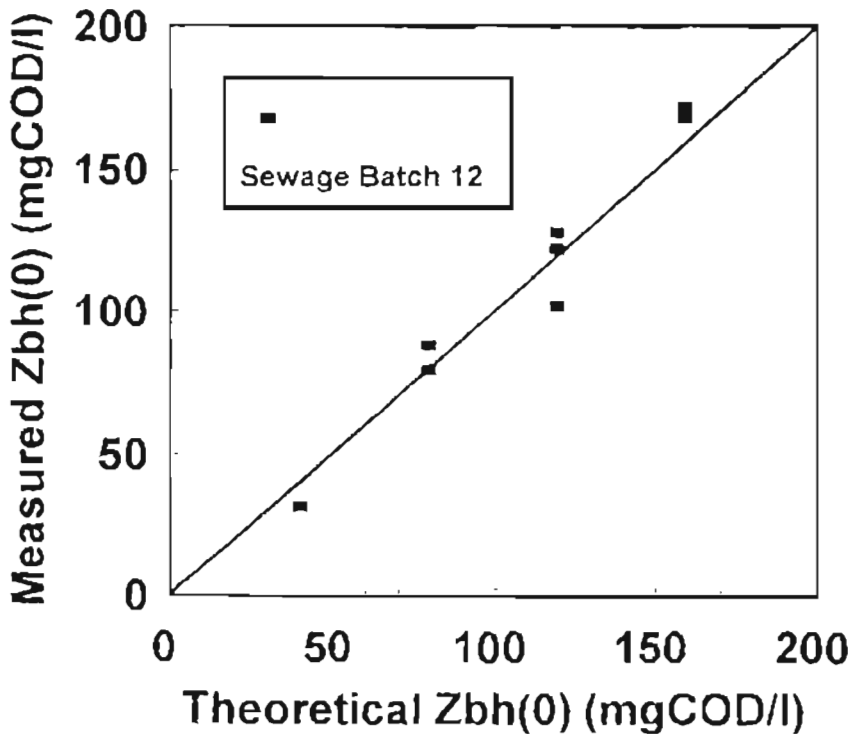


Figure 5.7: Measured versus theoretical heterotrophic active biomass concentration ($Z_{\text{BH}(\text{O})}$) in the batch test due to addition of mixed liquor drawn from the parent laboratory-scale activated sludge system (Fig. 5.1).

CHAPTER 6

EVALUATION OF THE BATCH TEST METHOD TO QUANTIFY HETEROTROPHIC ACTIVE BIOMASS

6.1 INTRODUCTION

In Chapter 5 a batch test method has been developed to quantify the heterotrophic active biomass component of activated sludge mixed liquor. Results from eight batch tests conducted on mixed liquor drawn from the parent laboratory-scale activated sludge system while it was receiving one batch of sewage (Batch No 12, Tables 4.3 and 4.4) were used to illustrate the batch test and calculation procedures. Results from this preliminary set of batch tests indicate that the method holds considerable promise; the heterotrophic active biomass concentrations measured in the batch test correspond closely with those calculated theoretically for the parent system, using the steady state design model (WRC, 1984). In this Chapter the intention is to more rigorously evaluate the batch test procedure. This will be done by comparing the heterotrophic active biomass results, derived from a number of batch tests on mixed liquor drawn from the parent system while it was receiving a number of sewage batches and was operated at two different sludge ages, with those calculated theoretically.

6.2 EXPERIMENTAL METHOD

6.2.1 Experimental approach

The experimental approach set out in Chapter 5, Section 5.2.1 was followed .

A well defined and controlled parent laboratory-scale anoxic/aerobic nitrification/denitrification system was operated and monitored, see Chapter 4. Mixed liquor samples were harvested from the parent system and various quantities combined with unsettled municipal wastewater in batch reactors under aerobic conditions. The oxygen utilization rate (OUR) response in the batch tests were monitored with time and used to derive estimates for heterotrophic active biomass. Parallel batch tests were run without addition of mixed liquor to quantify the heterotrophic active biomass present in the wastewater itself. The difference in heterotrophic active biomass between the batch tests with and without mixed liquor addition gives the heterotrophic active biomass due to the mixed liquor addition. For the heterotrophic active biomass measurements, the values were evaluated by comparing the results from the batch tests with the results calculated using the steady state design models.

6.2.2 Parent system

The parent laboratory-scale system and its operation have been described in detail in Chapter 4. Mixed liquor samples for the batch tests were drawn from the parent system only while it was operated in the Modified Ludzack Ettinger (MLE) configuration, see Figure 4.4, at system sludge ages of 12 d and 20 d. With the parent system at a sludge age of 12 d, batch tests were conducted

during 7 sewage batches, and at a system sludge age of 20 d, batch tests were conducted during 5 sewage batches; the sewage batches during which batch tests were conducted are set out in Table 6.1.

Table 6.1: Parent system sludge age, sewage batch number and the dates it was used as feed, and the number of batch tests with wastewater (WW) only and wastewater + mixed liquor (WW+ML) for the particular sewage batch.

Parent System Sludge Age (d)	Sewage Batch No.	Dates	Number of Batch Tests	
			WW only	WW+ML
12	12	17 Oct - 31 Oct	4	8
	13	1 Nov - 17 Nov	1	4
	17	12 Jan - 25 Jan	11	11
	18	26 Jan - 7 Feb	11	11
	19	8 Feb - 21 Feb	12	12
	20	22 Feb - 5 Mar	8	13
	21	6 Mar - 19 Mar	4	7
20	22	4 Apr - 12 Apr	6	6
	23	13 Apr - 23 Apr	8	8
	24	24 Apr - 8 May	6	11
	26	20 May - 31 May	10	10
	27	1 Jun - 14 Jun	8	14
TOTAL			89	115

6.2.3 Batch tests

The batch test procedure set out in Chapter 5 was followed. In conducting the batch tests, the following modifications and observations were made :

- For batch tests with mixed liquor drawn from the parent system at 12 d sludge age volumes of variously 100, 200, 300 and 400 ml of mixed liquor were added to the batch test. These volumes gave OUR-time profiles that could be readily analysed using the procedures set out in Chapter 5. In particular, sufficient OUR data could be collected

before the precipitous drop in OUR, to analyse the \ln OUR-time plot using linear regression. An example OUR-time plot for 100ml mixed liquor added to 2.9l raw wastewater is given in Fig. 6.1. With the parent system operated at 20 d day sludge age, 400 ml of mixed liquor caused the precipitous drop in OUR to be reached before sufficient OUR data could be collected. An example OUR-time plot for 400 ml mixed liquor added to 2.6l raw wastewater is given in Figure 6.2. For this reason the volume of mixed liquor drawn from the 20d sludge age system and added to the batch tests was kept less than 300 ml. In general, the optimal mixed liquor volume to add to the batch test will depend on the parent system operation; this will have to be determined by trial-and-error.

- When the parent system was receiving sewage batch No. 24, the coldroom refrigerator in which the sewage was stored (for details on sewage collection and storage, see Chapter 4, Section 4.3) at 4°C broke down. This caused the temperature of the stored sewage to increase to 20°C. Batch tests were conducted on this sewage batch, despite the increase in temperature.
- It was observed that when the wastewater + mixed liquor batch tests were done on wastewater that had just been collected from the wastewater treatment works, the OUR-time data was scattered and often exhibited two peaks; for example see Figure 6.3. As the time that the new wastewater was fed to the parent system increased, the OUR-time data became more ordered and the profiles smoother, until after about 3 days the characteristic smooth OUR-time profile was observed. This would suggest that a short period of about 3 days was required for the heterotrophic organisms in the parent system mixed liquor to acclimatise to a new wastewater batch. Accordingly, when new batches of wastewater were collected, these were used as feed to parent system for at least 3 days before mixed liquor was harvested for the batch tests.

6.3 DATA ANALYSIS

6.3.1 Parent system

The approach adopted to analyse the parent system data has been set out in Chapters 4 and 5. The averaged data for each sewage batch (each sewage batch accepted as a steady state period) has been set out in Tables 4.3 (a and b). From this Table, the averaged data for sewage batches during which batch tests were conducted have been extracted and are set out in Table 6.2.

Table 6.2: Steady state results for parent anoxic/aerobic activated sludge system receiving sewage batches during which batch tests were conducted. For each sewage batch (sew btch) tested, the daily results have been averaged and the averages are listed with sample standard deviations in brackets.

ANOXIC/AEROBIC STEADY STATE SYSTEM												
Sew Btch	No. tests	COD (mg/l)		TKN (mg/l)		Nitrate+Nitrite(mgN/l)			OUR mgO/l.h	Mixed liquor (mg/l)		
		Inf	Eff	Inf	Eff	Anoxic	Aerobic	Eff		VSS	COD	TKN
12	15	517 (30)	49 (15)	41 (3)	3.6 (0.6)	0.4 (0.1)	5.3 (0.6)	4.9 (0.7)	24.6 (1.7)	2293 (149)	3433 (341)	255 (13)
13	15	492 (30)	46 (10)	47 (3)	3.5 (0.4)	1.7 (0.7)	10.9 (1.2)	10.4 (0.7)	23.7 (0.6)	1684 (118)	2833 (301)	210 (16)
17	14	481 (30)	44 (10)	48 (1)	3.7 (0.3)	1.6 (0.9)	8.7 (1.0)	8.8 (1.0)	25.8 (0.6)	2033 (78)	2839 (185)	222 (11)
18	12	450 (31)	72 (9)	37 (1)	3.5 (0.6)	0.6 (0.4)	5.3 (0.3)	5.4 (0.3)	22.7 (1.6)	1709 (85)	2513 (144)	193 (15)
19	13	492 (27)	59 (8)	45 (2)	3.2 (0.4)	0.5 (0.5)	5.9 (0.3)	6.3 (0.3)	23.5 (0.5)	1775 (28)	2640 (153)	222 (9)
20	13	500 (21)	48 (10)	49 (1)	3.4 (0.3)	6.0 (0.7)	13.1 (1.2)	13.5 (1.1)	24.3 (0.9)	2052 (118)	2958 (286)	221 (20)
21	14	503 (34)	49 (10)	52 (4)	3.8 (0.5)	1.6 (1.0)	7.9 (0.6)	8.2 (0.8)	25.9 (1.1)	2116 (112)	3477 (185)	258 (21)
22	9	476 (16)	38 (5)	58 (1)	3.0 (0.4)	9.6 (0.7)	19.7 (0.5)	19.8 (0.4)	27.4 (0.3)	2729 (108)	4284 (151)	294 (11)
23	11	493 (39)	33 (8)	57 (4)	3.2 (0.5)	6.8 (1.4)	16.0 (1.1)	16.5 (1.1)	27.6 (0.6)	2668 (51)	4236 (246)	314 (24)
24	14	489 (19)	43 (7)	53 (2)	3.1 (0.4)	3.2 (2.5)	13.0 (2.7)	12.9 (2.5)	29.3 (0.3)	2557 (66)	3659 (236)	284 (24)
26	11	458 (23)	51 (9)	58 (3)	3.1 (0.6)	12.8 (1.2)	23.4 (1.4)	23.4 (1.6)	27.9 (0.5)	2861 (51)	4297 (227)	303 (14)
27	13	479 (39)	46 (8)	47 (4)	3.0 (0.5)	2.8 (1.1)	9.8 (2.4)	10.7 (2.0)	23.9 (1.3)	3185 (101)	4873 (266)	333 (15)

From the data in Table 6.2, following the procedures set out in Chapter 4, the following were determined :

- Influent wastewater unbiodegradable soluble and particulate COD fractions ($f_{S,us}$ and $f_{S,up}$ respectively, from Eqs. (4.1) and (4.2) respectively); system COD and N mass balances (Ekama *et al.*, 1986); the COD and TKN to VSS ratios of the mixed liquor (f_{CV} and f_N respectively). These are listed in Table 6.3. From the discussion in Chapter 4, Section 4.9.2, data on sewage batches 13 and 21 should be rejected due to the low N mass balances. However, the data on these sewage batches will be analysed to illustrate the effect of poor mass balances on the results, but the data will be rejected in the final comparison between measured and theoretical heterotrophic active biomass concentrations.
- Following the procedure in Chapter 5, Section 5.3.1, the heterotrophic active biomass fractions of the mixed liquor organic suspended solids (f_{av}) were determined for each

sewage batch using the steady state design model [Eq. (5.2)] and the UCTOLD kinetic simulation computer programme, see Table 6.3. Comparing the values for f_{av} from the steady state design and kinetic simulation models (Table 6.3), in agreement with the observations in Chapter 5, Section 5.3.1 reasonably close agreement was obtained for the wastewater batches tested (average difference = 4.4%). As noted in Chapter 5, Section 5.3.1, the differences arise principally because (i) with the steady state design models $f_{S,up}$ and f_{av} were determined from the measured mixed liquor VSS concentration whereas with the kinetic simulation model these were determined from the measured mixed liquor COD concentration, and (ii) the kinetic simulation models include autotrophic active biomass and non-utilised slowly biodegradable COD in the mixed liquor whereas these are ignored in the steady state design models. Due to their near equality, the f_{av} from either the steady state design or kinetic simulation models could be used, but because of the simpler more direct analytical calculation procedure, the f_{av} from the steady state design model were used.

- Now, knowing f_{av} , the concentration of the mixed liquor VSS that was drawn from the parent system to be added to the batch tests (averaged parent system VSS concentration for the appropriate sewage batch, Table 6.2) and the volumes of mixed liquor and wastewater added to the batch tests (Appendix B, Table B3), the theoretical heterotrophic active biomass concentration in the batch reactor due to the added mixed liquor could be calculated using Eq. (5.3), see Appendix B, Table B3.

Table 6.3: Steady state COD and N mass balances, wastewater fractions and mixed liquor parameters for parent anoxic/aerobic activated sludge system. Data calculated from Table 6.2, either directly or using the steady state (SS) design (WRC, 1984) or kinetic simulation (sim.) models (Dold *et al.*, 1991).

ANOXIC/AEROBIC STEADY STATE SYSTEM									
Sew Batch	Mass Balance (%)		Wastewater COD fractions			Mixed liquor			
	COD	N	Unbiod. Soluble (f _{s,us})	Unbio. Particulate (f _{s,up})		COD/VSS ratio (mgCOD/mgVSS) (f _{cv})	TKN/VSS ratio (mgN/mgVSS) (f _N)	Active Fraction (f _{av})	
				SS Design	Kinetic Sim.			SS Design	Kinetic Sim.
1	94	95	0.095	0.167	0.154	1.50	0.111	0.348	0.349
2*	79	111	0.093	0.059	0.082	1.68	0.125	0.517	0.443
3	91	93	0.091	0.129	0.093	1.40	0.109	0.385	0.426
4	96	96	0.160	0.116	0.099	1.47	0.113	0.398	0.408
5	88	91	0.120	0.081	0.061	1.49	0.125	0.462	0.474
6	83	92	0.096	0.123	0.097	1.44	0.108	0.397	0.420
7*	97	84	0.097	0.161	0.170	1.64	0.122	0.368	0.326
8	81	92	0.080	0.106	0.100	1.57	0.107	0.331	0.316
9	80	90	0.067	0.081	0.080	1.59	0.118	0.367	0.343
10	84	98	0.088	0.065	0.038	1.43	0.111	0.377	0.404
11	85	96	0.111	0.142	0.125	1.50	0.106	0.278	0.283
12	87	93	0.096	0.168	0.159	1.53	0.105	0.258	0.253

6.3.2 Batch tests

From Chapter 5, two types of batch tests were conducted, one type with wastewater only and the other type with wastewater and mixed liquor.

6.3.2.1 Wastewater only

Eighty-nine batch tests with wastewater only were conducted on twelve sewage batches. The OUR time plots for these batch tests are set out in detail in Appendix A. No nitrate or nitrite was detected in this series of batch tests indicating the absence of nitrification, that is, no autotrophic biomass was present in the wastewater.

Following the procedures set out in Chapter 5, Section 5.3.2, the data were analysed as follows:

- Detailed data are shown in Appendix A.
- COD recoveries for the batch tests were calculated using Eq. (5.4), see Appendix A, Table A1. Batch tests with %COD recovery $< 90\%$ or $> 110\%$ should be rejected; no batch tests had COD recoveries outside the range 90-110%. For each wastewater batch, the %COD recoveries were averaged and the averages, sample standard deviations and number of tests are listed in Appendix A, Table A2.
- The OUR values for the data up to the precipitous drop in OUR were plotted \ln OUR versus time; plots are given in Appendix A. Linear regression was applied to the \ln OUR-time data to determine y-intercept, slope and correlation coefficient; these are listed in Appendix A, Table A1. Batch tests with correlation coefficients (R^2) < 0.9 were rejected for further analysis (1 test); these are shown marked in Table A1 (test number W12).
- From the slopes and y-intercepts the wastewater heterotrophic active biomass concentrations at the start of the batch test ($Z_{BH(o)}$) were determined using Eq. (5.5); see Appendix A, Table A1. These values represent the heterotrophic active biomass present in the wastewater.
- For a particular sewage batch, the $Z_{BH(o)}$ values were analysed and outliers rejected at the 95% confidence interval (7 batch tests); these are shown marked in Appendix A, Table A1.
- Excluding the rejected data, for each sewage batch the $Z_{BH(o)}$ values were averaged; the average concentrations, standard deviations of the means and number of tests are listed in Appendix A, Table A2.
- The COD concentrations at the start of the batch tests (Appendix A, Table A1) were averaged for each sewage batch; see Appendix A, Table A2. For each sewage batch, the heterotrophic active biomass as a percentage of total COD was calculated from the average $Z_{BH(o)}$ and COD concentrations at the start of the batch test; see Appendix A, Table A2.

6.3.2.2 Wastewater and mixed liquor

One hundred and fifteen batch tests with wastewater and mixed liquor were conducted on twelve sewage batches. The OUR-time plots for these batch tests are set out in Appendix B. Since the mixed liquor was drawn from a nitrifying activated sludge system and added to the batch test, nitrification can be expected and indeed was observed. Nitrate concentration- time profiles for the batch tests are given in Appendix B. Following the procedures set out in Chapter 5, Section 5.3.2, the data were analysed as follows :

- Negligible nitrites were observed in all batch tests. The OUR for nitrification (OUR_N) was determined from the nitrate concentration-time profiles: Linear regression was applied to the profiles to determine the y-intercept, slope and correlation coefficient. In the initial batch tests, nitrate concentrations were only monitored up to the precipitous drop in OUR; these profiles exhibited a constant nitrification rate for this period indicated by the linearity of the profiles, for example see Fig. 6.4. Subsequently, nitrate concentrations were monitored over the full period of the batch test. A number of these plots did not exhibit a single linear profile, for example see Fig. 6.5. Consequently, the nitrification rate could not be accepted to be constant over the full batch test period. Examination of the nitrate-time profiles indicated that these could be closely approximated by two linear rates of increase, one linear rate being operative up to the precipitous drop in OUR and the second linear rate being operative from the precipitous drop in OUR to the end of the batch test; see Fig. 6.5. For these profiles, linear regression was applied to the data up to precipitous drop in OUR, and y-intercept, slope and correlation coefficient determined, see Appendix B, Table B2; a second linear regression was applied to the data from the precipitous drop in OUR to the end of the batch test, and y-intercept, slope and correlation coefficient determined. For each of the two slopes, the OUR for nitrification (OUR_N) could be determined using Eq. (5.6); OUR_N for the first slope in the batch tests are listed in Appendix B, Table B2. The OUR_N for the first slope (up to the precipitous drop in OUR) influences the determination of the heterotrophic active biomass, while the OUR_N for both slopes influence the COD recovery. In most cases OUR_N is relatively small compared to the measured OUR and so its influence on the results is limited.
- For all the batch tests, the OUR for heterotrophic growth ($OUR_{H(t)}$) was determined from Eq. (5.6), i.e. for each batch test, the appropriate nitrification OUR value was subtracted from the measured OUR, to give the OUR due to heterotrophs only.
- Having determined $OUR_{H(t)}$ for the batch tests, the % COD recoveries were calculated using Eq. (5.4); see Appendix B, Table B1. Batch tests with % COD recovery < 90% or > 100% were rejected; these are shown marked in Appendix B, Table B1 (9 batch tests).
- For each batch test, the $OUR_{H(t)}$ values up to the precipitous drop in OUR were plotted $\ln OUR_H$ versus time; plots are given in Appendix B. Linear regression was applied to the $\ln OUR$ -time data to determine y-intercept, slope and correlation coefficient; these are listed in Appendix B, Table B1. Batch tests with correlation coefficients < 0.9 were rejected; these are shown marked in Appendix B, Table B1 (11 batch tests). From the

slopes and y-intercepts, the heterotrophic active biomass at the start of the batch test (due to both the wastewater and added mixed liquor) $[Z_{\text{BH}(o)} (\text{ML}+\text{WW})]$ was calculated using Eq. (5.5), see Appendix B, Table B1.

- To calculate the heterotrophic active biomass in the batch test due to the wastewater, the average heterotrophic active biomass concentration determined from the wastewater only batch tests for the particular sewage batch (Appendix A, Table A1) were used taking due account of the dilution caused by adding the mixed liquor, i.e. using Eq. (5.7) to give $Z_{\text{BH}(o)} (\text{WW})_{\text{D}}$, see Appendix B, Table B3
- The measured heterotrophic active biomass concentrations in the batch tests due to the added mixed liquor $[Z_{\text{BH}(o)} (\text{ML})]$ were calculated by subtracting the heterotrophic active biomass due to the wastewater $[Z_{\text{BH}(o)} (\text{WW})_{\text{D}}]$ from the total measured heterotrophic active biomass $[Z_{\text{BH}(o)} (\text{ML}+\text{WW})]$, i.e. using Equation (5.8). Data are listed in Appendix B, Table B3.

6.4 RESULTS

6.4.1 Wastewater only batch tests

COD recovery

For the wastewater only batch tests, the COD recoveries are listed in Appendix A, Table A1. The % COD recovery is a function of the batch test method and so should not be specific to each batch of wastewater tested. Accordingly, a statistical plot of % COD recovery for all the wastewater only batch tests was constructed; see Fig. 6.6. (The method used to construct the statistical plot and how to interpret it is given in Appendix D). From the statistical plot, the mean % COD recovery for the wastewater only batch tests was determined to be 96% with sample standard deviation of 4%. COD recoveries all fell in the range 90-108%, so that no batch tests were rejected on the basis of poor COD recoveries. It is interesting to note that the wastewater only batch tests on sewage batch No. 24 gave the lowest %COD recovery (92.8%). This is the sewage batch where the coldroom refrigerator broke down and the sewage temperature increased to 20°C, see Section 6.2.3 above. It was observed for this sewage batch that the time to the precipitous drop in OUR decreased in each sequential batch test; this would indicate that the RBCOD was being consumed during storage, and that the nature of the wastewater was changing with time.

It is evident that the good % COD recoveries lend credibility to the reliability of the measurements and to the batch test procedure with wastewater only.

Heterotrophic active biomass

In calculating the heterotrophic active biomass concentration in the wastewater, the following remarks are of relevance:

- The correlation coefficients (R^2) for the linear regression on the \ln OUR-time data (see

Appendix A, Table A1) were very good; for the vast majority of batch tests $R^2 > 0.98$. Only one batch test (W12, Appendix A, Table A1) had $R^2 < 0.9$ and this batch test was rejected for further analysis. This indicates that the observed response conforms to the hypothesized behaviour.

- In the statistical analysis of the heterotrophic active biomass concentrations measured for each wastewater batch, only 7 out of a total of 89 batch tests were rejected as outliers at the 95% confidence interval. This indicates that the estimates for heterotrophic active biomass are consistent.

The mean heterotrophic active biomass for each wastewater batch as concentrations and as % of total COD (S_{ij}) are listed in Appendix A, Table A2. A statistical plot of the measured means of heterotrophic active biomass for the different wastewater batches is given in Fig. 6.7. For the wastewater tested (Mitchell's Plain, Cape Town), the heterotrophic active biomass ranged from 2.1 to 6.5% of total COD, with a mean of 4.5% and sample standard deviation of 1.1%. This mean agrees reasonably closely with the value measured by Mbewe *et al.* (1995) for the same wastewater (6.1%).

The relatively low heterotrophic active biomass concentration for Mitchell's Plain wastewater is to be expected; this wastewater is primarily of domestic origin with a small industrial component (< 20%) and the sewers are anaerobic and have a relatively short retention time (4-6 hours).

6.4.2 Wastewater and mixed liquor batch tests

COD recovery

For this set of batch tests, the % COD recoveries are listed in Appendix B, Table B1. As for the wastewater only batch tests, the % COD recovery is a function of the batch test method and so should not be specific to each batch of wastewater tested. Accordingly, a statistical plot of % COD recovery for all wastewater and mixed liquor batch tests was constructed; see Fig. 6.8. From the statistical plot, the COD recoveries ranged from 74 to 120%; batch tests with % COD recoveries < 90% or > 110% clearly are outliers and were rejected for further analysis (marked in Appendix B, Table B1), only 9 batch tests. Neglecting the rejected batch tests, the statistical plot was reconstructed, see Fig. 6.9. From the statistical plot the mean % COD recovery was 102% with sample standard deviation of 4%. The good % COD recoveries lend credibility to the reliability of the measurements and to the batch test procedure.

It is interesting to note that the batch tests with sewage batch No. 24 (where the sewage storage coldroom broke down, see Section 6.2.3 above) exhibited the highest mean %COD recovery (Appendix B, Table B1); no definitive explanation for this observation could be advanced, but it may be due to the change in the nature of the wastewater, see Section 6.4.1 above.

Nitrification

As noted in Section 6.3.2.2 above, negligible nitrites were observed in all batch tests. Also, the increase in nitrate due to nitrification could be approximated by two linear rates (for example, see Fig. 6.5; detailed plots are given in Appendix B); an initial slower linear rate that lasts

approximately until the OUR drops precipitously, followed by a faster linear rate that lasts to the end of the batch test. This would imply that the nitrification rate is influenced by the presence readily biodegradable COD. Up to the precipitous drop in OUR, RBCOD from the wastewater is present and is being consumed by the heterotrophic organisms; when the wastewater RBCOD is depleted, the OUR drops precipitously. It would appear that the presence of RBCOD inhibits to some degree the nitrification rate so that when the RBCOD is depleted the nitrification rate increases. No explanation can be advanced for this inhibition. It should, however, be remembered that the RBCOD/organism ratio in the batch tests is unusually high (by design) and so this inhibition may be an artifact of the batch test conditions.

The nitrification rates for the first linear nitrification are listed in Appendix B, Table B2. As expected, the nitrification rates are closely linked to the volume of mixed liquor added to the batch test; the more mixed liquor added (with more nitrifier organism mass), the higher the nitrification rate.

Heterotrophic active biomass

The heterotrophic active biomass concentrations at the start of the batch tests with wastewater and mixed liquor are listed in Appendix B, Table B1. In calculating these values, the following remarks are of relevance.

- The correlation coefficients (R^2) for the linear regression of the \ln OUR time data (Appendix B, Table B1) generally were good; for the majority of batch tests $R^2 > 0.98$. Only 11 batch tests had $R^2 < 0.9$ and were rejected for further analysis (marked in Appendix B, Table B1). In general, the more mixed liquor added to the batch test, the lower the R^2 . This is because with increased mixed liquor addition, the RBCOD is consumed more quickly and the precipitous drop in OUR reached sooner; this causes that less OUR data is collected before the precipitous drop in OUR, so that less data are available for regression analysis of the \ln OUR-time plot, resulting in lower R^2 values.

The measured heterotrophic active biomass concentrations in the batch tests due to the added mixed liquor are listed in Appendix B, Table B3. These will be compared below with the values calculated theoretically.

6.4.3 Comparison of measured and theoretical heterotrophic active biomass

The theoretical and measured heterotrophic active biomass concentrations are listed in Appendix B, Table B3; these are the *concentrations in the batch reactor due to the added mixed liquor*. Also shown marked in Appendix B, Table B3 are those batch tests rejected because

- $R^2 < 0.9$ in linear regression of \ln OUR-time plot
- % COD recovery in batch test $< 90\%$ or $> 110\%$.

Additionally, three batch tests (19, 43, 70 - Appendix B, Table B3) gave measured heterotrophic active biomass concentrations that are negative (i.e. heterotrophic active biomass due to wastewater $>$ that due to wastewater and mixed liquor). Clearly, this is not possible and these

three tests also were rejected for further analysis. Thus, in total 19 out of 115 batch tests were rejected.

Excluding the rejected batch tests, for each wastewater batch the measured versus theoretical mixed liquor heterotrophic active biomass concentration in the batch test were plotted; see Figs. 6.10 to 6.21. Wastewater batches 12, 13, 17, 18, 19, 20 and 21 were on mixed liquor drawn from the parent system when it was operated at 12 d sludge age and wastewater batches 22, 23, 24, 26, 27 at 20 d sludge age.

Parent system 12 d sludge age

For the parent system operated at 12 d sludge age, data for wastewater batches 13 and 21 were rejected because of the poor N mass balance (see Chapter 4, Section 4.9.2). Only one data point is available for wastewater batch No. 13 so no conclusion on the effect of the poor mass balance on the test procedure can be made for this wastewater batch. However, for wastewater batch No. 21, a number of data points are available. Comparing the data for this sewage batch with those from the other sewage batches at parent system sludge age 12d, very poor correspondence between the measured and theoretical mixed liquor heterotrophic active biomass was obtained. This underlines the importance of the mass balance as a tool to evaluate the parent system data. Rejecting sewage batches 13 and 21, the measured and theoretical data for the remaining sewage batches (12, 17, 18, 19 and 20) are shown plotted in Fig. 6.22. With the exception of sewage batch No. 19, the measured and theoretical mixed liquor heterotrophic active biomass concentrations correspond remarkably closely.

Parent system 20 d sludge age

For the parent system operated at 20d sludge age, no data were rejected because of poor mass balances on the parent system. The measured versus theoretical mixed liquor heterotrophic active biomass data for all the sewage batches at 20d sludge age (22, 23, 24, 26, 27) are shown plotted in Fig. 6.23. From Fig. 6.23, it would appear that the measured data for sewage batch No. 24 are not consistent with the measured data from the other sewage batches; the measured data from this sewage batch are consistently lower compared to the measured data from the other sewage batches. As noted earlier, during this sewage batch the coldroom refrigerator where the sewage was stored broke down and the sewage storage temperature increased from 4°C to 20°C. Accordingly, this data were rejected from the comparison between the measured and theoretical heterotrophic active biomass. Excluding sewage batch No. 24, the measured versus theoretical heterotrophic active biomass are shown plotted in Fig. 6.24. From Fig. 6.24, it is evident that the measured values are consistently lower, only about half the theoretical values. No logical explanation could be found for this inconsistency with the data from the parent system at 20d sludge age.

6.5 CONCLUSIONS

From this series of tests it can be concluded:

- For both the wastewater only and wastewater + mixed liquor batch tests, the %COD recoveries were good, with means of 96% and 102% respectively and sample standard deviations of 4% and 4% respectively. The good %COD recoveries lend credibility to the reliability of the measurements and to the batch test procedure.
- No nitrification was observed in the batch tests with wastewater only, indicating the absence of autotrophic organisms in the wastewater.
- For the batch tests with wastewater + mixed liquor, nitrification was observed since the mixed liquor added to the batch tests was drawn from a nitrifying activated sludge system. This nitrification could be closely approximated by two linear rates, a slower rate operating up to approximately the precipitous drop in OUR, followed by a second faster rate operating to the end of the batch test. This would indicate an inhibition of nitrification at the start of the batch test, possibly due to the RBCOD present in the wastewater
- The correlation coefficients (R^2) in linear regression of the $\ln \text{OUR}_{\text{H}(t)}$ - time plots generally are good; 1 out of 89 and 11 out of 115 batch tests for wastewater only and wastewater + mixed liquor respectively had $R^2 < 0.9$.
- For the wastewater only batch tests, the wastewater heterotrophic active biomass ranged from 2.1 to 6.5% of total COD, with a mean of 4.5% and sample standard deviation of 1.1%. This mean agrees reasonably closely with the value measured by Mbewe *et al.* (1995) for the same wastewater (6.1%). The relatively low heterotrophic active biomass concentration for Mitchell's Plain wastewater is to be expected; this wastewater is primarily of domestic origin with a small industrial component (<20%) and the sewers are anaerobic and have a relatively short retention time (4-6 hours).
- With the parent system at 12d sludge age the measured and theoretical mixed liquor heterotrophic active biomass correspond remarkably closely. With the parent system at 20d sludge age the measured and theoretical values show a close correlation; however, the values are not in agreement - the measured values are consistently lower, only about half the theoretical values. No logical explanation could be found for this inconsistency, and this aspect warrants further investigation.

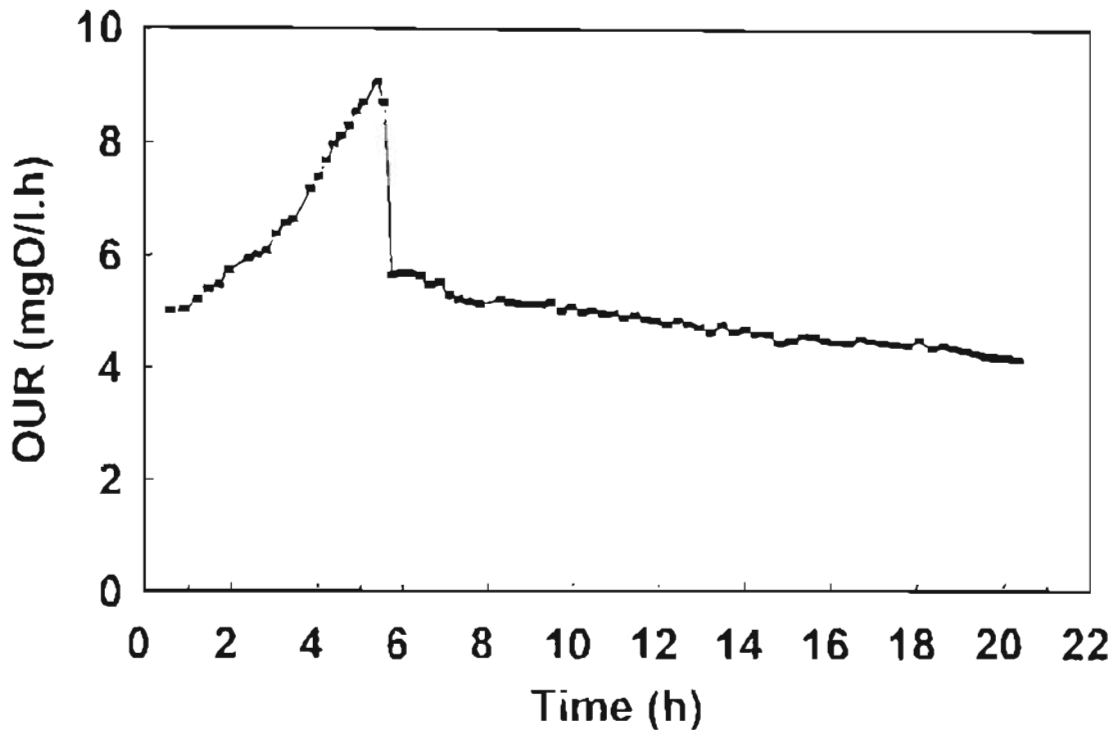


Figure 6.1: Oxygen utilization rate (OUR) response with time for aerobic batch test on a mixture of raw municipal wastewater (2.9ℓ) from Mitchell's Plain (Cape Town, South Africa) and mixed liquor (0.1ℓ) drawn from the aerobic reactor of the parent laboratory-scale. (Batch test No. M1, Table 5.4).

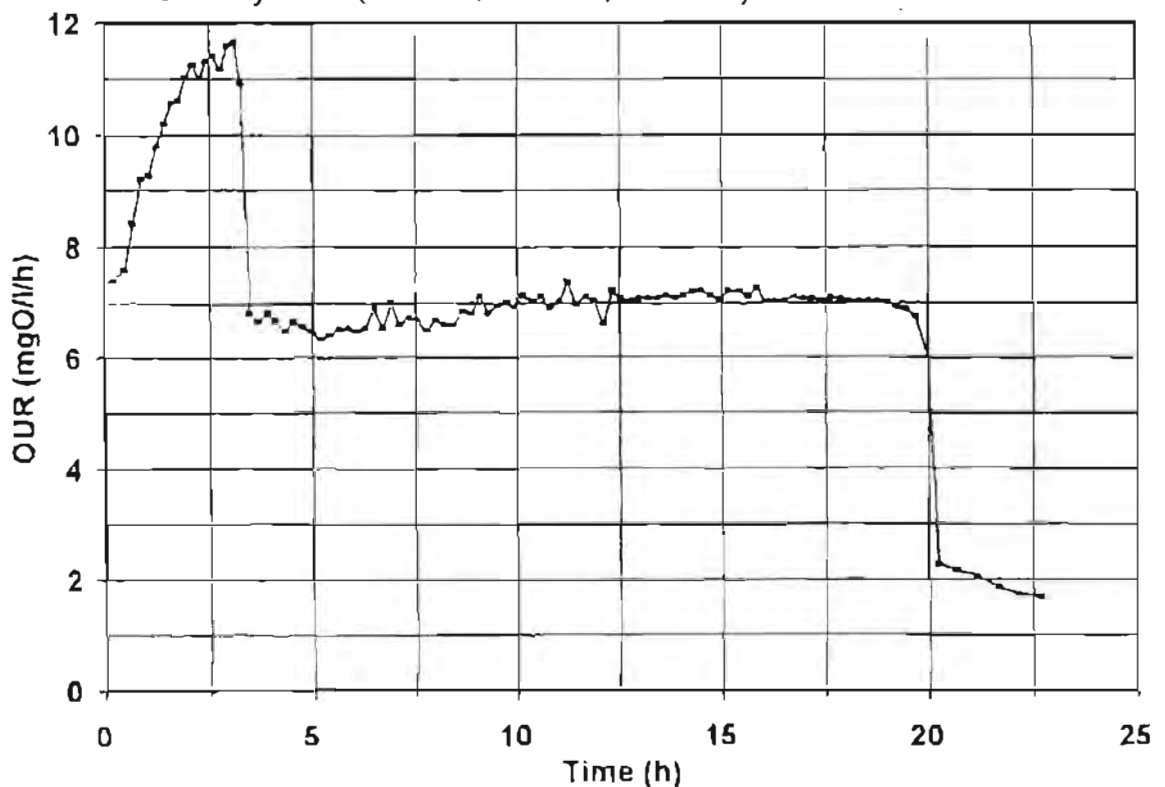


Figure 6.2: Oxygen utilization rate (OUR) response with time for aerobic batch test on a mixture of raw municipal wastewater (2.6ℓ) from Mitchell's Plain (Cape Town, South Africa) and mixed liquor (0.4ℓ) drawn from the aerobic reactor of the parent laboratory-scale.

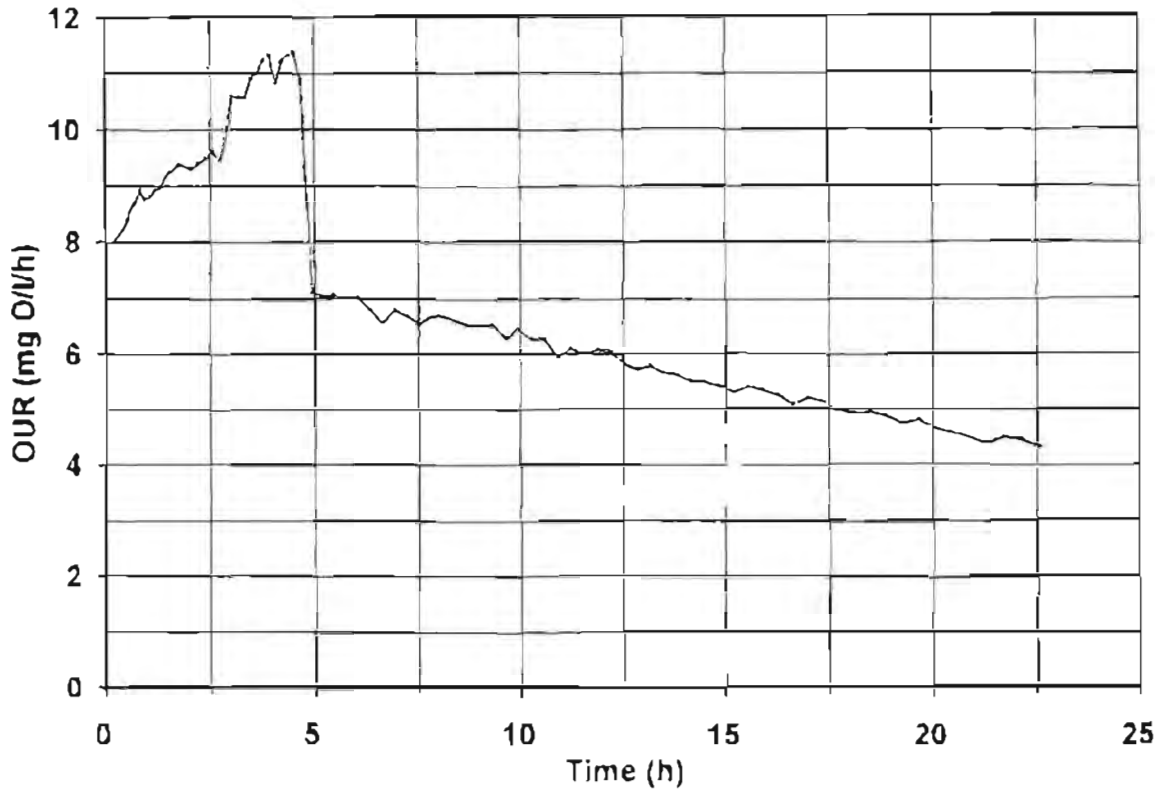


Figure 6.3: Oxygen utilization rate (OUR) response with time for aerobic batch test on a mixture of raw municipal wastewater that has just been collected from Mitchell's Plain (Cape Town, South Africa) and mixed liquor drawn from the aerobic reactor of the parent laboratory-scale.

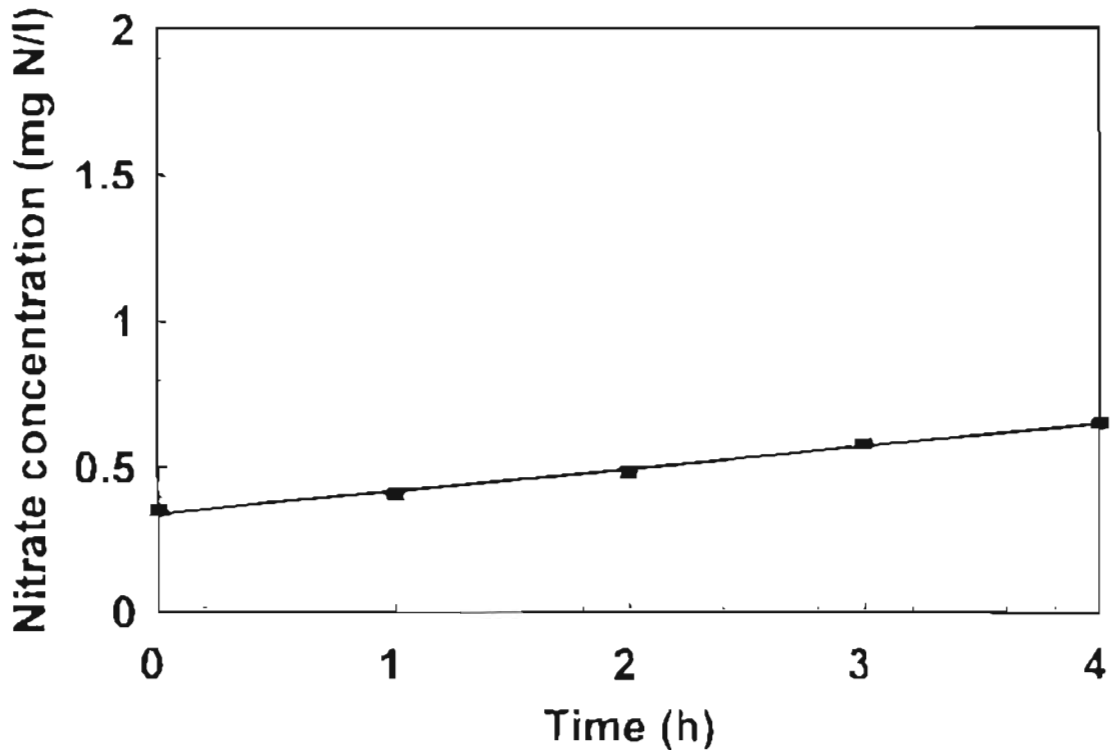


Figure 6.4: Nitrate concentration with time for wastewater and mixed liquor aerobic batch test.

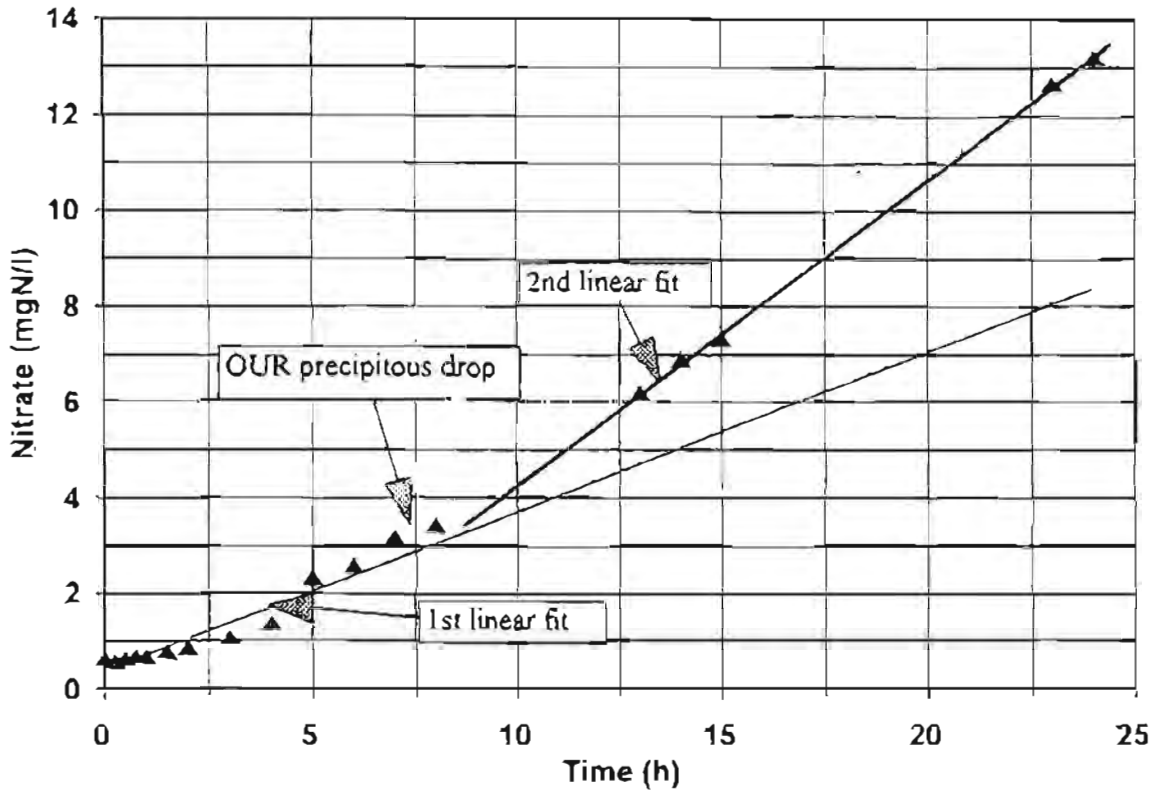


Figure 6.5: Nitrate concentration with time for wastewater and mixed liquor aerobic batch test exhibiting two linear profiles.

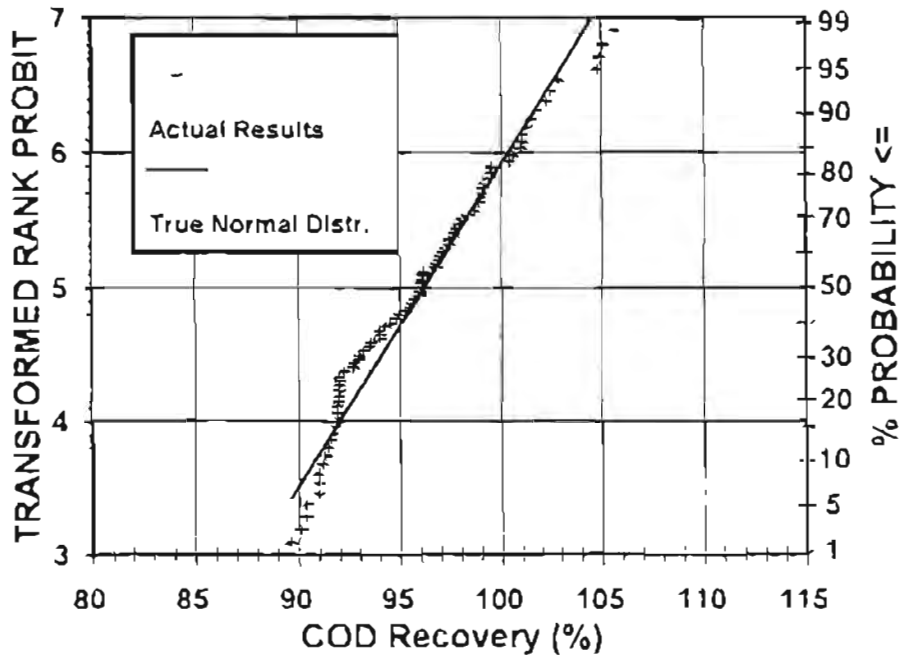


Figure 6.6: Statistical plot of %COD recovery for all the wastewater only batch tests.

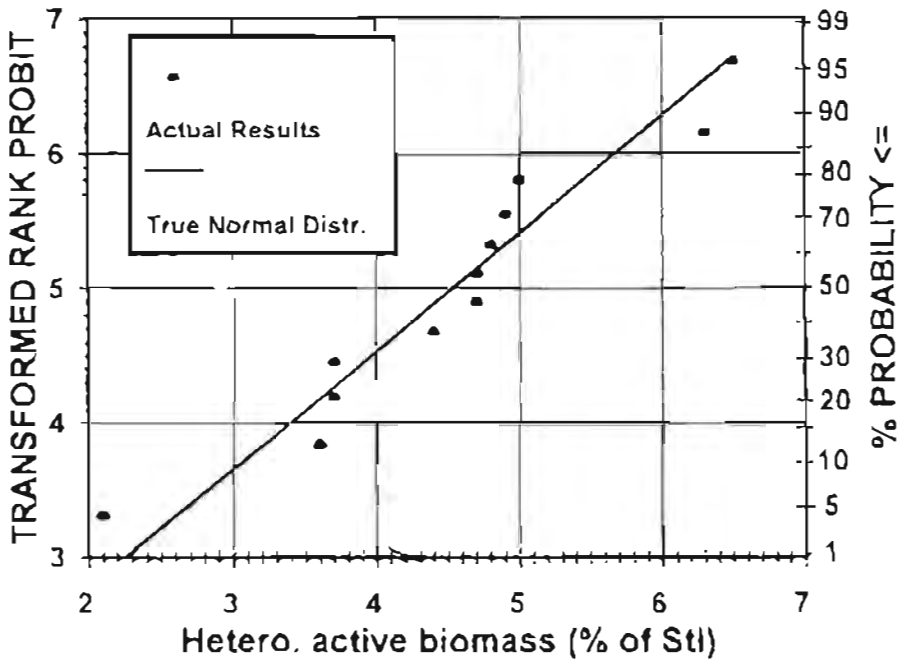


Figure 6.7: Statistical plot of measured means of heterotrophic active biomass for the different wastewater only batch tests.

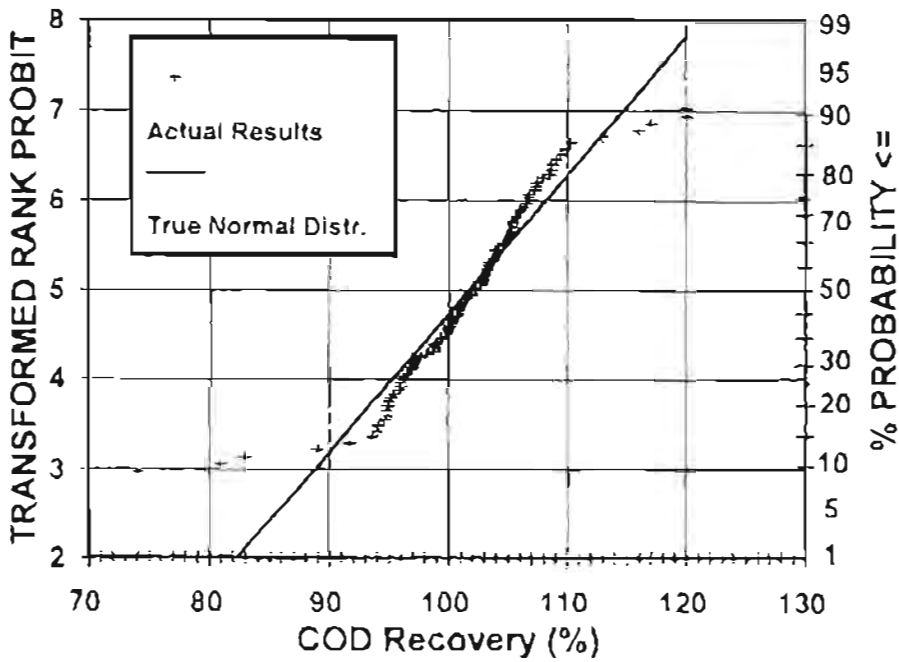


Figure 6.8: Statistical plot of %COD recovery for all the wastewater and mixed liquor batch tests.

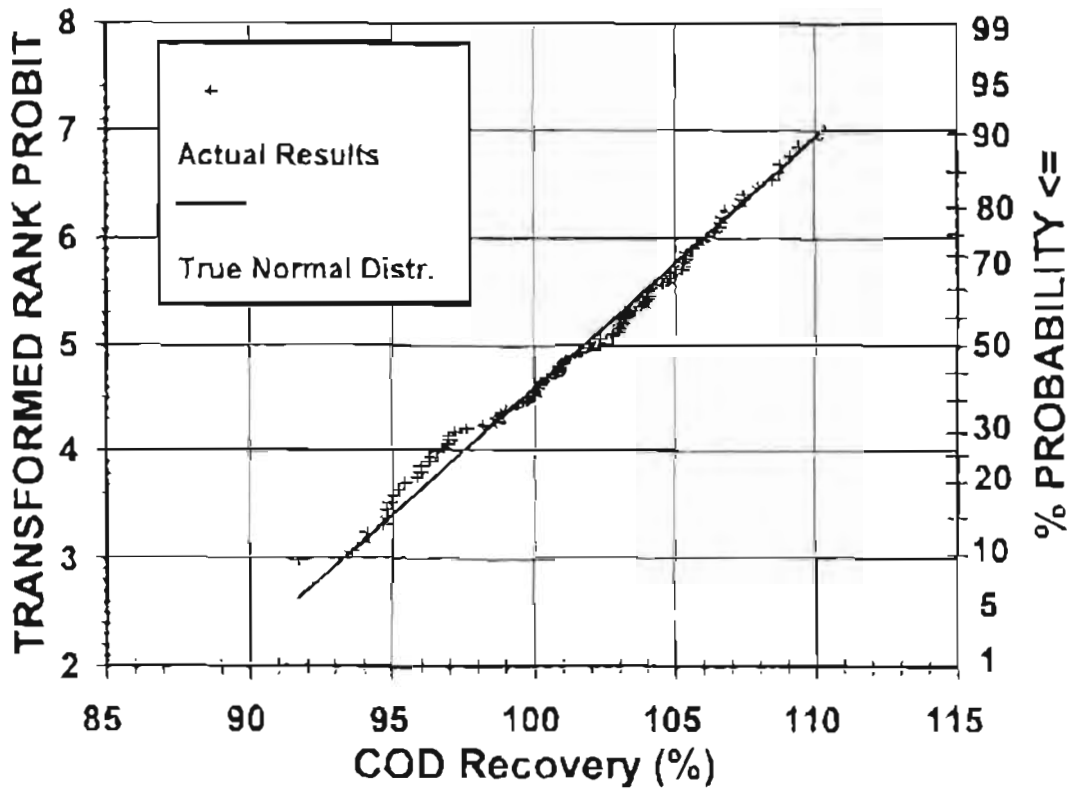


Figure 6.9: Statistical plot of %COD recovery for the wastewater and mixed liquor batch tests, with batch tests with %COD recoveries <90% and >110% rejected (9 batch tests), see Fig. 6.8

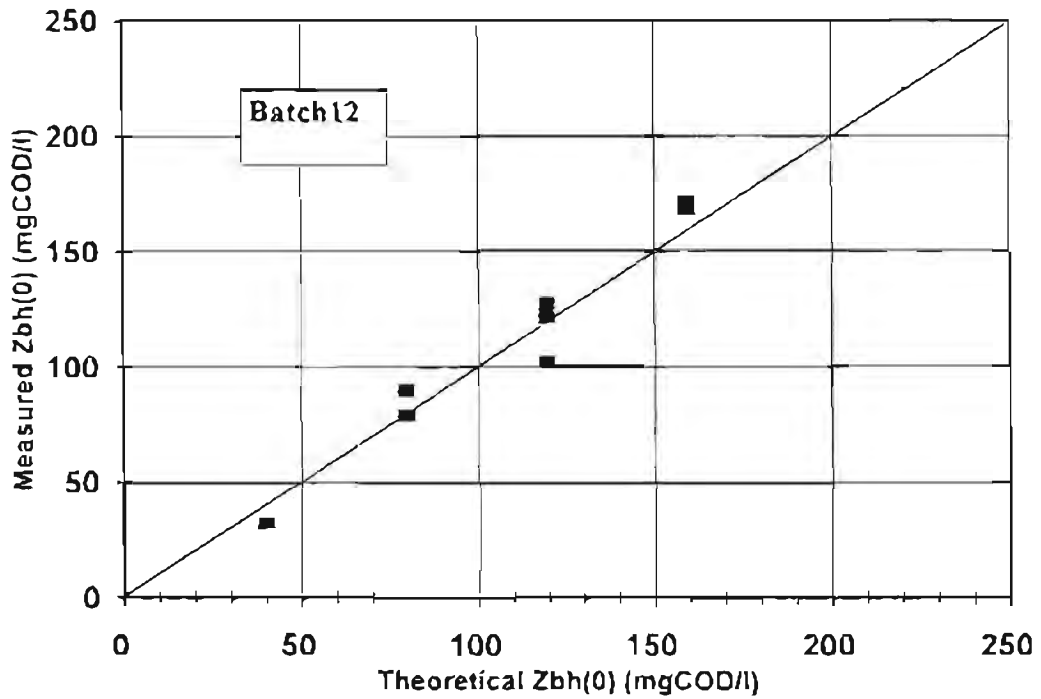


Fig 6.10 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 12

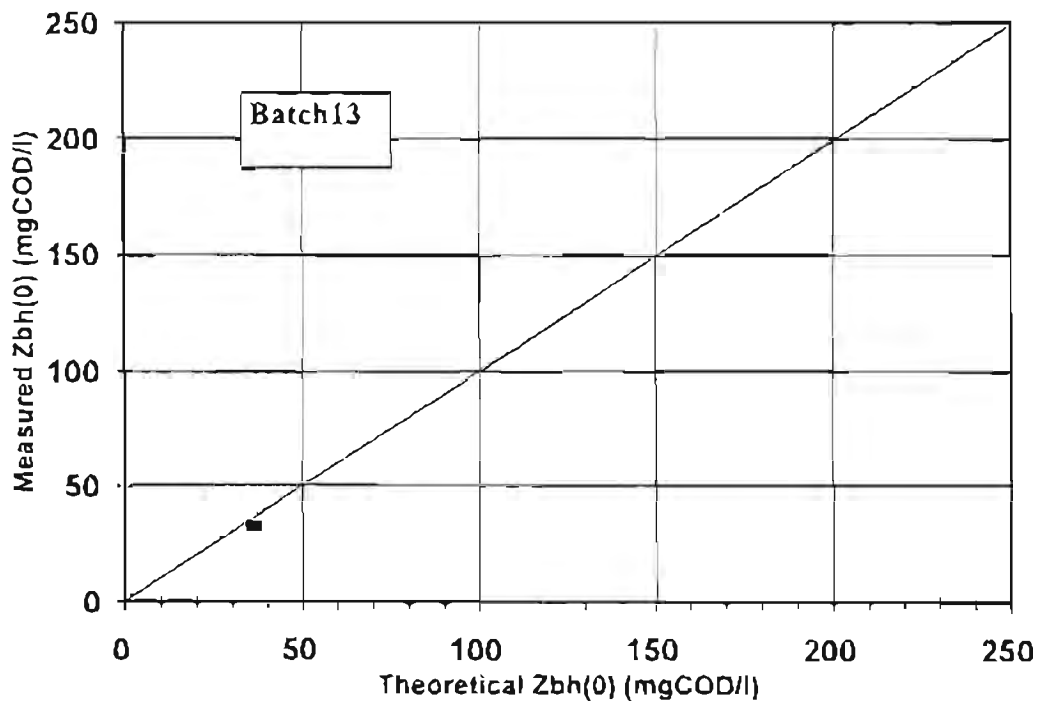


Fig 6.11 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 13

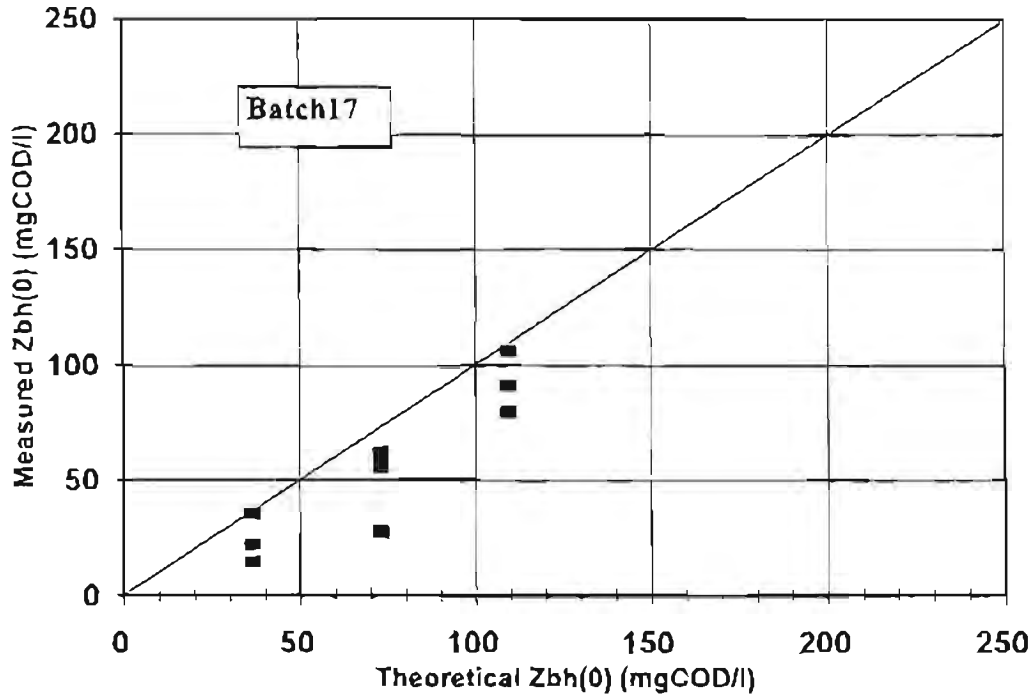


Fig 6.12 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 17

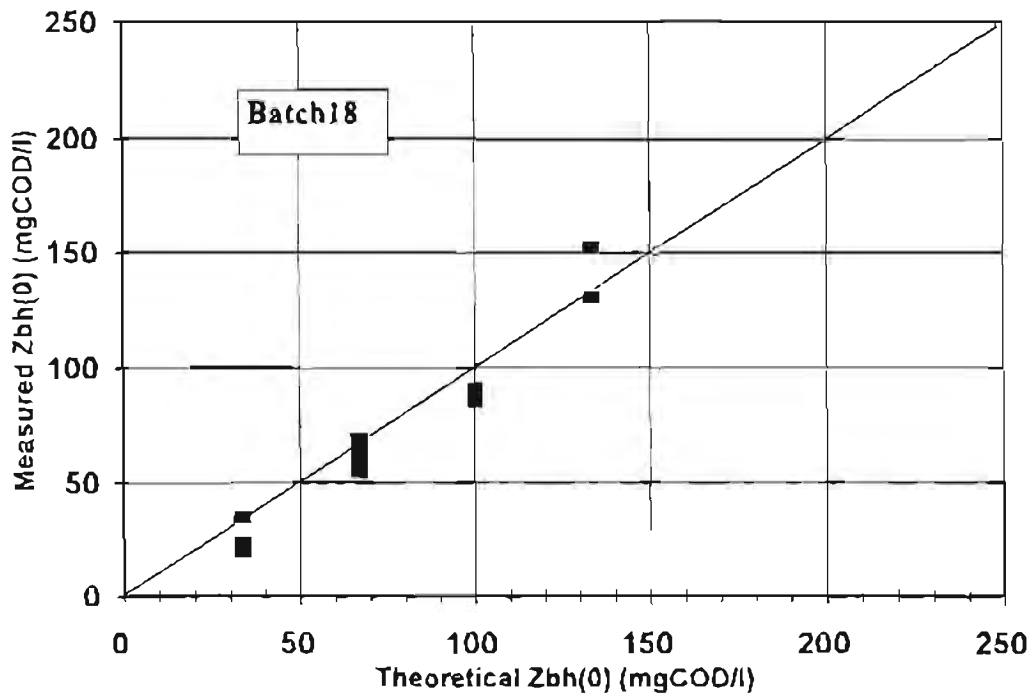


Fig 6.13 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 18

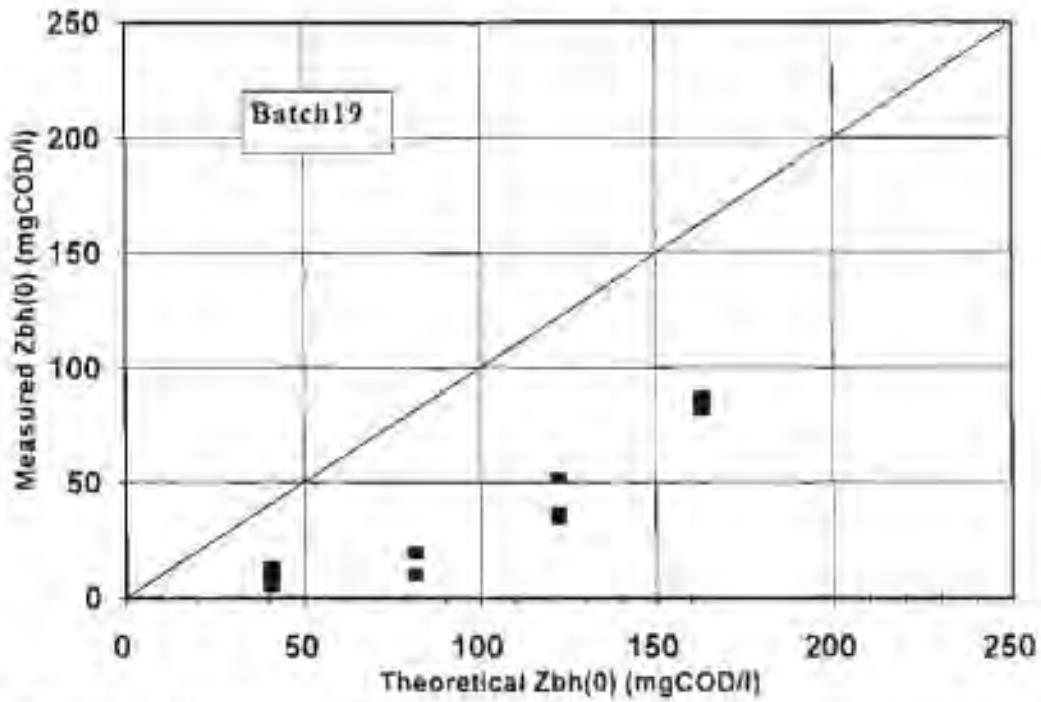


Fig 6.14 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 19

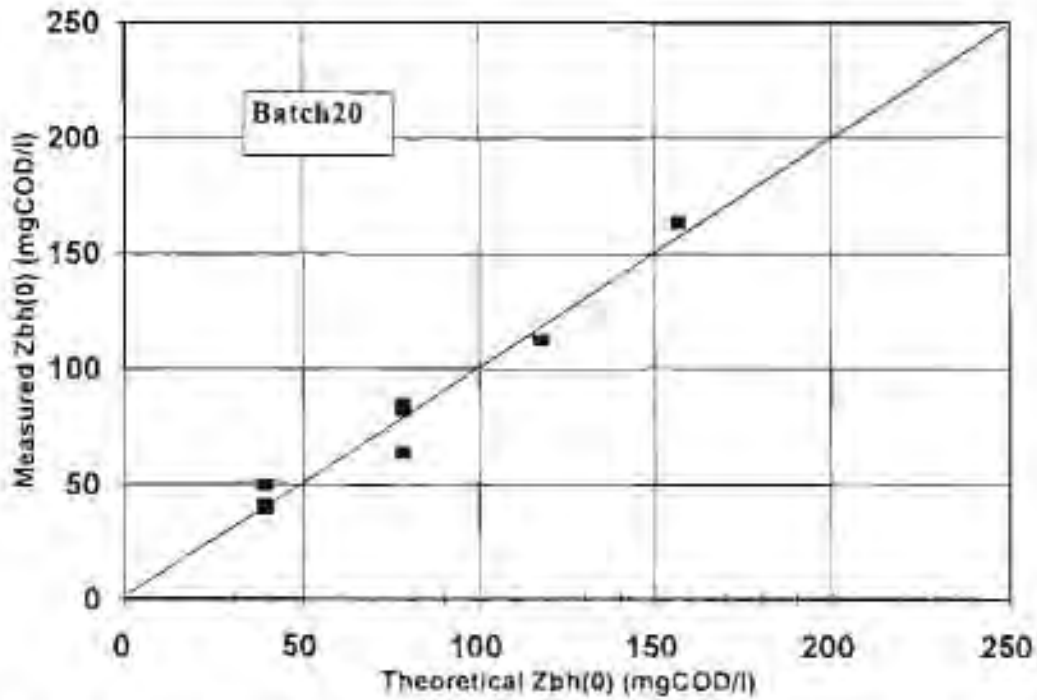


Fig 6.15 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 20

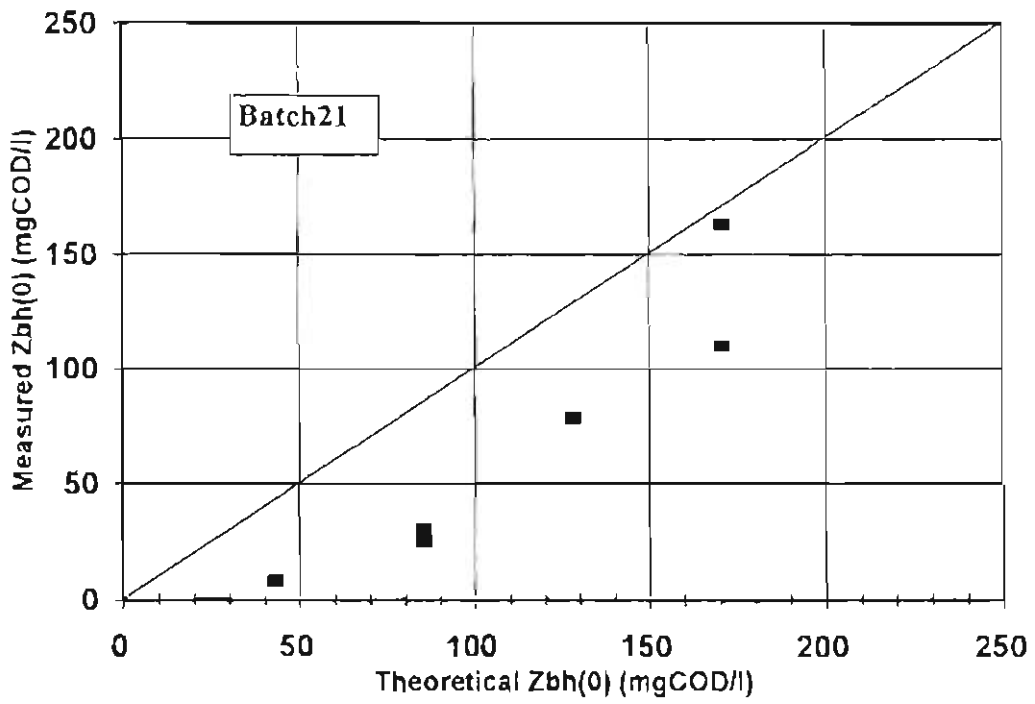


Fig 6.16 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 21

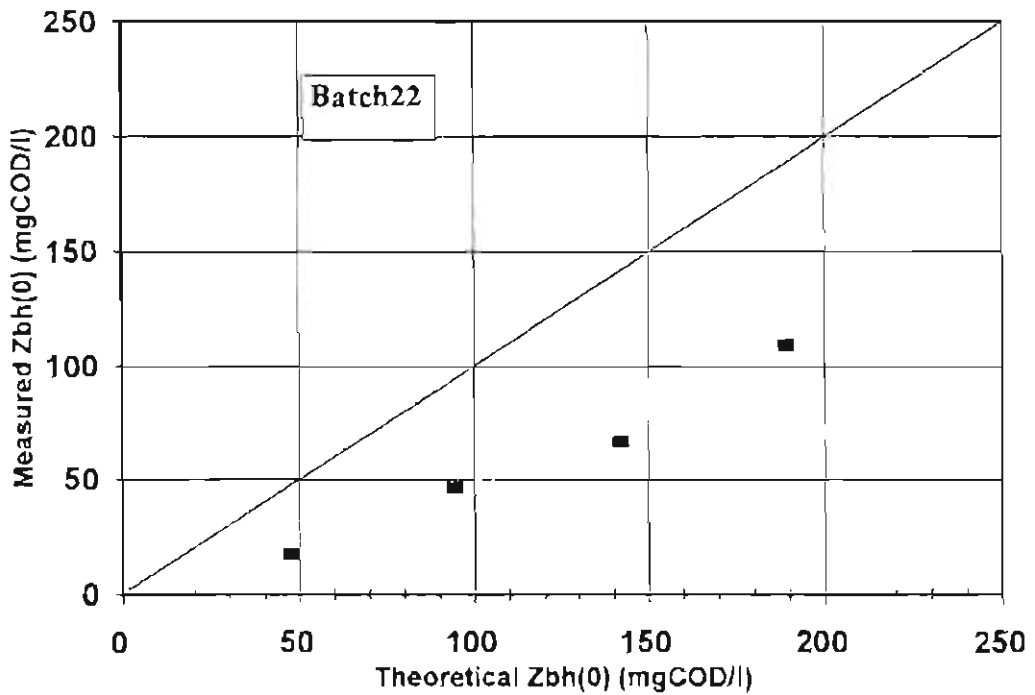


Fig 6.17 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 22

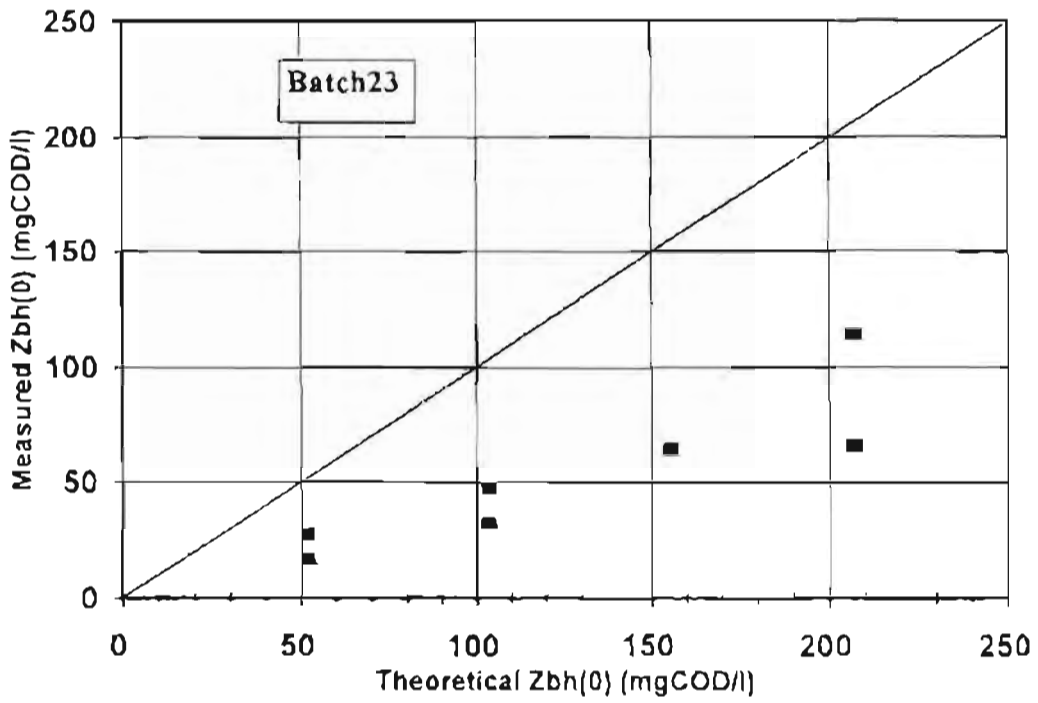


Fig 6.18 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 23

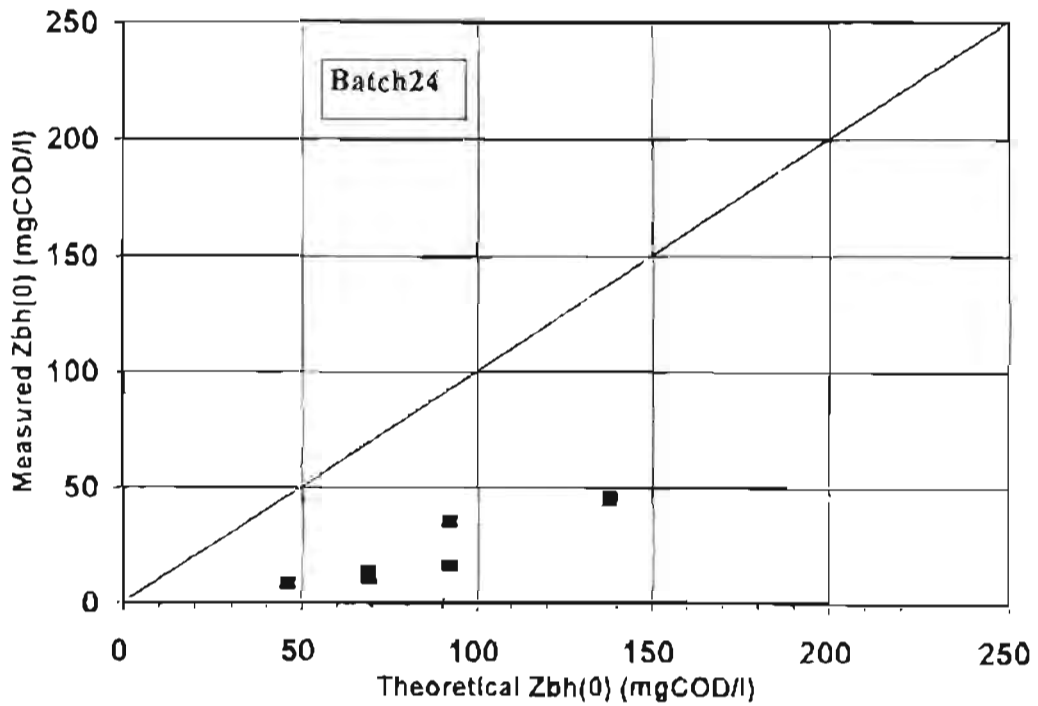


Fig 6.19 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 24

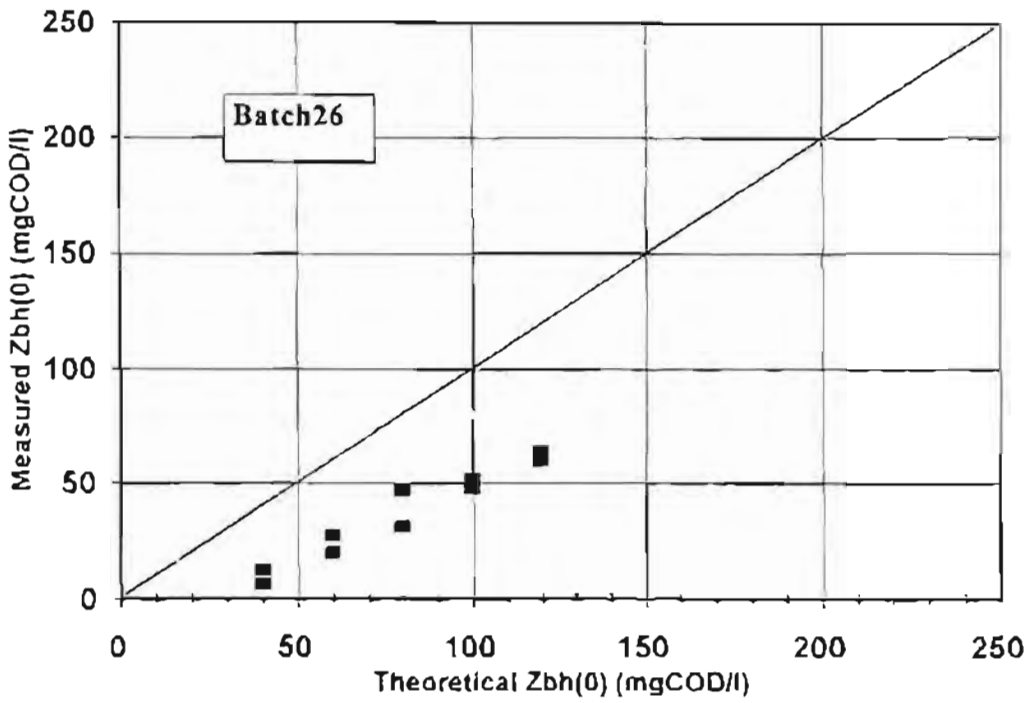


Fig 6.20 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 26

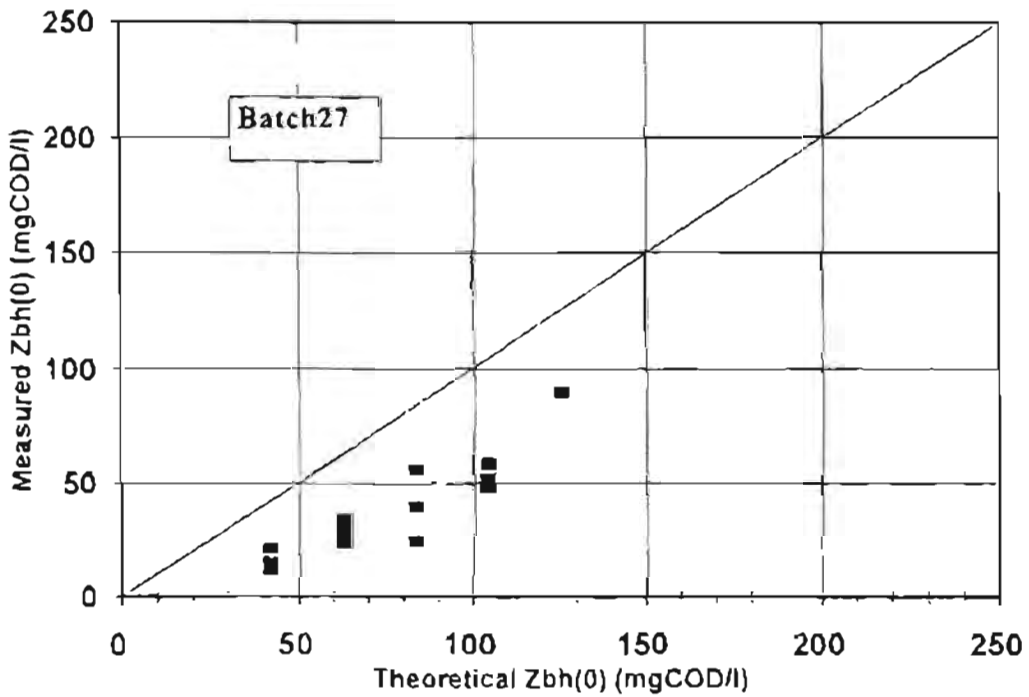


Fig 6.21 Measured vs theoretical heterotrophic active biomass for wastewater batch no. 27

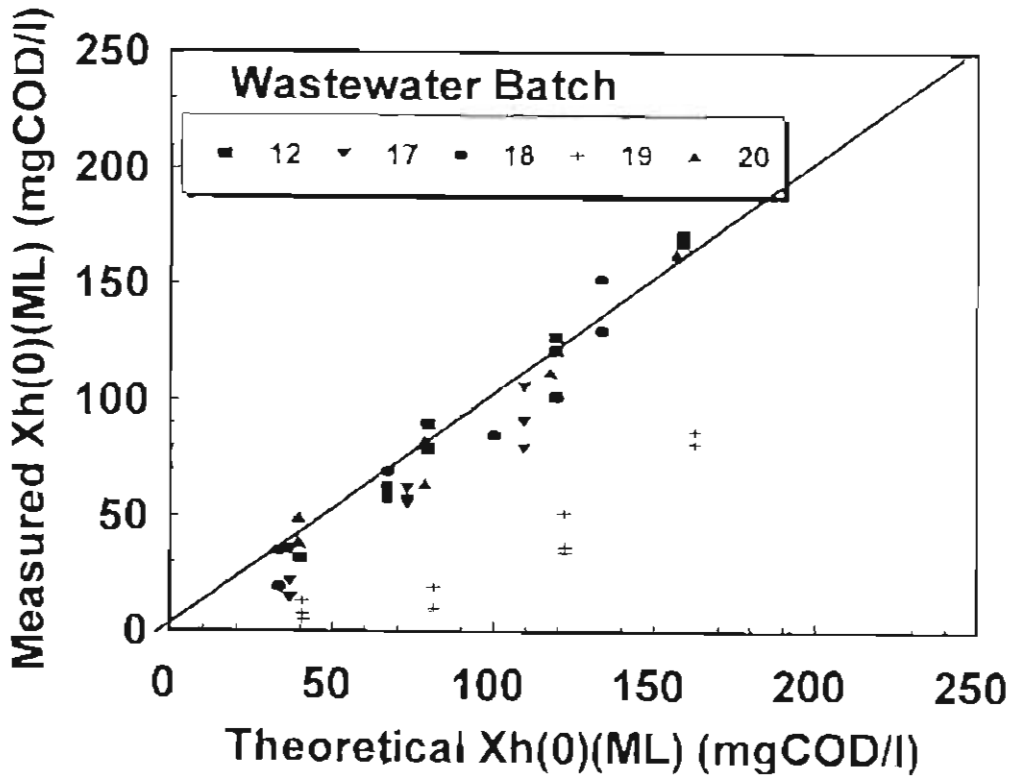


Fig. 6.22. Graph of measured vs theoretical heterotrophic active biomass for the various wastewater batches with the parent laboratory-scale system operating at 12 days sludge age.

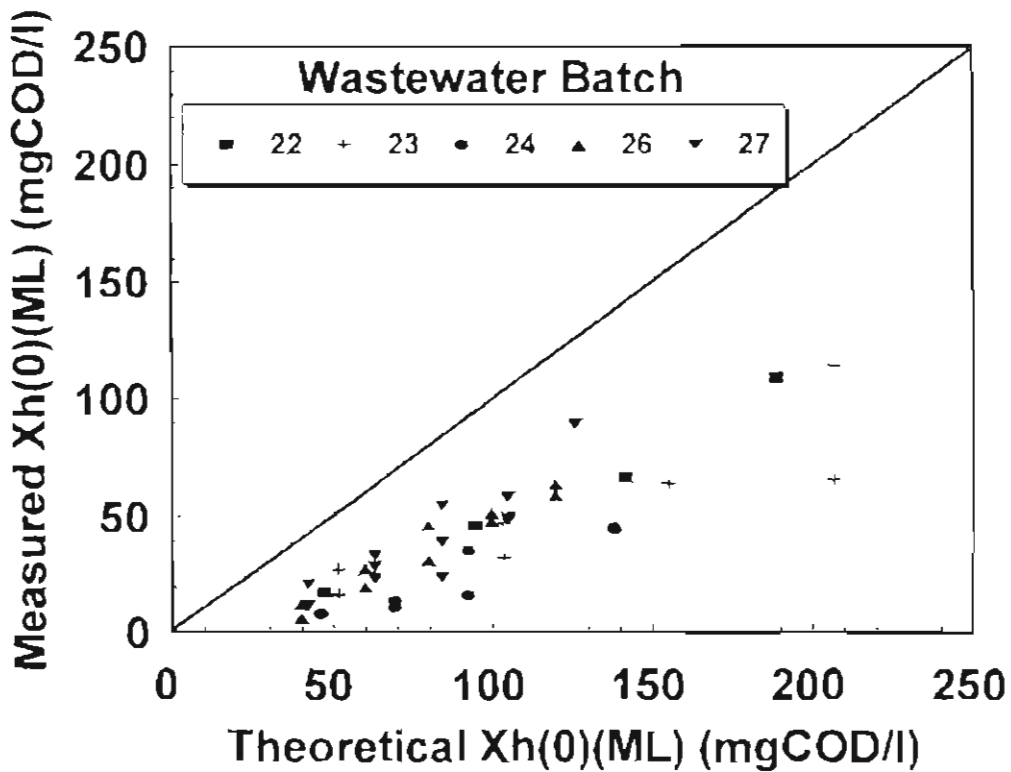


Fig. 6.23: Graph of measured vs theoretical heterotrophic active biomass for the various wastewater batches with the parent laboratory-scale system operating at 20 days sludge age.

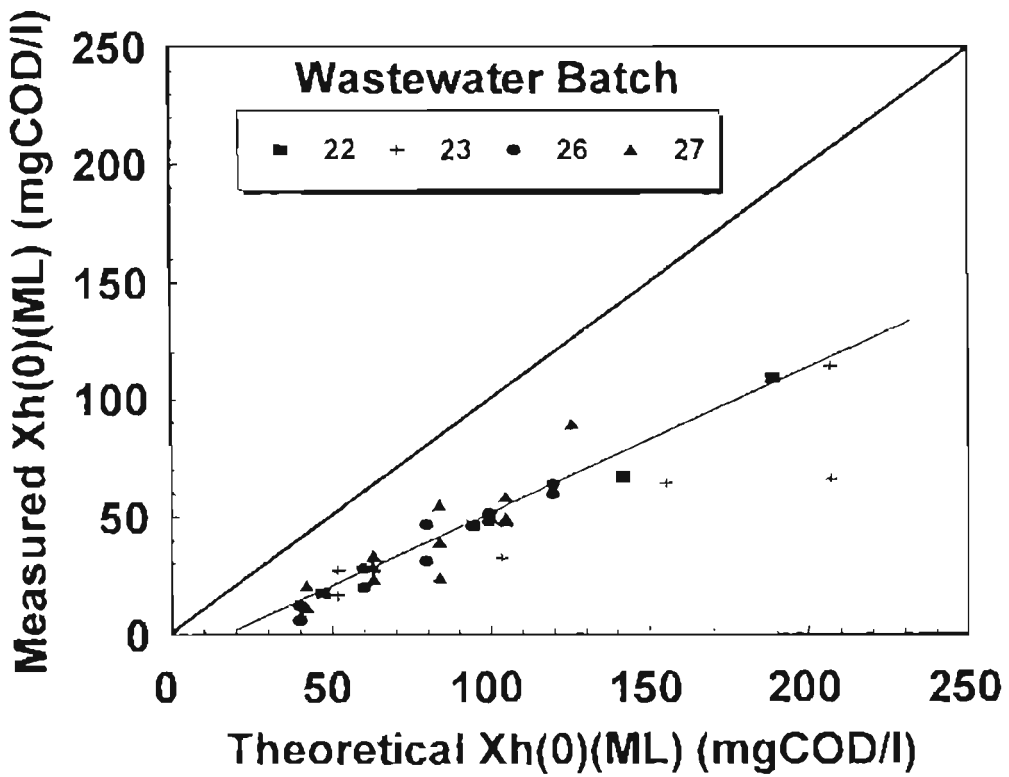


Fig. 6.24: Graph of measured vs theoretical heterotrophic active biomass for the various wastewater batches (excluding wastewater batch No.24) with the parent laboratory-scale system operating at 20 days sludge age.

CHAPTER 7

ACTIVATED SLUDGE MIXED LIQUOR INORGANIC FRACTION

7.1 INTRODUCTION

In the bioreactor of the activated sludge system, the mixed liquor is made up of organic and inorganic materials. The mixed liquor organic suspended solids (MLOSS) are commonly quantified by means of the volatile suspended solids (VSS) measurement (Standard Methods, 1985), and less commonly by means of the COD measurement (e.g. Henze *et al.*, 1987). The organic plus inorganic materials are quantified by means of the total suspended solids (TSS) measurement (Standard Methods, 1985). The difference between the TSS and VSS measurements quantifies the inorganic suspended solids (ISS).

In both the design procedures (e.g. WRC, 1984) and simulation models (e.g. Dold *et al.*, 1980, 1991; Henze *et al.*, 1987), the influent wastewater characteristics and biological processes that influence the bioreactor MLOSS are explicitly included (see Chapter 2). However, the mixed liquor TSS is calculated simply from an empirical ratio of VSS/TSS, the value for this ratio being accepted as one constant for activated sludge systems treating raw (unsettled) wastewater (VSS/TSS = 0.75 mgVSS/mgTSS) and another for those treating settled wastewater (VSS/TSS = 0.83 mgVSS/mgTSS), WRC (1984). The TSS concentration (X_t) is fundamental in the design of secondary settling tanks and waste activated sludge disposal. Clearly, the empirical approach to obtaining an estimate for X_t is not satisfactory within the framework of a fundamentally based model. Accordingly, the incorporation of the inorganic material present in the influent wastewater into the mixed liquor was investigated.

To address this objective, the following specific tasks were identified:

- To determine the distribution of the inorganic materials in the influent wastewater, that is, dissolved (soluble) and particulate (suspended).
- To determine the fate of the various influent inorganic fractions in the activated sludge system bioreactor, e.g. does the particulate (suspended) material become solubilised, or *vice versa*.
- To set up design procedures that will enable the mixed liquor inorganic suspended solids (ISS), and hence TSS, to be calculated from measurements made on the influent wastewater inorganic materials.

7.2 TOTAL SOLIDS COMPONENTS

From Chapter 2, in considering the total solids in the influent, bioreactor and effluent, these can be subdivided into components, see Fig. 7.1. The total solids (TS) consist of both total

dissolved/soluble (TDS) and total suspended/particulate (TSS) solids. The total dissolved solids (TDS) consist of the organic/volatile (VDS) and the inorganic (IDS) dissolved solids. Similarly, the total suspended solids (TSS) consist of the organic/volatile (VSS) and the inorganic (ISS) suspended solids. The VDS + VSS gives the total organic/volatile solids (TVS) and the IDS + ISS gives the total inorganic solids (TIS). Of particular importance to this part of the research project are the inorganic fractions, which, from the subdivision above, may be in a particulate/suspended or soluble/dissolved form. In terms of the conceptual framework developed for the organics, both inorganic fractions will be present in the influent wastewater. On entry of the influent into the bioreactor, biological and possibly chemical and physical processes will act on the influent fractions, transforming part of them from particulate/suspended to soluble/dissolved and *visa versa*. Accordingly, these fractions will be present in the bioreactor also, but the relative magnitude of the fractions may differ from those present in the influent. On passing to the secondary settling tank, the particulate/suspended material will settle out to be retained in the system, and the soluble/dissolved material will pass through to the effluent. Thus, by measuring the distribution of inorganic materials in the influent, in the bioreactor and in the effluent of a steady state activated sludge system, it may be possible to gain an initial understanding of the fate of the various influent inorganic fractions in the activated sludge system bioreactor, i.e. what transformations in the bioreactor act on the inorganics, to solubilize the particulate material and *vice versa*. With this understanding it may prove possible to set up procedures (design and simulation) that will enable the inorganic solids (and hence total solids) in the bioreactor to be calculated from measurements made on the influent. This approach was adopted in this part of the research project.

As noted above, the focus of this part of the research project is on the inorganic fractions. However, the inorganics are quantified by the difference between the total solids and organic/volatile solids. Thus, to monitor and trace the fate of the inorganics, the total and organic/volatile solids fractions in Fig. 7.1 will have to be monitored in the influent, bioreactor and effluent. In effect, all fractions in Fig. 7.1 will have to be quantified for influent, bioreactor and effluent.

7.3 RESEARCH APPROACH

The parent laboratory-scale system described in Chapter 4 was used for the investigation. For this system, all the parameters described in Section 7.2 above were measured on the influent, bioreactor and effluent. By comparing the data on the influent, bioreactor and effluent, the fate of the inorganic materials in the parent system were traced.

7.4 TEST PROCEDURE

7.4.1 Parent laboratory-scale system

The steady state parent laboratory-scale system and its operation have been described in detail in Chapter 4 (see Fig. 4.2). This system was used also for this investigation.

7.4.2 Sampling procedure

Influent

Daily, after thorough mixing, an 800ml unsettled wastewater sample was taken from the unsettled diluted influent wastewater (500mgCOD/l) used as feed for the parent system; this sample was stored at 4°C for analysis the following day. The 800ml unsettled wastewater sample was thoroughly mixed before a volume (initially 250ml and later 650ml) was filtered through 0.45µm filter paper. Two 100ml filtered influent wastewater samples were poured into preweighed crucibles. The remaining unfiltered wastewater was thoroughly mixed and a 100ml sample poured into a preweighed crucible. For the filtered samples, it was found that the sample weight relative to the crucible weight was small; thus the initial two filtered influent wastewater samples tested daily were increased later to six samples. These six samples were analysed statistically (see Appendix D) and the calculated mean used as the correct value for the day.

Bioreactor

Two 50ml mixed liquor samples were drawn from the aerobic reactor of the parent system. These samples were centrifuged at 3 500rev/min for 20 minutes. The supernatant was decanted and the pellet transferred with distilled water to a preweighed crucible.

Effluent

Daily, after mixing the effluent in the effluent bucket, an 800ml unfiltered effluent sample was taken. After thorough mixing, a volume (initially 250ml and later 650ml) of unfiltered effluent was filtered through 0.45µm filter paper. Two 100ml filtered effluent samples were poured into preweighed crucibles. The remaining unfiltered effluent was thoroughly mixed and a 100ml sample poured into a preweighed crucible. For the filtered samples, it was found that the sample weight relative to the crucible weight was small; thus the initial two filtered effluent wastewater samples tested daily were increased later to six samples. These six samples were analysed statistically (see Appendix D) and the calculated mean used as the correct value for the day.

7.4.3 Measurements

Following Standard Methods (1985), all crucibles + samples were dried in a 105°C oven for 24 hours. The crucibles + contents were removed from the 105°C oven, allowed to cool to room temperature in a desiccator and weighed. The crucibles + contents were then incinerated in a 600°C oven for at least 20 minutes, removed and allowed to cool to room temperature in a desiccator and weighed. (All organic/volatile material will burn off at 600°C within 20 minutes, and only inorganic material (ash) will remain in the crucible). The difference in weight between the crucibles and the crucibles + contents after 105°C drying gives the total solids, and the difference in weight between the crucibles + contents after 600°C incineration and after 105°C drying gives the organic/volatile solids. The difference between the total and organic/volatile solids gives the inorganic solids. Accordingly:

From the *unfiltered* influent and effluent data the following were determined:

- Total solids (TS), influent and effluent.

- Total volatile solids (TVS), influent and effluent.
- Total inorganic solids (TIS), influent and effluent.

Accepting that filtration through $0.45\mu\text{m}$ separates reasonably closely the dissolved and suspended fractions, from the *filtered* influent and effluent data the following were determined:

- Total dissolved solids (TDS), influent and effluent.
- Volatile dissolved solids (VDS), influent and effluent.
- Inorganic dissolved solids (IDS), influent and effluent.

By difference between the *unfiltered and filtered* fractions respectively above, the suspended/particulate fractions for the influent and effluent were calculated as follows:

- Total suspended solids (TSS) = TS - TDS, influent and effluent.
- Volatile suspended solids (VSS) = TVS - VDS, influent and effluent.
- Inorganic suspended solids (ISS) = TIS - IDS, influent and effluent.

For the bioreactor, the samples were centrifuged and thus are suspended/particulate. Accordingly, the bioreactor samples give directly:

- Total suspended solids (TSS), bioreactor.
- Volatile suspended solids (VSS), bioreactor.
- TSS - VSS = Inorganic suspended solids (ISS), bioreactor.

7.4.4 Measurements for precision and accuracy evaluation

It was recognized that for the influent and effluent samples, the mass of the sample relative to the mass of the crucible would be small, especially for the filtered samples. Accordingly, the precision and accuracy of the test procedure were evaluated. A NaCl stock solution (concentration $\sim 500\text{mgNaCl}/\ell$) was prepared and tests conducted on the solution. The stock solution concentration was selected after observing that the total solids concentrations of the filtered influent and effluent were approximately in this range ($500\text{mg}/\ell$). Periodically, 10 samples of 100ml each of the stock solution were poured into preweighed crucibles and dried in a 105°C oven for 24 hours, removed and allowed to cool to room temperature in a desiccator and then weighed. The difference in weight of the crucible and the crucible + contents after 105°C drying gives the total solids (TS) of the stock solution. This should equal the known expected concentration of the stock solution (TS = $500\text{mg}/\ell$). The ten samples' TS were analysed by plotting on a statistical probability plot (see Appendix D for construction and interpretation of this plot), to determine if the data were normally distributed and to determine the mean and standard deviation. As an example, one set of data are shown plotted in Fig. 7.2(a): The data are normally distributed, with a mean value of $505.6\text{mgTS}/\ell$ and a standard deviation of $5.8\text{mgTS}/\ell$. The mean values were found to compare very well with the expected known concentration of the stock solution ($500\text{mgTS}/\ell$), and the sample standard deviations were small ($< 1.2\%$ of the mean value). This indicated that the testing procedure was both precise and accurate.

Also, as noted above, six measurements were taken daily on each of the filtered influent and effluent samples. Statistical analysis indicated relatively small sample standard deviations for these sample sets; for example see Fig. 7.2(b). This indicates that the testing procedure is precise (i.e. reproducible), but does not provide information on the accuracy since the "real" values for these tests are not known.

A “quality control” check on the testing procedure was also implemented: Daily one 100mℓ sample from the NaCl stock solution was tested under the same conditions as for the influent, bioreactor and effluent samples. The experimental NaCl concentration obtained was compared to the mean and standard deviation obtained from the ten NaCl samples above. The daily experimental NaCl concentration obtained was deemed acceptable if it lay within two times the standard deviation above or below the mean value for the set of 10 NaCl samples (i.e. approximately within the 95% confidence interval); in the example here, the data would be acceptable if it lay within the boundaries 488.3 and 519.5mgTS/ℓ. Most of the test data lay within this envelope; if the data did not lie within the envelope, the tests were rejected or repeated.

7.4.5 Treatment of crucibles

After completing the above daily tests, all crucibles were emptied, washed and incinerated in a 600°C oven for at least 20 minutes. This was done to dry out the crucibles, as well as to burn off any residual organic/volatile material that may be in the crucible. The crucibles were then allowed to cool to room temperature in a desiccator and weighed. The crucibles were then used for testing. Crucibles were marked in pencil and only used for specific sample types; for example, a set of crucibles was used exclusively for filtered effluent samples. A particular problem with the crucibles was that the glazing on the crucibles gradually eroded due to cleaning. When the glazing had eroded significantly, it influenced the water retention properties of the crucible when drying at 105°C and thus influenced the measurements. Accordingly, the crucibles were replaced regularly, and always in sets.

7.5 RESULTS AND DATA INTERPRETATION

7.5.1 Wastewater batches

The daily results for the unfiltered sample TS, TVS, TIS and filtered TDS, VDS, IDS are listed in Appendix E, Tables E1 and E2 for the influent and effluent respectively. The daily results for the bioreactor TSS and VSS are listed in Appendix C, Table C4 (ISS = TSS - VSS).

Twenty eight separate wastewater batches served as feed to the parent laboratory-scale system, see Chapter 4. Each wastewater batch was accepted as a steady state period. For each wastewater batch, the daily results were analysed to determine outliers; data lying outside the range (mean \pm 2 • sample standard deviation) (i.e. outside approximately the 95% confidence interval) were rejected (these data are shown marked in Appendix E, Tables E1 and E2). Excluding the rejected data, for each wastewater batch the means, the number of tests and the sample standard deviations were determined, and are listed in Appendix E as follows:

- Unfiltered influent TS, TIS, TVS; Table E3.
- Filtered influent TDS, IDS, VDS; Table E4.
- Unfiltered effluent TS, TIS, TVS; Table E5.
- Filtered effluent TDS, IDS, VDS; Table E6.
- Bioreactor TSS, VSS, ISS; Table E7.

The inorganic data for the wastewater batches have been abstracted from Appendix E and are presented in Table 7.1.

Table 7.1: Parent system influent, effluent and bioreactor inorganic solids concentrations; for each sewage batch mean, sample standard deviation and number of tests. TIS = total inorganic solids; IDS = inorganic dissolved solids; ISS = inorganic suspended solids.

Sew. Batch No.	Dates of Test	Influent						Effluent						Bioreactor			Inorganics Recovery (%)
		Unfiltered, TIS (mg/l)			Filtered, IDS (mg/l)			Unfiltered, TIS (mg/l)			Filtered, IDS (mg/l)			Centrifuged, ISS (mg/l)			
		Mean	sample std. dev.	No. tests	Mean	sample std. dev.	No. tests	Mean	sample std. dev.	No. tests	Mean	sample std. dev.	No. tests	Mean	sample std. dev.	No. tests	
1	30Mar-12Apr	440	69	14	375	43	13	387	46	14	373	42	13	437	27	11	93
2	13Apr-25Apr	410	29	9	360	33	10	366	35	9	365	47	10	337	86	10	94
3	26Apr-14May	408	86	18	361	66	18	358	51	17	366	48	18	269	26	18	92
4	20Jun-27Jun	389	56	8	355	22	7	330	49	7	326	31	8	332	33	7	90
5	29Jun-20Jul	384	60	19	310	36	17	345	64	18	312	34	18	310	57	20	94
6	21Jul-3Aug	544	116	13	520	133	14	500	87	14	497	92	14	320	33	13	95
7	4Aug-22Aug	476	133	18	385	111	18	409	82	18	413	76	18	271	59	19	89
8	23Aug-06Sept	416	109	13	353	97	12	357	81	13	343	60	12	251	37	13	89
9	07Sept-20Sept	469	103	14	373	82	13	366	52	13	363	53	13	237	62	14	81
10	21Sept-02Oct	401	101	11	313	102	11	361	77	12	347	76	12	350	40	11	95
11	03Oct-16Oct	417	83	13	345	103	14	337	51	13	314	62	13	376	64	14	86
12	17Oct-31Oct	387	70	14	361	91	15	324	50	14	320	61	15	401	62	14	89
13	01Nov-17Nov	229	41	13	208	50	14	198	52	14	192	33	13	293	53	14	93
14	18Nov-04Dec	227	54	16	233	65	68	184	41	16	193	43	66	281	43	16	88
15	05Dec-14Dec	202	38	9	180	73	48	195	41	7	195	61	55	306	23	9	105
16	08Jan-11Jan	223	69	4	193	71	24	216	51	4	202	46	24	303	27	4	104
17	12Jan-25Jan	269	81	14	238	78	75	246	46	12	230	27	70	322	28	13	98
18	26Jan-07Feb	290	40	12	253	43	73	268	46	11	260	40	74	281	37	13	98
19	08Feb-21Feb	327	26	12	277	29	70	287	21	13	282	26	71	274	32	13	92
20	22Feb-05Mar	308	39	12	265	43	73	281	22	12	275	34	74	341	46	11	97
21	06Mar-19Mar	366	39	14	344	33	79	320	26	14	334	23	82	362	38	14	93
22	04Apr-12Apr	318	60	9	287	56	50	304	34	9	309	38	54	491	46	9	104
23	13Apr-23Apr	400	41	10	364	62	60	346	33	11	354	34	62	500	20	11	94
24	24Apr-08May	479	35	9	455	43	60	420	47	10	423	29	58	474	34	14	93
25	09May-19May	493	122	10	458	103	58	483	88	10	505	69	66	541	37	10	104
26	20May-31May	449	77	11	402	82	48	420	82	12	431	84	54	538	10	12	100
27	01Jun-14Jun	498	71	12	433	84	36	465	36	11	449	45	34	602	30	13	100
28	15Jun-27Jun	493	175	13	447	171	39	461	97	13	462	100	39	589	29	12	100

7.5.2 Inorganic mass balances

The reliability of the experimental measurements was checked by means of mass balances on the inorganics (Table 7.1). For the mass balance, the total mass of inorganic material that enters the system via the influent wastewater should closely equal that leaving the system, via the daily sludge wastage and the effluent:

Mass of total inorganics entering the system = Mass of total inorganics leaving the system

$$\text{i.e. } M(\text{TIS}_{\text{inf}}) = M(\text{TIS}_{\text{eff}}) + M(\text{TIS}_{\text{waste}}) \quad (7.1)$$

$$\therefore Q_{\text{inf}} \cdot \text{TIS}_{\text{inf}} = Q_{\text{eff}} \cdot \text{TIS}_{\text{eff}} + Q_{\text{waste}} \cdot \text{TIS}_{\text{waste}} \quad (7.2)$$

where

$$\begin{aligned} M(\text{TIS}_{\text{inf}}) &= \text{mass of total inorganic solids in influent (mgTIS/d)} \\ M(\text{TIS}_{\text{eff}}) &= \text{mass of total inorganic solids in effluent (mgTIS/d)} \\ M(\text{TIS}_{\text{waste}}) &= \text{mass of total inorganic solids wasted from bioreactor (mgTIS/d)} \\ \text{TIS}_{\text{inf}}, \text{TIS}_{\text{eff}}, \text{TIS}_{\text{waste}} &= \text{concentrations of above total inorganic solids (mgTIS/l)} \\ Q_{\text{inf}}, Q_{\text{eff}}, Q_{\text{waste}} &= \text{influent, effluent and waste flow rates respectively (l/d)} \end{aligned}$$

In Eq. (7.2), noting that the total inorganic solids in the waste stream ($\text{TIS}_{\text{waste}}$) is made up of the particulate/suspended and soluble/dissolved inorganic fractions ($\text{ISS}_{\text{waste}}$ and $\text{IDS}_{\text{waste}}$ respectively), that the concentration of dissolved inorganics in the waste stream equals the concentration in the effluent (i.e. $\text{IDS}_{\text{waste}} = \text{IDS}_{\text{eff}}$) and that the particulate/suspended inorganics concentration in the waste stream equals the concentration in the bioreactor (i.e. $\text{ISS}_{\text{waste}} = \text{ISS}_{\text{reac}}$) (waste drawn from aerobic bioreactor which immediately precedes the secondary settling tank), then:

$$\% \text{Inorganics recovery} = \frac{Q_{\text{eff}} \cdot \text{TIS}_{\text{eff}} + Q_{\text{waste}} \cdot \text{IDS}_{\text{eff}} + Q_{\text{waste}} \cdot \text{ISS}_{\text{reac}}}{Q_{\text{inf}} \cdot \text{TIS}_{\text{inf}}} \quad (7.3)$$

where

$$\begin{aligned} \text{IDS}_{\text{eff}} &= \text{effluent inorganic dissolved solids concentration (mgIDS/l)} \\ \text{ISS}_{\text{reac}} &= \text{bioreactor inorganic suspended solids concentration (mgISS/l)} \end{aligned}$$

Using Eq. (7.3), the % inorganic recoveries were calculated for each wastewater batch, using the mean data listed in Table 7.1; these also are listed in Table 7.1. The % inorganic recoveries ranged from 81 to 105%. The % inorganic recoveries are shown plotted on a statistical probability plot (see Appendix D for construction and interpretation of this plot) in Fig. 7.3; for the wastewater batches the means are normally distributed with mean % inorganics recovery 94% and sample standard deviation 5.5%. Considering that the inorganics are determined as the difference between two measured parameters (total solids - volatile solids) and that for the influent and effluent samples the inorganic weight is relatively small compared to the crucible weight, the % inorganic recoveries are surprisingly good. In fact, 23 out of the 28 wastewater batches tested have % inorganic recoveries falling in the range 90 to 105%.

Since the % inorganic recoveries are normally distributed, and the acceptable range for the %

recoveries is not known, no wastewater batches were rejected for further analysis.

In Eq. (7.3) the term $(Q_{\text{eff}} \cdot \text{TIS}_{\text{eff}})$ is the total inorganic solids in the effluent, $(Q_{\text{waste}} \cdot \text{IDS}_{\text{waste}})$ is the dissolved/soluble inorganic solids in the waste stream and $(Q_{\text{waste}} \cdot \text{ISS}_{\text{read}})$ is the particulate/suspended inorganic solids in the waste stream; thus, the last term reflects the inorganics incorporated into the activated sludge mixed liquor. In Fig. 7.4, the relative contributions of each of these terms to the total inorganics mass balance are shown. From Fig. 7.4, it is evident that the relative amount of the influent inorganics that are incorporated into the activated sludge mixed liquor is very small, ranging from 2.8 to 7.5% of the influent inorganics. By far the majority of the inorganics present in the influent leave the system with the effluent, 75 to 92%, and a relatively small amount as dissolved/soluble inorganics in the waste stream, 3 to 5.5%. Considering the accuracy of the total mass balance on the inorganics, and the relatively small amount of inorganics incorporated into the mixed liquor, it would appear that it may not be possible to develop a method that will give a reasonable prediction of the inorganics in the mixed liquor from the measurements made on the influent - the relative accuracy of the measurement techniques would appear inadequate, and any error would accumulate for the sludge age. Nevertheless, it is of interest to analyse the inorganics more closely.

7.5.3 Influent inorganic solids fractions

The influent inorganic dissolved/soluble solids (IDS) and suspended/particulate solids (ISS) concentrations for the different wastewater batches are shown plotted in Fig. 7.5; the sum of these two concentrations equals the influent total inorganic solids (TIS) concentration. From Fig. 7.5, the inorganics present in the influent principally are in the dissolved form. The percentage influent inorganic dissolved to total solids (%IDS/TIS) for the different wastewater batches are shown plotted on a statistical probability plot in Fig. 7.6. The data are normally distributed with mean 88% and sample standard deviation 5%; that is, on average 88% of the inorganic solids present in the influent are in the dissolved/soluble form.

7.5.4 Effluent inorganic solids fractions

The effluent inorganic dissolved/soluble solids (IDS) and suspended/particulate solids (ISS) concentrations for the different wastewater batches are shown plotted in Fig. 7.7; the sum of these two concentrations equals the effluent total inorganic solids (TIS) concentration. From Fig. 7.7, the inorganics present in the effluent almost exclusively are in the dissolved form. The percentage effluent inorganic dissolved to total solids (%IDS/TIS) for the different wastewater batches are shown plotted on a statistical probability plot in Fig. 7.8. The data are normally distributed with mean 98.5% and sample standard deviation 3.0%; that is, on average 98.5% of the inorganic solids present in the effluent are in the dissolved/soluble form.

7.5.5 Comparison between influent and effluent total inorganic solids (TIS)

For the different wastewater batches, the influent and effluent total inorganic solids (TIS) concentrations are shown plotted in Figs. 7.5 and 7.7 respectively, and in a combined plot in Fig. 7.9; these values represent the means of a number of tests on each wastewater batch (see Appendix E, Tables E1 and E2). From Figs. 7.5 and 7.7 and Fig. 7.9, for all wastewater batches the influent TIS are larger than the effluent TIS; it would appear that there is a difference between influent and effluent TIS. To examine this difference more closely, a statistical test was used to

determine whether the differences between the influent and effluent values are statistically significant at the 95% confidence interval (see Appendix D for details on the test); the results of the statistical test are listed in Table 7.2. For the various wastewater batches, 14 out of 28 batches have TIS in the influent and effluent that are statistically significantly different at the 95% confidence interval; in the remaining 14 batches the differences are statistically insignificant at the 95% confidence interval. It would be expected that there should be a significant difference between the influent and effluent TIS (i.e. unfiltered inorganics); inorganic materials are entrapped in the activated sludge mixed liquor and leave the system with the waste mixed liquor and not with the effluent. The large number of wastewater batches with differences between influent and effluent TIS that are statistically insignificant at the 95% confidence interval would support the previous conclusion that the measurement techniques may not be accurate enough to conclusively trace the fate of the influent inorganics in the activated sludge system.

Table 7.2: Statistical test of significance of the difference between influent and effluent total inorganic solids (TIS); test at 95% confidence interval (see Appendix D).

Sew. Batch No.	Date of Test	UNFILTERED INFLUENT AND EFFLUENT TIS					Conclusion
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance	
1	30Mar-12Apr	18.5	12.7	22.4	53.3	8.4	stat. signif.
2	13Apr-25Apr	9.7	11.2	14.8	44.7	15.1	stat. signif.
3	26Apr-14May	20.2	12.0	23.5	49.2	2.3	stat. signif.
4	20Jun-27Jun	19.7	18.6	27.1	58.8	4.6	stat. signif.
5	29Jun-20Jul	13.8	15.4	20.7	38.7	-2.6	stat. insignif.
6	21Jul-3Aug	32.1	23.2	39.6	44.5	-34.8	stat. insignif.
7	4Aug-22Aug	31.3	19.2	36.7	67.6	-5.8	stat. insignif.
8	23Aug-06Sept	30.2	23.3	38.1	58.8	-17.5	stat. insignif.
9	07Sept-20Sept	27.4	14.5	31.0	102.4	40.4	stat. signif.
10	21Sept-02Oct.	30.3	23.1	38.1	40.5	-35.8	stat. insignif.
11	03Oct-16Oct	23.1	13.7	26.8	79.4	25.7	stat. signif.
12	17Oct-31Oct	18.6	12.8	22.6	63.0	17.9	stat. signif.
13	01Nov-17Nov	11.2	14.0	18.0	31.0	-4.9	stat. insignif.
14	18Nov-04Dec	13.5	5.0	14.4	42.7	13.9	stat. signif.
15	05Dec-14Dec	12.6	5.9	13.9	6.9	-21.0	stat. signif.
16	08Jan-11Jan	34.5	10.5	36.0	6.8	-65.3	stat. insignif.
17	12Jan-25Jan	21.8	5.3	22.4	23.7	-21.1	stat. insignif.
18	26Jan-07Feb	11.7	5.4	12.9	22.0	-3.7	stat. insignif.
19	08Feb-21Feb	7.6	2.5	8.0	39.5	23.5	stat. signif.
20	22Feb-05Mar	11.1	2.5	11.4	26.8	4.0	stat. signif.
21	06Mar-19Mar	10.5	3.0	10.9	45.9	24.1	stat. signif.
22	04Apr-12Apr	19.9	4.9	20.5	13.6	-27.3	stat. insignif.
23	13Apr-23Apr	12.8	4.2	13.5	53.6	26.5	stat. signif.
24	24Apr-08May	11.6	6.1	13.1	58.9	32.7	stat. signif.
25	09May-19May	38.7	11.5	40.4	10.1	-70.7	stat. insignif.
26	20May-31May	23.1	11.9	25.9	28.2	-23.7	stat. insignif.
27	01Jun-14Jun	20.5	6.0	21.4	32.5	-10.2	stat. insignif.
28	15Jun-27Jun	48.4	15.6	50.9	31.4	-70.3	stat. insignif.

7.5.6 Comparison between influent and effluent inorganic dissolved solids (IDS)

The influent and effluent inorganic dissolved/soluble solids (IDS) concentrations for the different wastewater batches are shown plotted in Fig. 7.10; the IDS concentrations in the effluent correspond closely to those in the influent. The % effluent IDS to influent IDS for the wastewater batches are shown plotted on a statistical probability plot (for details on the plot, see Appendix D) in Fig. 7.11; the data are normally distributed with mean 100% and sample standard deviation 7%. This would indicate that the influent and effluent IDS concentrations are closely equal.

The data for the individual wastewater batches were analysed statistically to determine whether the differences between the influent and effluent IDS were statistically significant at the 95% confidence interval (see Appendix D for details on the test); the results of the statistical test are listed in Table 7.3. In 22 out of 28 wastewater batches, the differences between influent and effluent IDS are statistically insignificant at the 95% confidence interval; 6 out of 28 wastewater batches have differences that are statistically significant. This would suggest that a simplified model for the incorporation of inorganics into the activated sludge mixed liquor can be developed, by assuming that the influent and the effluent IDS concentrations are equal, and that the influent ISS are incorporated into the mixed liquor. This model is developed and evaluated below.

Table 7.3: Statistical test of significance of difference between influent and effluent inorganic dissolved solids (IDS); test at 95% confidence interval (see Appendix D).

Sew. Batch No.	Date of Test	FILTERED INFLUENT AND EFFLUENT IDS					
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance	Conclusion
1	30Mar-12Apr	12.1	11.5	16.7	1.6	-31.7	stat. insignif.
2	13Apr-25Apr	10.5	14.8	18.1	4.8	-31.5	stat. insignif.
3	26Apr-14May	15.4	11.3	19.2	5.2	-33.2	stat. insignif.
4	20Jun-27Jun	8.2	10.8	13.6	29.2	2.0	stat. signif.
5	29Jun-20Jul	8.7	8.0	11.8	2.0	-21.7	stat. insignif.
6	21Jul-3Aug	35.6	24.5	43.2	23.0	-63.4	stat. insignif.
7	4Aug-22Aug	26.1	18.0	31.7	28.0	-35.4	stat. insignif.
8	23Aug-06Sept.	28.0	17.4	33.0	10.2	-55.8	stat. insignif.
9	07Sept-20Sept	22.7	14.7	27.0	10.2	-43.8	stat. insignif.
10	21Sept-02Oct.	30.9	21.9	37.9	34.5	-41.2	stat. insignif.
11	03Oct-16Oct	27.5	17.2	32.4	30.3	-34.6	stat. insignif.
12	17Oct-31Oct	23.5	15.9	28.4	41.4	-15.3	stat. insignif.
13	01Nov-17Nov	13.3	9.3	16.3	16.5	-16.0	stat. insignif.
14	18Nov-04Dec.	7.9	5.3	9.5	39.6	20.5	stat. signif.
15	05Dec-14Dec	10.5	8.2	13.3	15.3	-11.4	stat. insignif.
16	08Jan-11Jan	14.5	9.4	17.3	9.0	-25.5	stat. insignif.
17	12Jan-25Jan	9.0	3.2	9.5	7.5	-11.5	stat. insignif.
18	26Jan-07Feb	5.1	4.6	6.8	6.6	-7.1	stat. insignif.
19	08Feb-21Feb	3.5	3.1	4.7	5.7	-3.6	stat. insignif.
20	22Feb-05Mar	5.0	3.9	6.4	10.5	-2.2	stat. insignif.
21	06Mar-19Mar	3.7	2.5	4.5	10.4	1.5	stat. signif.
22	04Apr-12Apr	8.0	5.2	9.5	21.5	2.5	stat. signif.
23	13Apr-23Apr	8.0	4.4	9.1	10.4	-7.7	stat. insignif.
24	24Apr-08May	5.5	3.8	6.7	32.5	19.0	stat. signif.
25	09May-19May	13.5	8.5	15.9	47.0	15.1	stat. signif.
26	20May-31May	11.8	11.4	16.4	29.5	-3.3	stat. insignif.
27	01Jun-14Jun	14.0	7.7	16.0	16.6	-15.4	stat. insignif.
28	15Jun-27Jun	27.4	16.0	31.7	14.7	-48.7	stat. insignif.

7.6 DEVELOPMENT OF MODELS FOR THE INORGANICS

7.6.1 Simple model based on influent inorganic suspended solids (ISS_{inf})

Theoretically, if no solubilization of inorganic material occurs due to the action of the heterotrophic active biomass in the reactor, and no dissolved inorganic materials precipitate or are entrapped in the mixed liquor, or, the processes that cause solubilization and precipitation/entrapment are closely equal, then the inorganic dissolved solids (IDS) entering the system in the influent should equal the IDS leaving the system via the effluent. From the analysis of the data above, it would appear that this may be true, i.e. the amount of IDS entering the system in the influent is approximately equal to the IDS leaving the system via the effluent, see Figs. 7.10 and 7.11. Thus, to model the incorporation of the influent inorganics into the activated sludge mixed liquor, it can be assumed that all the inorganic suspended/particulate material in the influent, i.e. ISS_{inf}, gets enmeshed into the mixed liquor and leaves the bioreactor via the waste sludge, and all the influent inorganic dissolved/soluble material, i.e. IDS_{inf}, flows unmodified through the bioreactor and leaves the system via the effluent. Accordingly, by measuring the ISS_{inf} and IDS_{inf} influent inorganic fractions, the reactor and effluent inorganics can be readily calculated as follows:

For the bioreactor:

$$M(\text{ISS}_{\text{reac}}) = M(\text{ISS}_{\text{inf}}) \cdot R_s \quad (7.4)$$

where

$$\begin{aligned} M(\text{ISS}_{\text{reac}}) &= \text{mass of inorganic suspended solids in the bioreactor (mgISS)} \\ M(\text{ISS}_{\text{inf}}) &= \text{mass of inorganic suspended solids in the influent (mgISS/d)} \\ R_s &= \text{sludge age (d)} \end{aligned}$$

In Eq. (7.4), substituting for masses and rearranging gives:

$$\text{ISS}_{\text{reac}} = Q_{\text{inf}} \cdot \text{ISS}_{\text{inf}} \cdot R_s / V_p \quad (7.5)$$

where

$$\begin{aligned} \text{ISS}_{\text{reac}}, \text{ISS}_{\text{inf}} &= \text{inorganic suspended solids concentrations in bioreactor and} \\ &\quad \text{influent respectively (mgISS/ℓ)} \\ Q_{\text{inf}} &= \text{influent flow rate (ℓ/d)} \\ V_p &= \text{process volume (ℓ)} \end{aligned}$$

Hence, the mass and concentration of mixed liquor total suspended solids (TSS; MX_t and X_t respectively), can be calculated:

$$\text{MX}_t = \text{MX}_v + M(\text{ISS}_{\text{reac}}) \quad (7.6a)$$

$$X_t = X_v + \text{ISS}_{\text{reac}} \quad (7.6b)$$

where

$$\text{MX}_v, X_v = \text{mass and concentration respectively of bioreactor mixed liquor volatile suspended solids (mgVSS; mgVSS/ℓ)}$$

Also, the effluent inorganics will be exclusively in the dissolved/soluble form (i.e. IDS) and will equal the influent IDS. Accordingly, the effluent IDS can be calculated from:

$$IDS_{\text{eff}} = IDS_{\text{inf}} \quad (7.7)$$

where

$$IDS_{\text{eff}}, IDS_{\text{inf}} = \text{inorganic dissolved solids in effluent and influent respectively (mgIDS/}\ell\text{)}$$

This simple model for incorporation of influent inorganics into the activated sludge mixed liquor was evaluated by comparing the predicted results with those measured on the parent laboratory-scale system. For each wastewater batch, the influent ISS (TIS - IDS, Table 7.1) and IDS (Table 7.1) were inserted into Eqs. (7.5) and (7.7) respectively, and the bioreactor ISS and effluent IDS concentrations respectively were calculated. The predicted and measured concentrations are compared in Fig. 7.12 for bioreactor ISS and in Fig. 7.13 for effluent IDS. From these figures, the predicted and measured effluent IDS concentrations correspond closely. However, the predicted bioreactor ISS concentrations are all higher than those measured, by a variable amount. This would indicate that in the bioreactor, there is a net solubilization of the influent suspended/particulate inorganics (ISS_{inf}). The data indicates also that there is no consistent relationship between the influent and bioreactor ISS. This would suggest that some other processes are acting on the inorganics in the bioreactor that are not taken into account in the simple model. This observation is substantiated further by noting that the over prediction in bioreactor ISS concentration tends to be larger at the longer sludge age.

It can be concluded that this first simple model is not appropriate.

7.6.2 Simple model based on influent total inorganic solids (TIS_{inf})

In evaluating the model developed above, it was noted that the bioreactor ISS did not seem to be directly related to the influent ISS. As an alternative, it was proposed that the bioreactor ISS may be related to the influent TIS. A model was developed on this basis as follows:

For the bioreactor:

$$ISS_{\text{reac}} = Q_{\text{inf}} \cdot f_T \cdot TIS_{\text{inf}} \cdot R_s / V_p \quad (7.8)$$

where

$$\begin{aligned} TIS_{\text{inf}} &= \text{influent total inorganic solids concentration (mgTIS/}\ell\text{)} \\ f_T &= \text{fraction of } TIS_{\text{inf}} \text{ incorporated into activated sludge mixed liquor} \end{aligned}$$

And for the effluent, all influent inorganics not incorporated into the activated sludge mixed liquor appear as IDS in the effluent, i.e.:

$$IDS_{\text{eff}} = TIS_{\text{inf}} - ISS_{\text{reac}} \cdot V_p / (Q_{\text{inf}} \cdot R_s) \quad (7.9)$$

Using Eqs. (7.8) and (7.9) and the data in Table 7.1, predicted bioreactor ISS and effluent IDS values were calculated and are compared with measured values in Figs. 7.14 and 7.15 respectively. For the predictions, an f_T value of 0.05 gave the best correlation (i.e. a net 5% of

the influent TIS is entrapped in the activated sludge mixed liquor and the balance flows out as IDS in the effluent). The correlation between predicted and measured bioreactor ISS with this model (Fig. 7.14) is far superior to that with the model based on influent ISS (Fig. 7.12). However, the model does not predict correctly the effect of sludge age on the bioreactor ISS; when the 12d sludge age data are reasonably predicted, the 20d sludge age data are over predicted.

Again it can be concluded that this model is not appropriate.

7.6.3 Fundamentally based model

Due to the failure of the simple models above to predict correctly the bioreactor ISS, it was decided to develop a more fundamentally based model, using the approach of the existing steady state model for aerobic COD removal (WRC, 1984; see Chapter 2). In terms of this approach, utilization of the influent biodegradable COD results in the synthesis of the mixed liquor organic fraction heterotrophic active biomass, and endogenous respiration of this organic fraction results in the generation of endogenous mass. It was proposed that the synthesis of heterotrophic active biomass would cause inorganic materials to be taken up and stored by the organisms. This would seem reasonable since the heterotrophic active biomass would certainly contain inorganics (e.g. Mg, Ca, Na; Gaudy and Gaudy, 1980). For the endogenous mass, it was assumed that this also would contain inorganic materials equal in proportion to the heterotrophic active biomass; no information is available in the literature on the validity of this assumption. Additionally, it was proposed that there is an accumulation of inorganics within the mixed liquor matrix, due to processes such as entrapment, adsorption and precipitation.

Thus, for the heterotrophic active biomass and endogenous mass fractions:

$$ISS_{\text{react}} = f_B (X_H + X_E) \quad (7.10)$$

where

$$\begin{aligned}
 ISS_{\text{react}} &= \text{bioreactor inorganic suspended solids concentration due to heterotrophic active biomass and endogenous mass (mgISS/\ell)} \\
 f_B &= \text{fraction of heterotrophic active biomass and endogenous mass that is inorganic materials (mg ISS/mgVSS)} \\
 X_H &= \text{heterotrophic active biomass concentration (mgVSS/\ell)} \\
 &= MX_H/V_p \\
 MX_H &= \text{mass of heterotrophic active biomass, see Chapter 5, Eq. (5.1)} \\
 X_E &= \text{endogenous mass concentration (mgVSS/\ell)} \\
 &= MX_E/V_p \\
 MX_E &= \text{mass of endogenous mass, see Chapter 5, Eq.(5.1)}
 \end{aligned}$$

For the accumulation of inorganic material within the sludge matrix, this could be modelled as proportional to the influent ISS (see Section 7.6.1 above, Eq. (7.5)) or TIS (see Section 7.6.2 above, Eq. (7.8)); both approaches were tried.

Influent ISS approach

For the influent ISS approach, the bioreactor ISS due to entrapment etc. in the sludge matrix of influent ISS is given by:

$$ISS_{\text{reac}2} = Q_{\text{inf}} \cdot f_{\text{ISS}} \cdot ISS_{\text{inf}} \cdot R_s / V_p \quad (7.11)$$

where

$$\begin{aligned} ISS_{\text{reac}2} &= \text{bioreactor inorganic suspended solids concentration due to} \\ &\quad \text{accumulation/entrapment of influent inorganics (mgISS/\ell)} \\ f_{\text{ISS}} &= \text{fraction of influent ISS incorporated in activated sludge mixed liquor} \end{aligned}$$

Thus, the bioreactor ISS concentration (ISS_{reac}) is given by:

$$ISS_{\text{reac}} = ISS_{\text{reac}1} + ISS_{\text{reac}2} \quad (7.12)$$

For the effluent, all the influent inorganics not incorporated into the activated sludge mixed liquor appear as IDS in the effluent; thus Eq. (7.9) applies.

Using Eqs. (7.10), (7.11) and (7.12), for each wastewater batch the predicted bioreactor ISS concentrations were calculated and compared to the measured values, see Fig. 7.16. Also, using Eq. (7.9), for each wastewater batch the effluent IDS was calculated and compared to the measured values, see Fig. 7.17. For the predictions, estimates are required for f_B and f_{ISS} . With regard to f_B , this is the inorganic content of the biological active and endogenous masses. A wide range of values for this constant are reported in the literature, with the ash content of microorganisms (i.e. ISS/TSS) varying from 5 to 30 percent (Gaudy and Gaudy, 1980). To select a value for f_B , for each wastewater batch the VSS/TSS ratio for the mixed liquor was calculated and the values plotted on a statistical probability plot; from an analysis of the data, 3 data points were rejected as outliers (wastewater batches 2, 5 and 7) and the data replotted, see Fig. 7.18. The mixed liquor VSS/TSS ratios are normally distributed with mean 0.855 mgVSS/mgTSS and sample standard deviation 0.0125 mgVSS/mgTSS. Accepting this mean as the best available estimate for the VSS/TSS ratio of the heterotrophic active biomass and endogenous mass, a value for f_B can be calculated as $f_B = \text{ISS/VSS} = 0.17 \text{ mgISS/mgVSS}$; this is equal to $\text{ISS/TSS} = 0.145$, i.e. an ash content of 14.5%, which falls within the range of values quoted in the literature. Accordingly, this value was used in the predictions.

With regard to f_{ISS} (the fraction of the influent inorganic suspended solids entrapped in the activated sludge mixed liquor), no guidance on an acceptable value for this constant could be found in the literature; the value used $f_{\text{ISS}} = 0.2$ was found by "trial and error" fitting of predicted to experimental data.

Accepting the above values for f_B and f_{ISS} , for the wastewater batches the predicted and measured bioreactor ISS concentrations are shown in Fig. 7.16 and effluent IDS in Fig. 7.17. With some exceptions, reasonably close correlation was obtained between predicted and measured data. In particular, the model is able to correctly predict the change in bioreactor ISS concentration when the sludge age is changed from 12 to 20d.

Influent TIS approach

Accepting that the accumulation of inorganic material due to entrapment etc. is proportional to the influent TIS:

$$\text{ISS}_{\text{reac2}} = Q_{\text{inf}} \cdot f_{\text{TIS}} \cdot \text{TIS}_{\text{inf}} \cdot R_s / V_p \quad (7.13)$$

where

$$f_{\text{TIS}} = \text{fraction of influent TIS entrapped in activated sludge mixed liquor}$$

Using Eqs. (7.10), (7.13) and (7.12), for each wastewater batch the predicted bioreactor ISS concentrations were calculated and compared to the measured values, see Fig. 7.19. Also, using Eq. (7.9), for each wastewater batch the predicted effluent IDS was calculated and compared to the measured values, see Fig. 7.20. For the predictions, the value $f_B = 0.17 \text{ mgISS/mgVSS}$ from above was accepted, and the $f_{\text{TIS}} = 0.017$ was found by “trial and error” curve fitting. Comparing the measured and predicted values, reasonably close correlation was obtained. Again, the effect of changing the sludge age from 12 to 20d was correctly predicted.

Influent ISS versus TIS approach

Comparing the predictions from the ISS approach (Figs. 7.16 and 7.17) with those from the TIS approach (Figs. 7.19 and 7.20), both approaches give reasonable predictions and are able to predict correctly the effect of the change in sludge age on the bioreactor ISS concentration. Although the TIS approach does appear superior in predicting the bioreactor ISS concentration, most likely the ISS approach will be superior in predicting the effect of primary sedimentation on the bioreactor VSS/TSS ratio: Experience indicates that the bioreactor VSS/TSS ratio is higher for settled wastewater than for raw wastewater (WRC, 1984; see Section 7.1 above). Since the ISS approach is based on the influent inorganic *suspended* solids which would be considerably reduced in primary sedimentation, it will predict correctly a higher bioreactor mixed liquor VSS/TSS ratio when the system treats settled wastewater than when it treats raw wastewater. For the TIS approach, the influent ISS is a relatively small fraction of the TIS (see Figs. 7.5 and 7.6) and so in primary sedimentation where the ISS would be reduced, the TIS may be reduced by only a small amount. This will result in bioreactor mixed liquor VSS/TSS ratios that are closely equal for systems treating raw and settled wastewaters, which does not agree with observations.

In conclusion, for the system predicted here the TIS approach provides better predictions than the ISS approach. However, observations on systems treating raw and settled wastewaters would suggest that the ISS approach may be superior. With the information available it is not possible to make a definitive judgement as to which approach is superior.

Sensitivity analysis

Accepting the influent ISS approach above, the sensitivity of predicted bioreactor mixed liquor VSS/TSS ratio to variations in sludge age, f_{ISS} and f_B were evaluated, see Figs. 7.21 to 7.25. For a wide range of f_{ISS} and f_B values, the predicted bioreactor mixed liquor VSS/TSS ratio is relatively insensitive to sludge age, i.e. the ratio remains approximately constant for variation in sludge age from 1 to 30d; this would agree with anecdotal observations. Also, the predicted VSS/TSS ratios span the range of values measured in practice (VSS/TSS = 0.7 to 0.9 mgVSS/mgTSS; WRC, 1984).

7.7 CONCLUSIONS/DISCUSSION

This part of the investigation has focussed on the incorporation of the influent inorganics into the activated sludge mixed liquor. From measurements made on the influent, effluent and bioreactor dissolved/soluble and particulate/suspended inorganic solids of a laboratory-scale system, the following observations/conclusions can be made:

- Considering that the inorganics were determined as the difference between two measured parameters (total solids - volatile solids) and that for the filtered influent and effluent samples the inorganic weights were relatively small compared to the weights of the crucibles, the % inorganic recoveries were surprisingly good; for the 28 wastewater batches tested the mean % inorganic recovery was 94%, with sample standard deviation 5.5%.
- Of the influent inorganics, only a small fraction were incorporated into the activated sludge mixed liquor, 2.8 to 7.5%; by far the vast majority of the influent inorganics left the system with the effluent, 75 to 92%, and a relatively small amount as dissolved/soluble inorganics in the waste stream, 3 to 5.5%.
- In the influent most of the inorganics were in the dissolved form; for the 28 wastewater batches tested, mean ratio of dissolved to total inorganics was 88%, with sample standard deviation 5%.
- In the effluent the inorganics were almost exclusively in the dissolved form; for the 28 wastewater batches tested, mean ratio of dissolved to total inorganics was 98.5%, with sample standard deviation 3%.
- For all the wastewater batches tested, the influent total inorganic solids concentrations were larger than the effluent total inorganic solids concentrations. However, for 14 of the 28 wastewater batches tested, the difference was statistically insignificant at the 95% confidence interval.
- Comparing the influent and effluent dissolved inorganic solids concentrations, the ratio effluent to influent was 100% with sample standard deviation 7%. In 22 out of 28 wastewater batches tested, the differences were statistically insignificant at the 95% confidence interval. This would indicate that the influent and effluent inorganic dissolved solids were closely equal.

From the measurements, a number of approaches to model the incorporation of the inorganics into the activated sludge mixed liquor were developed and evaluated. With regard to these models the following conclusions can be drawn:

- Simple models based on the incorporation of a fraction of the influent inorganic suspended solids (ISS) or total inorganic solids (TIS) are not appropriate: The predictions with the simple TIS model are superior to those from the ISS based model, but both models cannot predict correctly the observed effect of sludge age on bioreactor ISS.
- The more fundamental model, based on the concepts incorporated in the steady state model for aerobic COD removal (WRC, 1984), provides predicted bioreactor ISS and effluent inorganic dissolved solids (IDS) concentrations that correlate reasonably closely with those measured. In particular, the model predicts correctly the observed effect of sludge age on bioreactor ISS.

The more fundamental model above can form the basis for further investigations. Specific tasks that require attention are:

- The model was evaluated against data from the laboratory-scale system at sludge ages 12d

and 20d. The model needs to be tested over a wider range of sludge ages, say at 5d and 30d.

- The model includes incorporation of influent inorganic materials into the activated sludge matrix, to take account of processes such as inorganics entrapment, adsorption and precipitation. Two approaches to model these processes have been developed and evaluated, based on influent total inorganic solids (TIS) and inorganic suspended solids (ISS). For the laboratory-scale system operated here, the TIS approach provides better predictions than the ISS approach. However, observations on systems treating raw and settled wastewaters would suggest that the ISS approach may be superior. It was concluded that with the data available it is not possible to make a definitive judgement as to which approach is superior. This requires investigation. Also, factors influencing the relative magnitude of the incorporation of influent inorganic materials into the activated sludge matrix need to be investigated - is this closely constant for a wide range of systems, or are there a number of factors that influence it, e.g. pH, alkalinity, influent composition.

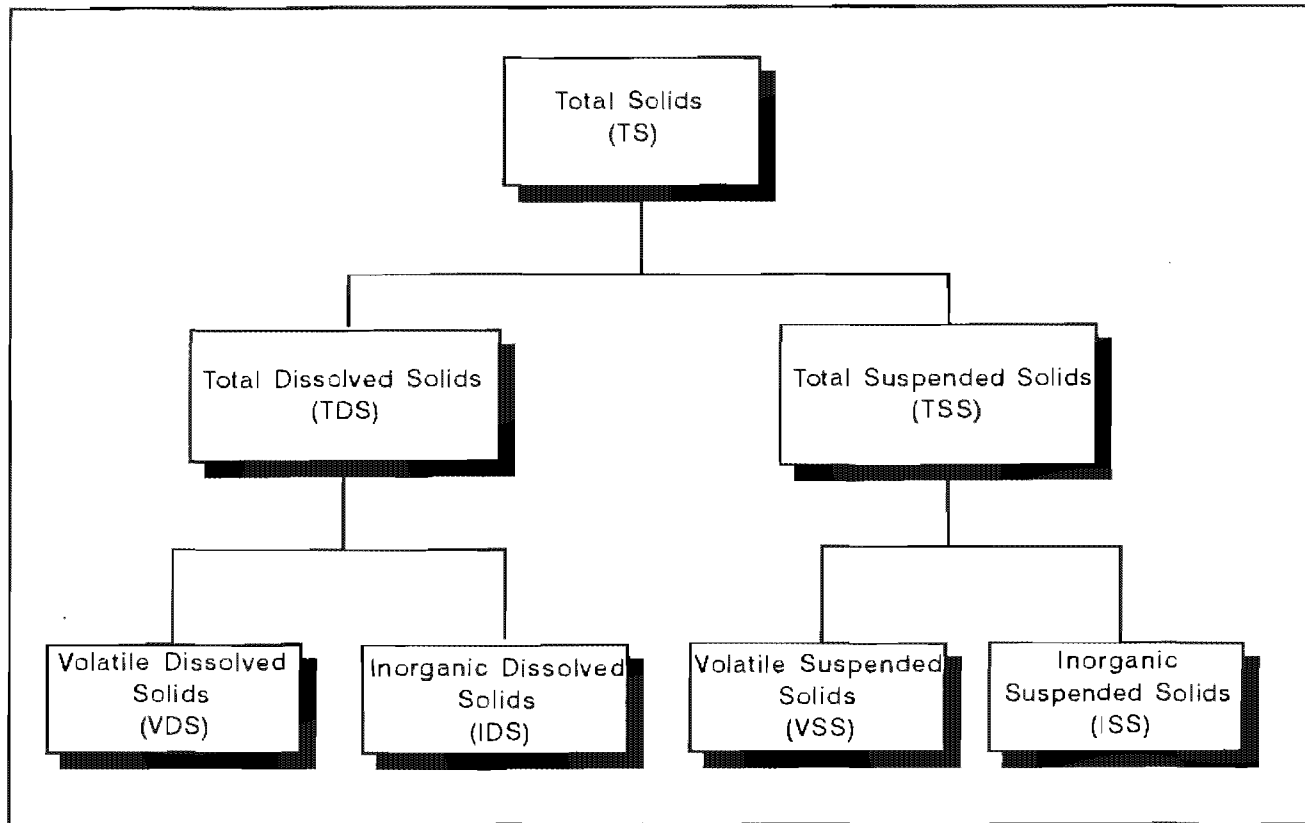


Fig. 7.1: Schematic showing division of solids into its' organic and inorganic fractions.

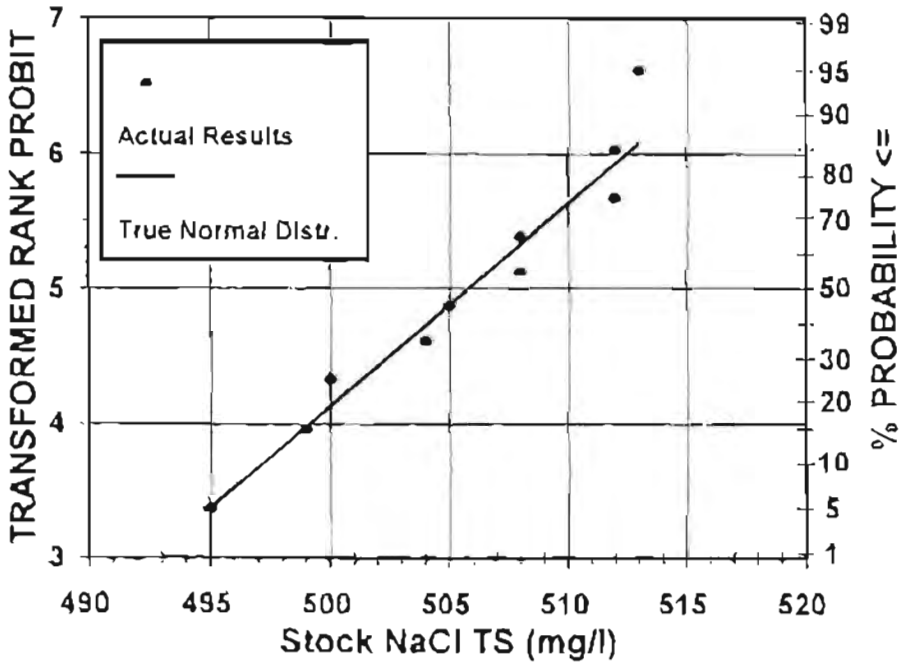


Fig. 7.2(a): Statistical plot of ten total solids (TS) tests on sodium chloride (NaCl) stock solution of known concentration (500mg/l).

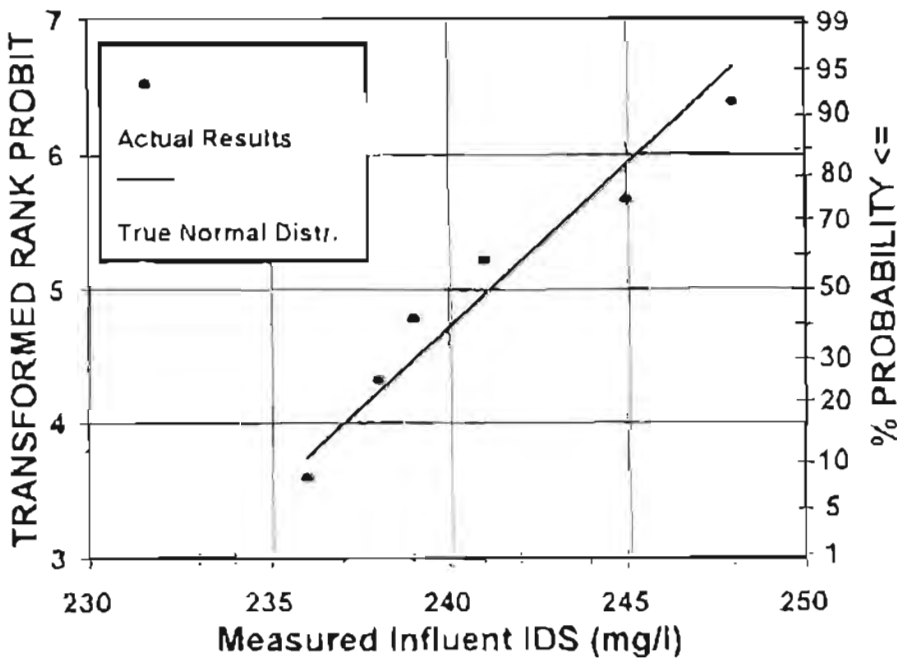


Fig. 7.2(b): Statistical plot of influent inorganic dissolved solids (IDS); samples filtered through 0.45 µm filters.

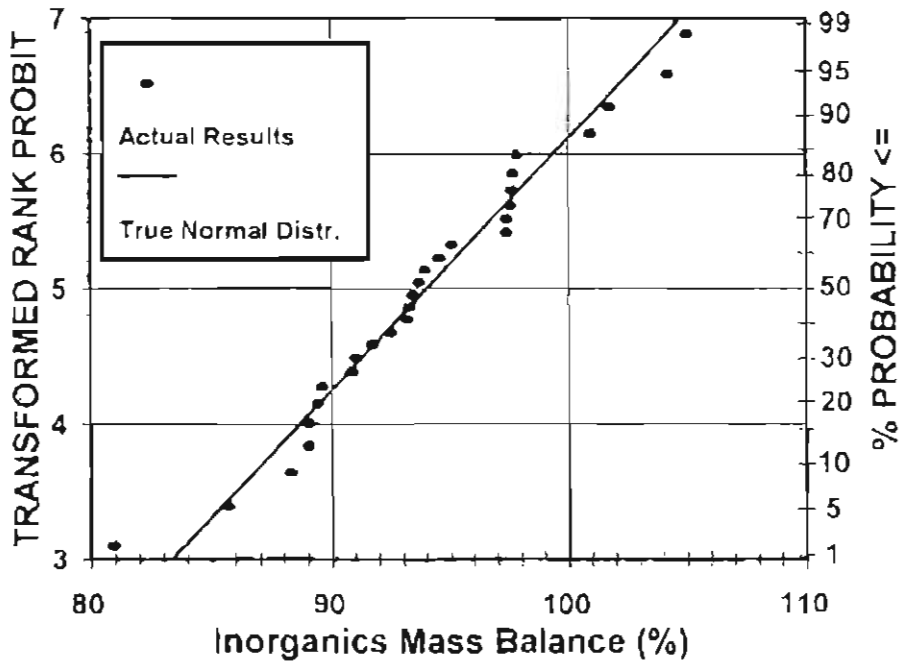


Fig. 7.3: Statistical plot of percentage inorganic recoveries for the different wastewater batches; each data point is the mean of a number of tests.

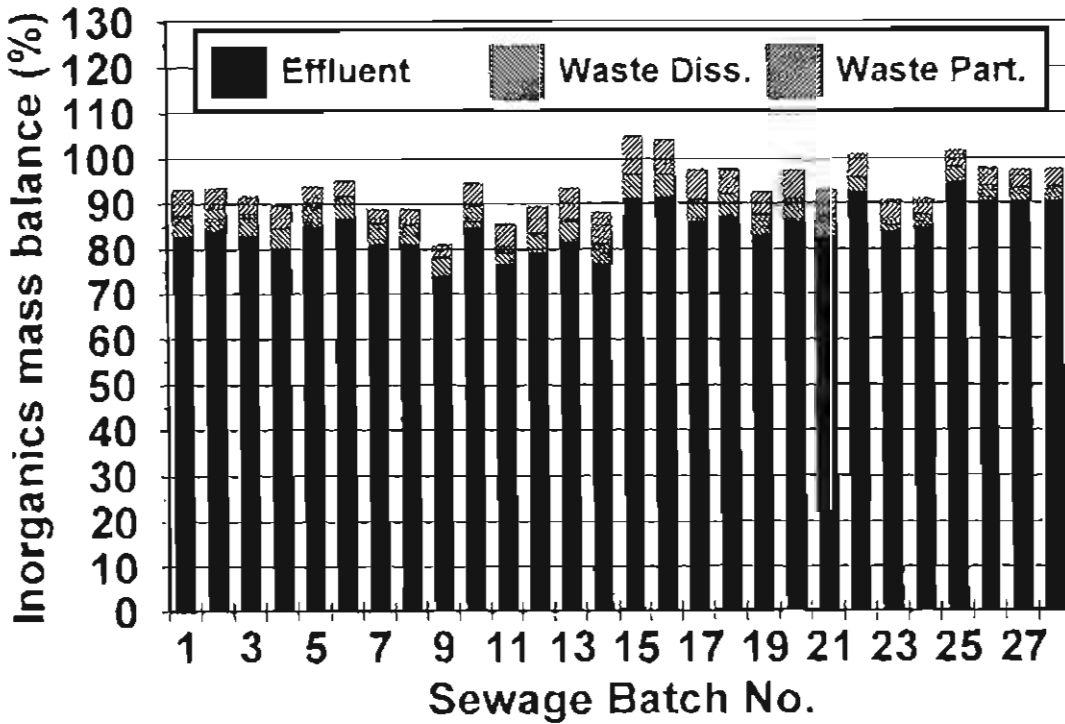


Fig. 7.4: Graphical representation of the percentage inorganic recoveries for the different wastewater batches; each data is the mean of a number of tests. Percentages of the different components, i.e. effluent inorganic solids, dissolved inorganic solids in the waste stream and suspended inorganic solids in the waste mixed liquor are also shown.

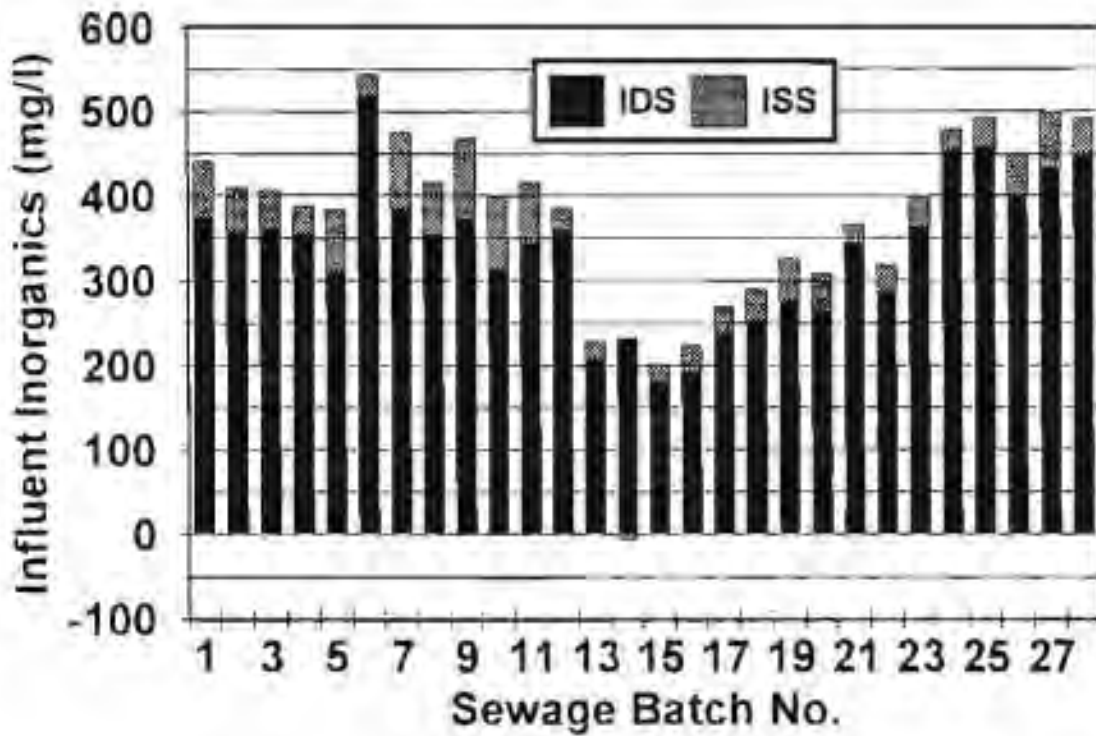


Fig. 7.5: Graphical representation of the influent inorganic dissolved/soluble solids (IDS) and suspended/particulate solids (ISS) concentrations for the different wastewater batches, each data is the mean of a number of tests.

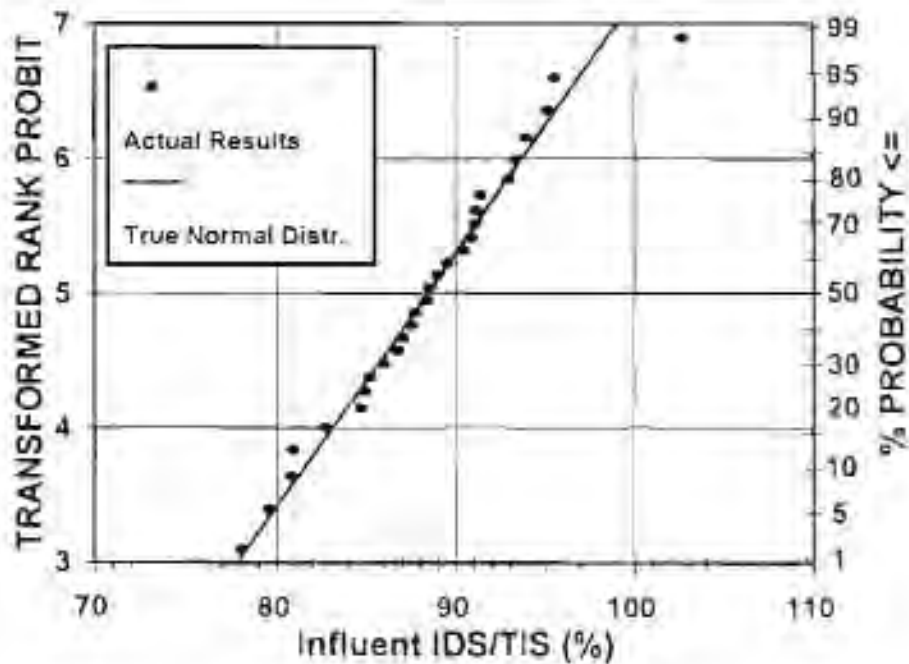


Fig. 7.6: Statistical plot of the percentage influent inorganic dissolved to total solids (%IDS/TIS) for the different wastewater batches, each data is the mean of a number of tests.

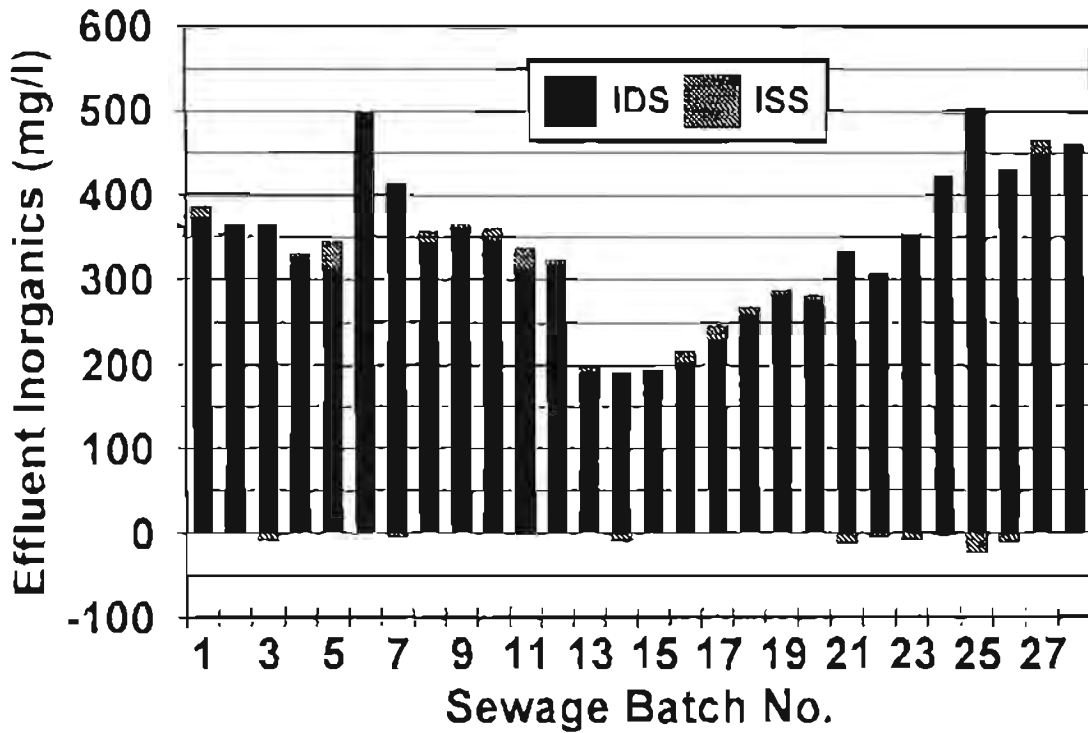


Fig. 7.7: Graphical representation of the effluent inorganic dissolved/soluble solids (IDS) and suspended/particulate solids (ISS) concentrations for the different wastewater batches; each data is the mean of a number of tests.

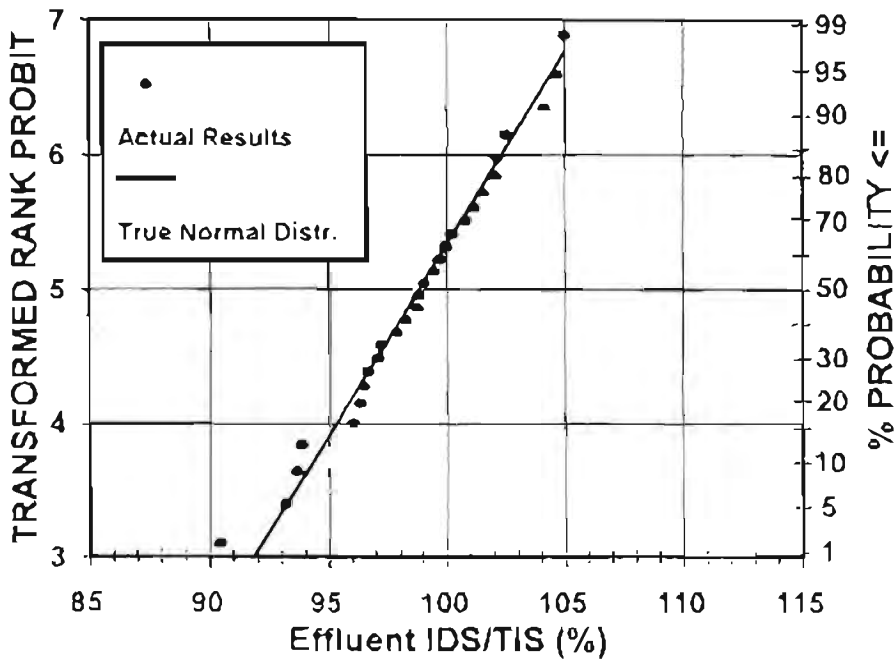


Fig. 7.8: Statistical plot of the percentage effluent inorganic dissolved to total solids (%IDS/TIS) for the different wastewater batches; each data is the mean of a number of tests.

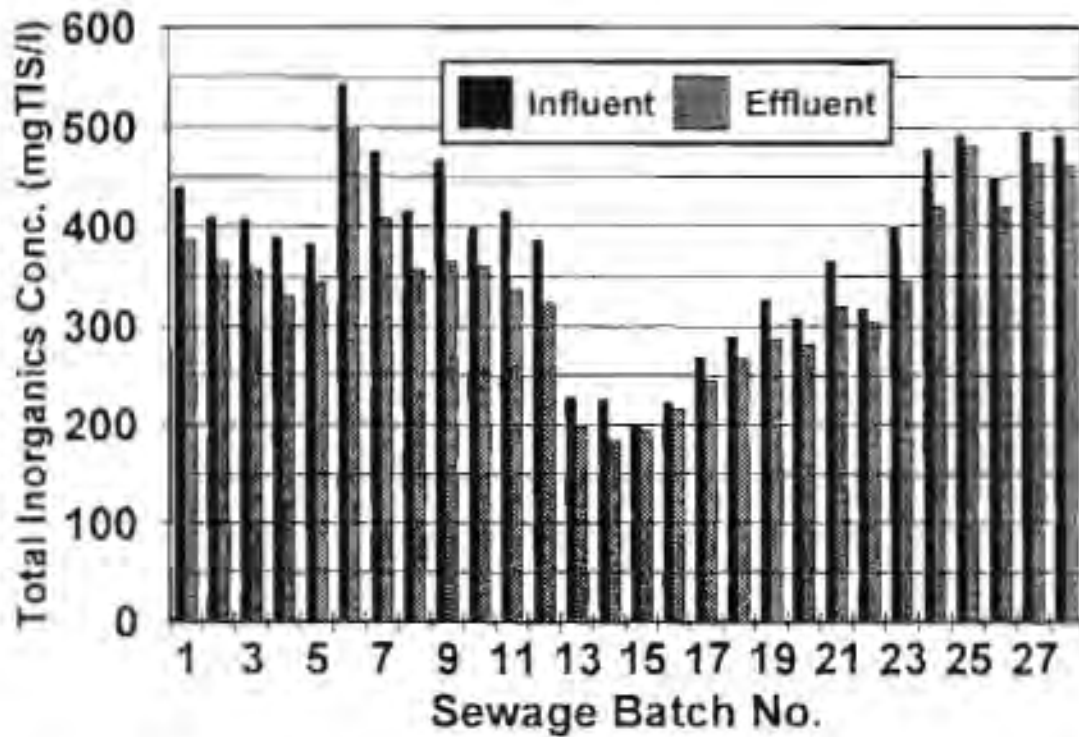


Fig. 7.9 Graphical representation of the influent and effluent total inorganic solids (TIS) concentrations for the different wastewater batches, each data is the mean of a number of tests.

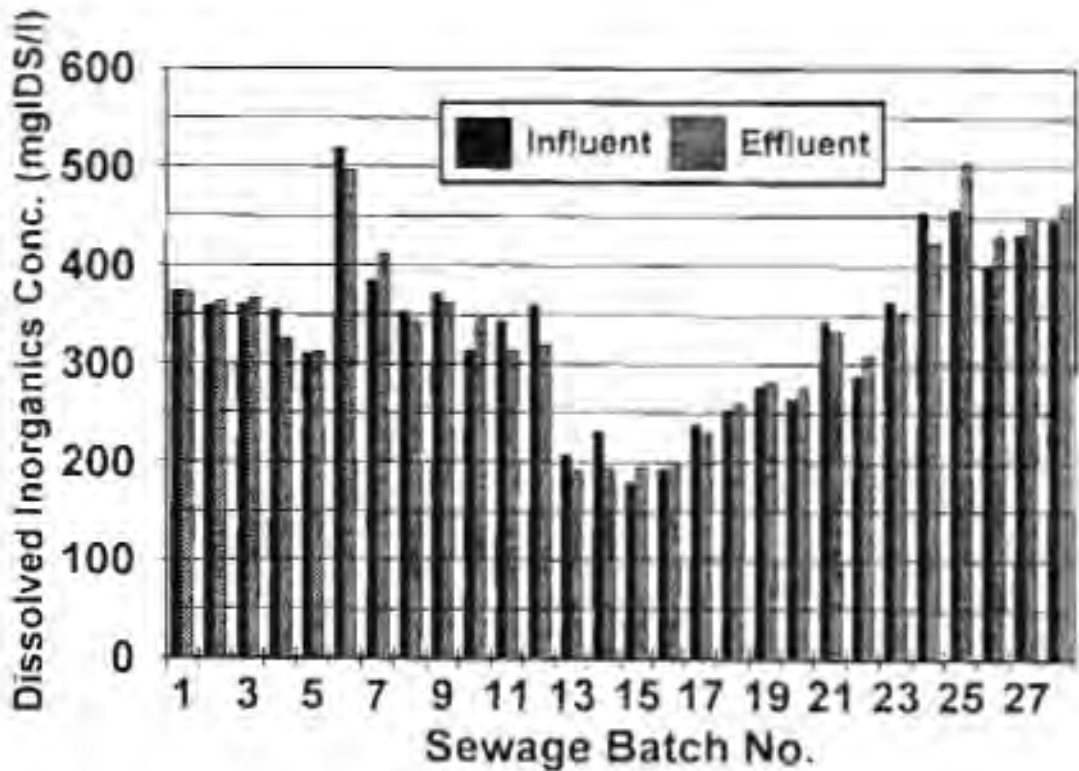


Fig. 7.10 Graphical representation of the influent and effluent inorganic dissolved/soluble solids (IDS) concentrations for the different wastewater batches, each data is the mean of a number of tests.

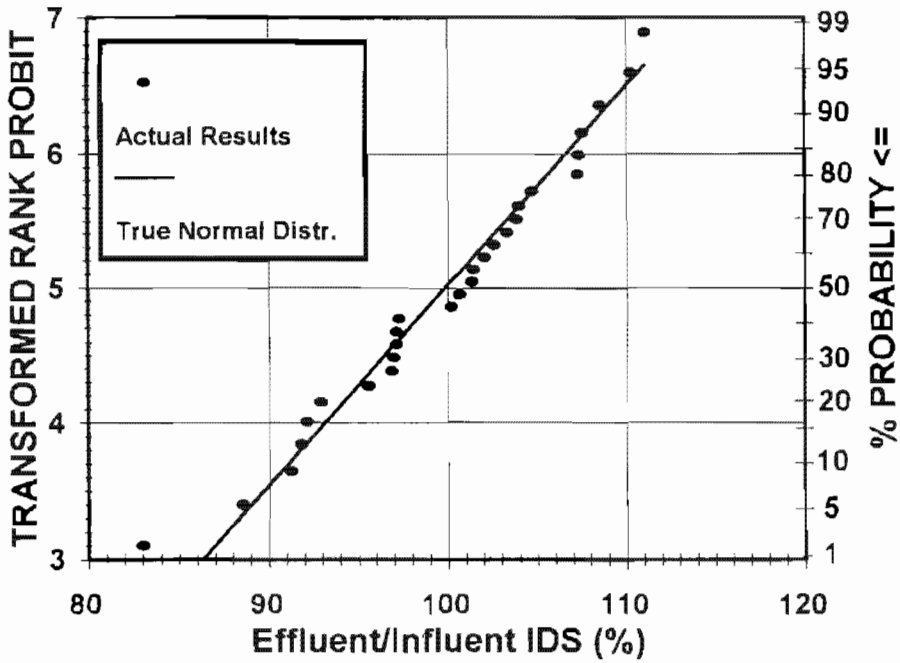


Fig. 7.11: Statistical plot of the percentage effluent inorganic dissolved solids (IDS) to influent IDS for the different wastewater batches; each data is the mean of a number of tests.

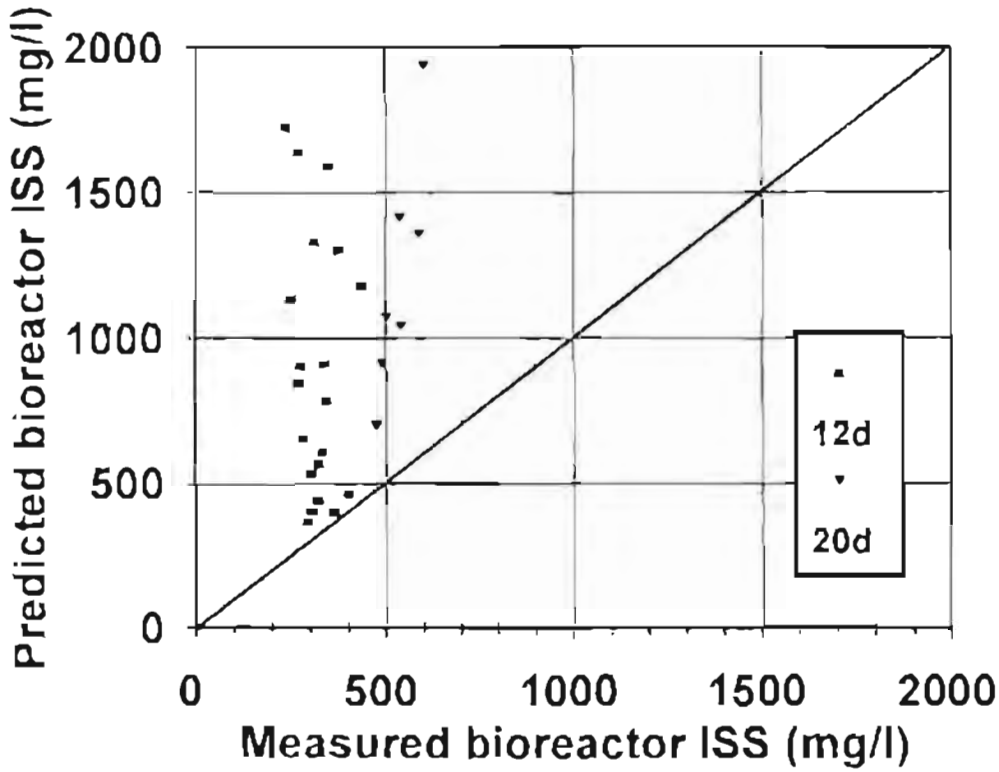


Fig. 7.12: Plot of predicted versus measured bioreactor inorganic suspended solids (ISS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using simple model based on influent ISS.

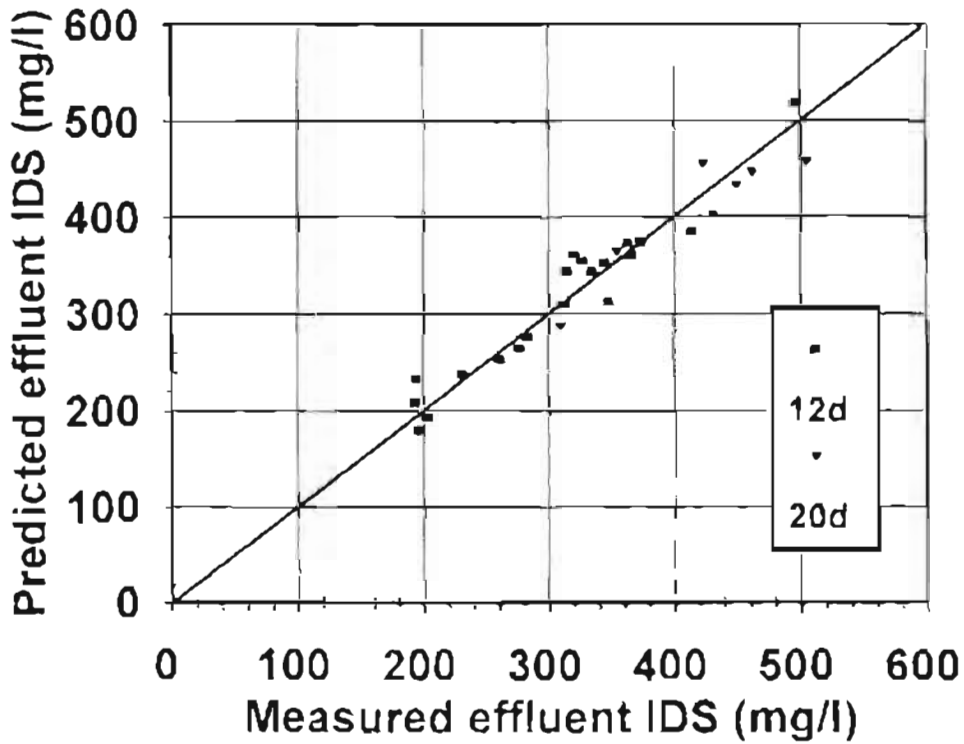


Fig. 7.13: Plot of predicted versus measured effluent inorganic dissolved solids (IDS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using simple model with influent IDS = effluent IDS.

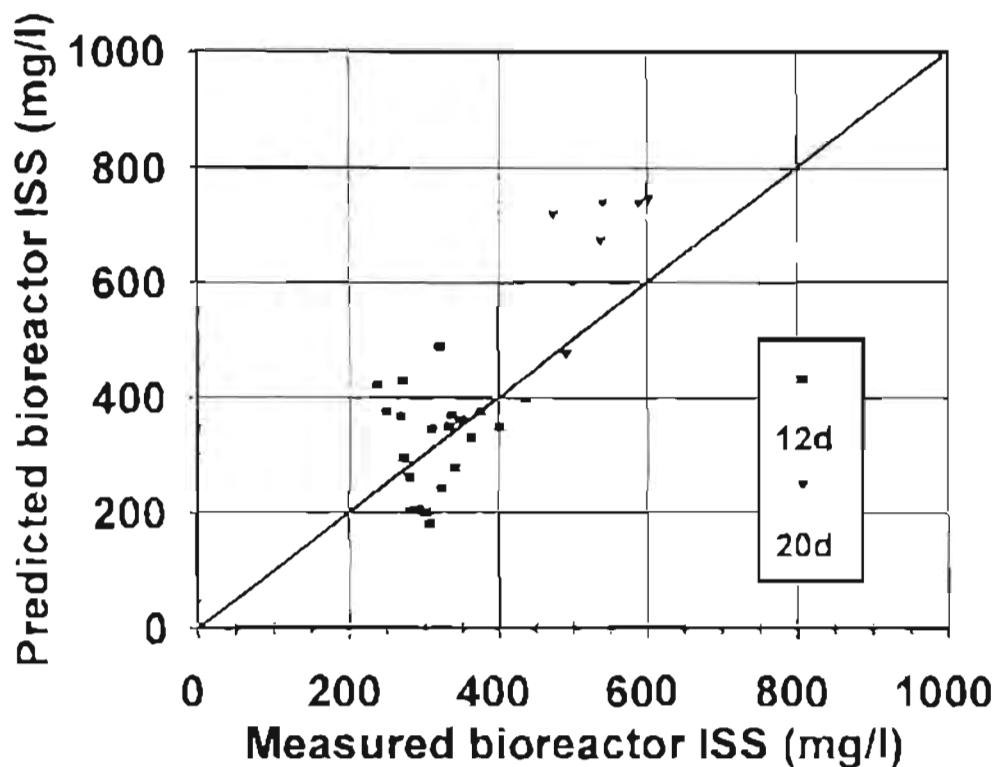


Fig. 7.14: Plot of predicted versus measured bioreactor inorganic suspended solids (ISS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using simple model based on influent total inorganic solids (TIS).

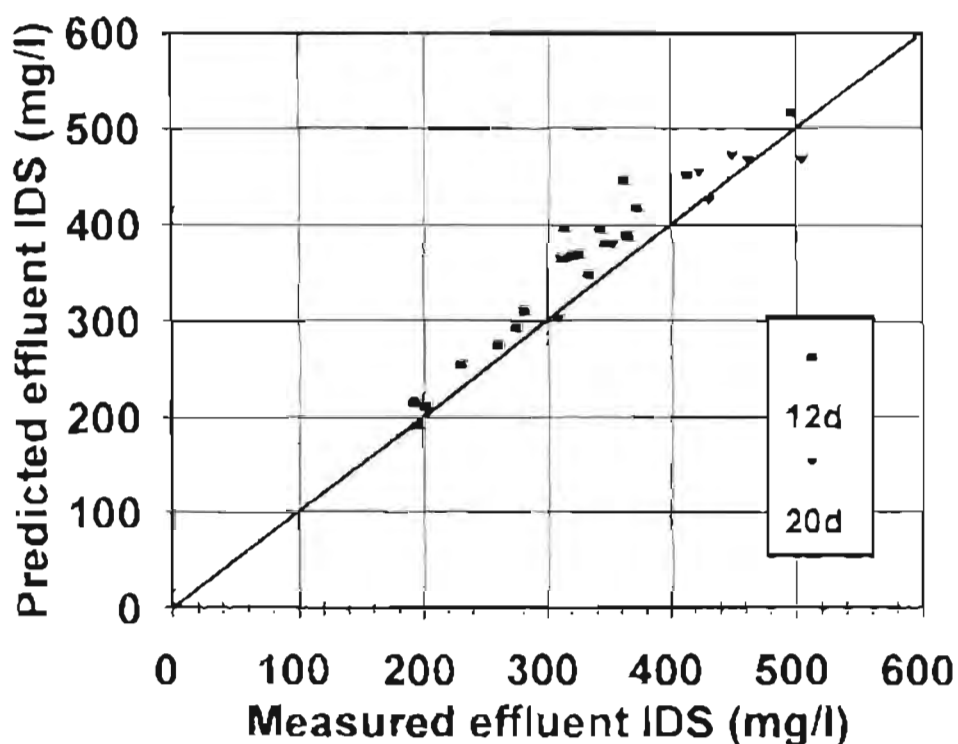


Fig. 7.15: Plot of predicted versus measured effluent inorganic dissolved solids (IDS) for sludge ages 12 and 20d. Predictions using simple model based on influent total inorganic solids (TIS).

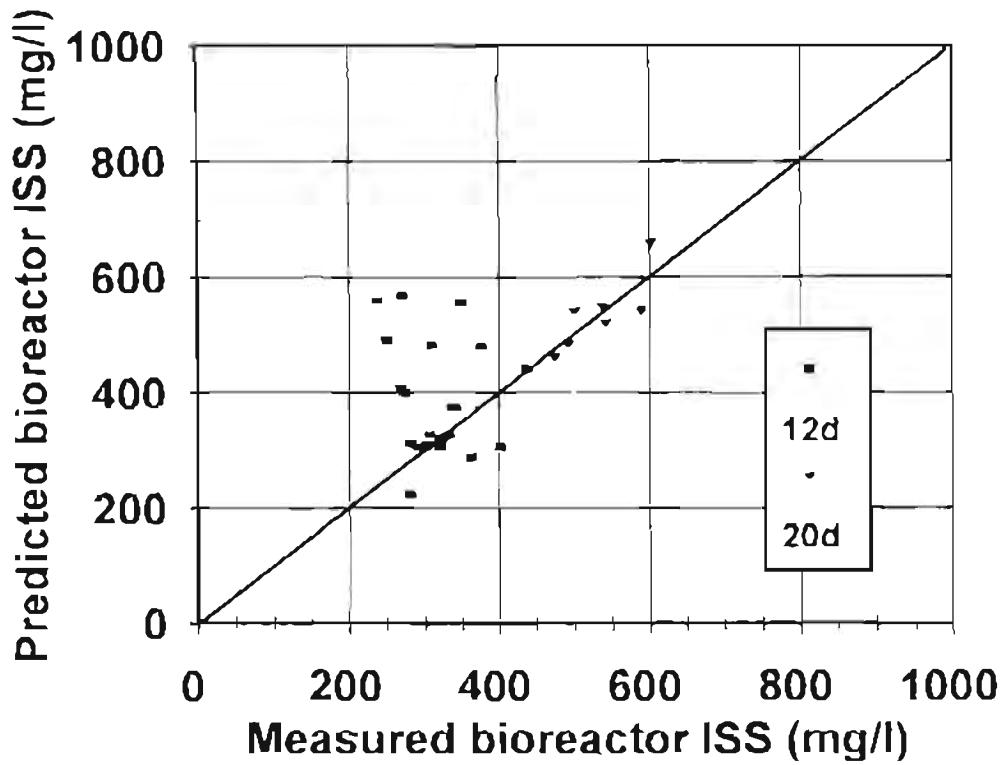


Fig. 7.16: Plot of predicted versus measured bioreactor inorganic suspended solids (ISS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using the fundamental model with entrapment etc. of inorganics from influent inorganic suspended solids (ISS).

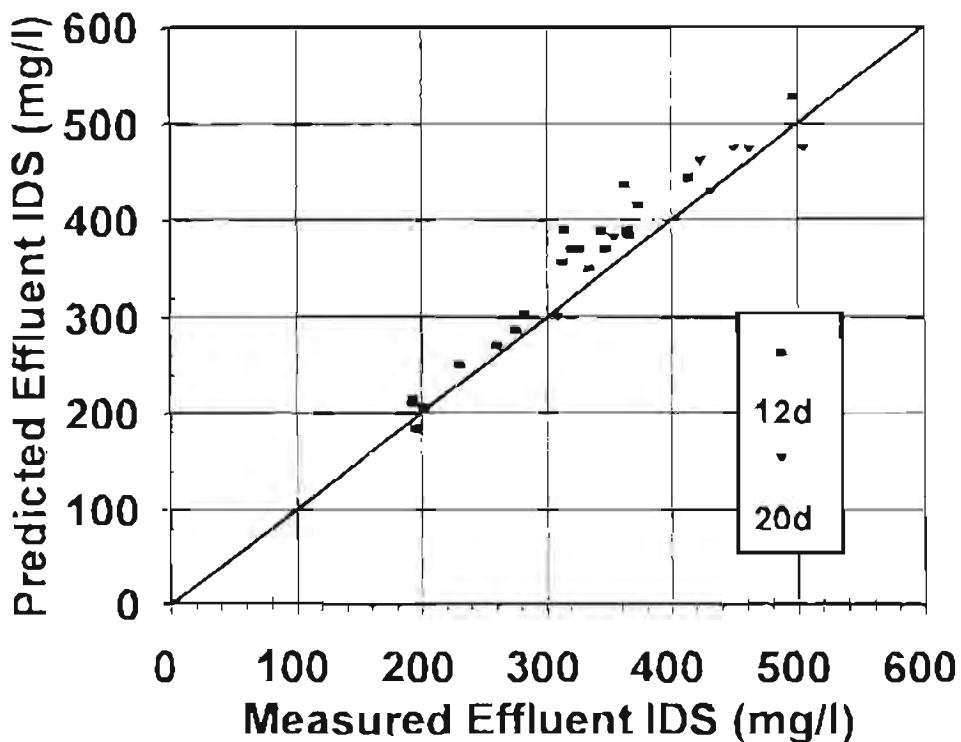


Fig. 7.17: Plot of predicted versus measured effluent inorganic dissolved solids (IDS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using the fundamental model with entrapment etc. of inorganics from influent inorganic suspended solids (ISS).

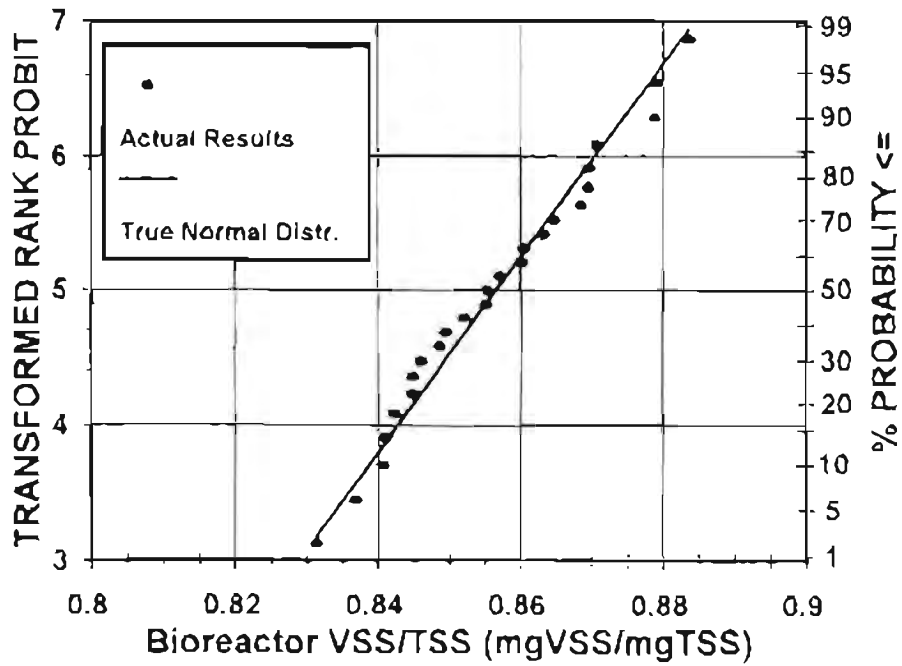


Fig. 7.18: Statistical plot of the bioreactor volatile suspended solids to total suspended solids (VSS/TSS) ratio for the different wastewater batches; each data is the mean of a number of tests (wastewater batches 2, 5 and 7 rejected as outliers).

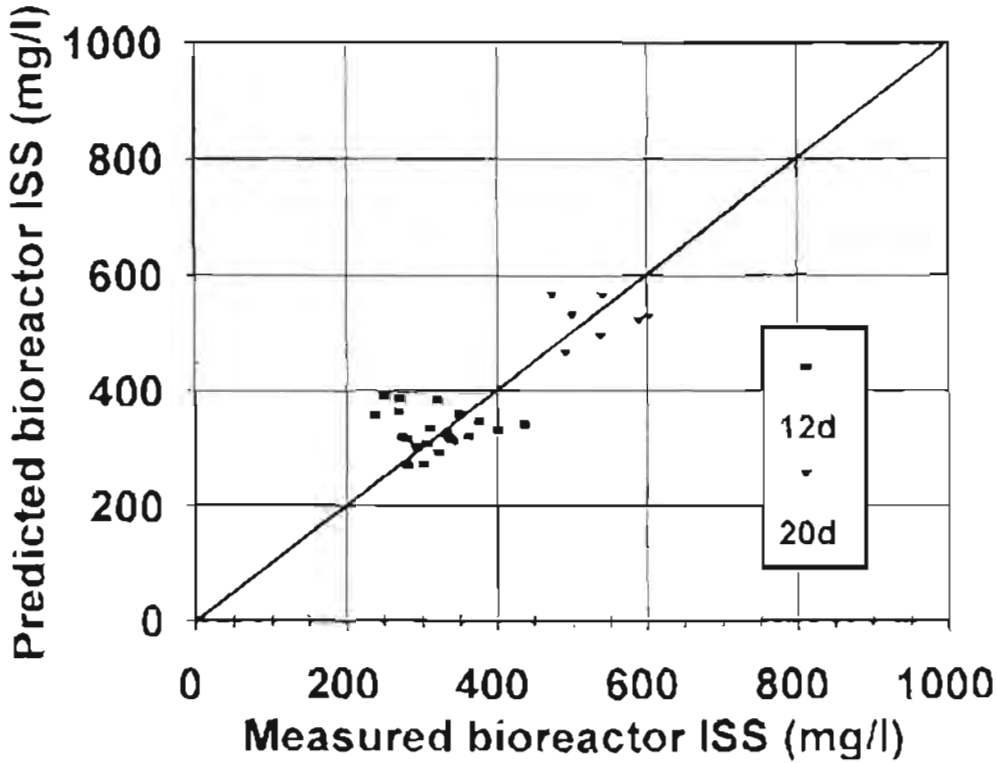


Fig. 7.19: Plot of predicted versus measured bioreactor inorganic suspended solids (ISS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using the fundamental model with entrapment etc. of inorganics from influent total inorganic solids (TIS).

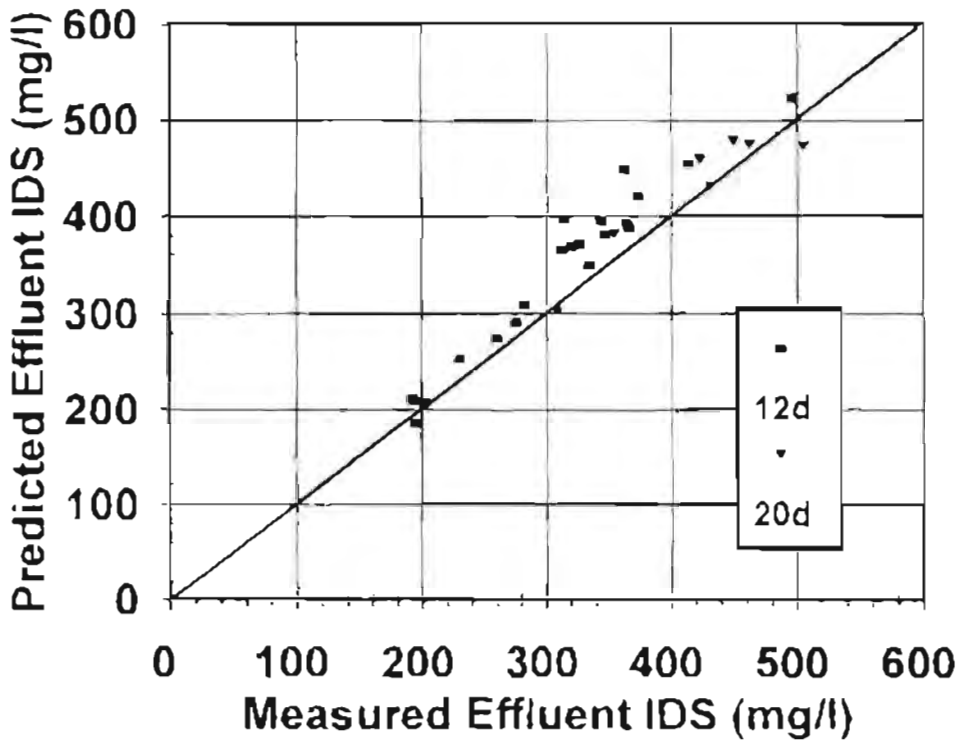


Fig. 7.20: Plot of predicted versus measured effluent inorganic dissolved solids (IDS) for sludge ages 12 and 20d; each data is the mean of a number of tests. Predictions using the fundamental model with entrapment etc. of inorganics from influent total inorganic solids (TIS)..

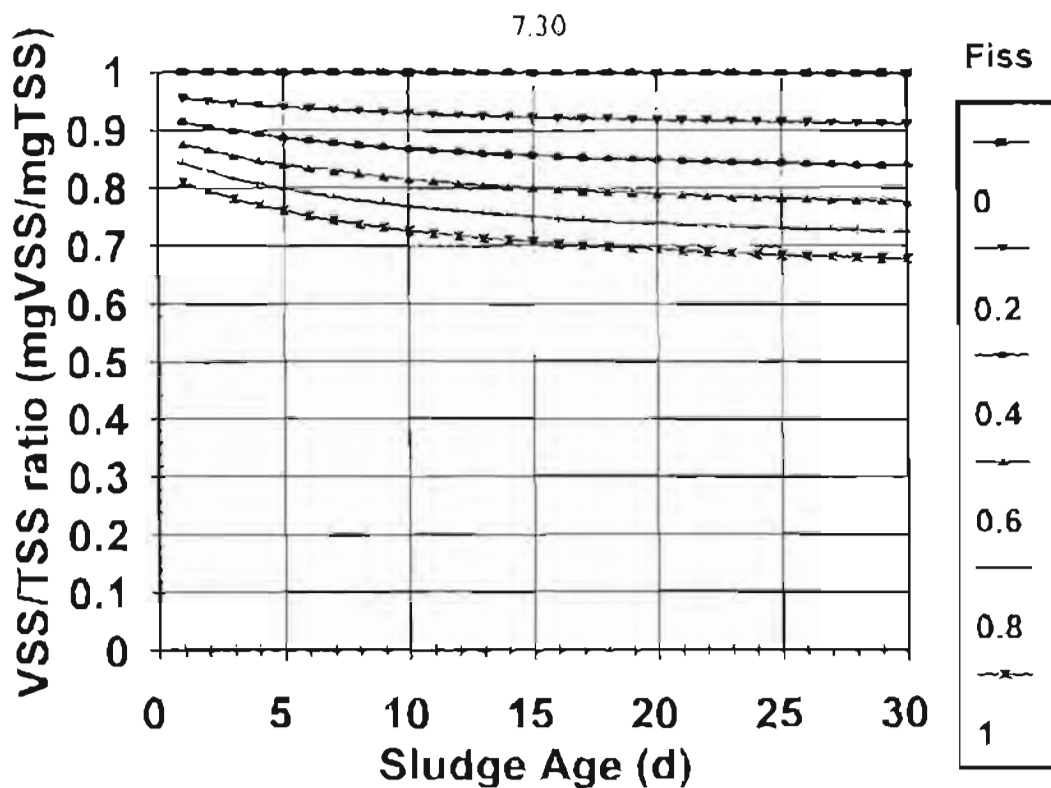


Fig. 7.21: Plot of the sensitivity of predicted bioreactor mixed liquor volatile to total suspended solids ratio (VSS/TSS) to variations in sludge age for the different fractions of influent inorganic suspended solids (ISS) incorporated in activated sludge mixed liquor (f_{iss}) at a constant heterotrophic active biomass and endogenous mass inorganic content (f_B) value ($f_B = 0$).

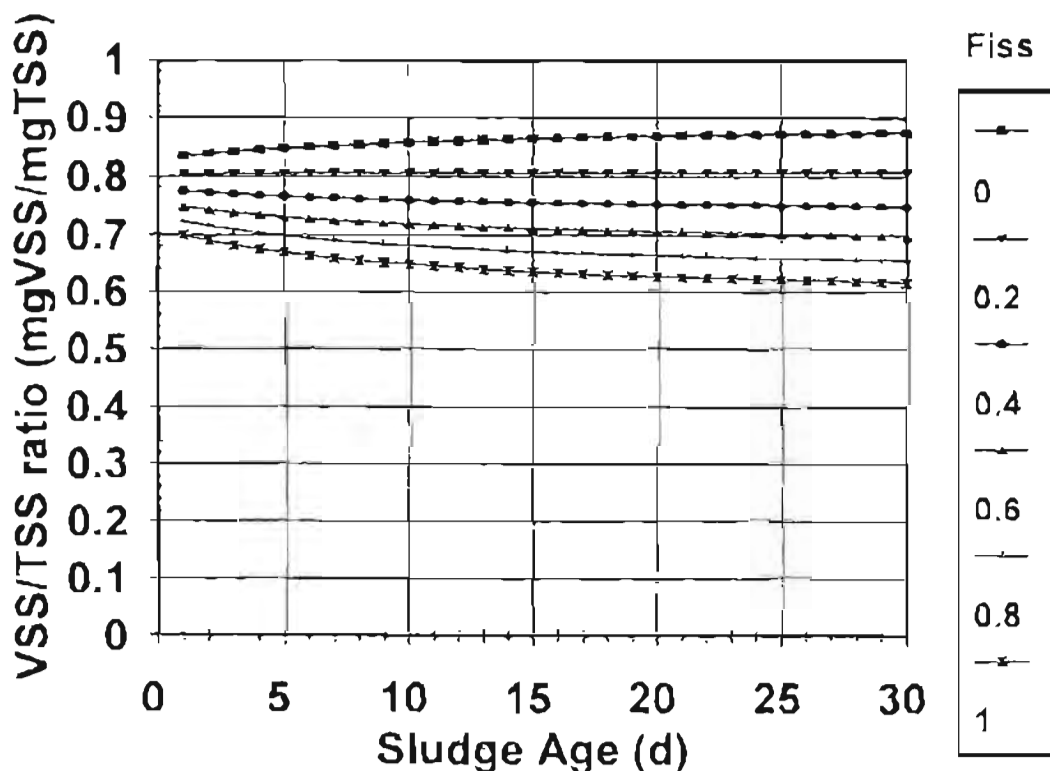


Fig. 7.22: Plot of the sensitivity of predicted bioreactor mixed liquor volatile to total suspended solids ratio (VSS/TSS) to variations in sludge age for the different fractions of influent inorganic suspended solids (ISS) incorporated in activated sludge mixed liquor (f_{iss}) at a constant heterotrophic active biomass and endogenous mass inorganic content (f_B) value ($f_B = 0.25$).

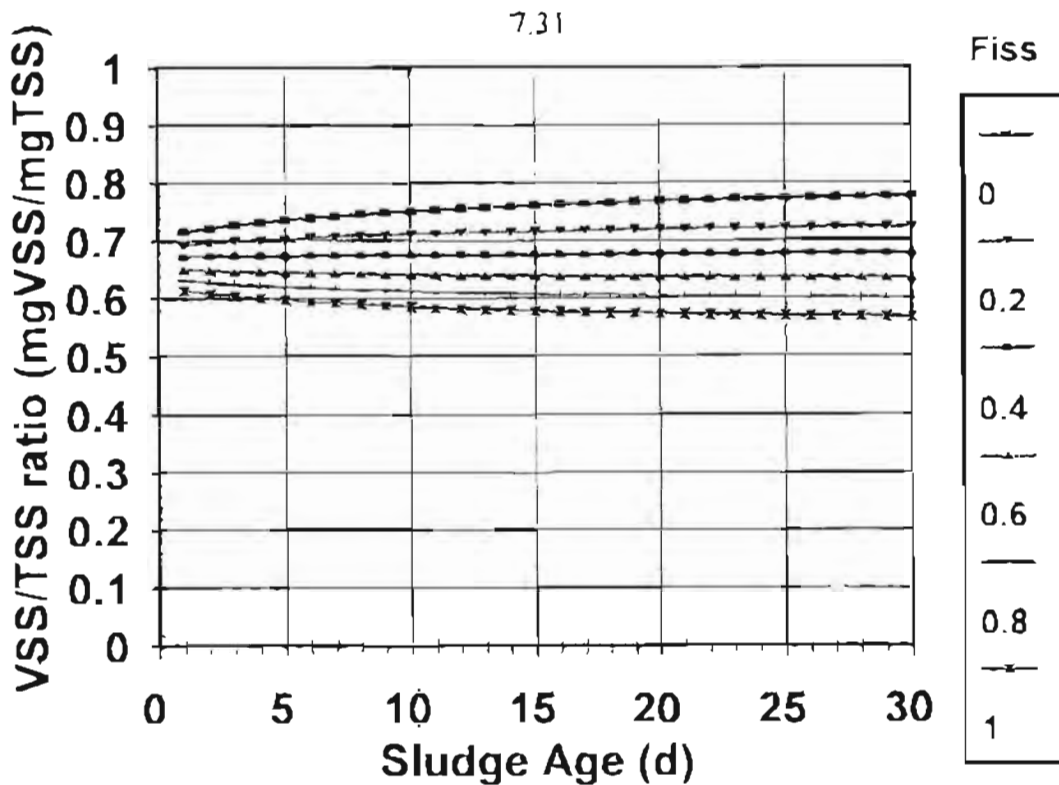


Fig. 7.23: Plot of the sensitivity of predicted bioreactor mixed liquor volatile to total suspended solids ratio (VSS/TSS) to variations in sludge age for the different fractions of influent inorganic suspended solids (ISS) incorporated in activated sludge mixed liquor (f_{ISS}) at a constant heterotrophic active biomass and endogenous mass inorganic content (f_B) value ($f_B = 0.50$).

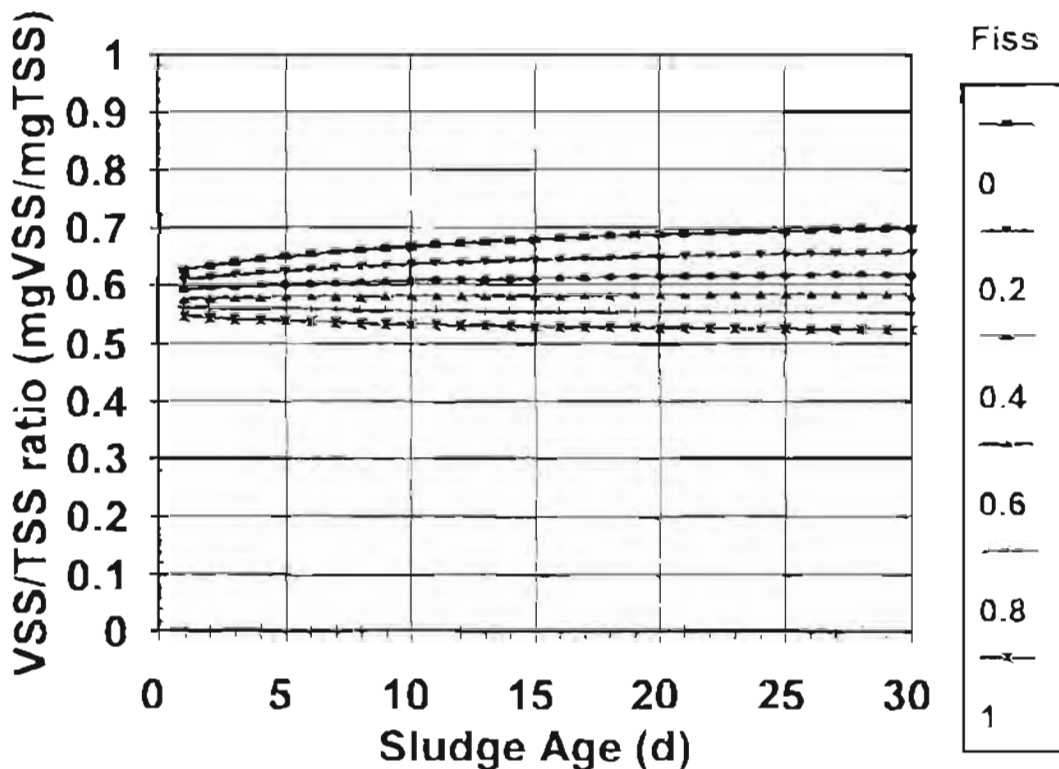


Fig. 7.24: Plot of the sensitivity of predicted bioreactor mixed liquor volatile to total suspended solids ratio (VSS/TSS) to variations in sludge age for the different fractions of influent inorganic suspended solids (ISS) incorporated in activated sludge mixed liquor (f_{ISS}) at a constant heterotrophic active biomass and endogenous mass inorganic content (f_B) value ($f_B = 0.75$).

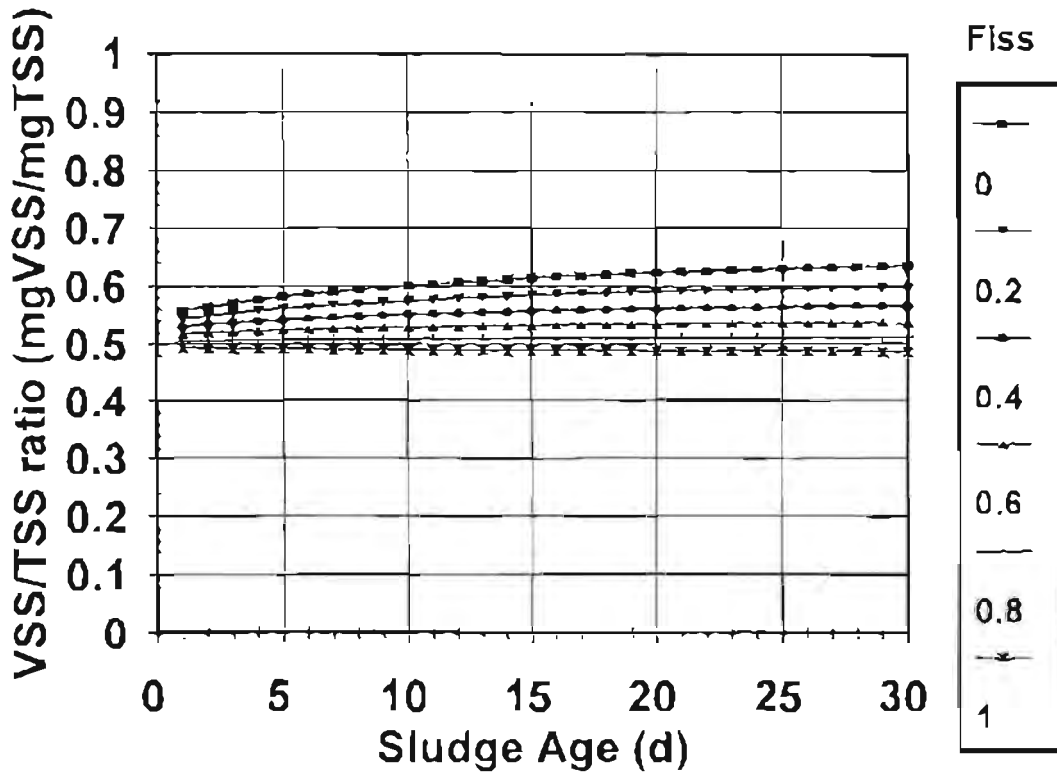


Fig. 7.25: Plot of the sensitivity of predicted bioreactor mixed liquor volatile to total suspended solids ratio (VSS/TSS) to variations in sludge age for the different fractions of influent inorganic suspended solids (ISS) incorporated in activated sludge mixed liquor (f_{ISS}) at a constant heterotrophic active biomass and endogenous mass inorganic content (f_B) value ($f_B = 1.0$).

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 OBJECTIVES

To aid research into, and to optimize the design and operation of the single sludge activated sludge system, over the past two decades a number of steady state design models (e.g. Marais and Ekama 1976; WRC, 1984; Wentzel *et al.*, 1990) and kinetic simulation models (e.g. Dold *et al.*, 1980, 1991; Van Haandel *et al.*, 1981; Henze *et al.*, 1987; Wentzel *et al.*, 1992; Henze *et al.*, 1995) have been developed. This group of models is based, to a large degree, on a common simplified conceptualization of the mechanisms operating in the system, which has developed particularly from an understanding of the interactions between the components making up the mixed liquor in the bioreactor of the activated sludge system, and the influent wastewater. In terms of these models, the mixed liquor in the bioreactor of the activated sludge system is made up of organic and inorganic materials. *The principle aim of this research project was to investigate the organic and inorganic components/materials making up the mixed liquor in the bioreactor of the activated sludge system.* In particular, the organic component heterotrophic active biomass and the inorganic components were investigated.

Heterotrophic active biomass

Fundamental to the steady state design and kinetic simulation models for activated sludge systems is the parameter heterotrophic active biomass. This mixed liquor organic suspended solids component mediates the biodegradation processes of COD removal and denitrification (and associated processes), and, in the models all relevant specific rates are expressed in terms of it. Although recently heterotrophic active biomass has gained more acceptance than in the past, it would seem that this is due to the convenience of computer programmes based on the models, rather than substantive proof of its validity so that the parameter remains hypothetical within the structure of the models. Thus, to promote confidence in application of the models for design, operation and control of activated sludge systems, and indeed in the models themselves, it is essential that the heterotrophic active biomass parameter is validated by experimental measurement. *Thus, measurement of heterotrophic active biomass was the first principle objective of this research.*

Mixed liquor inorganic components

In both the steady state design and kinetic simulation models, the influent wastewater characteristics and biological processes that influence the bioreactor mixed liquor organic solids (as volatile suspended solids, VSS, or COD) are explicitly included. However, the mixed liquor total suspended solids (TSS, i.e. organic + inorganic solids) is calculated simply from an empirical ratio of VSS/TSS, the value for this ratio being accepted as one constant for activated sludge systems treating raw (unsettled) wastewater ($VSS/TSS = 0.75 \text{ mgVSS/mgTSS}$, WRC, 1984) and another constant for those treating settled wastewater ($VSS/TSS = 0.83 \text{ mgVSS/mgTSS}$, WRC, 1984). The TSS concentration (X_t) is fundamental in the design of secondary settling tanks and waste activated sludge disposal. Clearly, the empirical approach to obtaining an estimate for X_t

is not satisfactory within a fundamentally based model. *Accordingly, incorporation of the inorganic material present in the influent wastewater into the mixed liquor requires investigation - This is the second principle objective of this research project.*

8.2 RESEARCH APPROACH

The research approach adopted was to operate and monitor a well-defined and controlled parent laboratory-scale activated sludge system. This parent system provided the mixed liquor samples required for measuring heterotrophic active biomass to address the first principle objective above. Also, the inorganics present in the influent wastewater to the parent system and in the bioreactor and effluent of the system were monitored, to address the second principle objective above.

8.3 HETEROTROPHIC ACTIVE BIOMASS

Recently a simple batch test method has been developed to quantify heterotrophic active biomass (Kappeler and Gujer, 1995; Wentzel *et al.*, 1995; Mbewe *et al.*, 1995). This batch test method was modified and adapted to quantify the heterotrophic active biomass of activated sludge mixed liquor. The modified method was evaluated by applying the batch test to mixed liquor samples drawn from a well defined laboratory-scale activated sludge system operated at sludge ages 12 and 20 d and comparing the measured values to those calculated theoretically with the models. From this series of tests it could be concluded:

- For both the wastewater only and wastewater + mixed liquor batch tests, the %COD recoveries were good, with means of 96% and 102% respectively and sample standard deviations of 4% and 4% respectively. The good %COD recoveries lend credibility to the reliability of the measurements and to the batch test procedure.
- No nitrification was observed in the batch tests with wastewater only, indicating the absence of autotrophic organisms in the wastewater.
- For the batch tests with wastewater + mixed liquor, nitrification was observed since the mixed liquor added to the batch tests was drawn from a nitrifying activated sludge system. This nitrification could be closely approximated by two linear rates, a slower rate operating up to approximately the precipitous drop in OUR, followed by a second faster rate operating to the end of the batch test. This would indicate an inhibition of nitrification at the start of the batch test, possibly due to the RBCOD present in the wastewater
- The correlation coefficients (R^2) in linear regression of the $\ln\text{OUR}_{H(t)}$ - time plots generally are good; 1 and 11 batch tests for wastewater only and wastewater + mixed liquor respectively had $R^2 < 0.9$.
- For the wastewater only batch tests, the wastewater heterotrophic active biomass ranged from 2.1 to 6.5% of total COD, with a mean of 4.5% and sample standard deviation of 1.1%. This mean agrees reasonably closely with the value measured by Mbewe *et al.*

(1995) for the same wastewater (6.1%). The relatively low heterotrophic active biomass concentration for Mitchell's Plain wastewater is to be expected; this wastewater is primarily of domestic origin with a small industrial component (<20%) and the sewers are anaerobic and have a relatively short retention time (4-6 hours).

- With the parent system at 12d sludge age the measured and theoretical mixed liquor heterotrophic active biomass correspond remarkably closely. With the parent system at 20d sludge age the measured and theoretical values show a close correlation; however, the values are not in agreement - the measured values are consistently lower, only about half the theoretical values. No logical explanation could be found for this inconsistency, and this aspect warrants further investigation.

The results do indicate that the batch test method may prove to be a valuable tool that can be used to provide greater insight into the behaviour of the aerobic and anoxic/aerobic activated sludge systems. However, in systems that include biological phosphorus removal the method will not be of use. In these systems the heterotrophic organisms mediating the phosphorus removal are present also and the batch test will not be able to distinguish between the two groups of heterotrophic organisms. Furthermore, experimental evidence from such systems indicates that there are behaviours in these systems that are not recognized in the models (Ekama and Wentzel, 1997). For example, for the same wastewater there is an inconsistency in the sludge production between aerobic and anoxic/aerobic systems on one hand and anaerobic/anoxic/aerobic systems on the other; also, the sludge production in anaerobic/anoxic/aerobic systems has been found to be linked to filamentous bulking. In the current models both these observations have to be taken into account by using different influent unbiodegradable particulate COD fractions (a wastewater characteristic) which markedly affects the heterotrophic active biomass as a fraction of the mixed liquor organic solids (active fraction, f_{av}), clearly an unacceptable solution.

8.4 ACTIVATED SLUDGE MIXED LIQUOR INORGANIC COMPONENT

This part of the investigation focussed on the incorporation of the influent inorganics into the activated sludge mixed liquor. From measurements made on the influent, effluent and bioreactor dissolved/soluble and particulate/suspended inorganic solids of a well defined laboratory-scale activated sludge system, the following observations/conclusions could be made:

- Considering that the inorganics were determined as the difference between two measured parameters (total solids - volatile solids) and that for the filtered influent and effluent samples the inorganic weights were relatively small compared to the weights of the crucibles, the % inorganic recoveries were surprisingly good; for the 28 wastewater batches tested the mean % inorganic recovery was 94%, with sample standard deviation 5.5%.
- Of the influent inorganics, only a small fraction were incorporated into the activated sludge mixed liquor, 2.8 to 7.5%; by far the vast majority of the influent inorganics left the system with the effluent, 75 to 92%, and a relatively small amount as dissolved/soluble inorganics in the waste stream, 3 to 5.5%.
- In the influent most of the inorganics were in the dissolved form; for the 28 wastewater batches tested, mean ratio of dissolved to total inorganics was 88%, with sample standard deviation 5%.

- In the effluent the inorganics were almost exclusively in the dissolved form; for the 28 wastewater batches tested, mean ratio of dissolved to total inorganics was 98.5%, with sample standard deviation 3%.
- For all the wastewater batches tested, the influent total inorganic solids concentrations were larger than the effluent total inorganic solids concentrations. However, for 14 of the 28 wastewater batches tested, the difference was statistically insignificant at the 95% confidence interval.
- Comparing the influent and effluent dissolved inorganic solids concentrations, the ratio effluent to influent was 100% with sample standard deviation 7%. In 22 out of 28 wastewater batches tested, the differences were statistically insignificant at the 95% confidence interval. This would indicate that the influent and effluent inorganic dissolved solids were closely equal.

From the measurements, a number of approaches to model the incorporation of the inorganics into the activated sludge mixed liquor were developed and evaluated. With regard to these models the following conclusions can be drawn:

- Simple models based on the incorporation of a fraction of the influent inorganic suspended solids (ISS) or total inorganic solids (TIS) are not appropriate: The predictions with the simple TIS model are superior to those from the ISS based model, but both models cannot predict correctly the observed effect of sludge age on bioreactor ISS.
- The more fundamental model, based on the concepts incorporated in the steady state model for aerobic COD removal (WRC, 1984), provides predicted bioreactor ISS and effluent inorganic dissolved solids (IDS) concentrations that correlate reasonably closely with those measured. In particular, the model predicts correctly the observed effect of sludge age on bioreactor ISS.

In developing models for the incorporation of inorganics into the activated sludge mixed liquor, it would appear that the best approach is to follow the concepts and principles used to develop the existing models for organic materials. A first simple model using this approach has been successfully developed and evaluated in this research project. The model can form the basis for further development, to focus and stimulate research into areas where knowledge is deficient; for example, the model highlights the lack of knowledge on the physical/chemical processes that lead to "entrapment" of inorganics in the activated sludge mixed liquor.

8.5 RECOMMENDATIONS

From this investigation the following recommendations can be made:

- For the activated sludge heterotrophic active biomass, the inconsistency between the results obtained at parent system sludge ages of 12d and 20d is of concern. From the data that are available, it is not possible to determine whether this inconsistency is due to the batch test method, or due to a deficiency in the models themselves, or simply due to an aberration in the behaviour of the parent activated sludge system from which the mixed liquor was drawn. This aspect clearly requires further investigation.
- For the activated sludge mixed liquor inorganics, the more fundamental model developed can form the basis for further investigations. Specific tasks that require attention are:

- The model was evaluated against data from the laboratory-scale system at sludge ages 12d and 20d. The model needs to be tested over a wider range of sludge ages, say at 5d and 30d.
- The model includes incorporation of influent inorganic materials into the activated sludge matrix, to take account of processes such as inorganics entrapment, adsorption and precipitation. Two approaches to model these processes have been developed and evaluated, based on influent total inorganic solids (TIS) and inorganic suspended solids (ISS). For the laboratory-scale system operated here, the TIS approach provides better predictions than the ISS approach. However, observations on systems treating raw and settled wastewaters would suggest that the ISS approach may be superior. It was concluded that with the data available it is not possible to make a definitive judgement as to which approach is superior. This requires investigation. Also, factors influencing the relative magnitude of the incorporation of influent inorganic materials into the activated sludge matrix need to be investigated - is this closely constant for a wide range of systems, or are there a number of factors that influence it, e.g. pH, alkalinity, influent composition?

8.6 CLOSURE

The models for the single sludge activated sludge system have achieved widespread acceptance and have had a significant impact on the approach to design, operation and control of the activated sludge system, and on the research into its' behaviour. However, this acceptance should not inhibit critical evaluation of the principles on which the models are based; the danger exists that through the convenience of computer programmes incorporating the models, the models will begin to adopt a reality of their own. The models will always need to be used with great circumspection and the results obtained interpreted in terms of experience from real systems; the models are a convenient tool to aid research, design and operation of activated sludge systems and should not be regarded as a substitute for knowledge and experience.

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APPENDIX A

COMPREHENSIVE DATA AND OUR vs TIME PROFILES FOR THE WASTEWATER ONLY BATCH TESTS

TABLE OF CONTENTS

- Table A1 Daily wastewater only batch test data, listing COD concentrations at the start and end of the batch test; y-intercept, slope and correlation coefficient (R^2) for $\ln(\text{OUR})$ vs time profile; the area under the OUR_H vs time profile; the %COD recovery; the heterotrophic active biomass calculated from the batch test, and the mean heterotrophic active biomass for each wastewater batch.
- Table A2 Summary of statistical data for wastewater only batch tests, and the wastewater heterotrophic active biomass as a percentage of total COD.

Fig A1a-A89b OUR vs time and $\ln(\text{OUR})$ vs time profiles for the wastewater only batch tests.

Table A1 Daily wastewater only batch test data, with calculated % COD recovery and heterotrophic active biomass

Sew. Batch No.	Batch Test No.	Date	COD (mgCOD/l)		Area (mgO/l)	Linear Regression data			% COD Recovery	ZBH(o) (mgCOD/l)
			Start	End		y-interc.	slope	R ²		
12	W1	20-Oct	463	304	124	1.344	0.287	0.992	92	26
	W2	23-Oct	415	306	102	1.059	0.276	0.981	98	19
	W3	27-Oct	409	303	71	0.544	0.198	0.998	91	18
	W4	28-Oct	413	322	68	0.521	0.198	0.999	94	16
										18.8
13	W5	04-Nov	428	299	112	0.537	0.342	0.888	97	9
										9
17	W6	11-Jan	407	357	83	1.173	0.235	0.978	108	24
	W7	12-Jan	476	365	116	0.948	0.244	0.981	101	19
	W8	15-Jan	486	353	130	1.007	0.275	0.972	99	18
	W9	16-Jan	529	357	130	1.013	0.273	0.972	92	18
	W10	17-Jan	506	361	134	0.858	0.316	0.972	98	13
	W11	18-Jan	498	327	131	1.067	0.241	0.987	92	21
	W12	19-Jan	473	343	133	1.206	0.182	0.895*	101	31**
	W13	21-Jan	446	345	124	0.751	0.283	0.992	105	13
	W14	22-Jan	491	345	127	0.887	0.251	0.979	96	17
	W15	23-Jan	464	297	127	1.025	0.222	0.978	91	22
	W16	24-Jan	559	367	134	0.851	0.284	0.994	90	16
										18.0
18	W17	25-Jan	402	296	95	1.242	0.246	0.991	96	26
	W18	26-Jan	419	266	120	1.756	0.239	0.994	92	43
	W19	29-Jan	496	396	127	1.286	0.244	0.986	106	26
	W20	30-Jan	449	332	81	1.440	0.220	0.995	92	33
	W21	31-Jan	447	299	112	1.530	0.183	0.995	92	43
	W22	01-Feb	445	323	101	1.036	0.236	0.991	95	21
	W23	02-Feb	433	282	115	1.114	0.217	0.990	92	24
	W24	03-Feb	419	293	116	1.086	0.234	0.994	98	22
	W25	04-Feb	406	311	105	0.920	0.213	0.996	102	20
	W26	05-Feb	450	294	118	1.028	0.233	0.983	91	21
	W27	06-Feb	460	327	99	1.465	0.200	0.968	93	37
										26.6
19	W28	07-Feb	476	368	111	1.768	0.242	0.985	105	41**
	W29	08-Feb	499	347	110	1.593	0.240	0.980	92	36
	W30	09-Feb	527	325	148	1.642	0.254	0.976	90	36
	W31	11-Feb	452	369	129	1.283	0.263	0.960	97	24
	W32	12-Feb	491	358	130	1.421	0.259	0.992	99	28
	W33	13-Feb	485	358	123	1.286	0.260	0.998	99	25
	W34	14-Feb	496	336	128	1.128	0.263	0.992	94	21
	W35	15-Feb	463	332	116	0.948	0.252	0.993	97	18
	W36	16-Feb	461	324	111	1.046	0.260	0.996	94	19
	W37	17-Feb	449	313	116	0.936	0.275	0.994	96	16
	W38	18-Feb	442	315	116	1.030	0.291	0.985	97	17
	W39	19-Feb	458	300	114	1.080	0.264	0.994	90	20
20	W40	24-Feb	505	351	117	1.335	0.224	0.998	93	30
	W41	25-Feb	497	400	103	1.089	0.201	0.989	101	25
	W42	26-Feb	520	406	117	1.276	0.223	0.994	100	28
	W43	27-Feb	492	340	103	1.130	0.223	0.996	90	24
	W44	29-Feb	432	307	112	1.042	0.240	0.998	97	21
	W45	01-Mar	457	324	101	0.806	0.240	0.998	93	16
	W46	02-Mar	512	373	116	0.674	0.233	0.998	96	16
	W47	04-Mar	481	335	128	1.546	0.182	0.986	96	44**
										22.7

* test rejected on $R^2 < 0.9$ ** test rejected as an outlier on Z_{grain} at 95% confidence interval

Table A1-cont.

Daily wastewater only batch test data, with calculated % COD recovery and heterotrophic active biomass.

Sew. Batch No.	Batch Test No.	Date	COD (mgCOD/l)		Area (mgO/l)	Linear Regression data			% COD Recovery	ZBH(o) (mgCOD/l)
			Start	End		y-interc.	slope	R ²		
21	W48	11-Mar	517	381	133	1.318	0.243	0.995	96	27
	W49	12-Mar	509	362	128	1.349	0.229	0.996	96	29
	W50	14-Mar	517	387	125	1.015	0.227	0.992	99	21
	W51	15-Mar	546	389	129	1.098	0.231	0.997	91	23
25.0										
22	W52	08-Apr	474	364	99	1.192	0.243	0.989	98	24
	W53	07-Apr	454	307	103	1.151	0.254	0.995	90	22
	W54	08-Apr	466	313	111	1.002	0.235	0.992	91	20
	W55	09-Apr	460	338	116	0.948	0.223	0.982	99	20
	W56	10-Apr	482	320	119	1.119	0.209	0.987	95	28
	W57	11-Apr	449	304	110	1.085	0.216	0.987	92	24
22.7										
23	W58	15-Apr	508	389	113	1.385	0.240	0.985	99	29
	W59	16-Apr	482	380	103	1.240	0.255	0.996	96	24
	W60	17-Apr	521	368	109	1.343	0.234	0.994	92	29
	W61	18-Apr	498	372	95	1.103	0.230	0.995	94	23
	W62	19-Apr	540	391	107	1.078	0.235	0.996	92	22
	W63	20-Apr	511	378	109	0.974	0.218	0.986	95	21
	W64	21-Apr	531	383	113	1.035	0.217	0.996	93	23
	W65	22-Apr	527	382	136	1.561	0.212	0.990	98	39**
24.4										
24	W66	28-Apr	507	384	104	1.003	0.279	0.998	92	18
	W67	29-Apr	495	352	111	1.153	0.273	0.996	94	21
	W68	30-Apr	759*	606	111	1.080	0.267	0.996	96	20
	W69	01-May	491	342	107	0.866	0.245	0.992	91	17
	W70	02-May	507	353	113	0.881	0.264	0.995	92	16
	W71	03-May	487	342	111	1.433	0.250	0.996	93	30**
18.4										
26	W72	21-May e	415	343	83	1.427	0.245	0.990	103	30
	W73	21-May	415	335	83	1.347	0.272	0.980	101	26
	W74	22-May	465	358	98	1.568	0.231	0.990	100	36
	W75	22-May e	465	365	98	1.606	0.194	0.990	99	44**
	W76	23-May	440	338	95	1.433	0.263	0.980	98	28
	W77	24-May	461	358	98	1.359	0.265	0.990	99	26
	W78	25-May	422	332	100	1.429	0.213	0.960	102	34
	W79	26-May	418	324	101	1.248	0.258	0.990	102	24
	W80	27-May	451	371	102	1.145	0.255	0.990	105	22
	W81	28-May	466	361	103	1.219	0.250	0.990	99	24
27.7										
27	W82	2-Jun e	377	299	82	0.563	0.230	0.990	101	14
	W83	02-Jun	377	287	78	0.514	0.237	0.990	97	12
	W84	03-Jun	383	289	85	0.738	0.245	0.990	97	16
	W85	04-Jun	449	342	89	0.810	0.269	0.990	96	15
	W86	05-Jun	473	381	99	1.222	0.258	0.990	101	23**
	W87	06-Jun	465	365	88	0.957	0.264	0.990	97	18
	W88	07-Jun	466	353	95	0.834	0.270	0.990	96	15
	W89	08-Jun	365	265	80	0.663	0.246	0.990	94	14
14.7										

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on $Z_{BH(o)}$ at 95% confidence interval

Table A2 Summary of statistical data for wastewater only batch tests, and the wastewater heterotrophic active biomass as a percent of total COD.

Sewage Batch No	%COD Recovery			Het. Active Biomass (mgCOD/l)			COD (mgCOD/l)			Het. Biomass as % of total COD
	Mean	std.dev. of mean	No. of Tests	Mean	std. dev. of mean	No. of Tests	Mean	std. dev. of mean	No. of Tests	
12	93.8	3.1	4	18.8	4.5	4	425	25	4	4.4
13	97		1	9		1	426		1	2.1
17	97.2	6.2	10	18.0	3.7	10	485	42	10	3.7
18	95.4	4.8	11	28.6	8.8	11	439	27	11	6.5
19	95	3.3	11	23.6	7.1	11	475	25	11	5
20	95.7	4.0	7	22.7	5.7	7	488	32	7	4.7
21	95.5	3.3	4	25.0	3.7	4	522	16	7	4.8
22	94.2	3.9	6	22.7	2.4	6	461	9	6	4.9
23	94.4	2.5	7	24.4	3.3	7	515	19	7	4.7
24	92.8	1.6	5	18.4	2.1	5	500	8	4	3.7
26	101	2.2	9	27.7	4.8	9	439	22	9	6.3
27	97	2.1	7	14.7	1.8	7	412	46	9	3.6

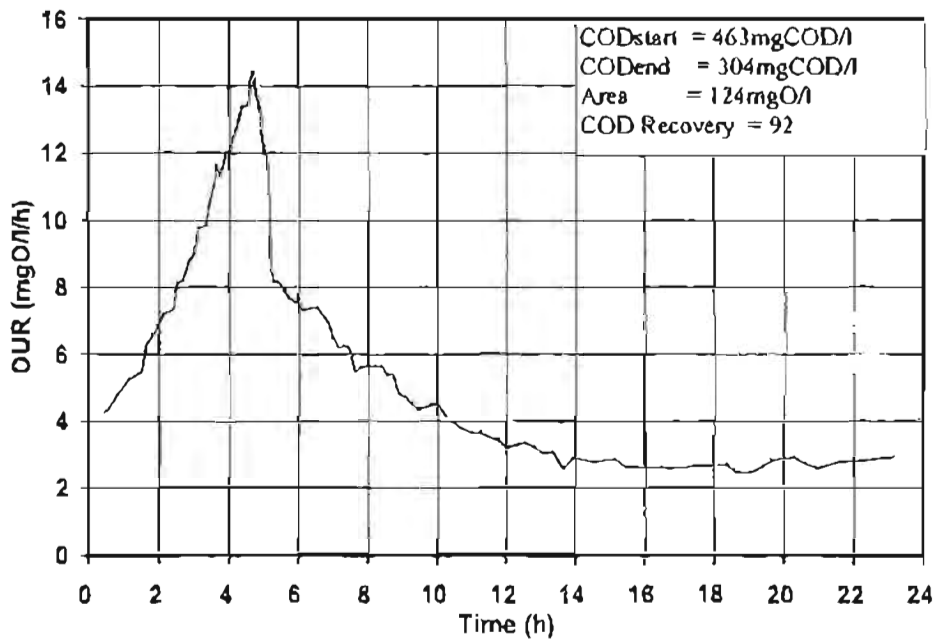


Fig A 1a OUR graph for wastewater only batch test, 20-10, wastewater batch no. 12

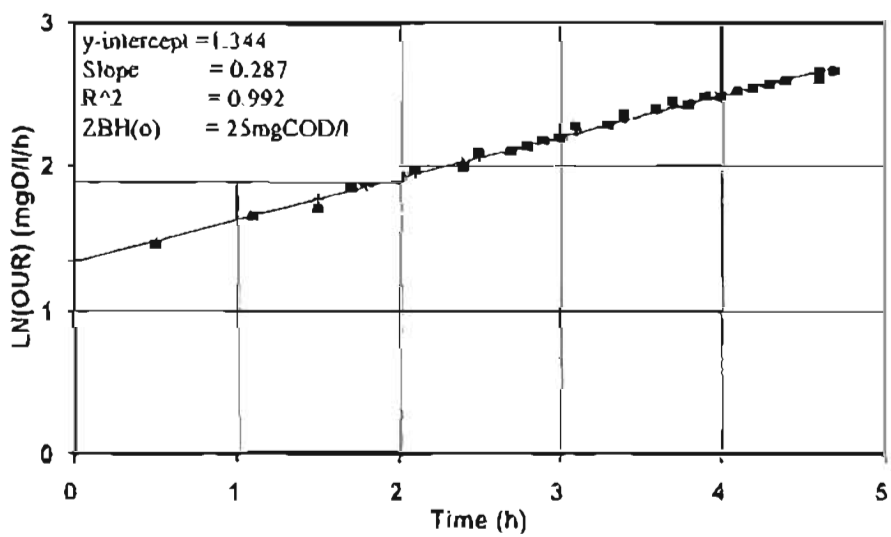


Fig A 1b ln(OUR) graph for wastewater only batch test, 20-10, wastewater batch no. 12

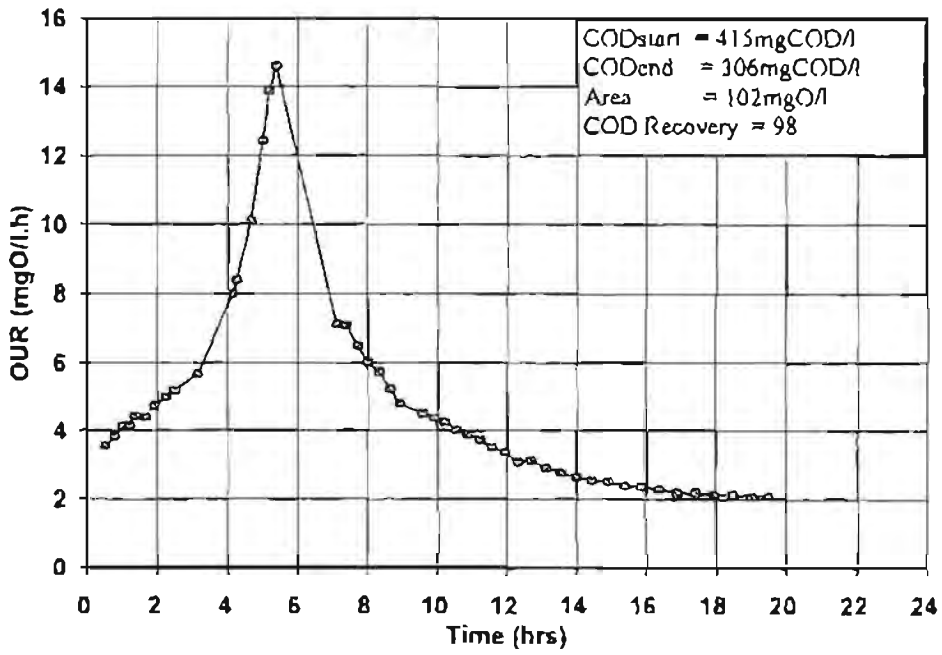


Fig A2a OUR graph for wastewater only batch test, 23-10, wastewater batch no. 12

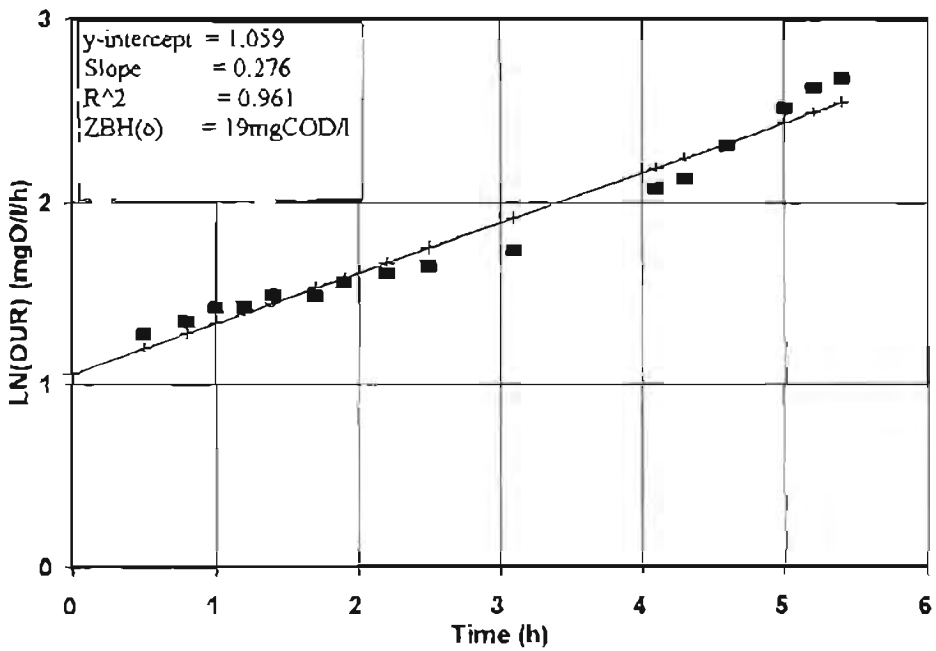


Fig A2b ln(OUR) graph for wastewater only batch test, 23-10, wastewater batch no. 12

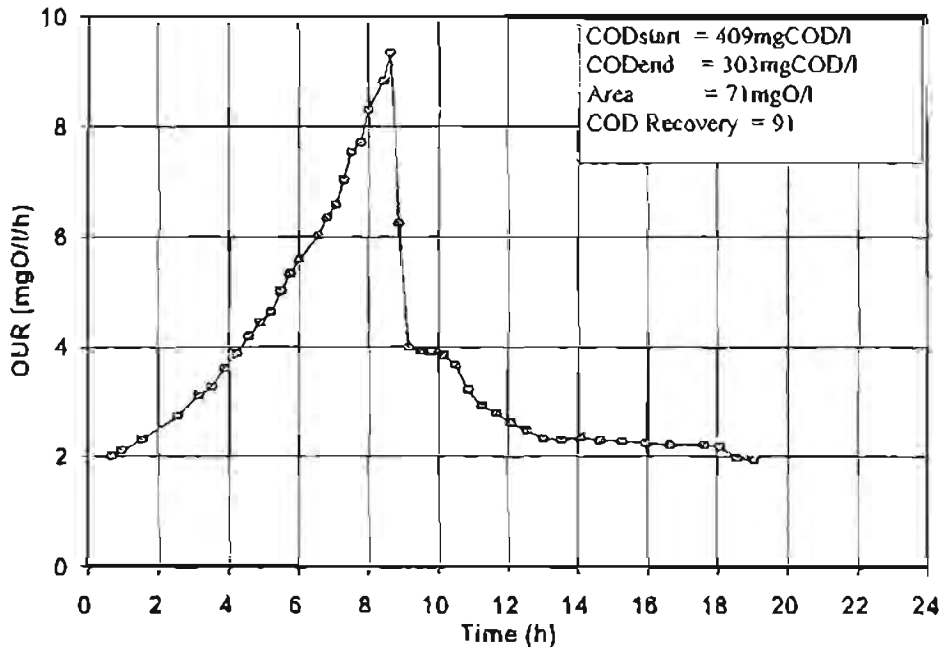


Fig A3a OUR graph for wastewater only batch test, 27-10, wastewater batch no. 12

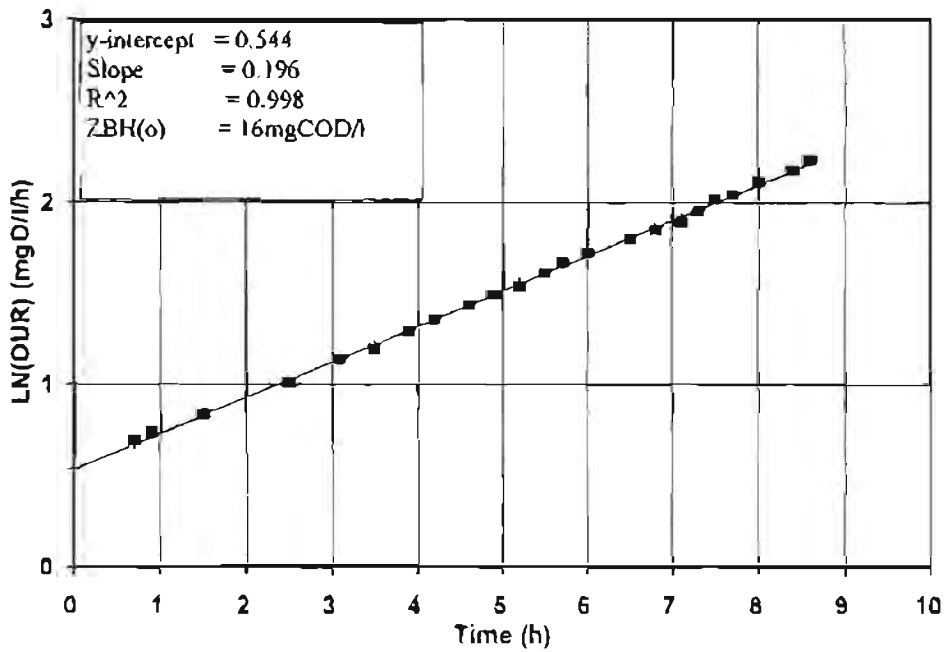


Fig A3b LN(OUR) graph for wastewater only batch test, 27-10, wastewater batch no. 12

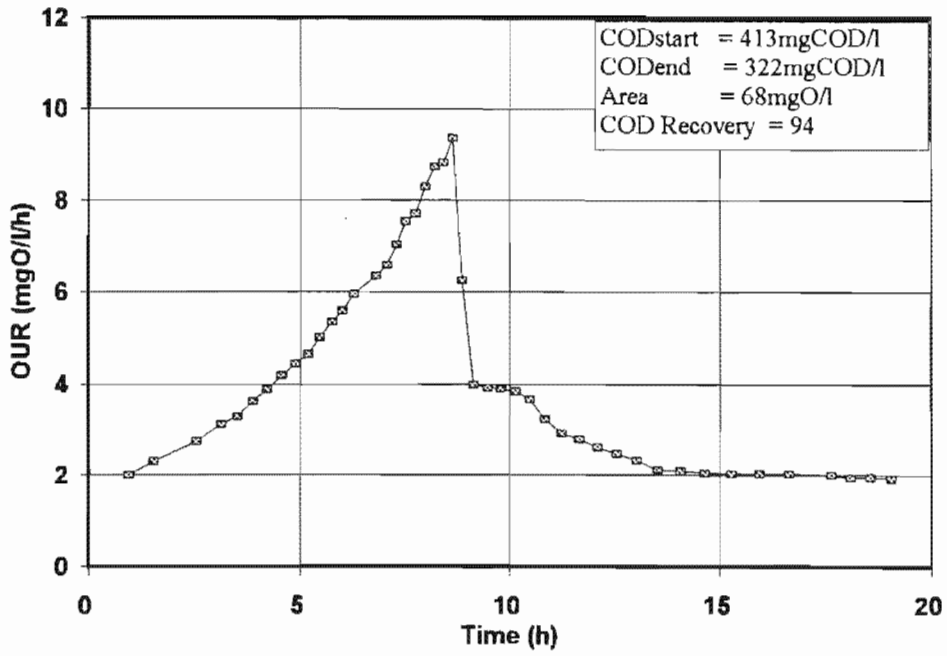


Fig A4a graph for wastewater only batch test, 28-10, wastewater batch no. 12

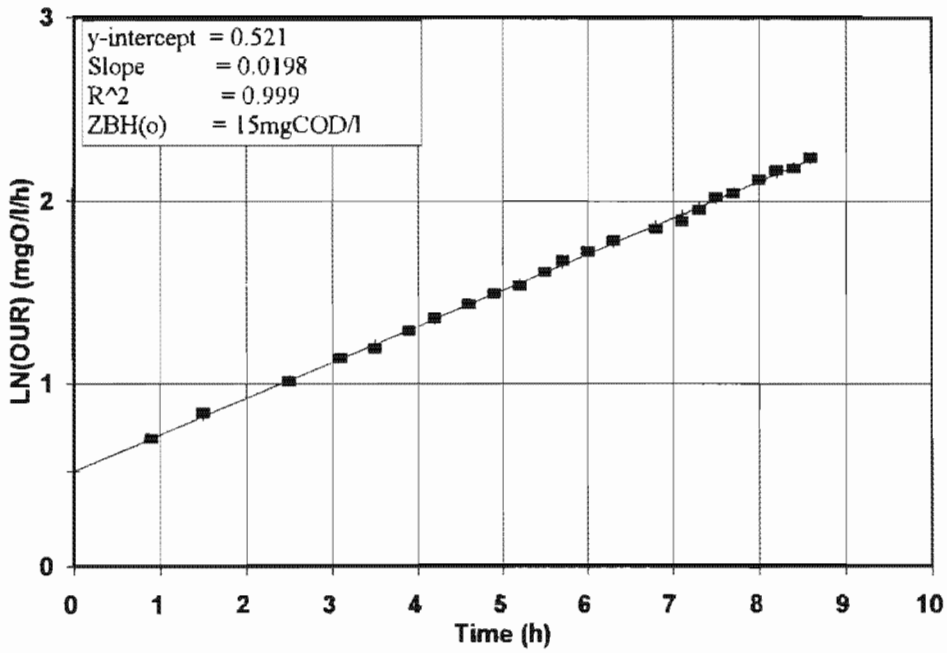


Fig A4b ln(OUR) graph for wastewater only batch test, 28-10, wastewater batch no. 12

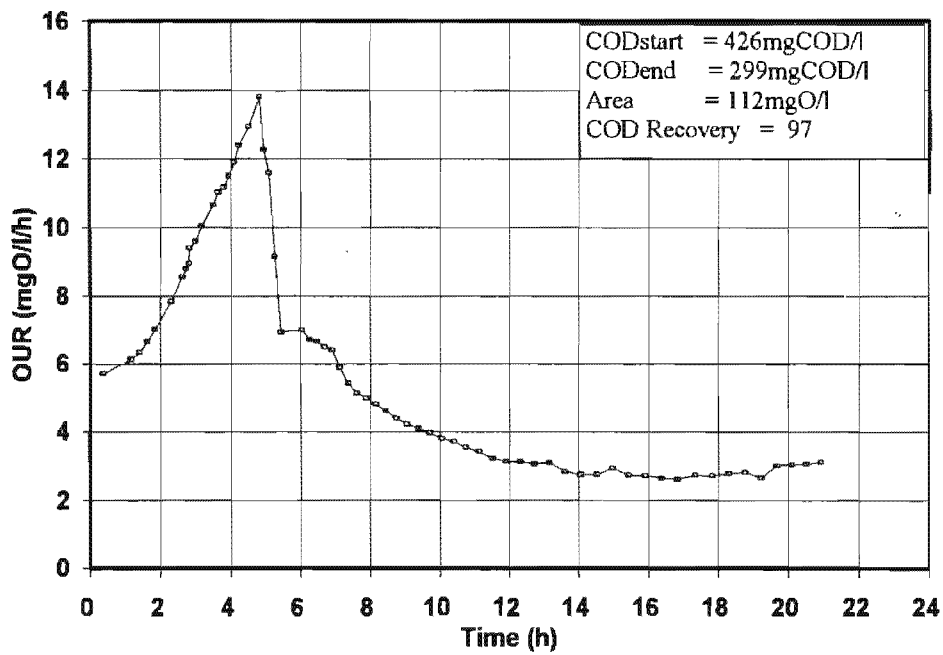


Fig A5a OUR graph for wastewater only batch test, 04-11, wastewater batch no. 13

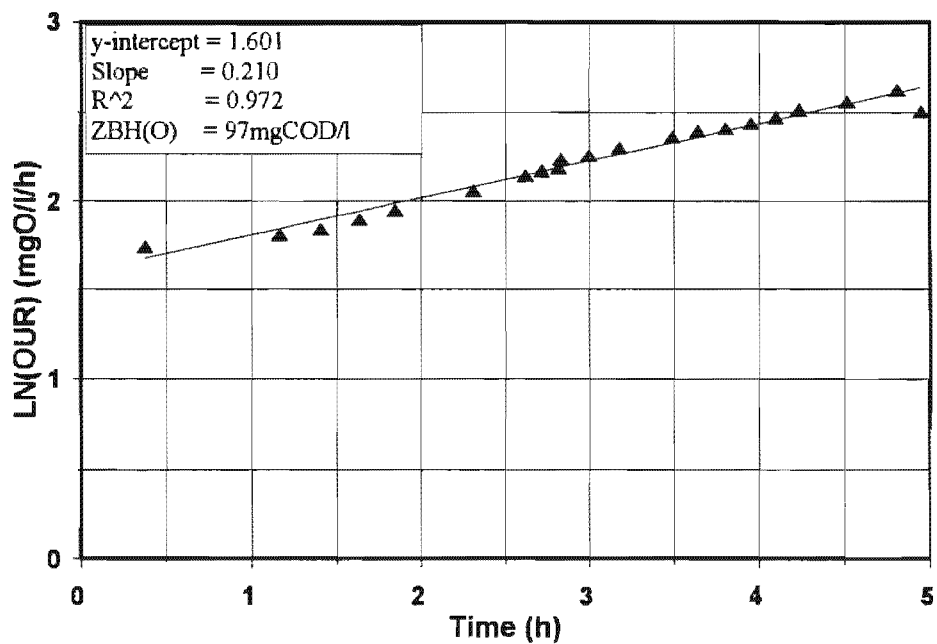


Fig A5b ln(OUR) graph for wastewater only batch test, 04-11, wastewater batch no. 13

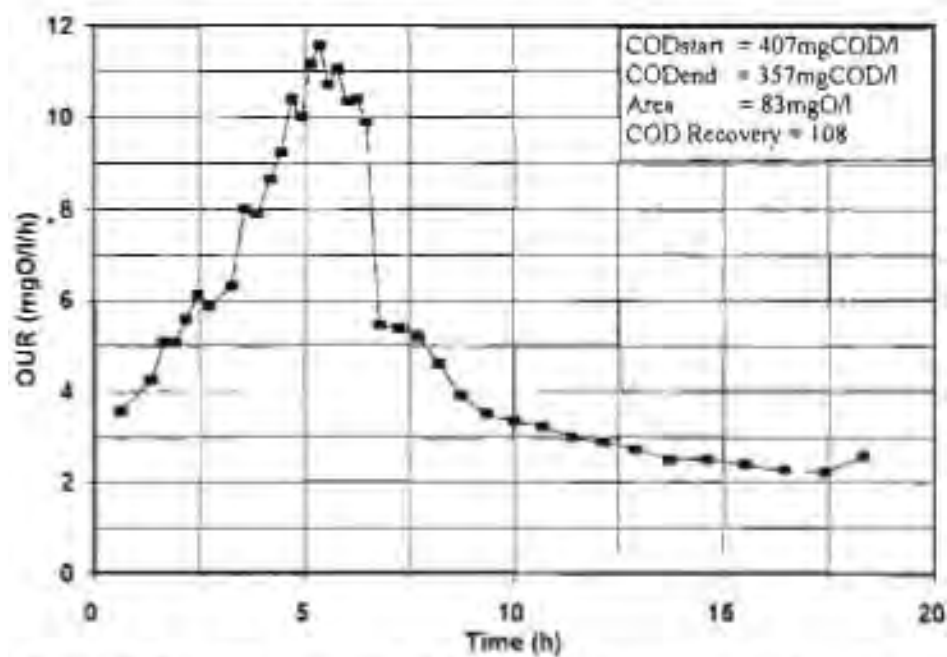


Fig A6a OUR graph for wastewater only batch test, 11-01, wastewater batch no. 17

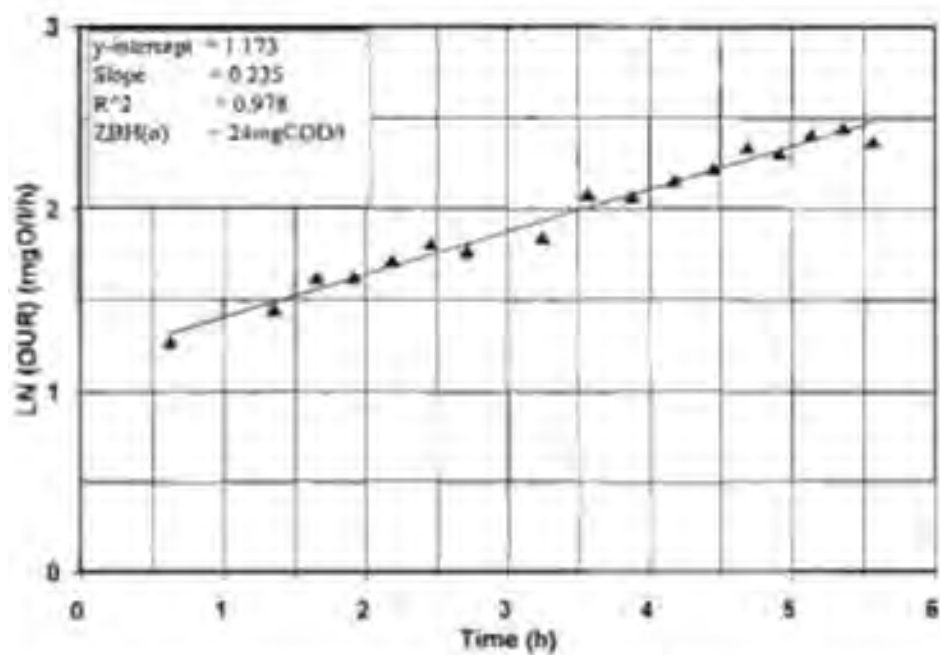


Fig A6b ln(OUR) graph for wastewater only batch test, 11-01, wastewater batch no. 17

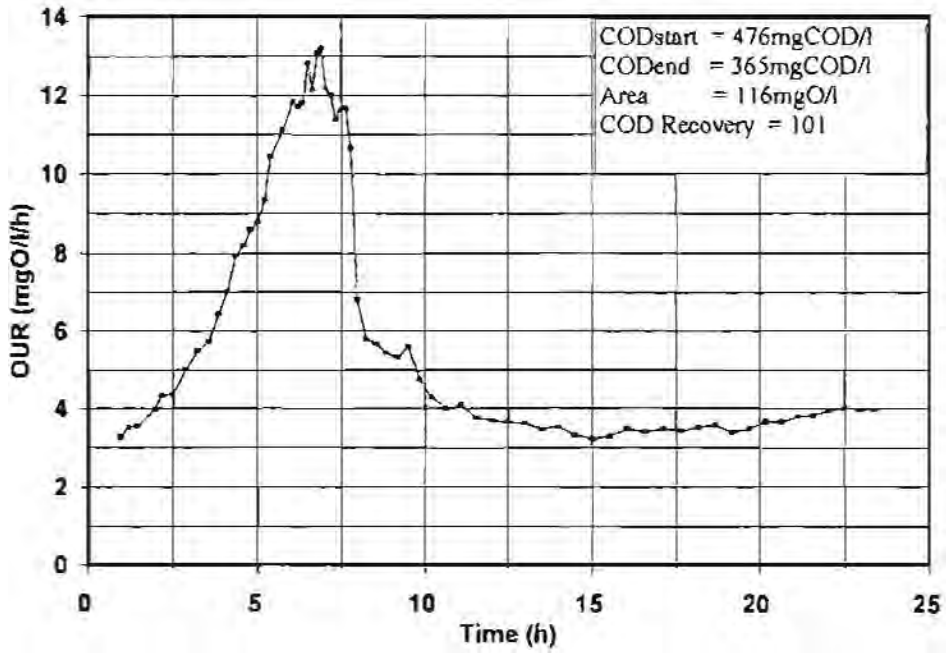


Fig A7a OUR graph for wastewater only batch test, 12-01, wastewater batch no. 17

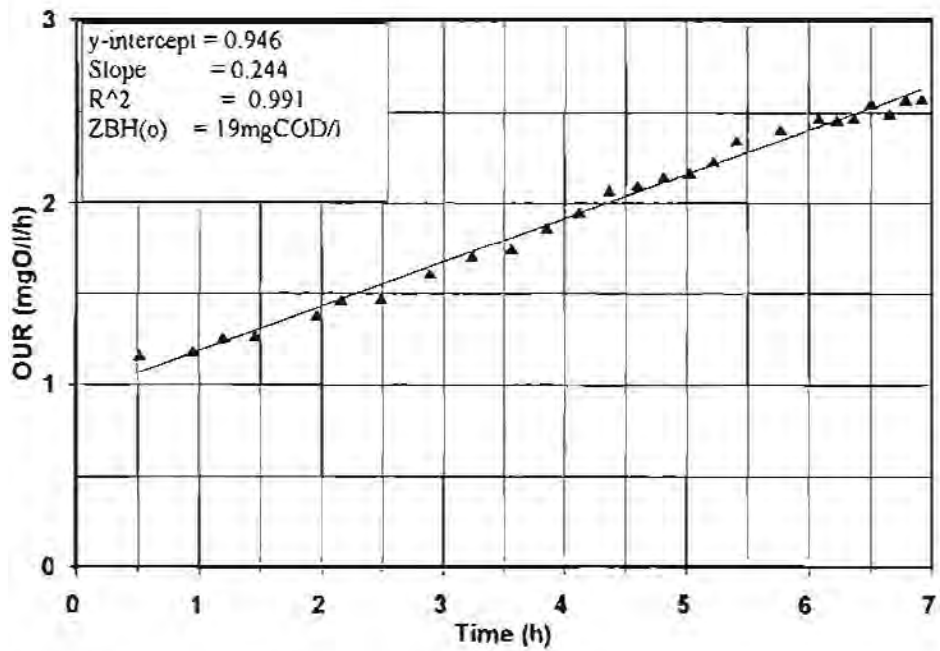


Fig A7b ln(OUR) graph for wastewater only batch test, 12-01, wastewater batch no. 17

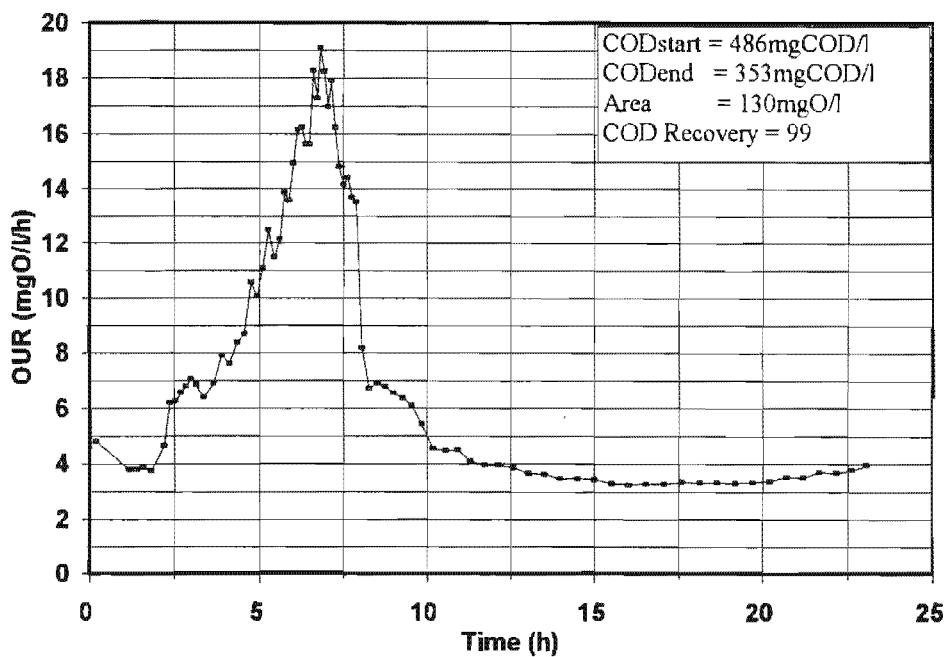


Fig A8a OUR graph for wastewater only batch test, 15-01, wastewater batch no. 17

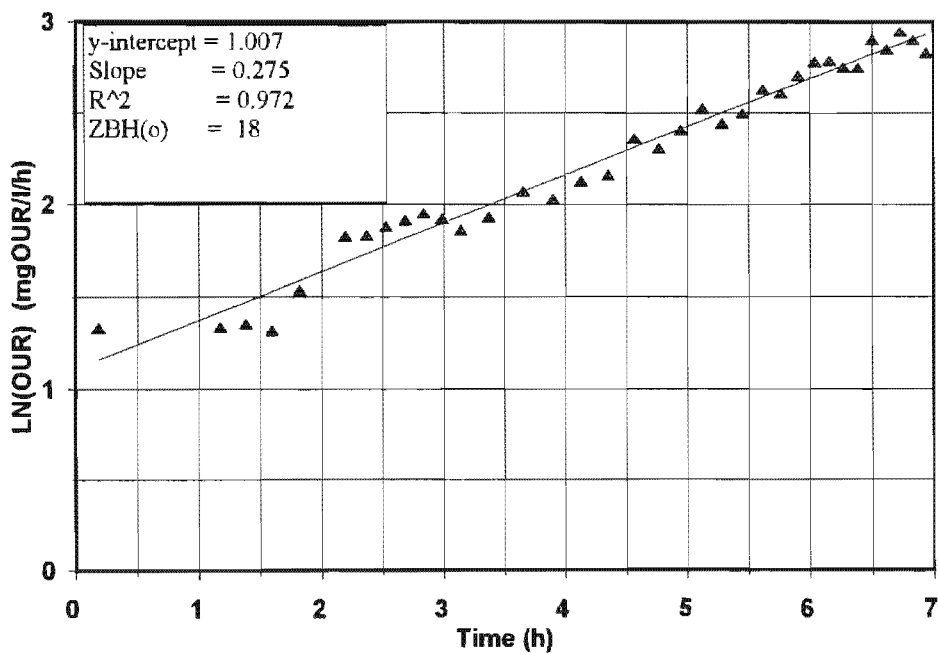


Fig A8b ln(OUR) graph for wastewater only batch test, 15-01, wastewater batch no. 17

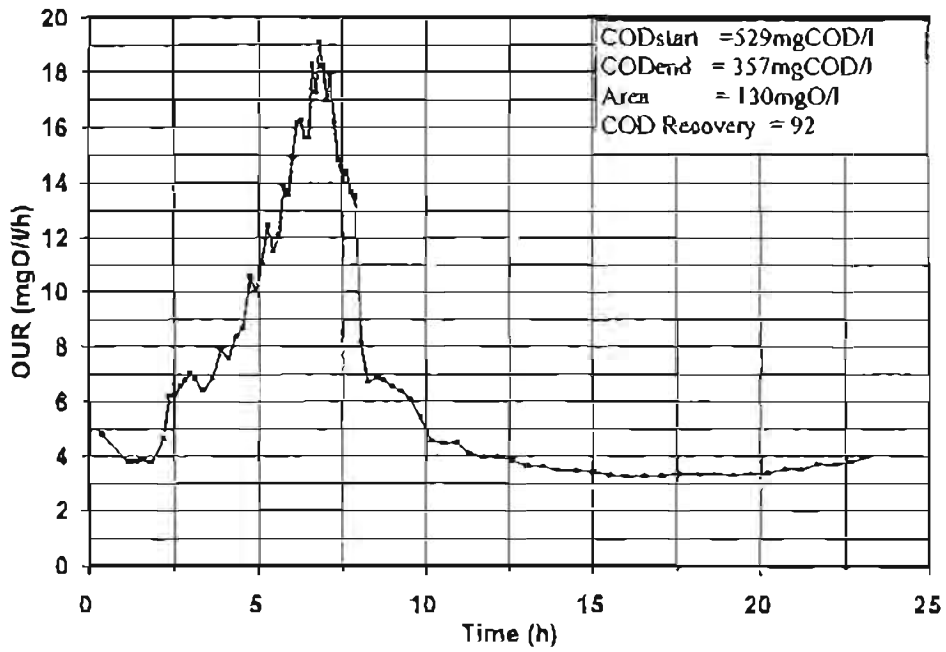


Fig A9a OUR graph for wastewater only batch test, 16-01, wastewater batch no. 17

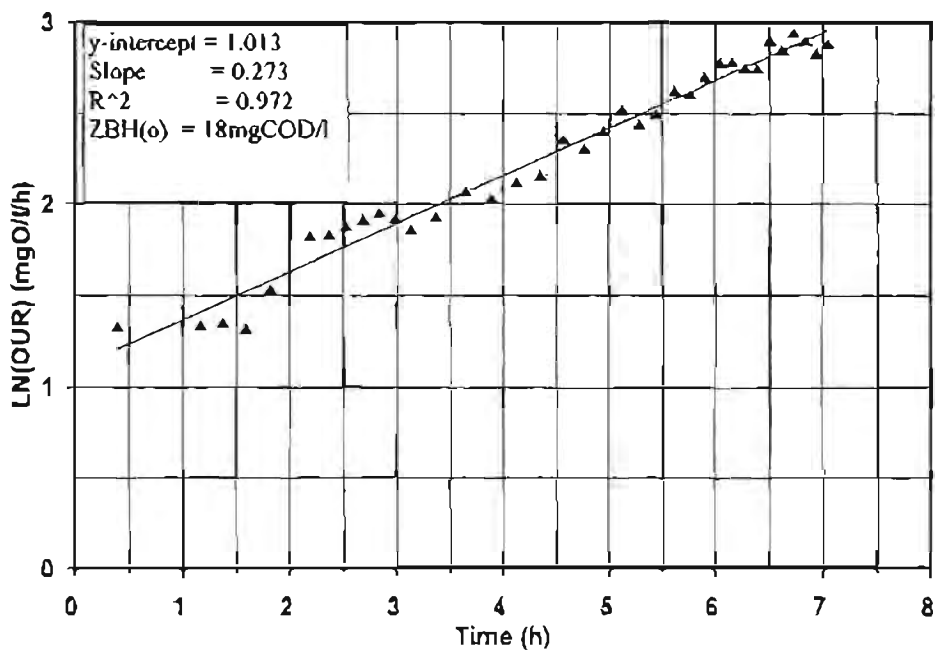


Fig A9b ln(OUR) graph for wastewater only batch test, 16-01, wastewater batch no. 17

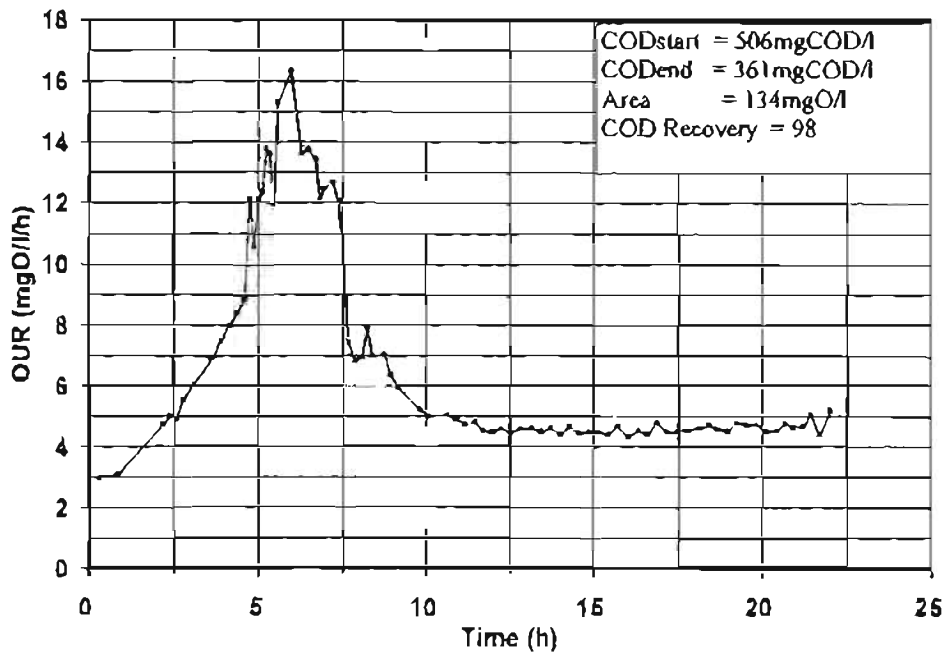


Fig A 10a OUR graph for wastewater only batch test, 17-01, wastewater batch no. 17

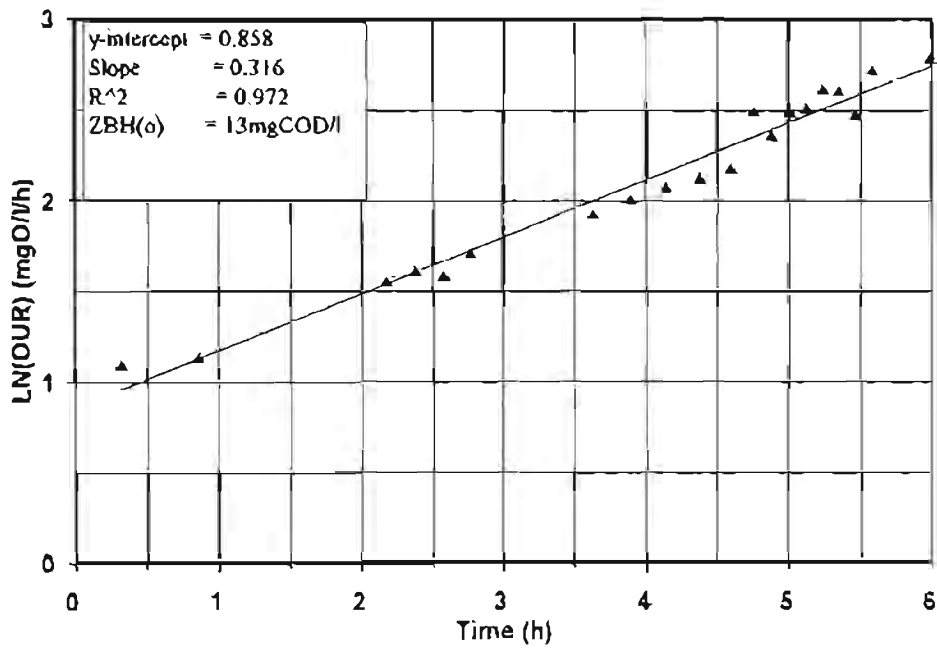


Fig A 10b ln(OUR) graph for wastewater only batch test, 17-01, wastewater batch no. 17

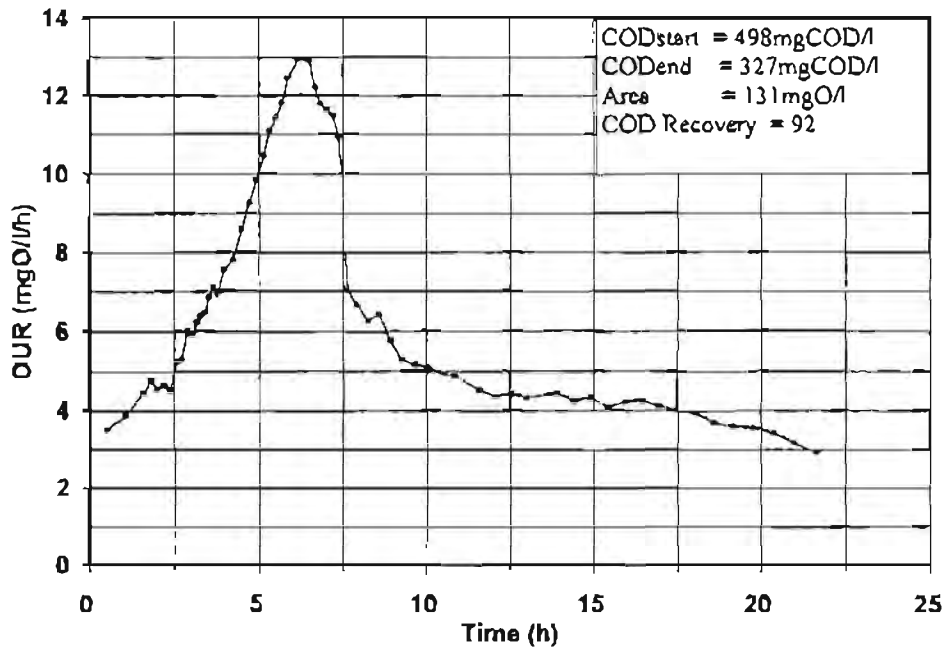


Fig A11a OUR graph for wastewater only batch test, 18-01, wastewater batch no. 17

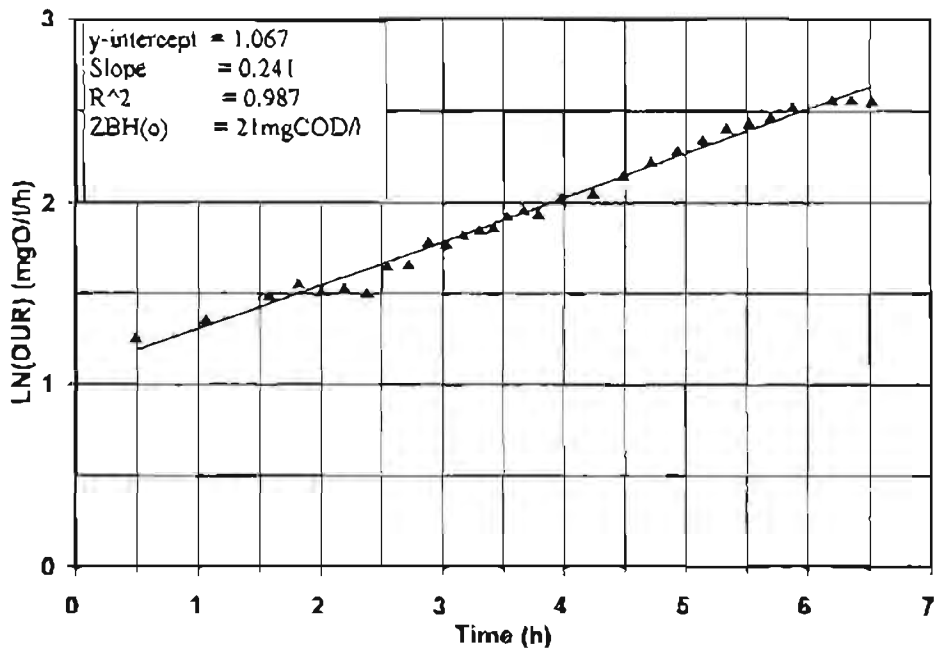


Fig A11b ln(OUR) graph for wastewater only batch test, 18-01, wastewater batch no. 17

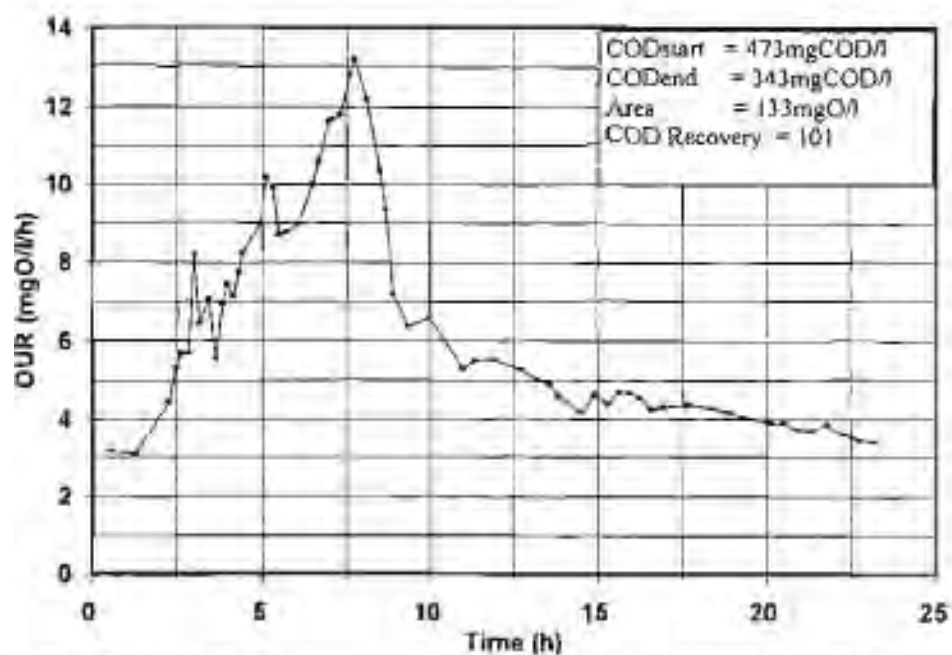


Fig A12a OUR graph for wastewater only batch test, 19-01, wastewater batch no. 17

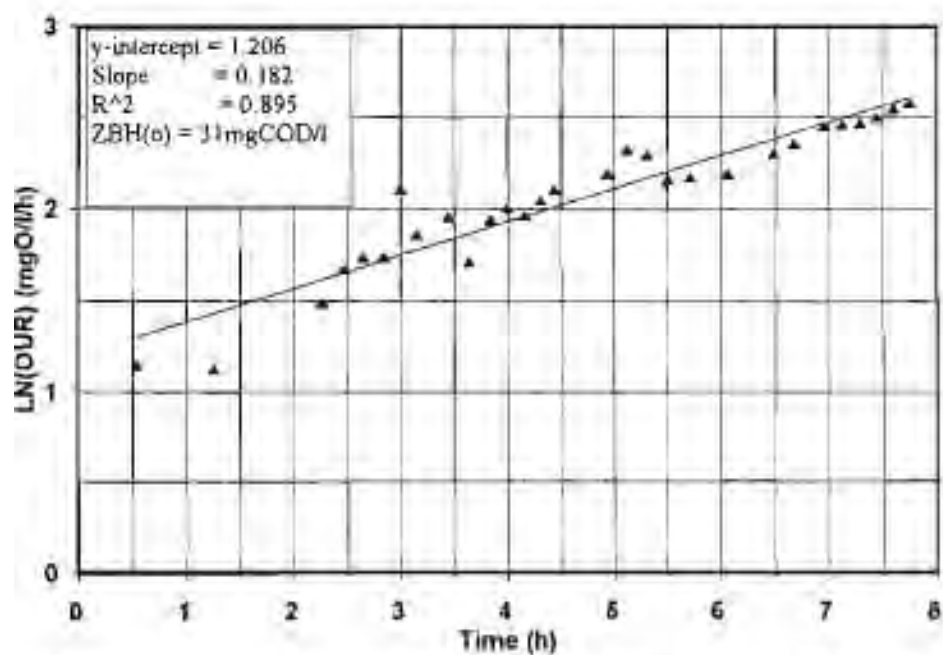


Fig A12b Ln(OUR) graph for wastewater only batch test, 19-01, wastewater batch no. 17

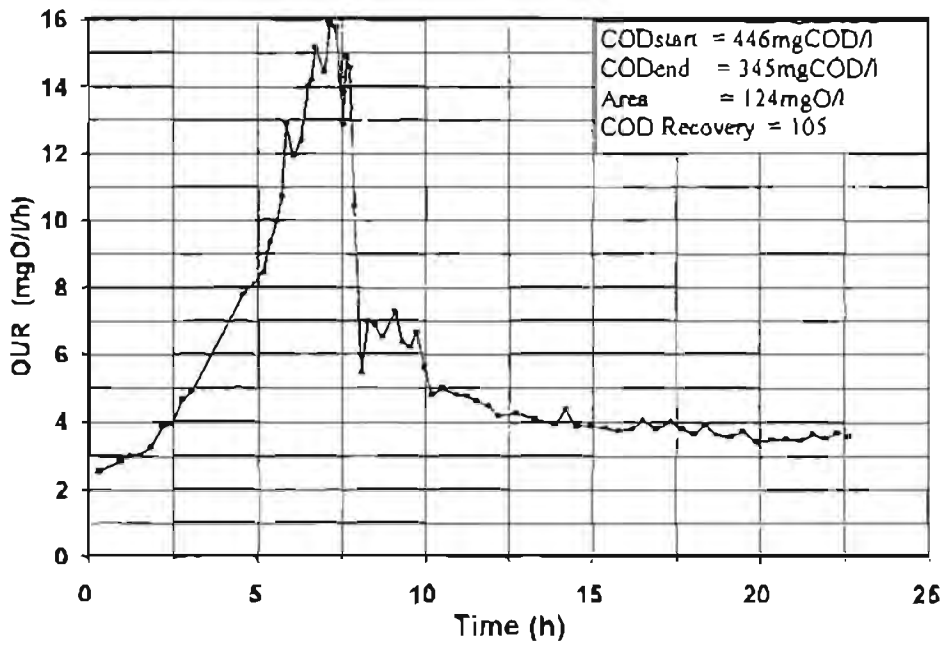


Fig A13a OUR graph for wastewater only batch test, 21-01, wastewater batch no. 17

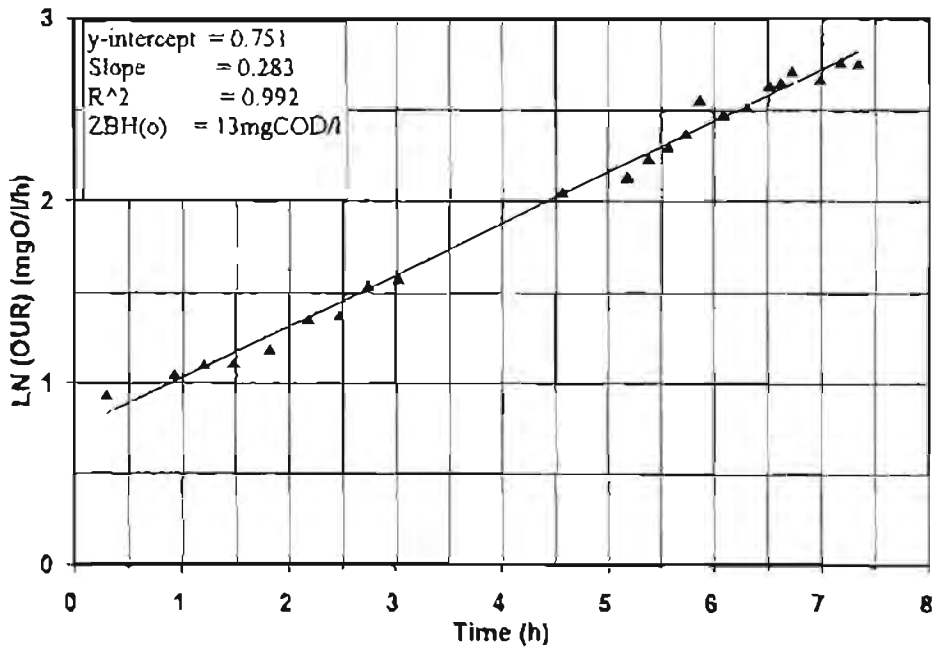


Fig A13b ln(OUR) graph for wastewater only batch test, 21-01, wastewater batch no. 17

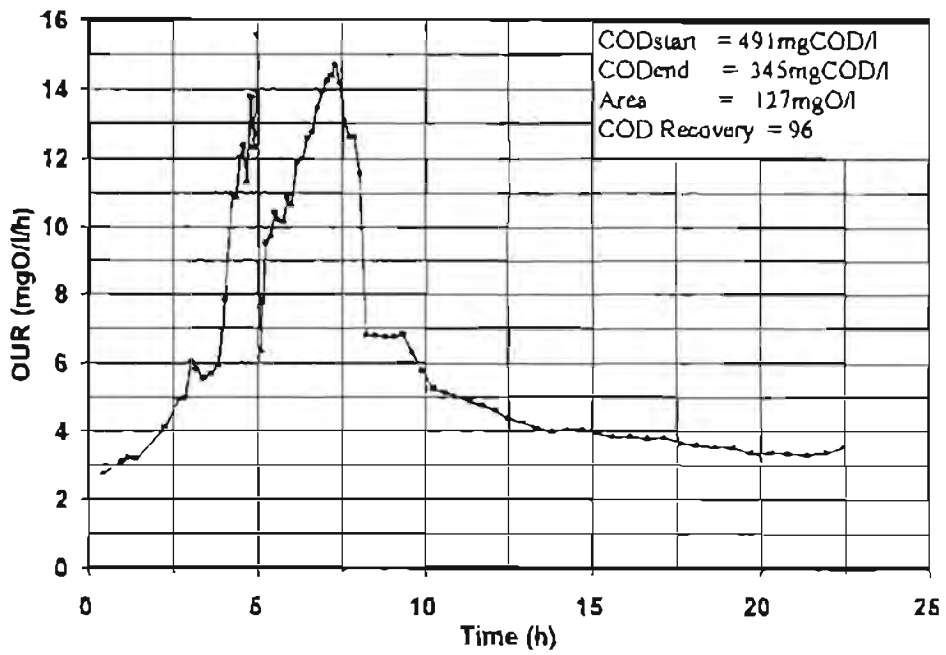


Fig A14a OUR graph for wastewater only batch test, 22-01, wastewater batch no. 17

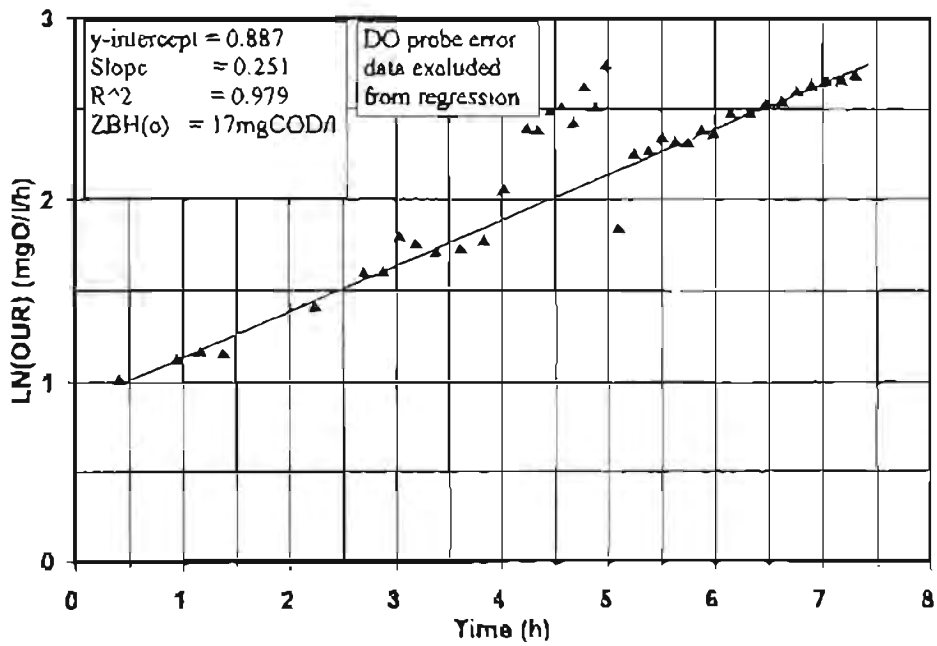


Fig A14b ln(OUR) graph for wastewater only batch test, 22-01, wastewater batch no. 17

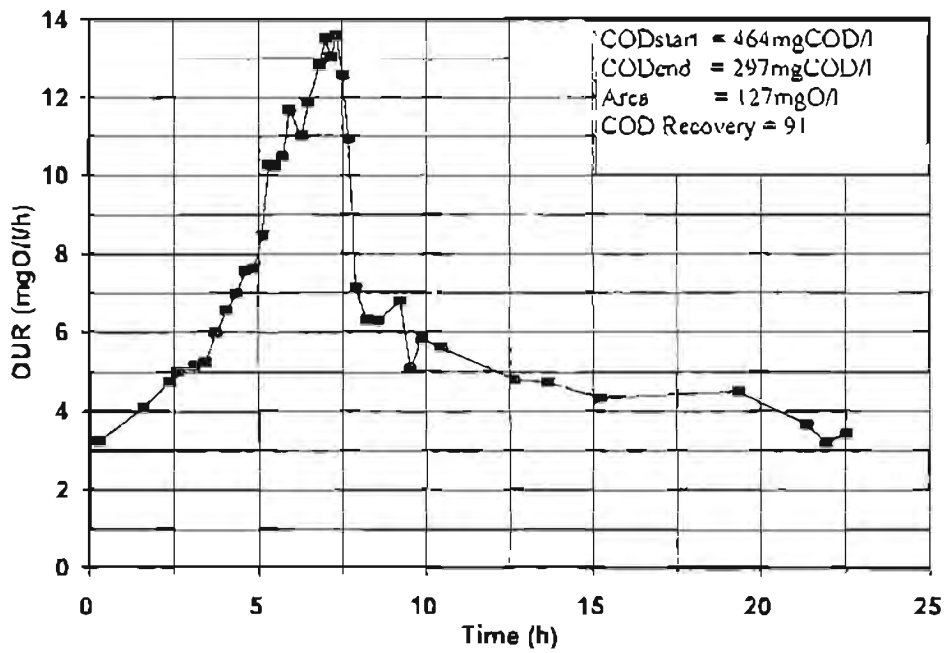


Fig A 15a OUR graph for wastewater only batch test, 23-01, wastewater batch no. 17

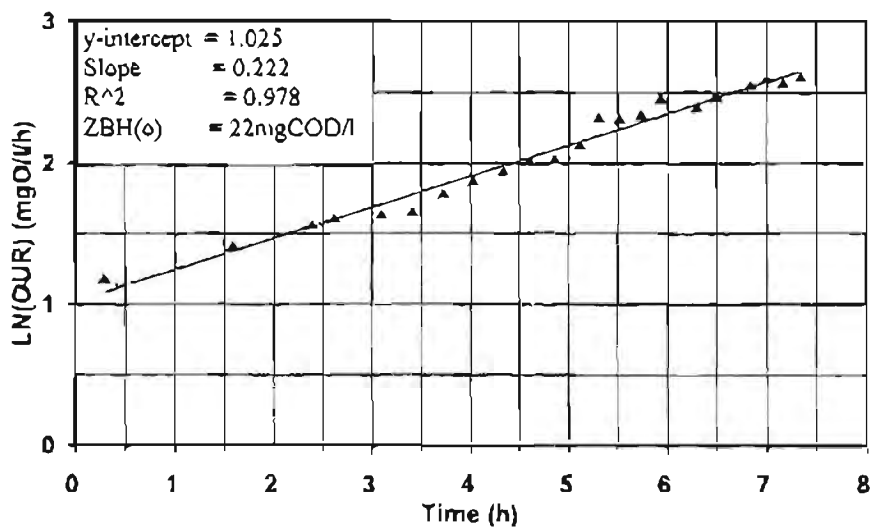


Fig A 15b ln(OUR) graph for wastewater only batch test, 23-01, wastewater batch no 17

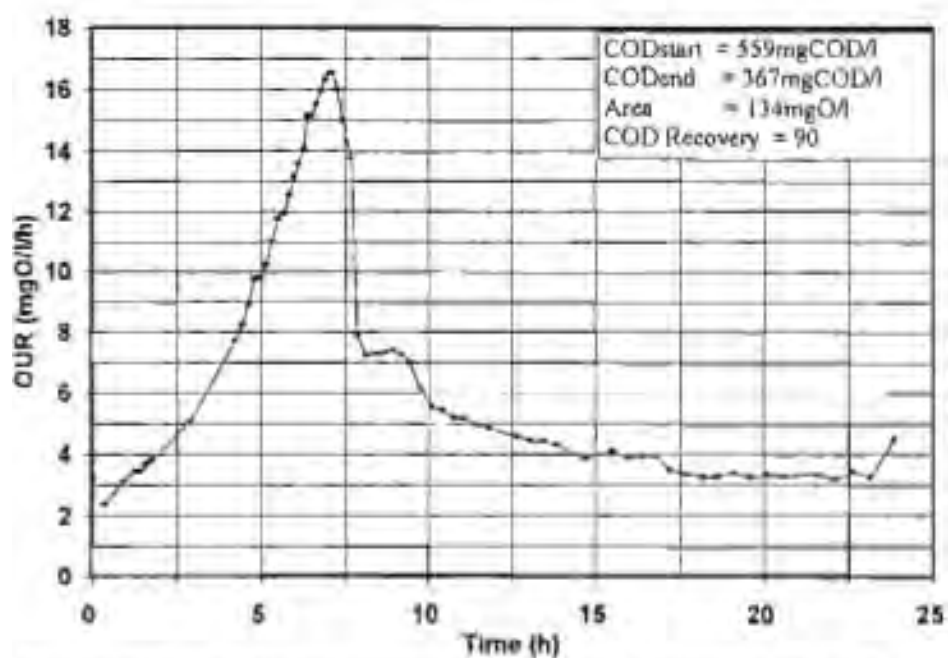


Fig A16a OUR graph for wastewater only batch test, 24-01, wastewater batch no. 17

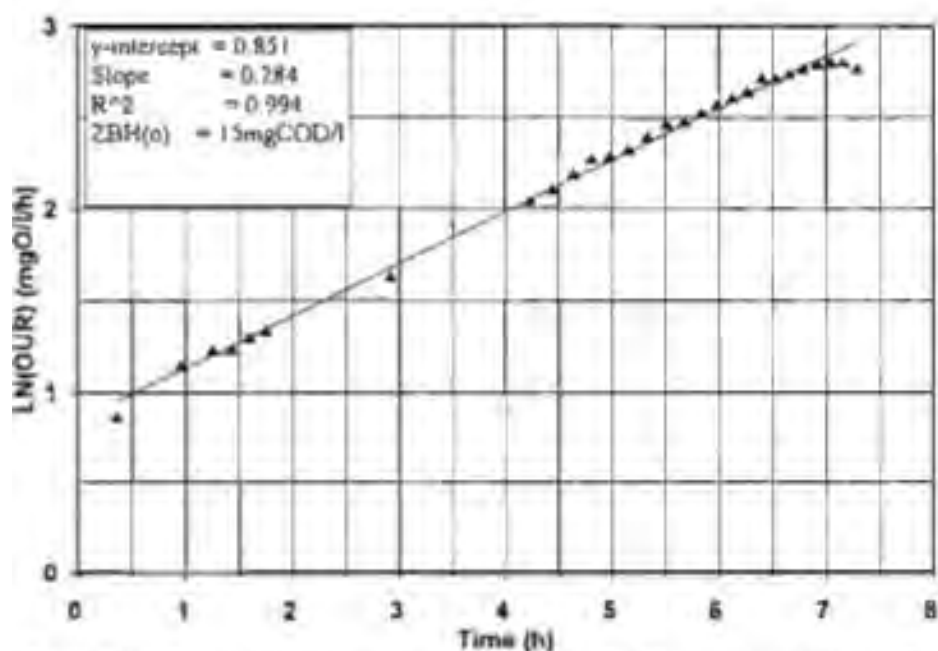


Fig A16b ln(OUR) graph for wastewater only batch test, 24-01, wastewater batch no. 17

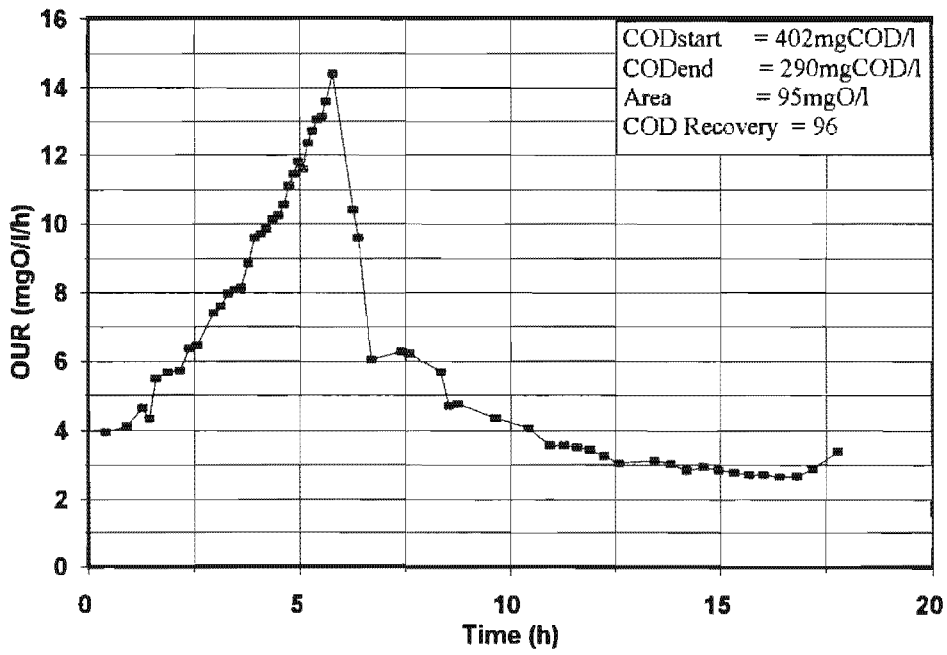


Fig A17a OUR graph for wastewater only batch test, 25-01, wastewater batch no. 18

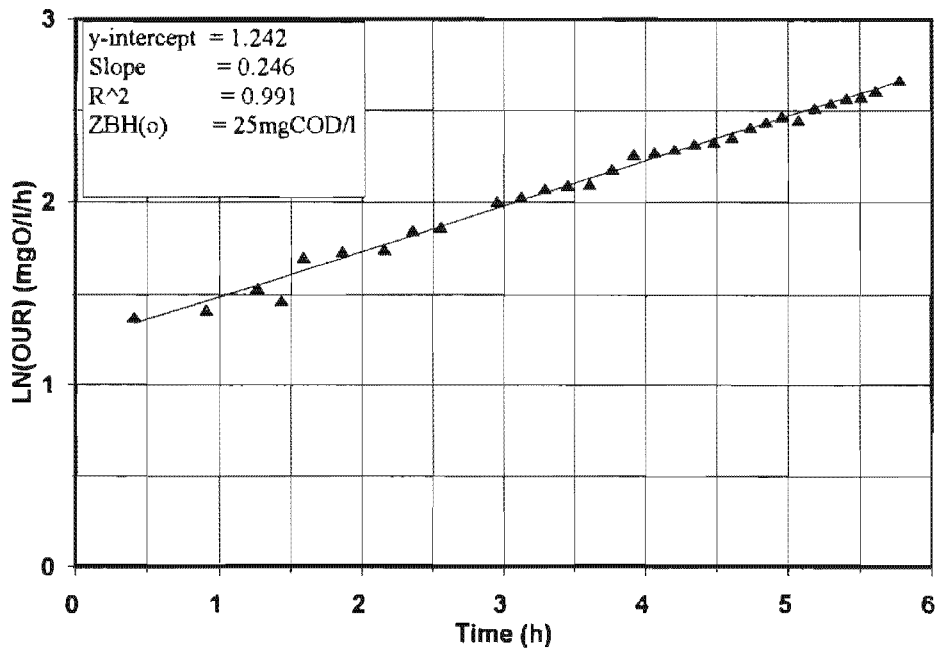


Fig A17b LN(OUR) graph for wastewater only batch test, 25-01, wastewater batch no. 18

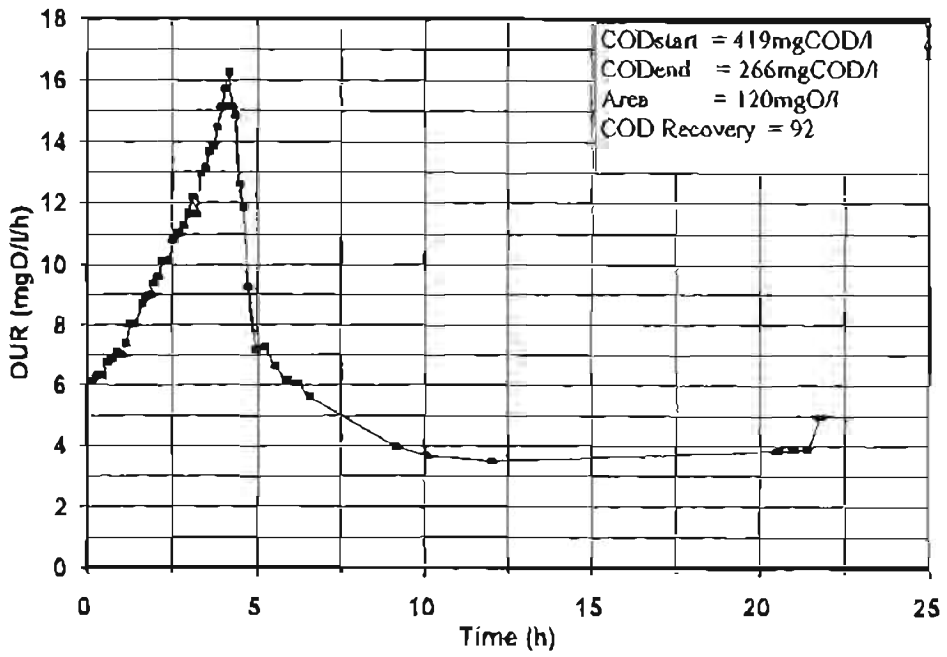


Fig A 18a OUR graph for wastewater only batch test, 26-01, wastewater batch no. 18

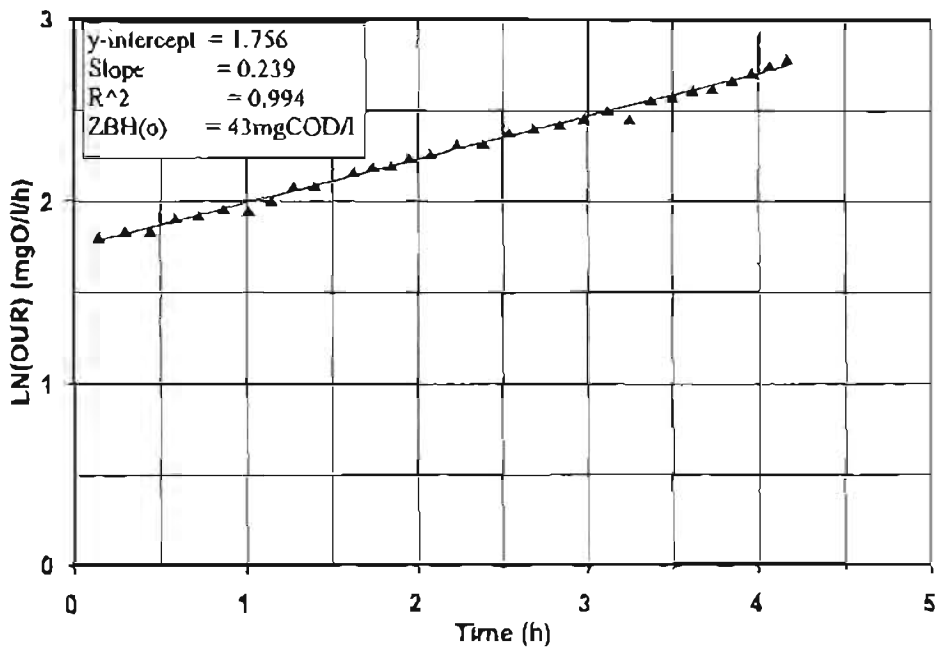


Fig A 18b ln(OUR) graph for wastewater only batch test, 26-01, wastewater batch no. 18

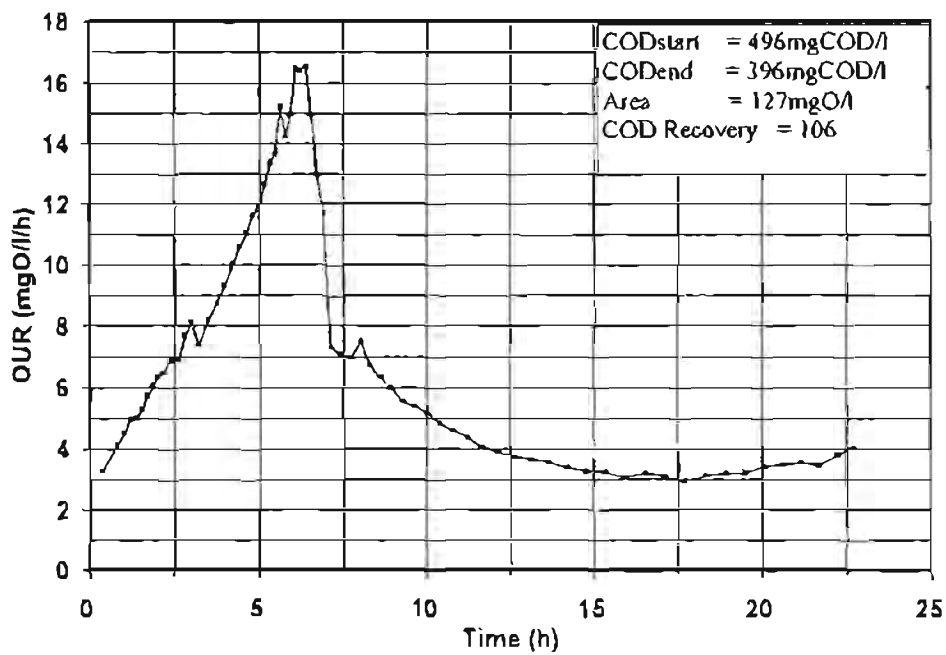


Fig A 19a OUR graph for wastewater only batch test, 29-01, wastewater batch no. 18

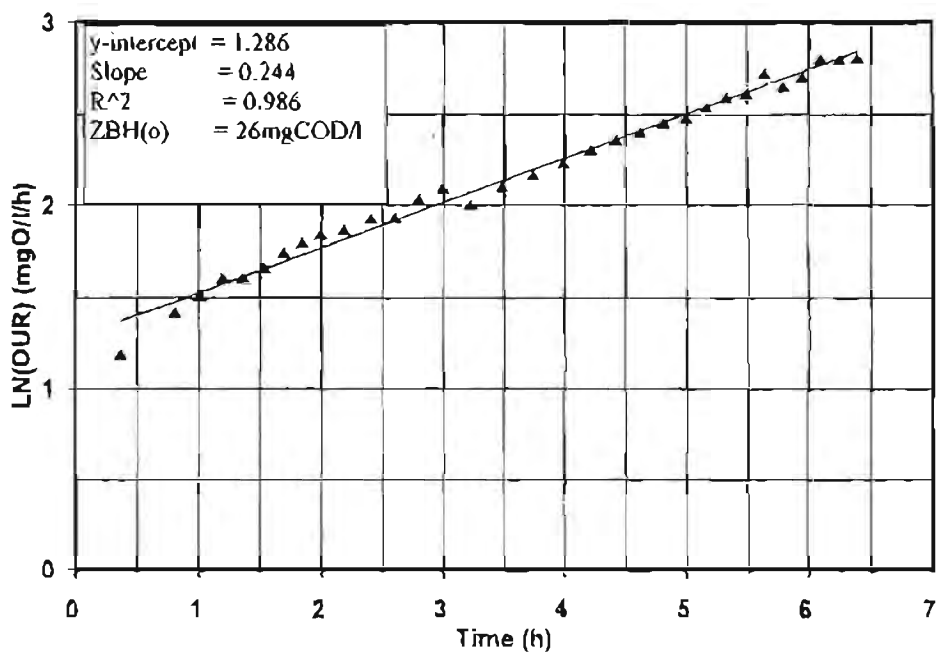


Fig A 19b ln(OUR) graph for wastewater only batch test, 29-01, wastewater batch no. 18

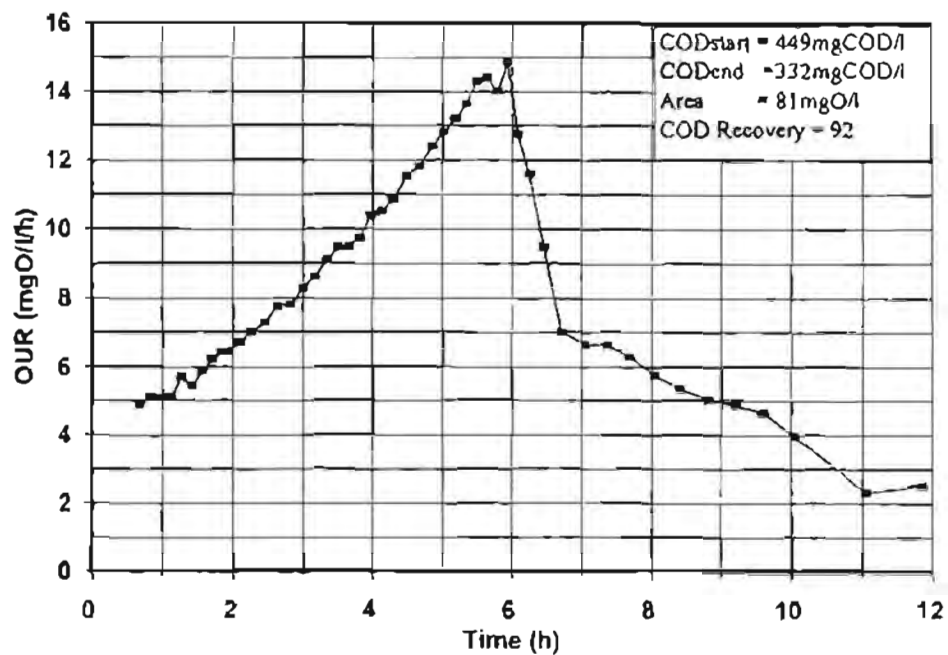


Fig A20a OUR graph for wastewater only batch test, 30-01, wastewater batch no. 18

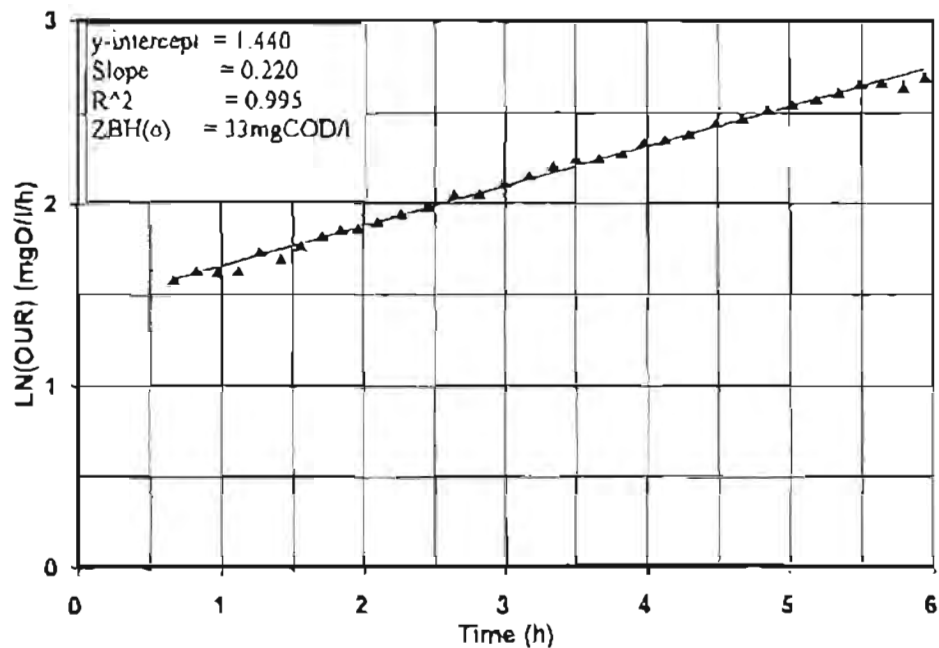


Fig A20b ln(OUR) graph for wastewater only batch test, 30-01, wastewater batch no. 18

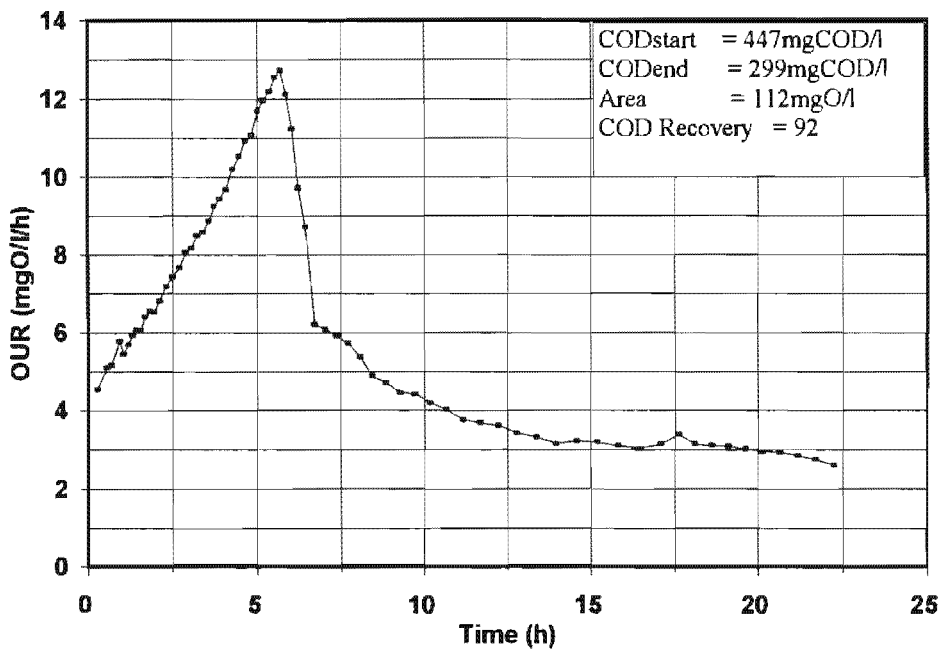


Fig A21a OUR graph for wastewater only batch test, 31-01, wastewater batch no. 18

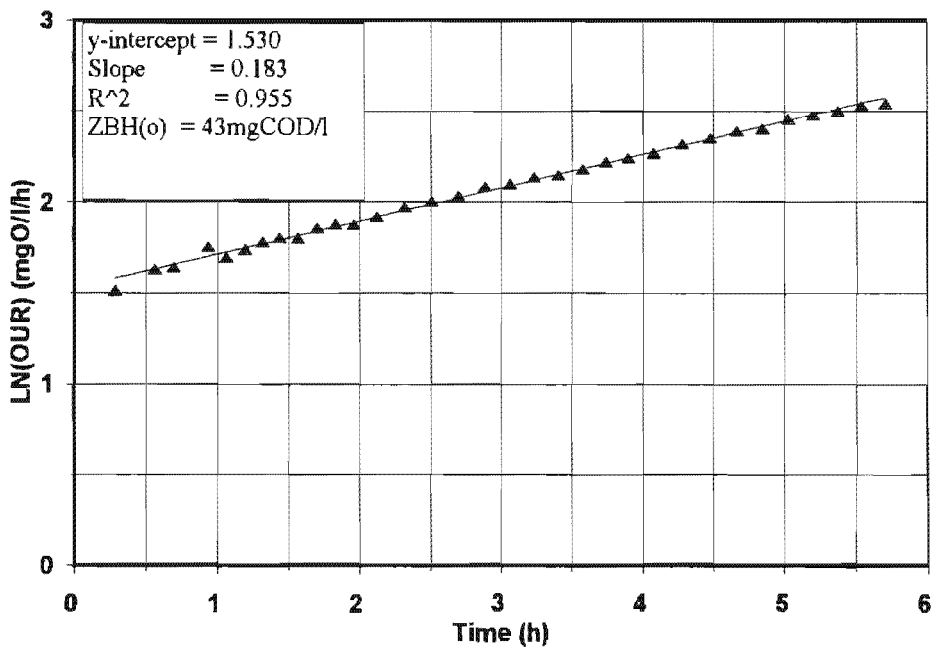


Fig A21b ln(OUR) graph for wastewater only batch test, 31-01, wastewater batch no. 18

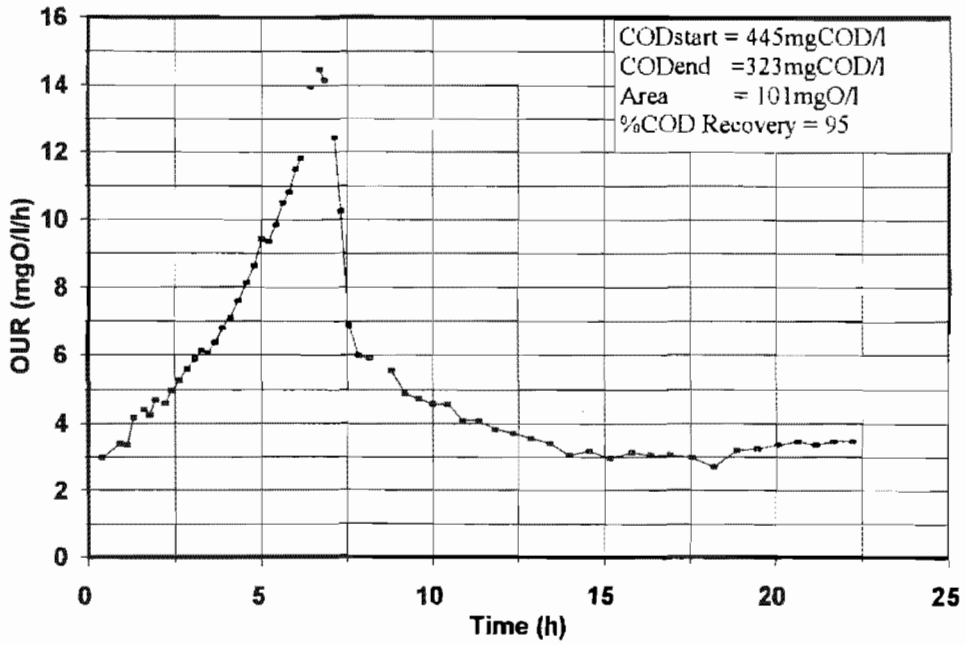


Fig.A.22a OUR graph for wastewater only batch test conducted on 01-02-96 wastewater batch no.18

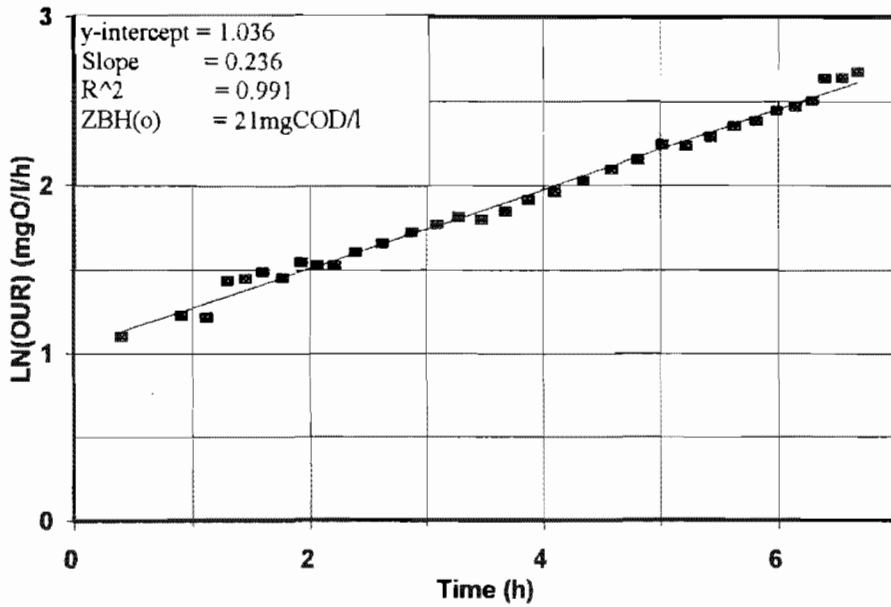


Fig. A.22b ln(OUR) graph for wastewater only batch test, 01-02-96 on wastewater batch no. 18

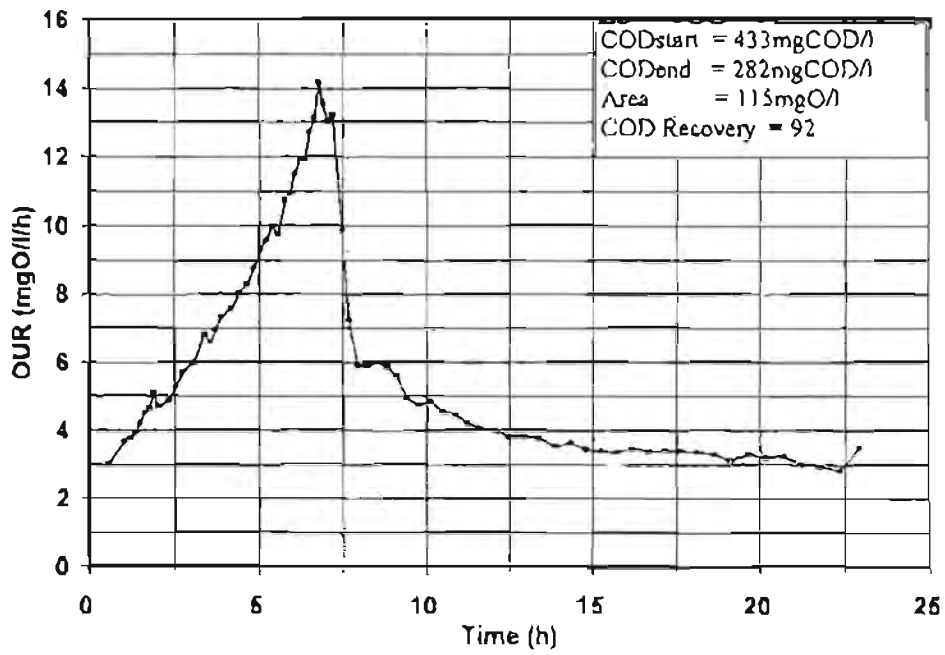


Fig A23a OUR graph for wastewater only batch test, 02-02, wastewater batch no. 18

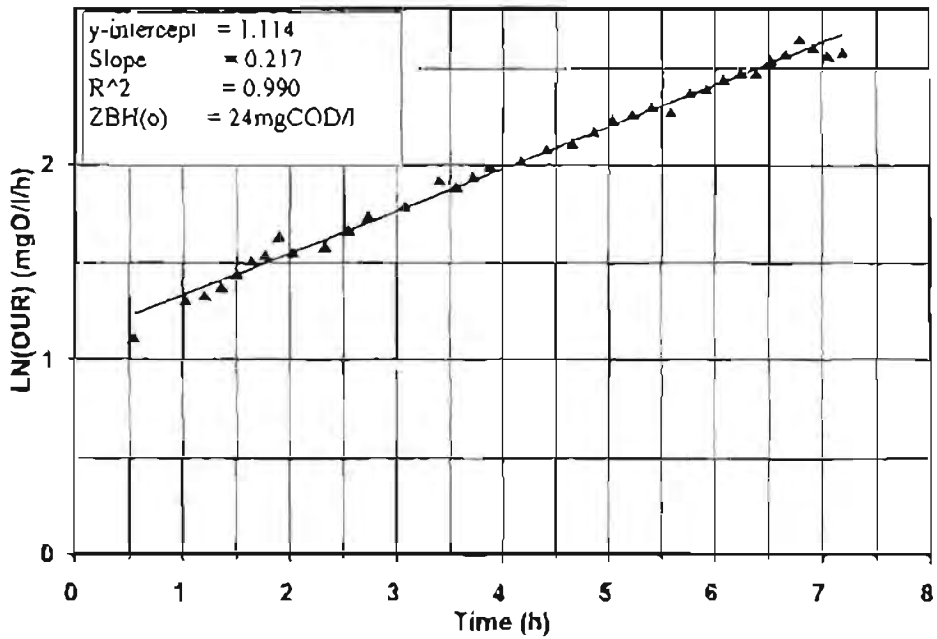


Fig A23b Ln(OUR) graph for wastewater only batch test, 02-02, wastewater batch no. 18

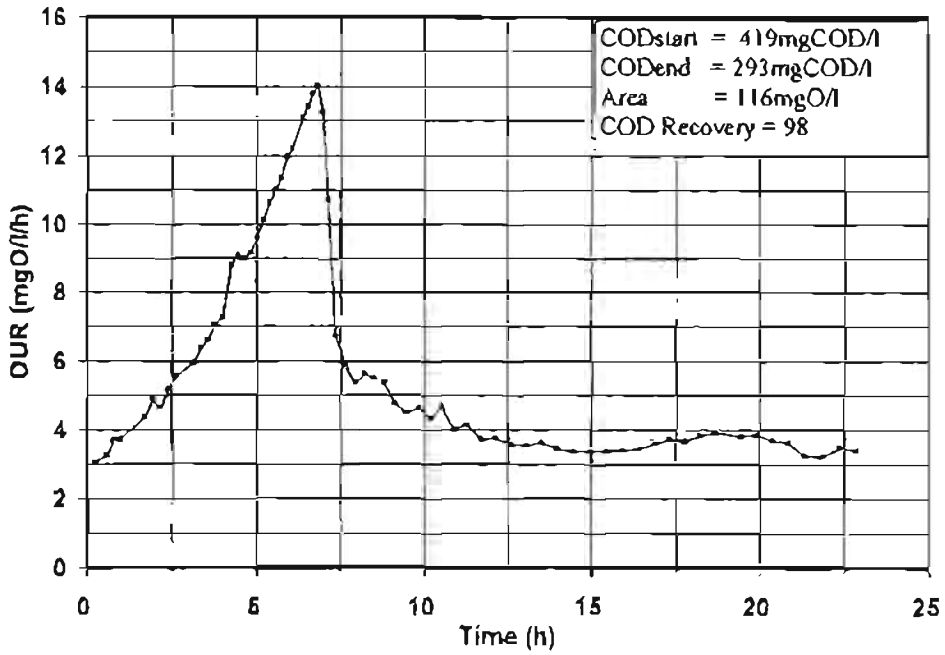


Fig A24a OUR graph for wastewater only batch test, 03-02, wastewater batch no.18

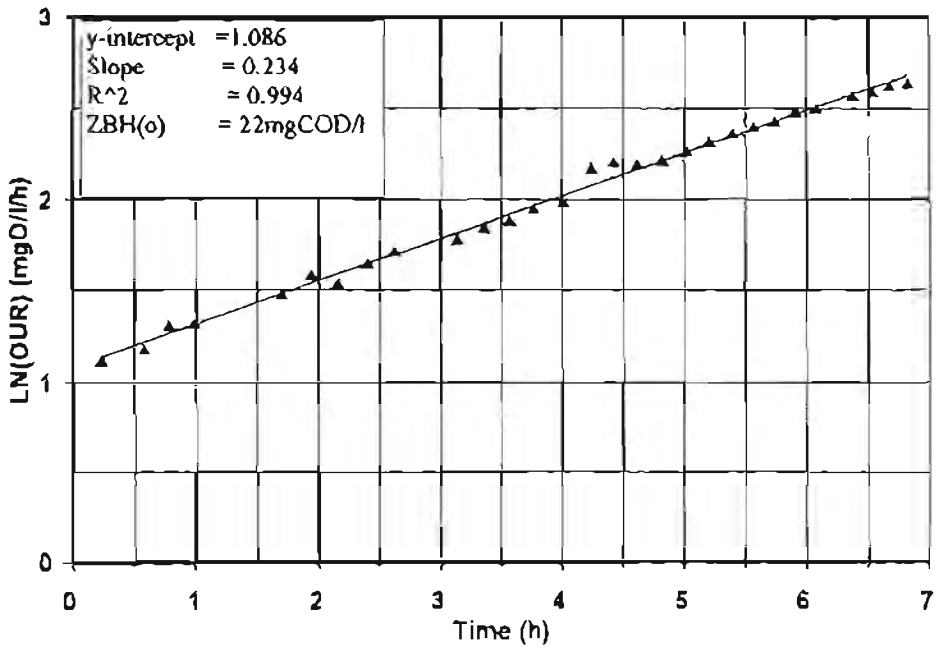


Fig A24b ln(OUR) graph for wastewater only batch test, 03-02, wastewater batch no.18

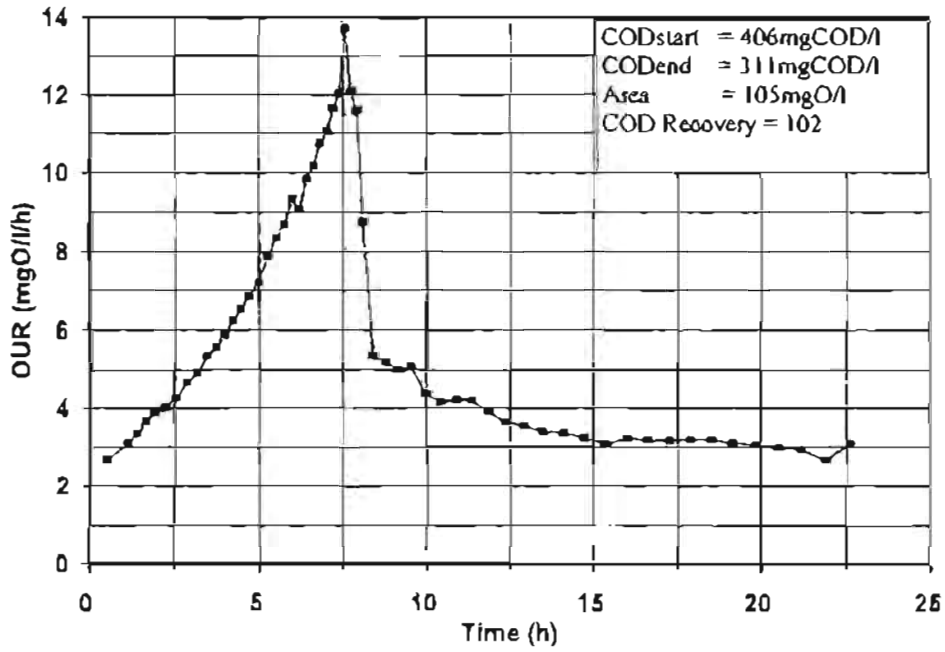


Fig A25a OUR graph for wastewater only batch test, 04-02, wastewater batch no.18

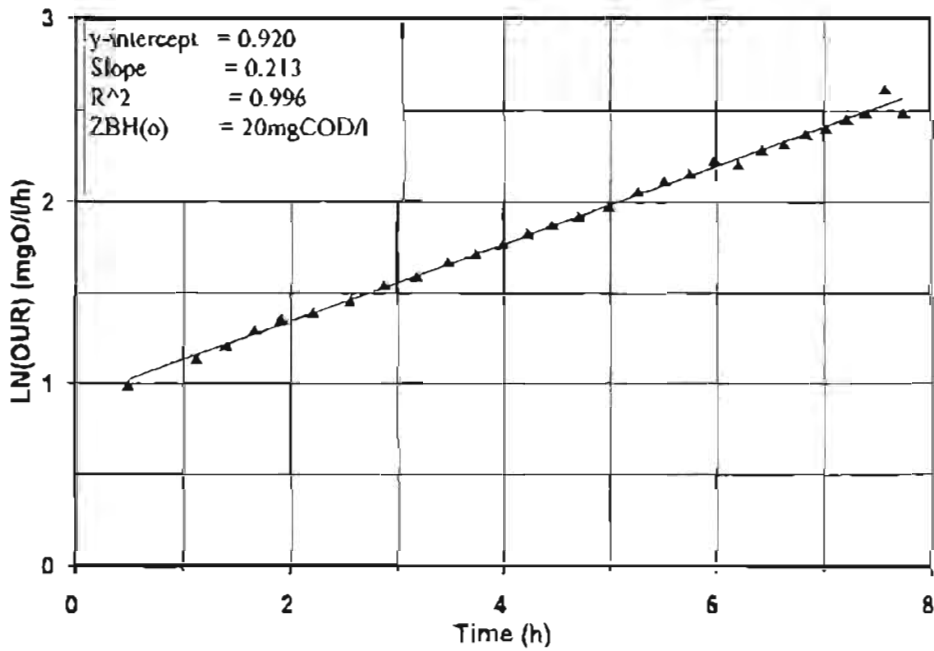


Fig A25b ln(OUR) graph for wastewater only batch test, 04-02, wastewater batch no. 18

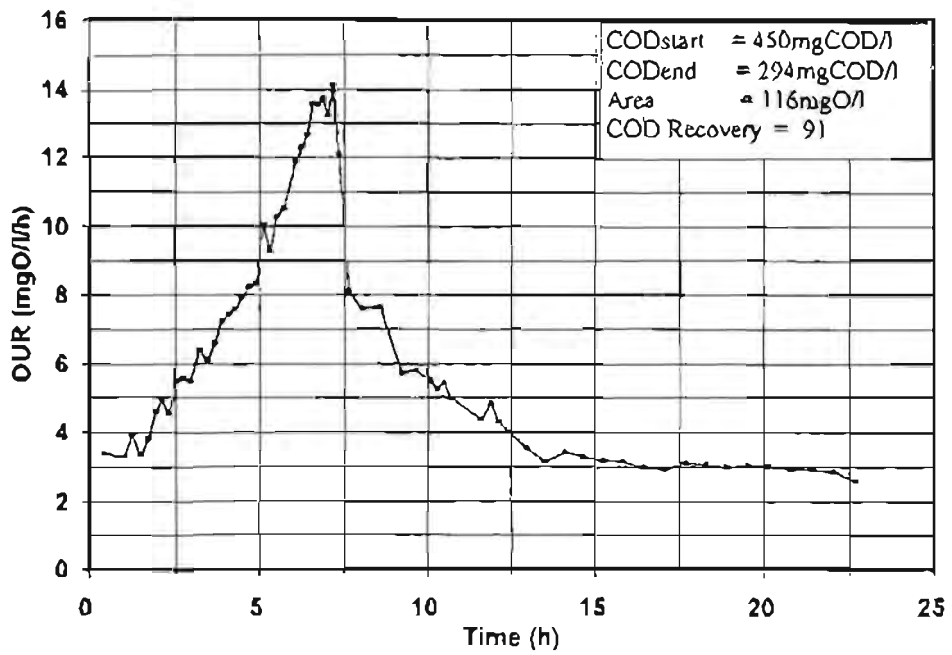


Fig A26a OUR graph for wastewater only batch test, 05-02, wastewater batch no. 18

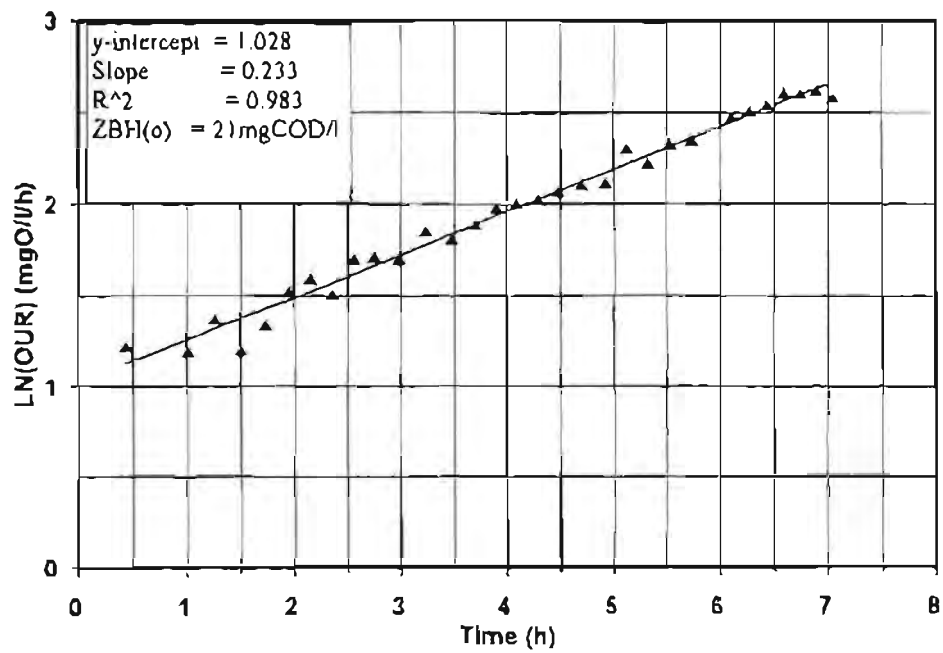


Fig A26b ln(OUR) graph for wastewater only batch test, 05-02, wastewater batch no. 18

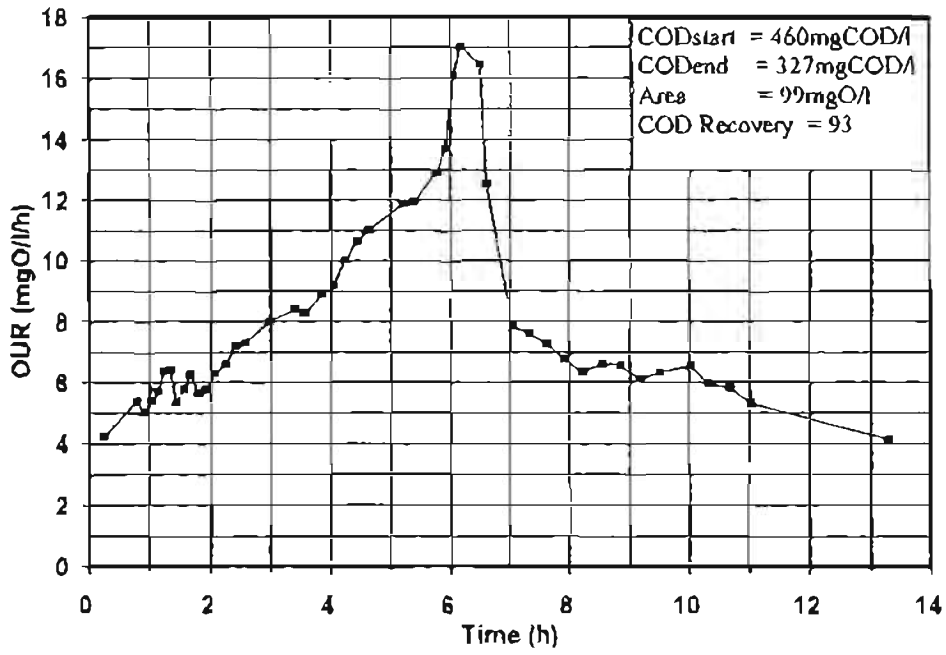


Fig A27a OUR graph for wastewater only batch test, 06-02, wastewater batch no. 18

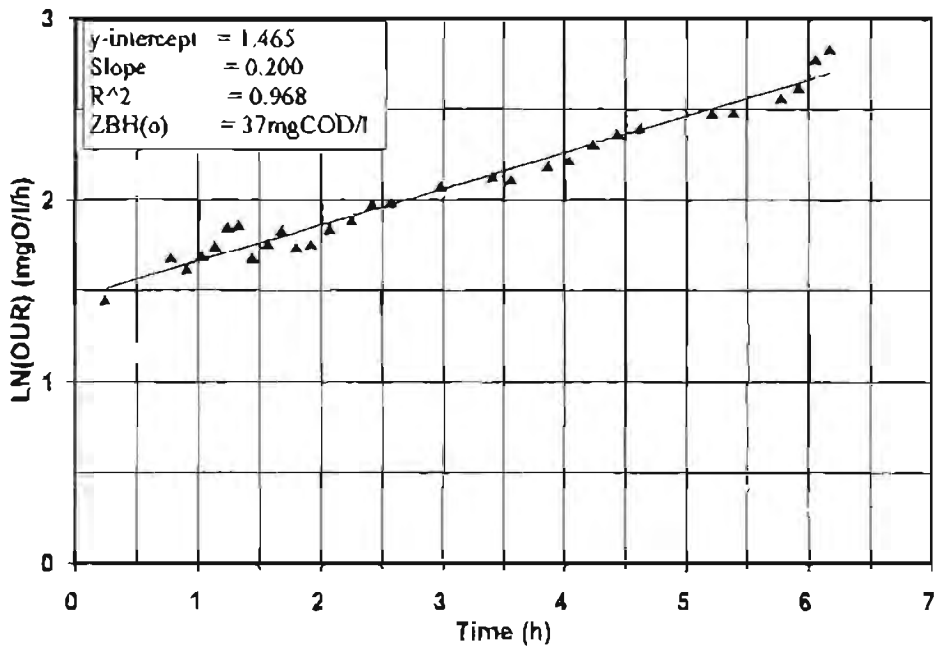


Fig A27b ln(OUR) graph for wastewater only batch test, 06-02, wastewater batch no. 18

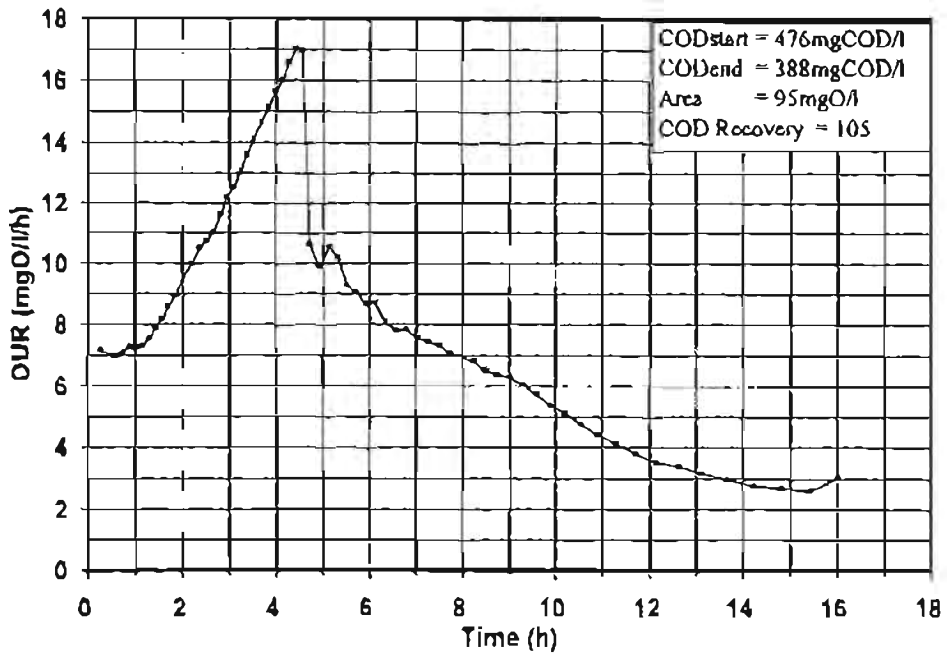


Fig A28a OUR graph for wastewater only batch test, 07-02, wastewater batch no. 19

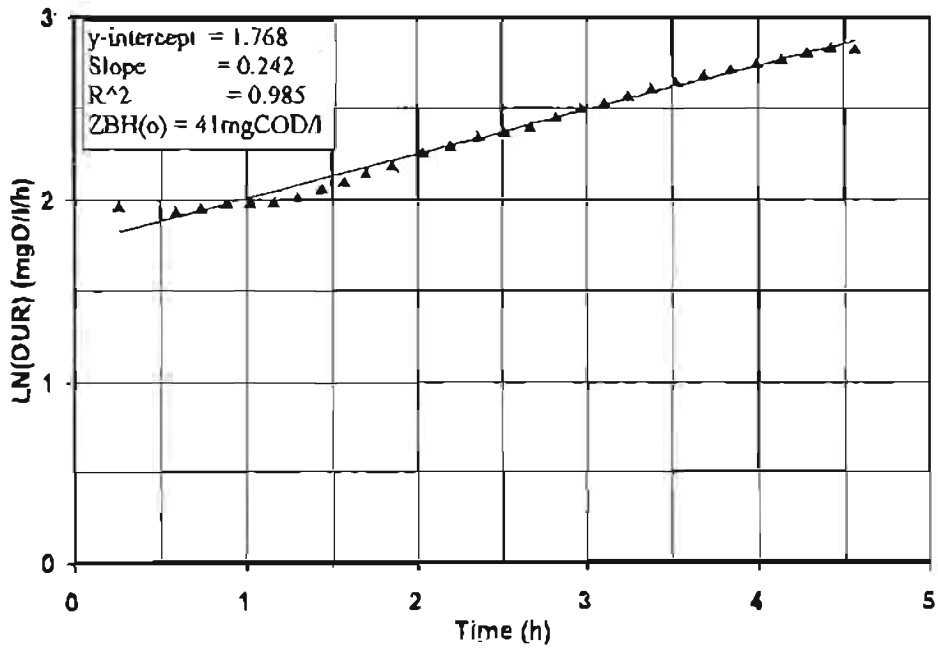


Fig A28b OUR graph for wastewater only batch test, 07-02, wastewater batch no. 19

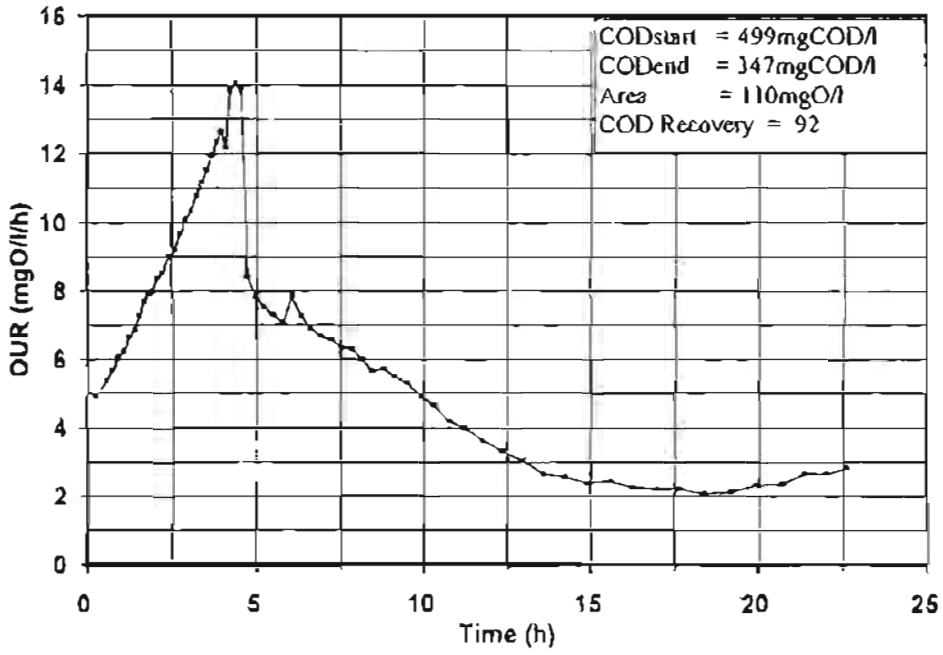


Fig A29a OUR graph for wastewater only batch test, 08-02, wastewater batch no. 19

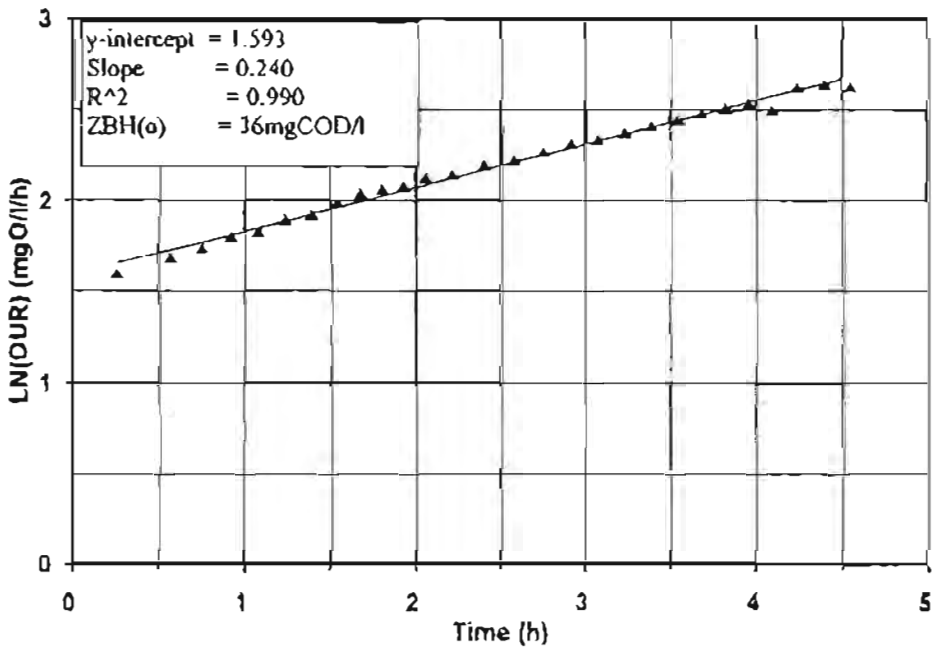


Fig A29b Ln(OU) graph for wastewater only batch test, 08-02, wastewater batch no. 19

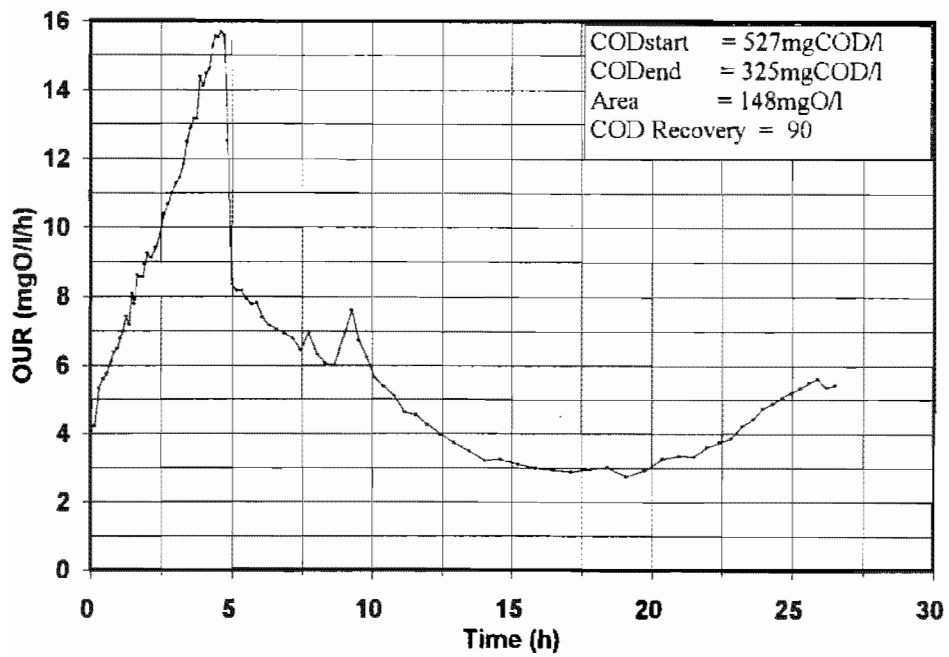


Fig A30a OUR graph for wastewater only batch test, 09-02, wastewater batch no.19

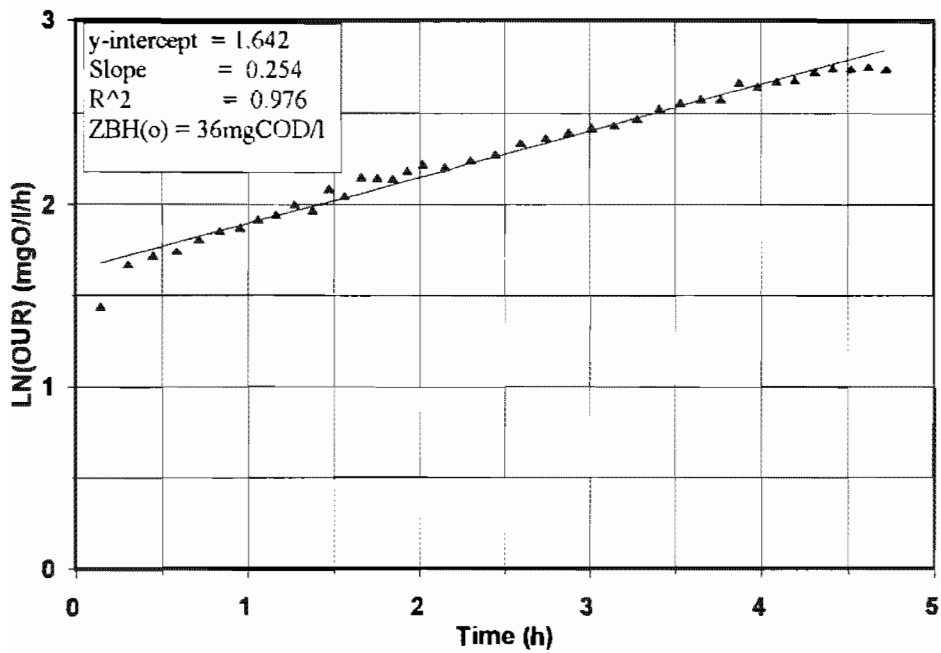


Fig A30b ln(OUR) graph for wastewater only batch test, 09-02, wastewater batch no.19

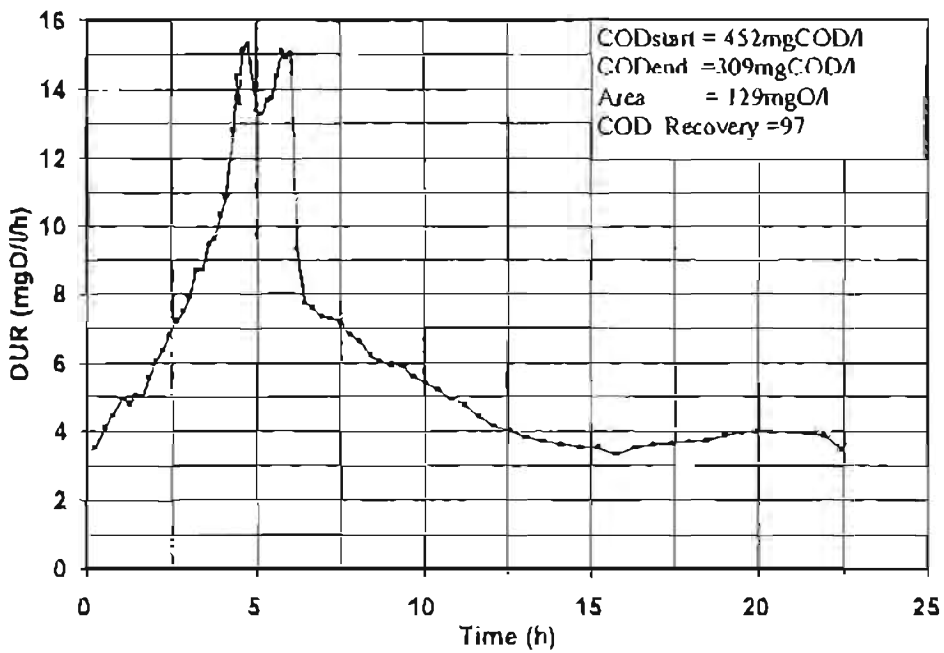


Fig 31a OUR graph for wastewater only batch test, 11-02, wastewater batch no. 19

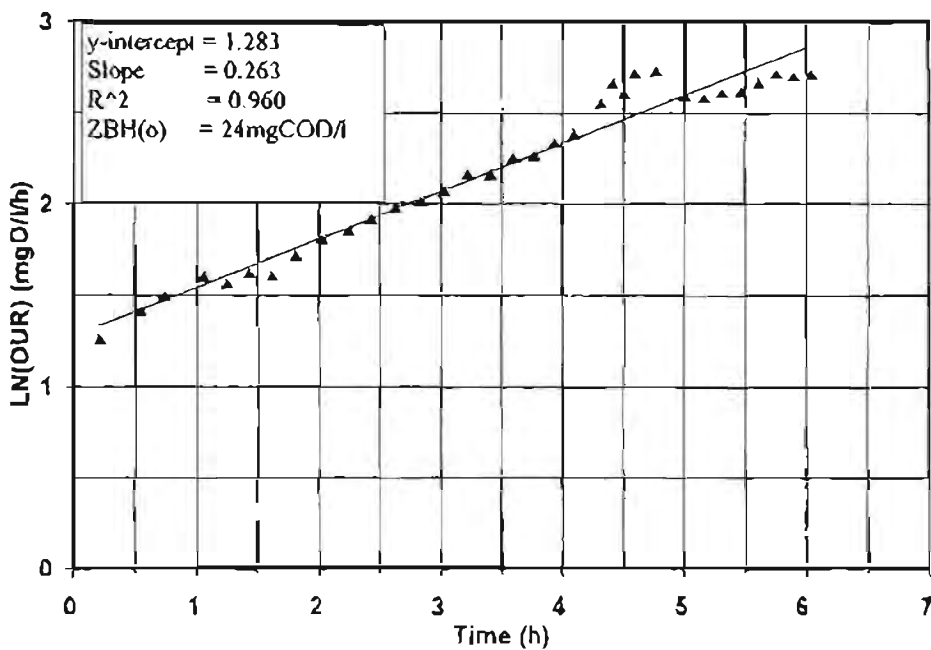


Fig A31b ln(OUR) graph for wastewater only, 11-02, wastewater batch no. 19

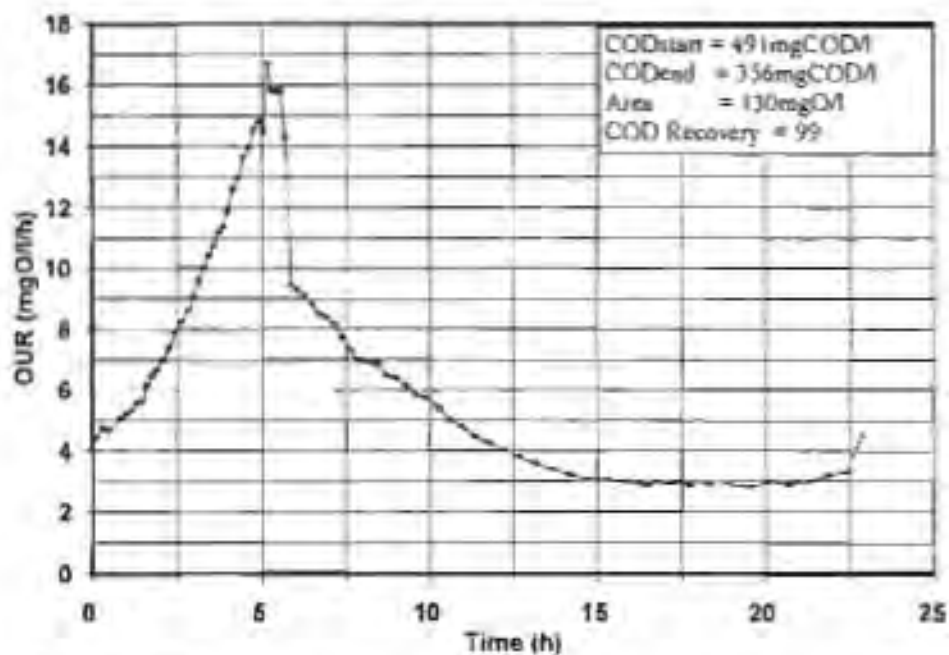


Fig A32a OUR graph for wastewater only batch test, 12-02, wastewater batch no. 19

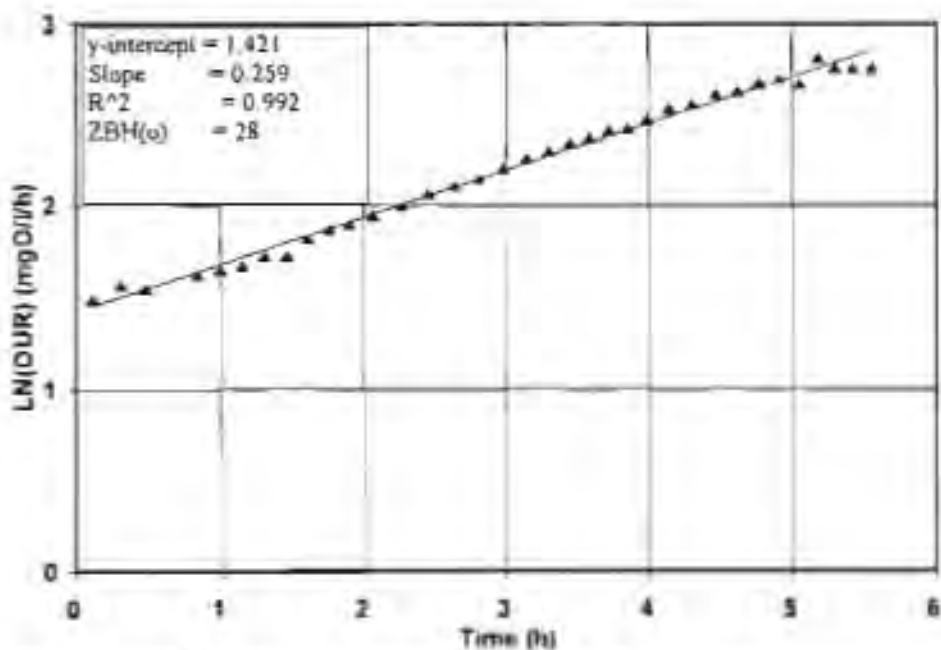


Fig A32b ln(OUR) graph for wastewater only batch test, 12-02, wastewater batch no. 19

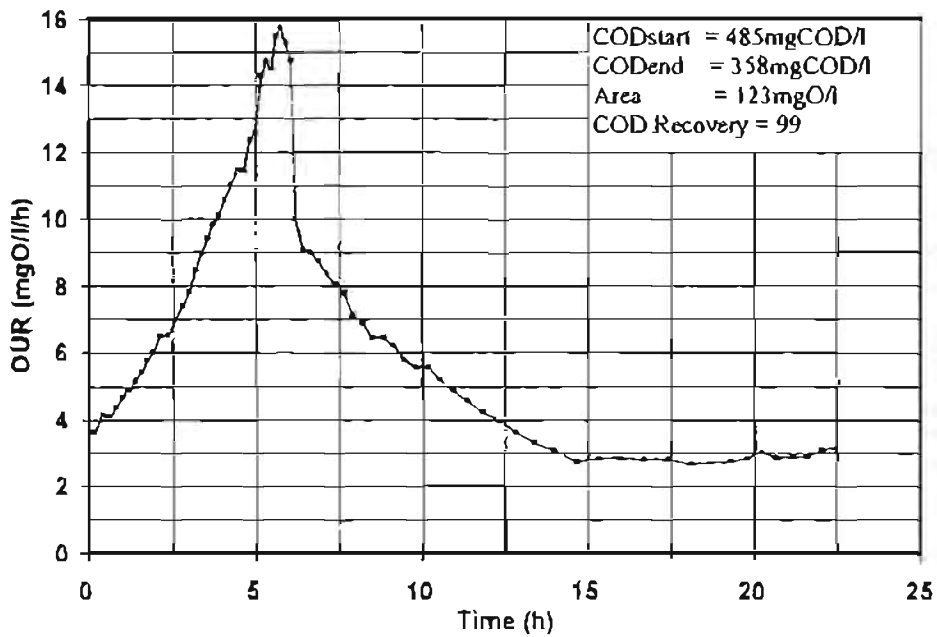


Fig A33a OUR graph for wastewater only batch test, 13-02, wastewater batch no. 19

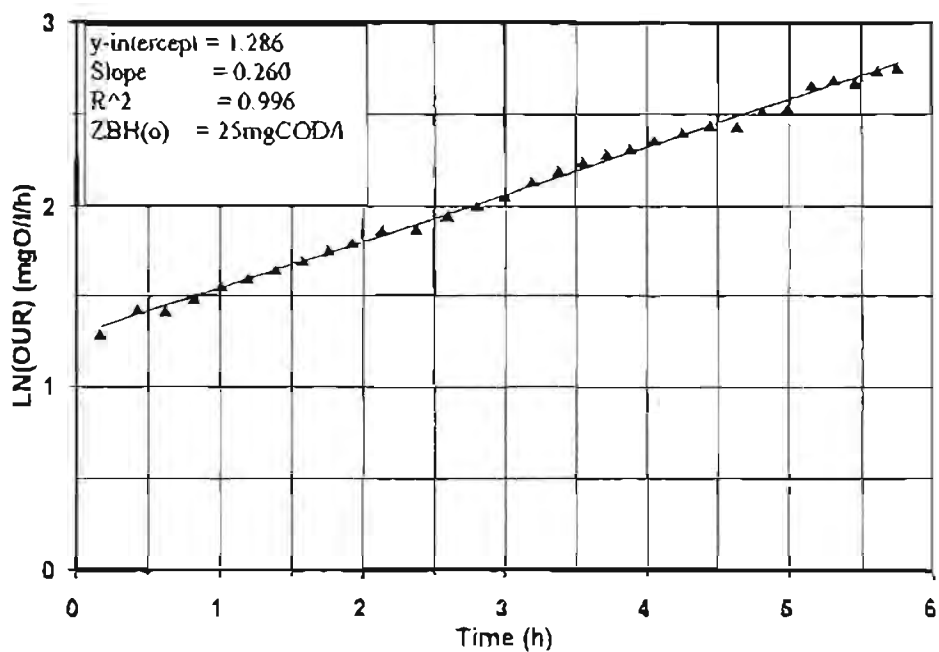


Fig A33b ln(OUR) graph for wastewater only batch test, 13-02, wastewater batch no. 19

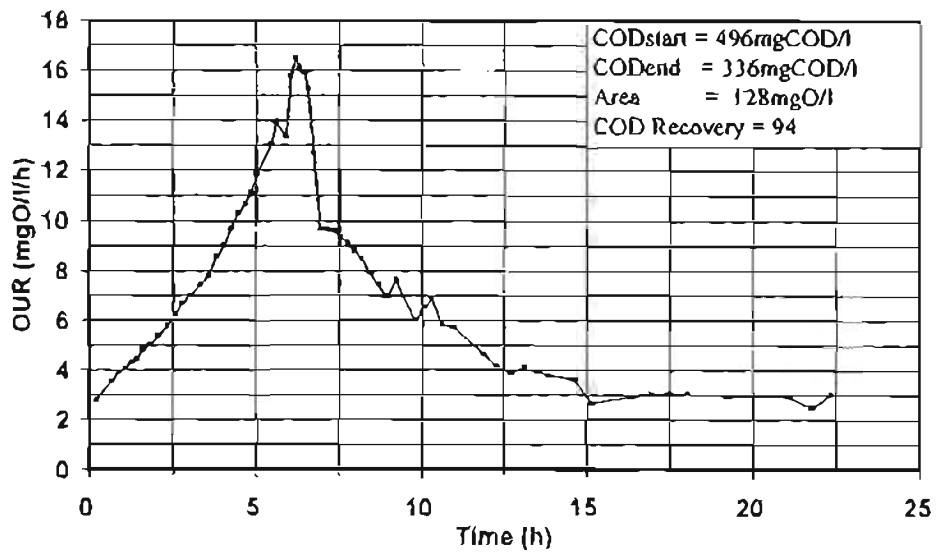


Fig A34a OUR graph for wastewater only batch test, 14-02, wastewater batch no. 19

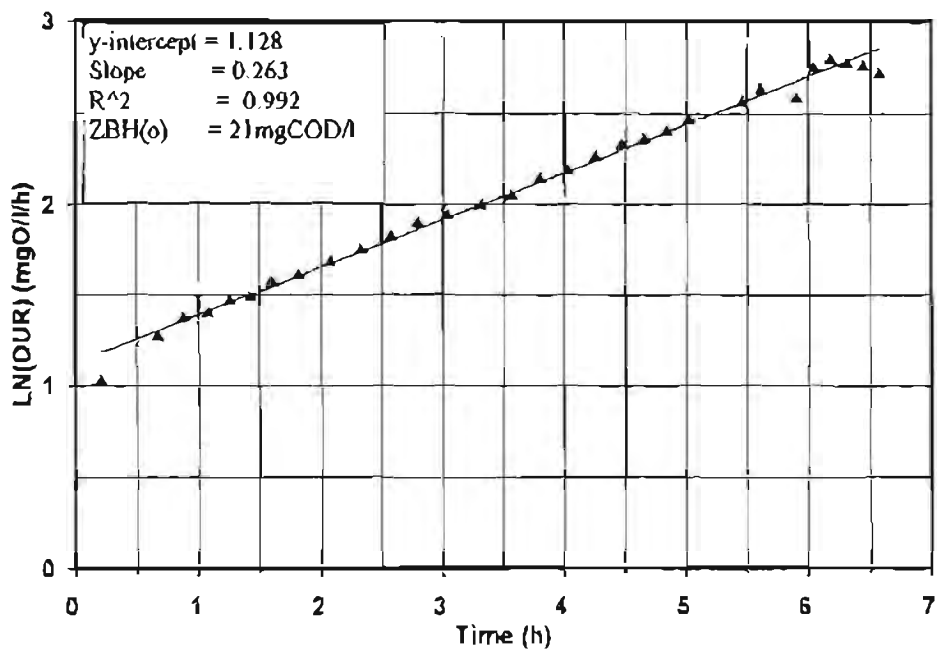


Fig A34b Ln(OUR) graph for wastewater only batch test, 14-02, wastewater batch no. 19

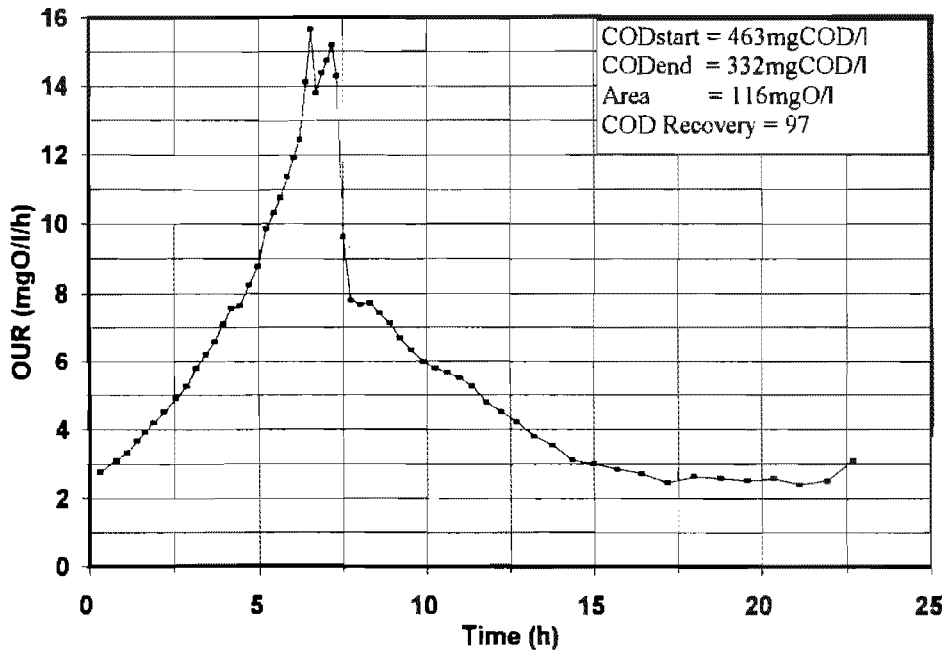


Fig A35a OUR graph for wastewater only batch test, 15-02, wastewater batch no. 19

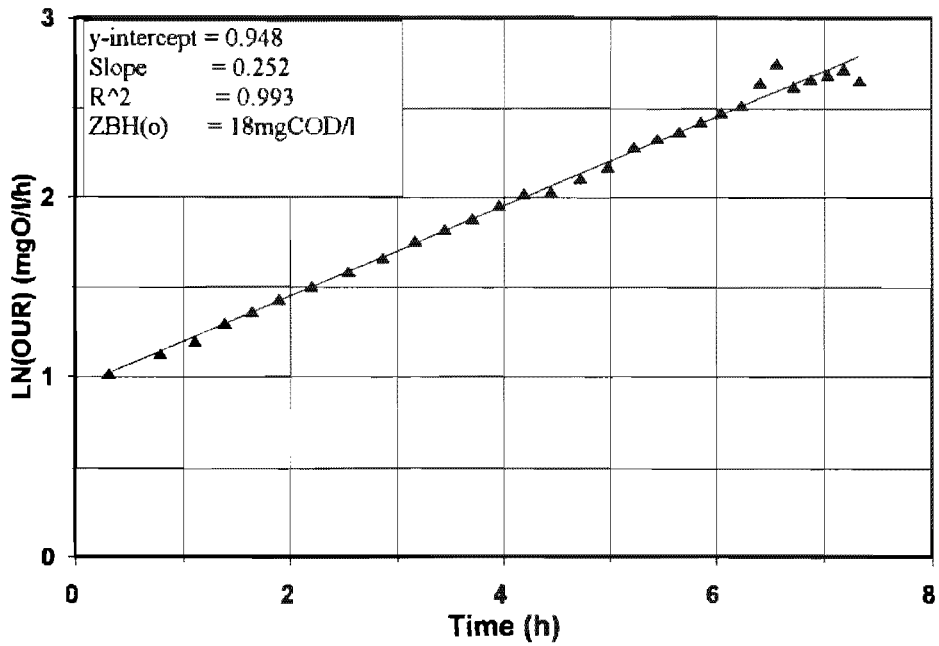


Fig A35b ln(OUR) graph for wastewater only batch test, 15-02, wastewater batch no. 19

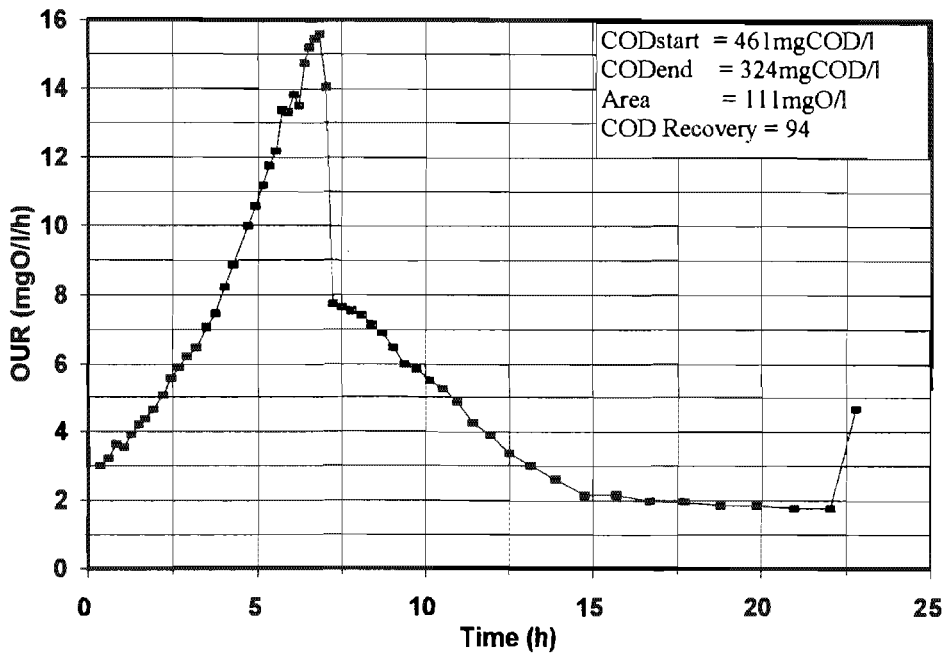


Fig A36a OUR graph for wastewater only batch test, 16-02, wastewater batch no. 19

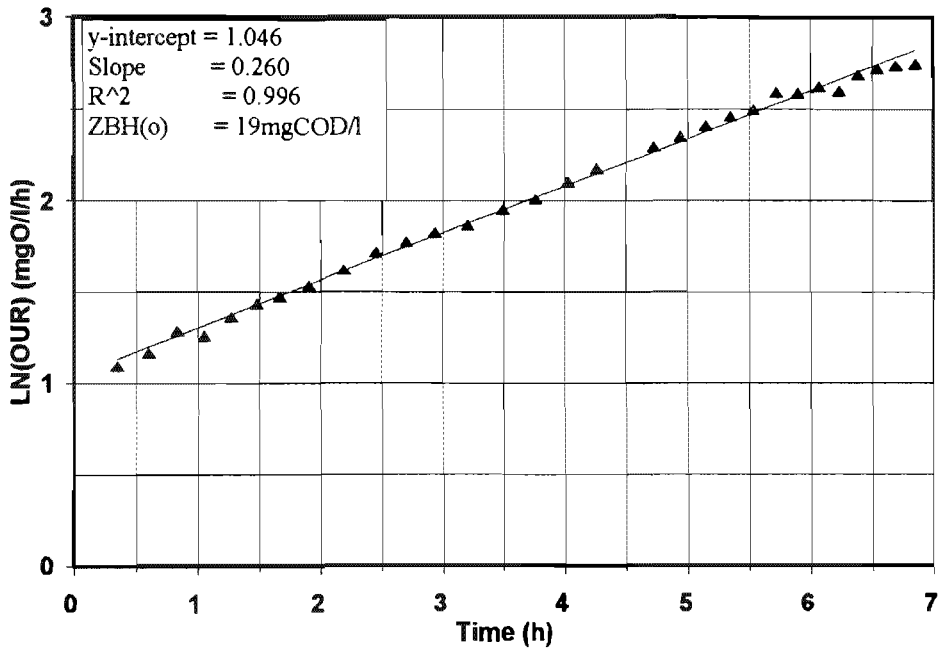


Fig A36b ln(OUR) graph wastewater batch test only, 16-02, wastewater batch no. 19

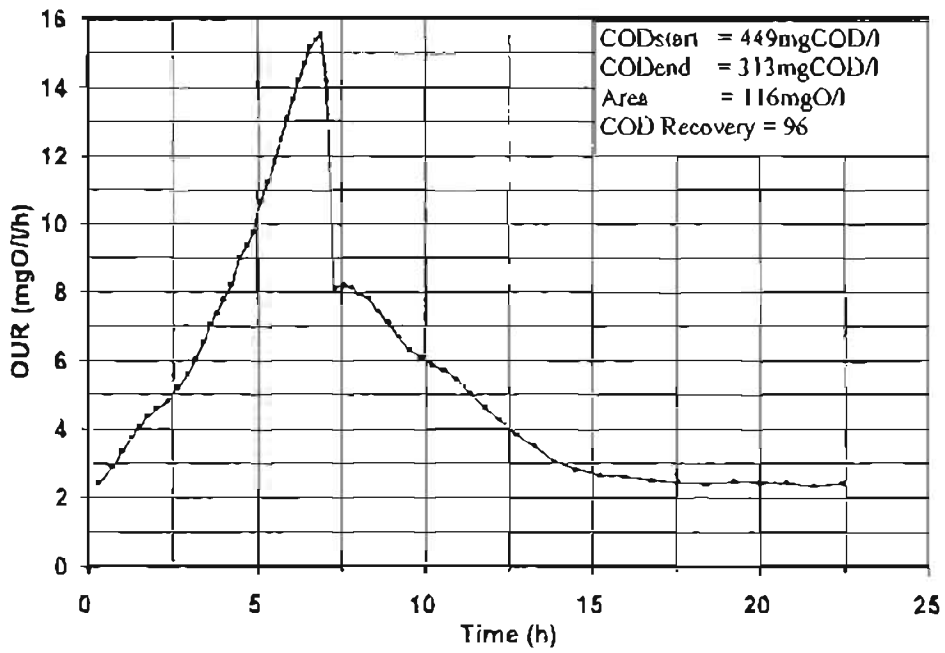


Fig A37a OUR graph for wastewater only batch test, 17-02, wastewater batch no 19

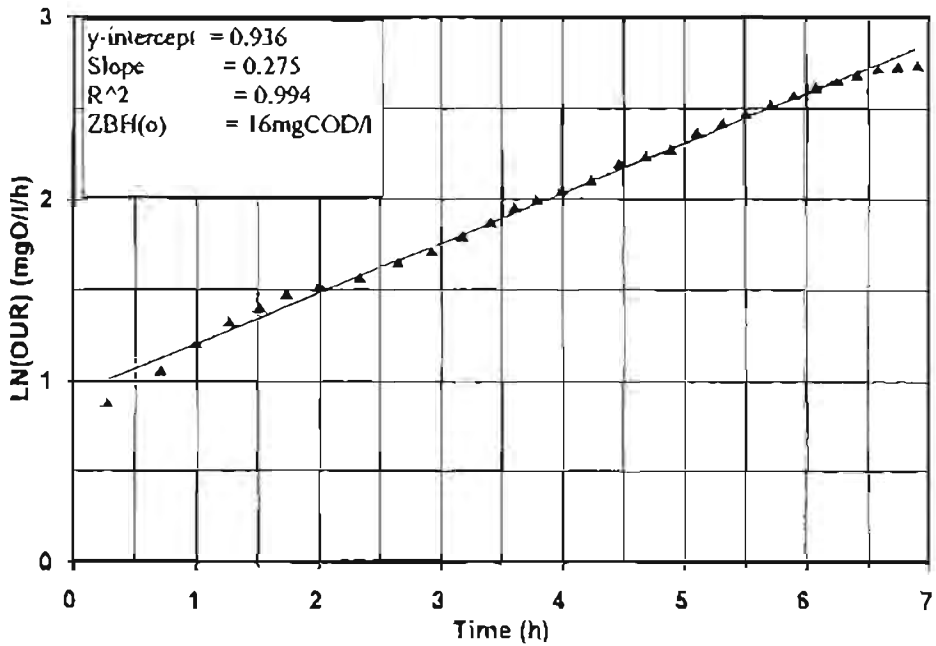


Fig A37b LN(OUR) graph for wastewater only batch test, 17-02, wastewater batch no.19

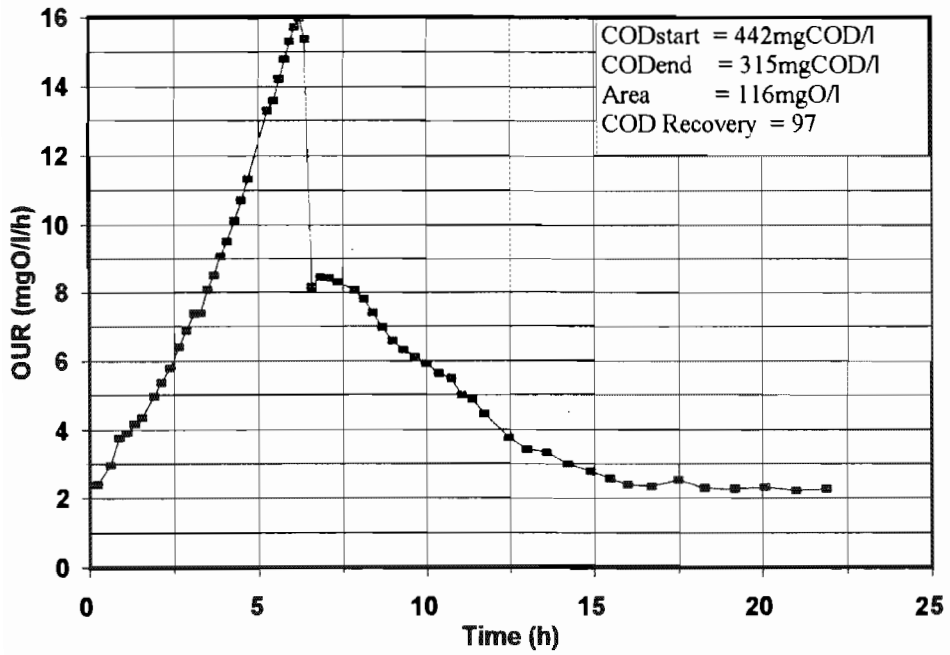


Fig A38a OUR graph for wastewater only batch test, 18-02, wastewater batch no. 19

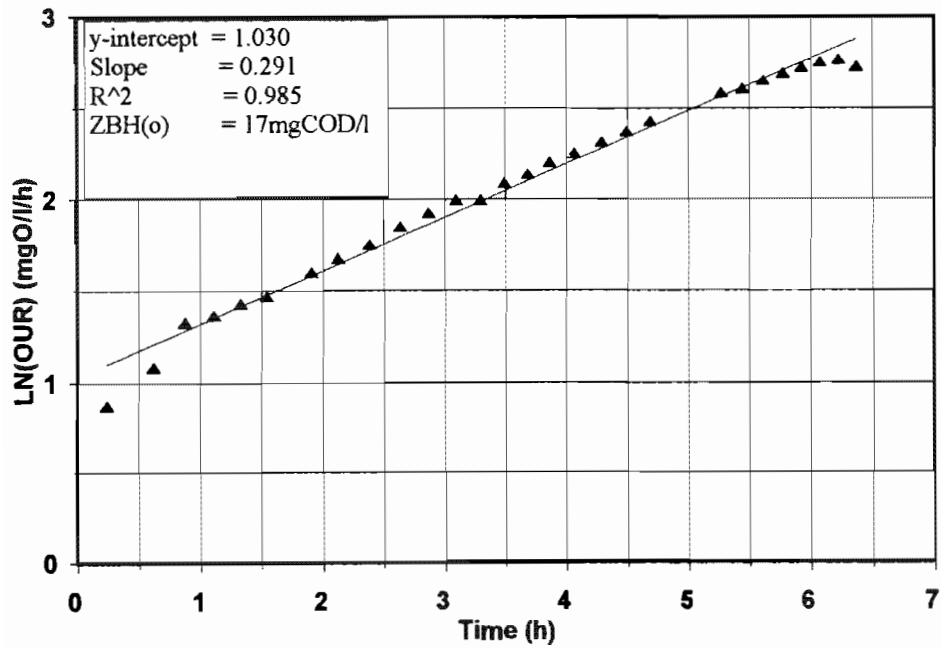


Fig A38b ln(OUR) graph for wastewater only batch test, 18-02, wastewater batch no.19

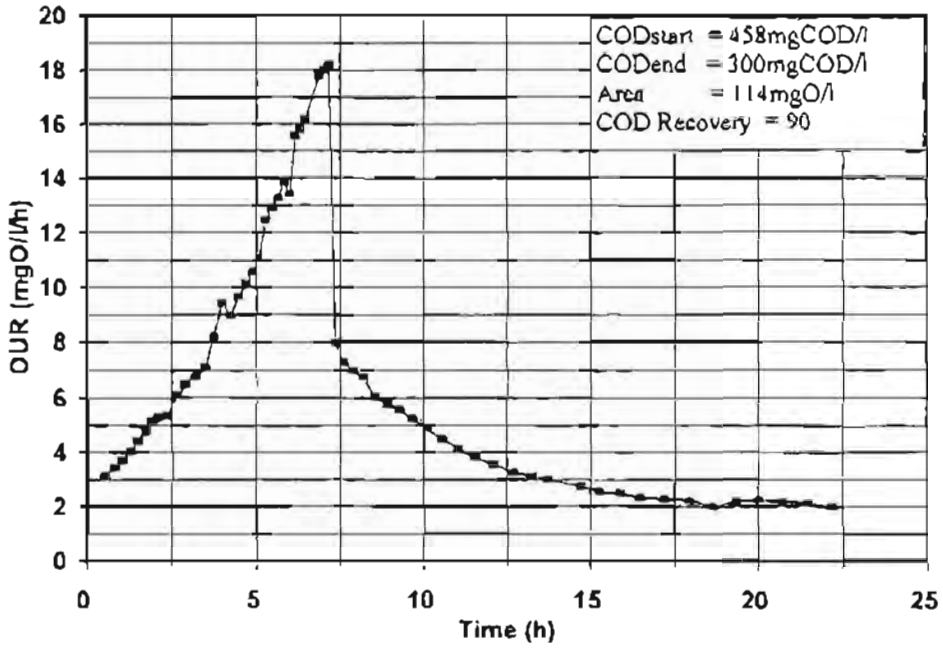


Fig A39a OUR graph for wastewater only batch test, 19-02, wastewater batch no. 19

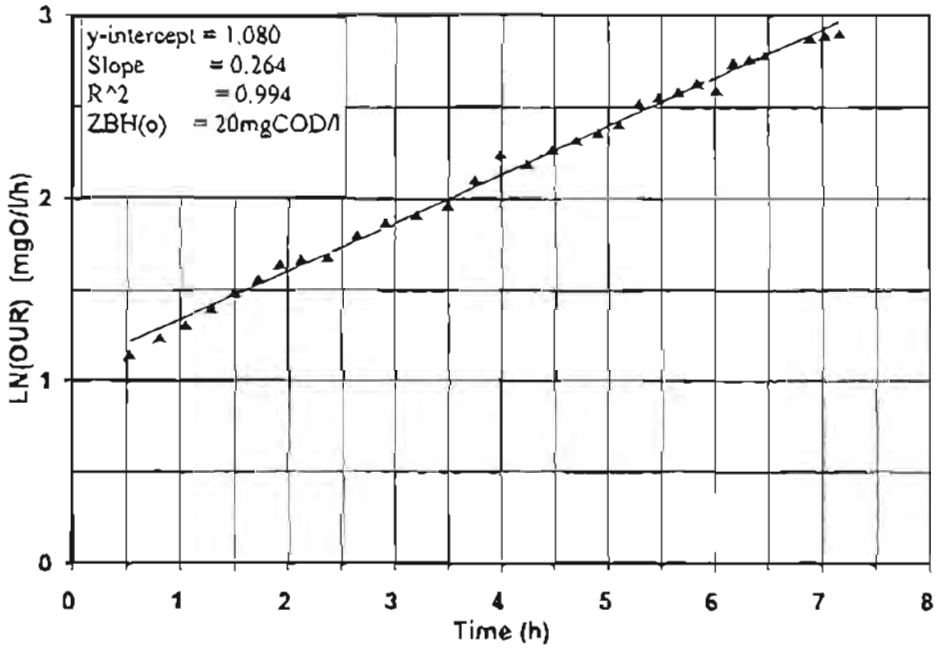


Fig A39b Ln(OUR) graph for wastewater only batch test, 19-02, wastewater batch no. 19

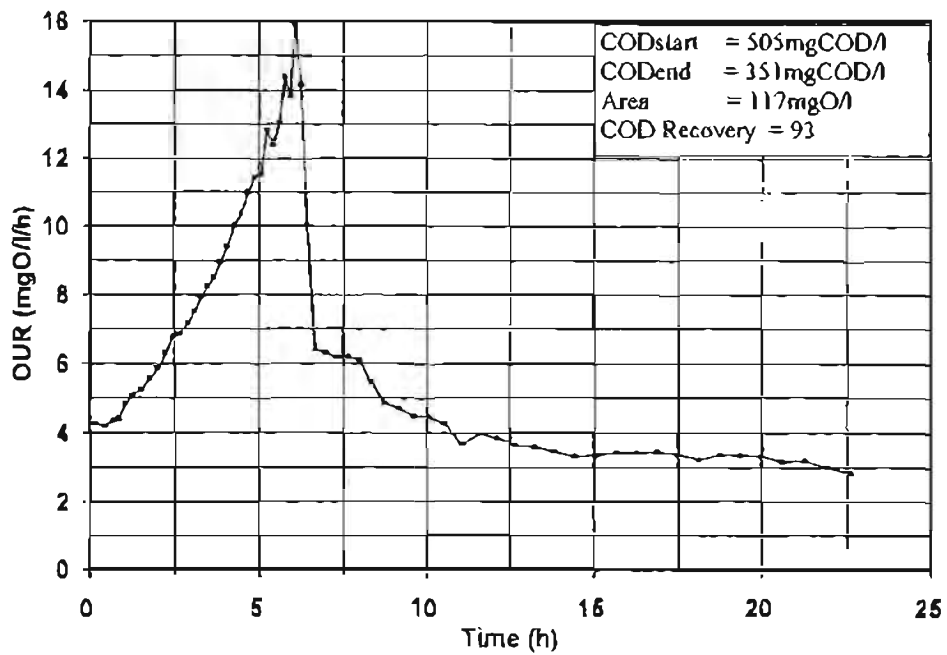


Fig A40a OUR graph for wastewater only batch test, 24-02, wastewater batch no. 20

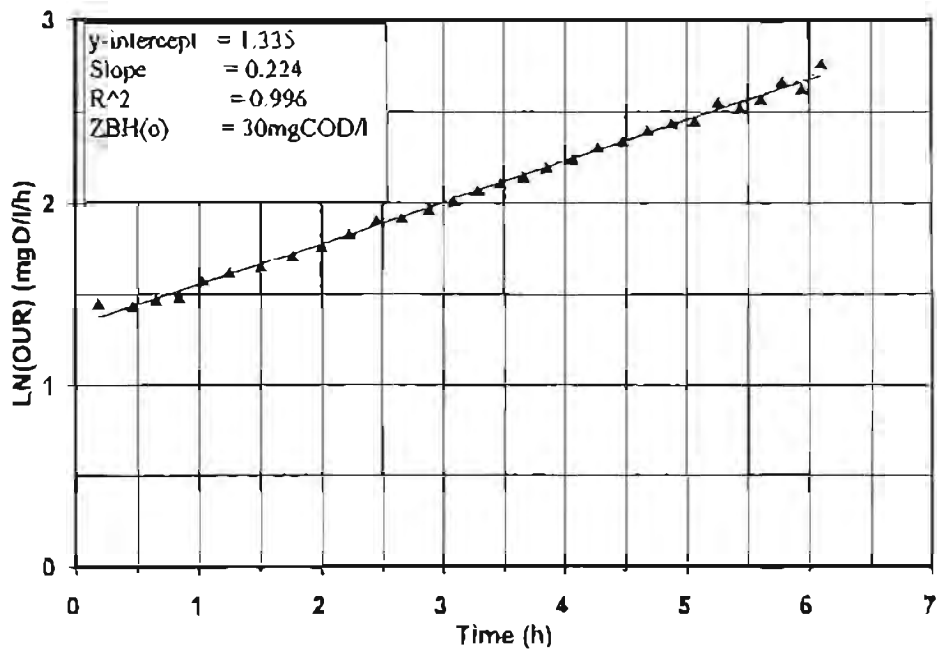


Fig A40b ln(OUR) graph for wastewater only batch test, 24-02, wastewater batch no. 20

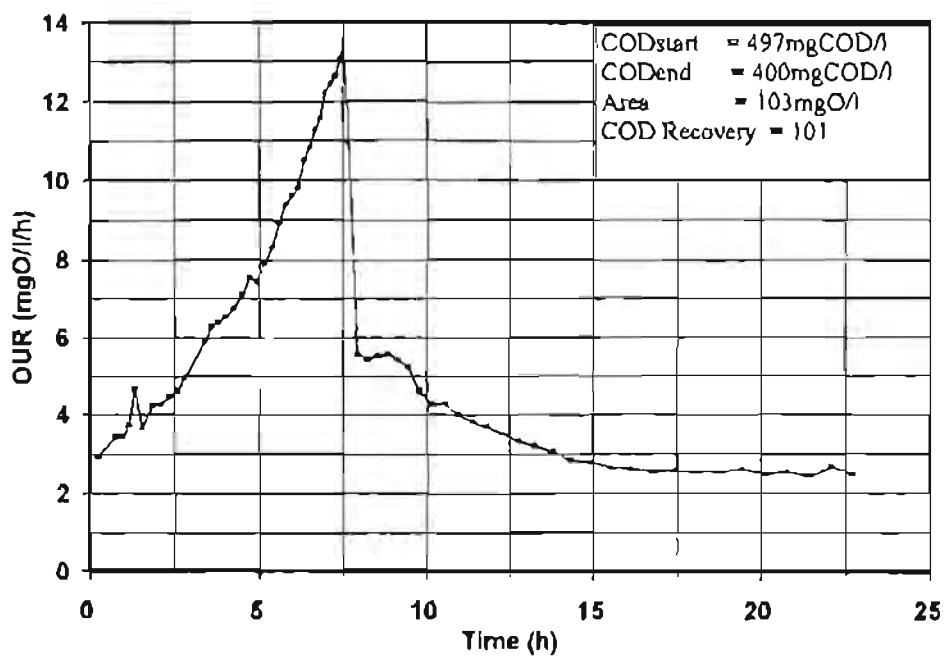


Fig A41a OUR graph for wastewater only batch test, 25-02, wastewater batch no. 20



Fig A41b ln(OUR) graph for wastewater only batch test, 25-02, wastewater batch no. 20

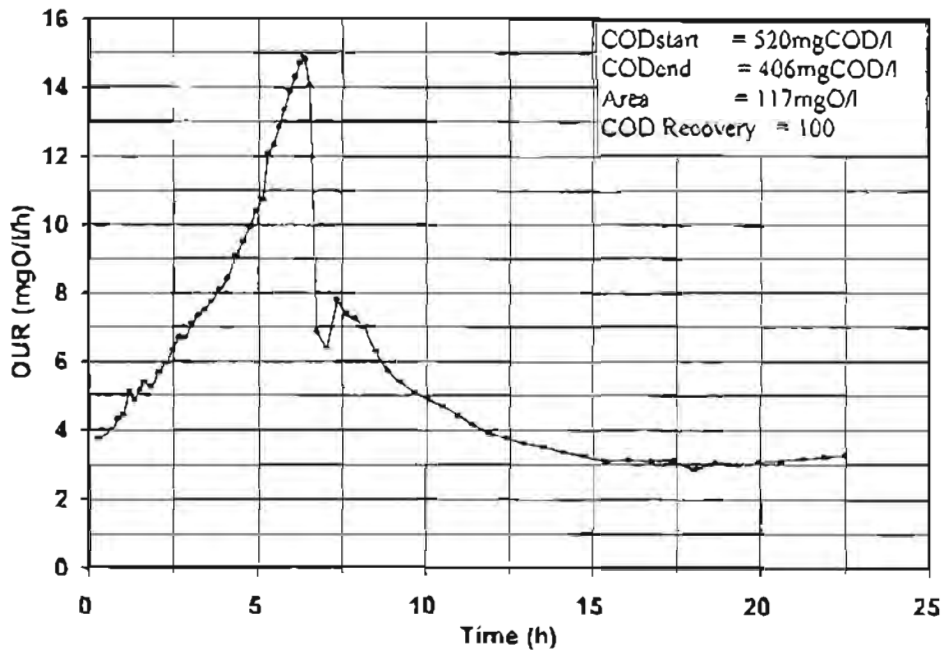


Fig A42a OUR graph for wastewater only batch test, 26-02, wastewater batch no.20

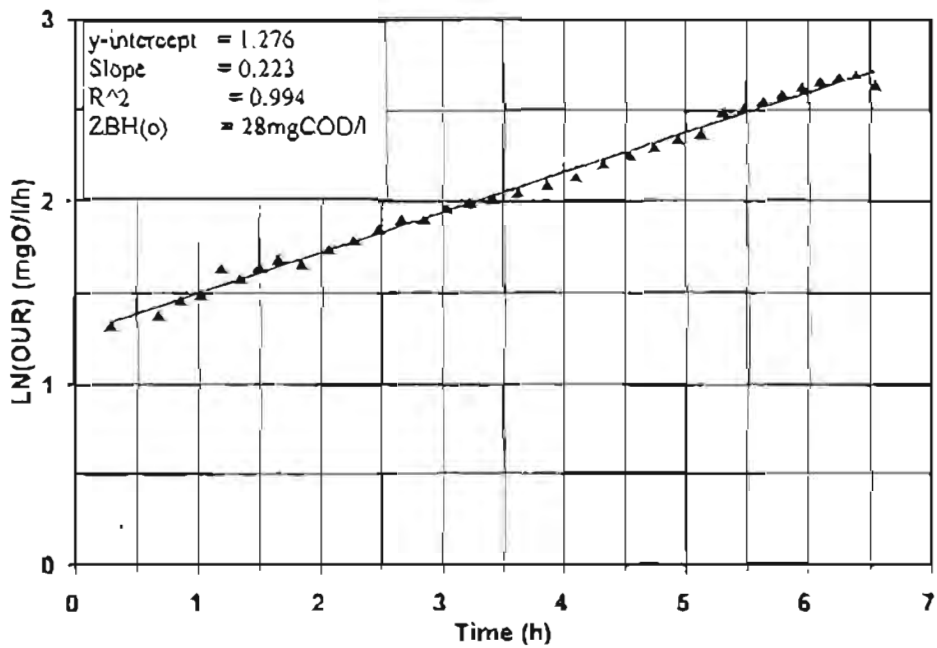


Fig A42b ln(OUR) graph for wastewater only batch test, 26-02, wastewater batch no. 20

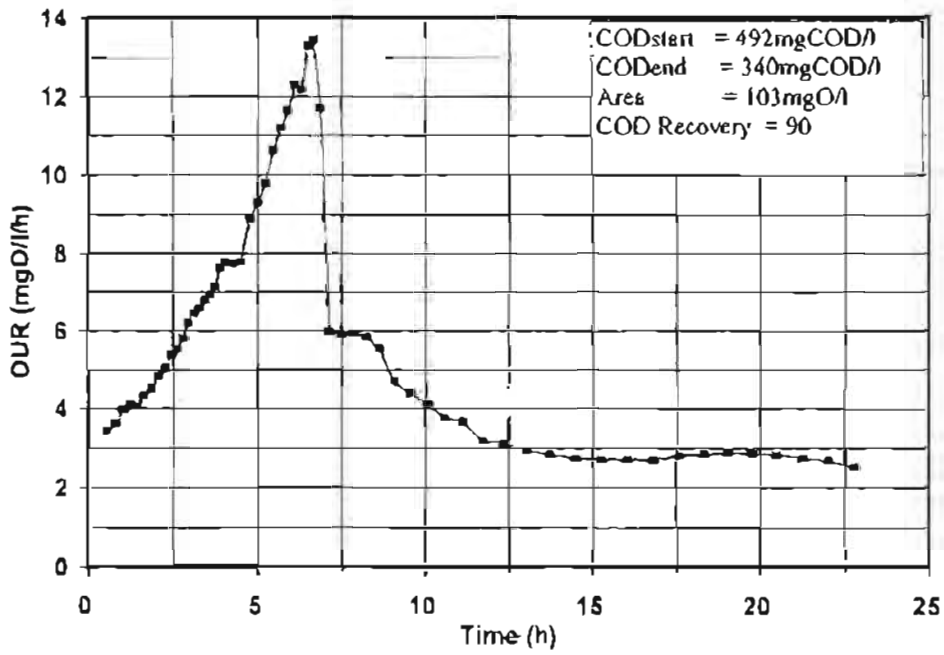


Fig A43a OUR graph for wastewater only batch test, 27-02, wastewater batch no 20

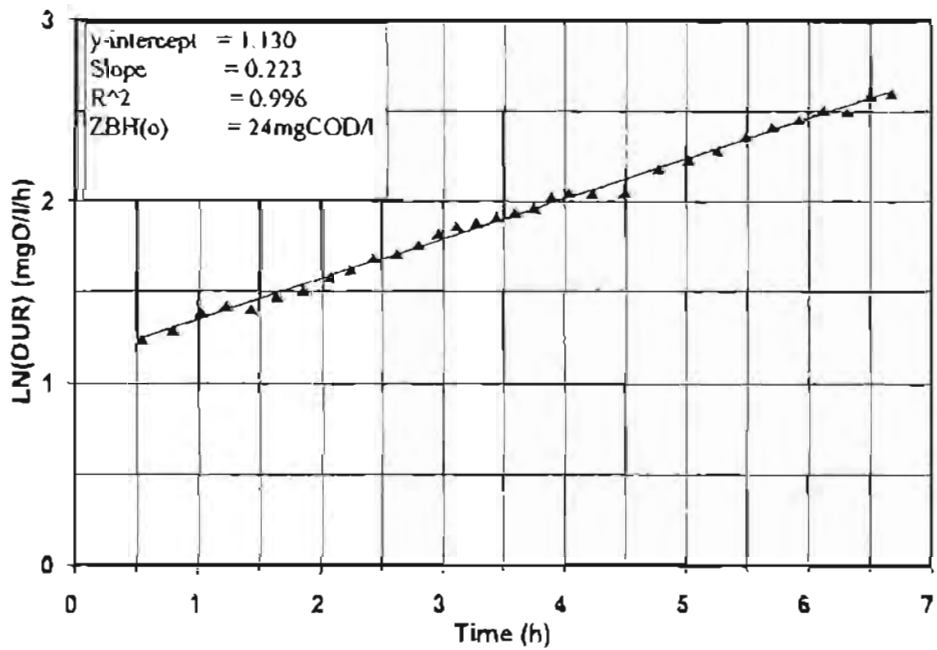


Fig A43b ln(OUR) graph for wastewater only batch test, 27-02, wastewater batch no.20

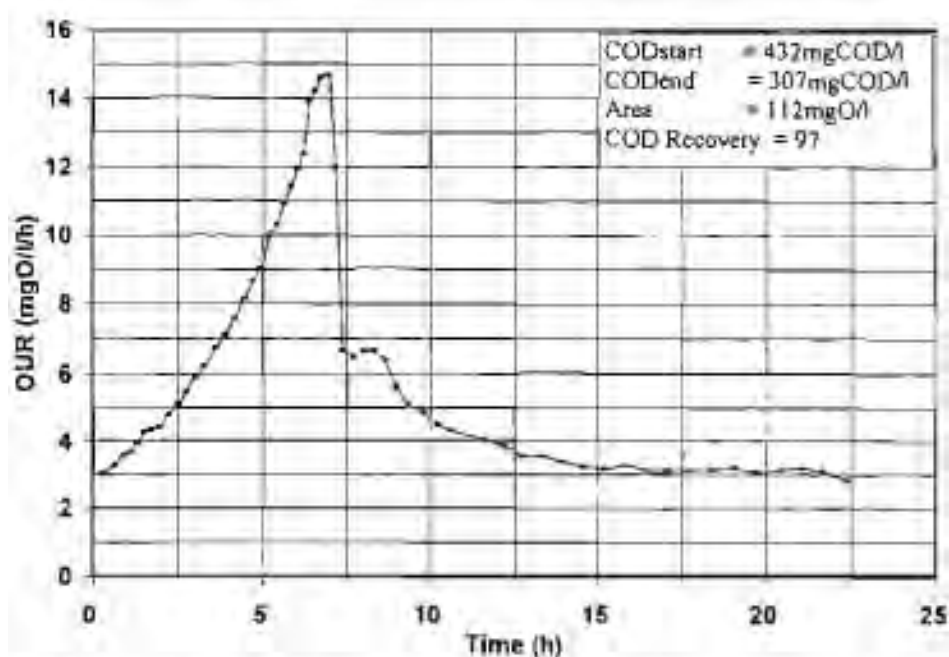


Fig A44a OUR graph for wastewater only batch test, 29-02, wastewater batch no. 20

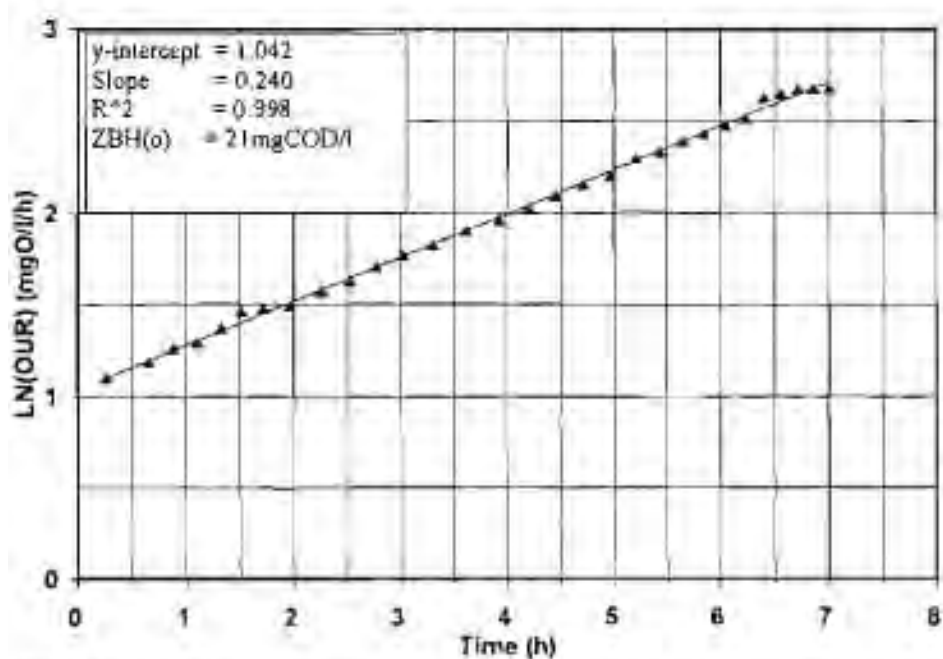


Fig A44b ln(OUR) graph for wastewater only batch test, 29-02, wastewater batch no. 20

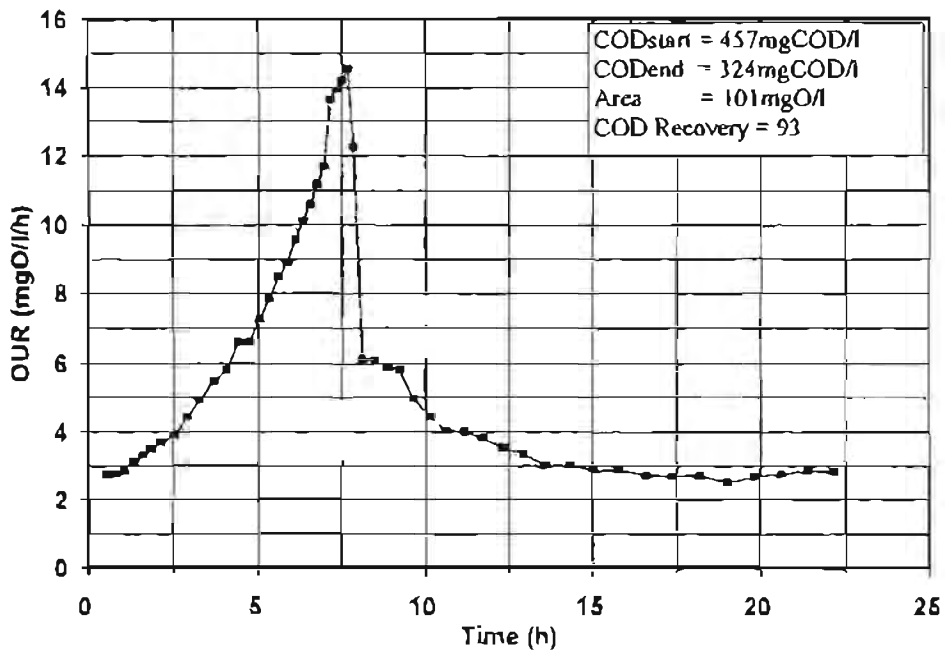


Fig. A45a OUR graph for wastewater only batch test, 01-03, wastewater batch no. 20

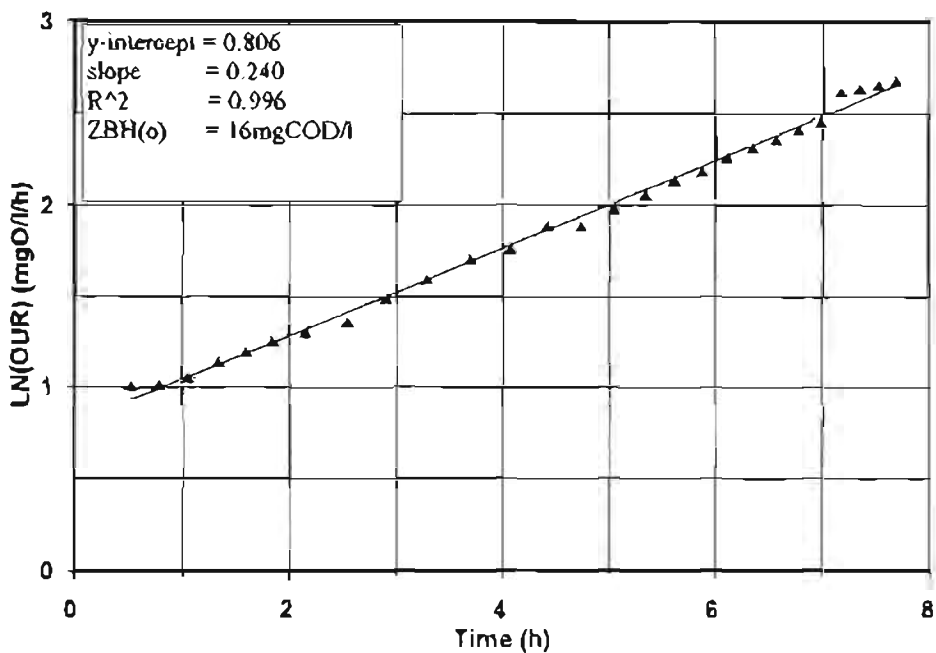


Fig A45b Ln(OUR) graph for wastewater only batch test, 01-03, wastewater batch no. 20

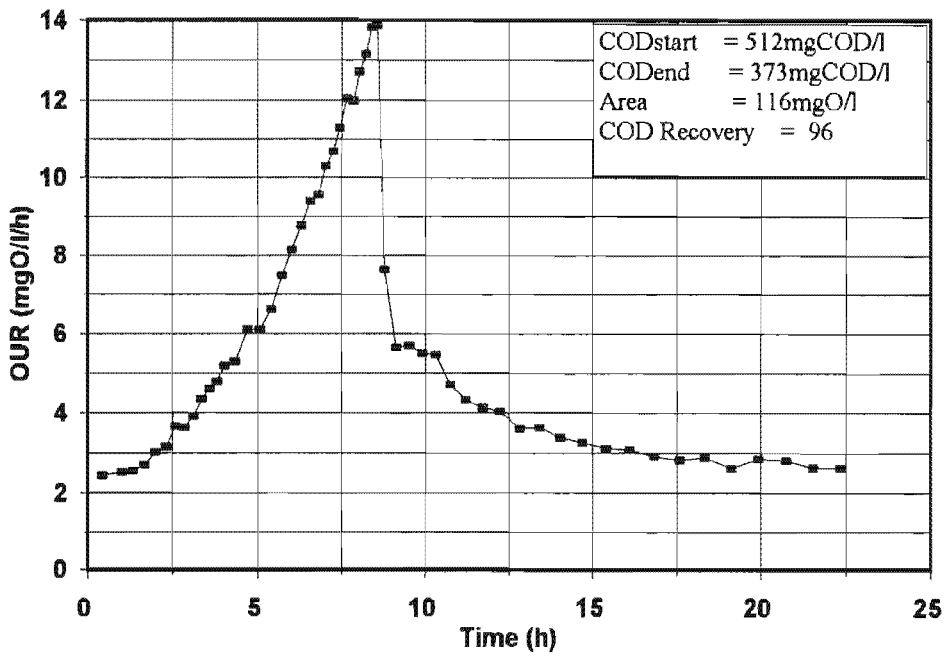


Fig A46a OUR graph for wastewater only batch test, 02-03, wastewater batch no.20

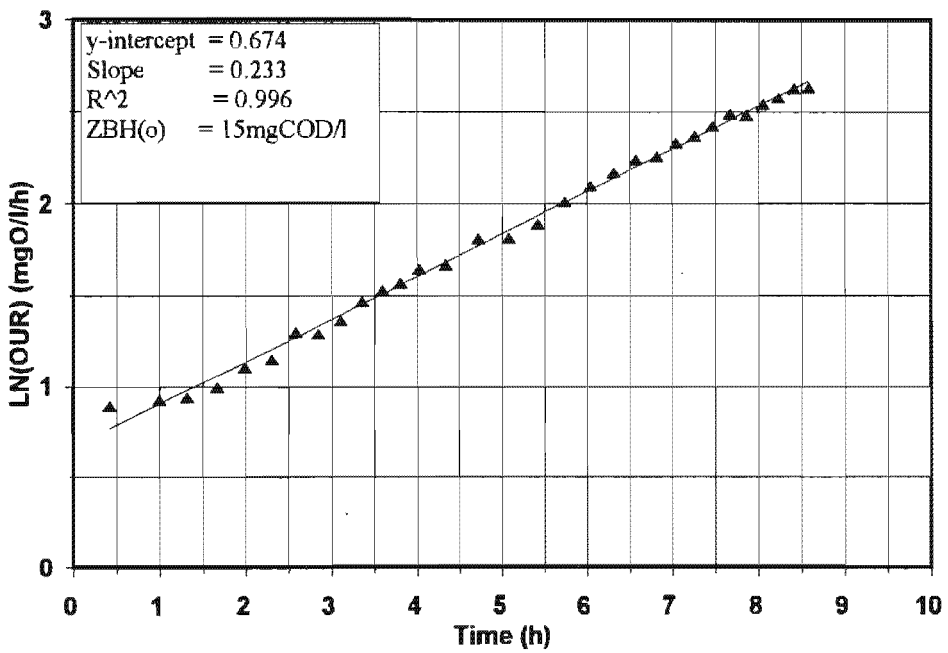


Fig A46b ln(OUR) graph for wastewater only batch test, 02-03, wastewater batch no. 20

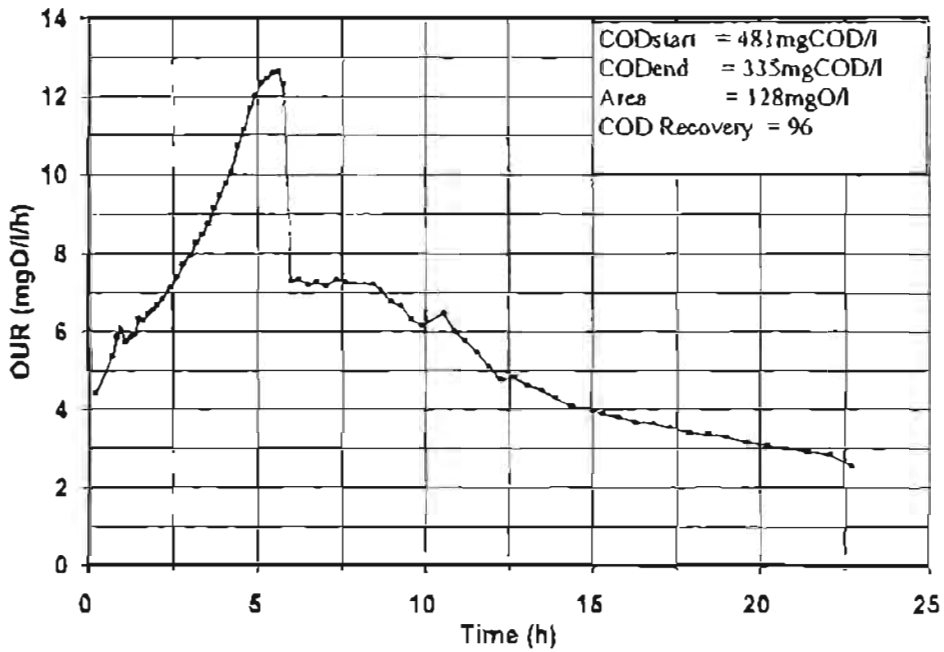


Fig A47a OUR graph for wastewater only batch test, 04-03, wastewater batch no. 20

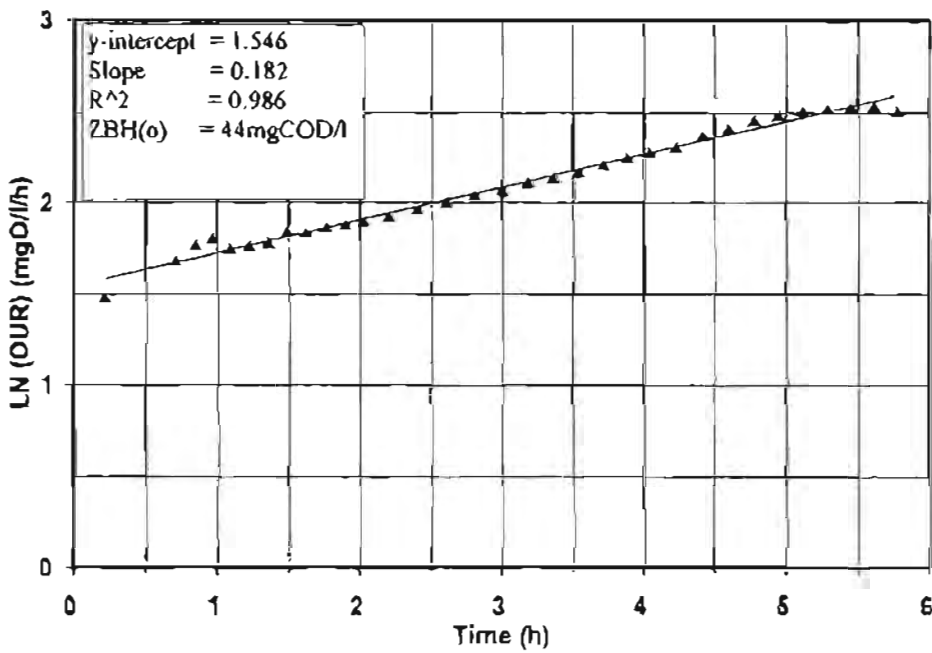


Fig A47b Ln(OUR) graph for wastewater only batch test, 04-03, wastewater batch no. 20

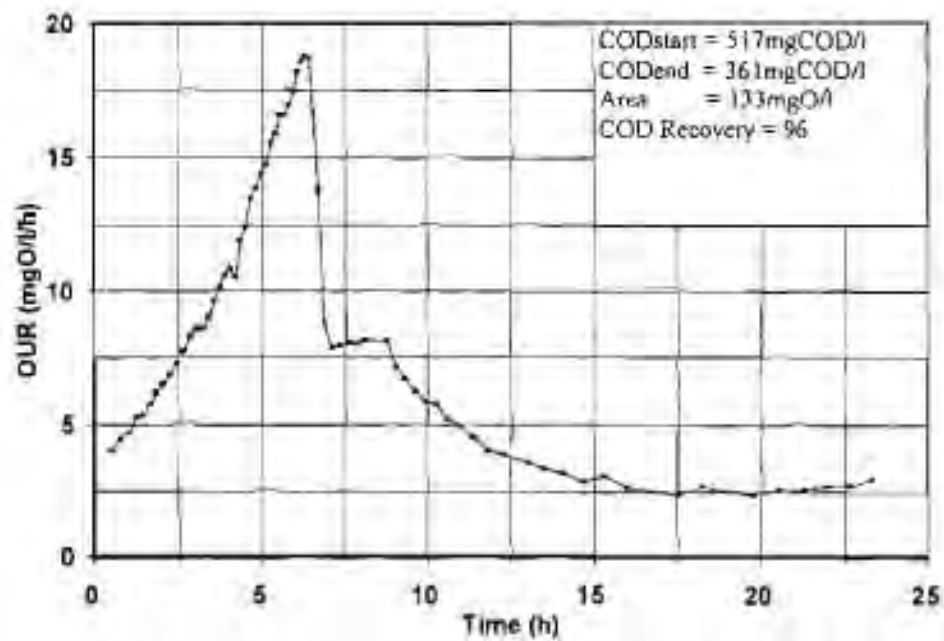


Fig A48a OUR graph for wastewater only batch test, 11-03, wastewater batch no. 21

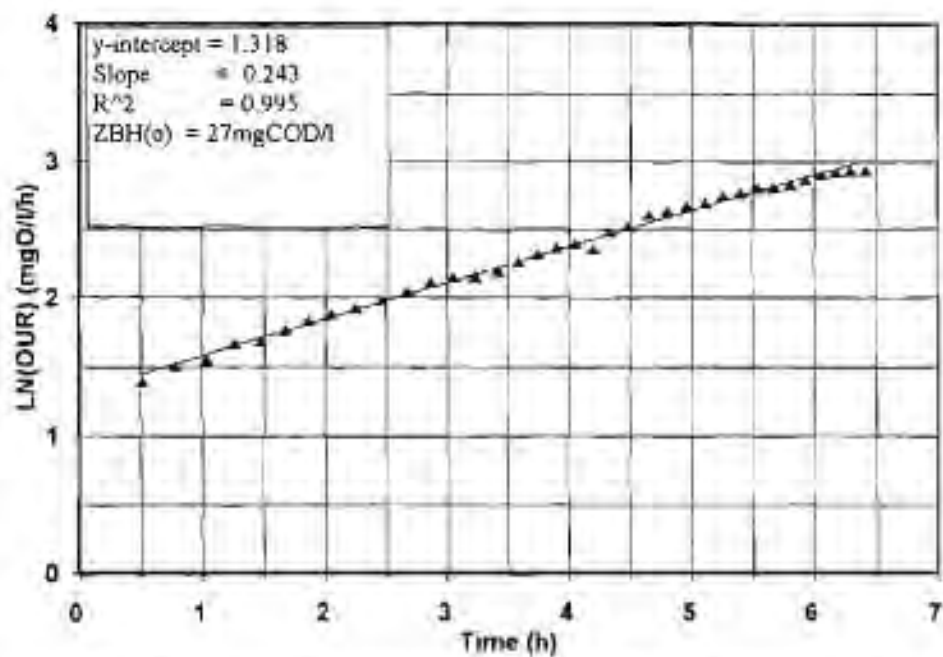


Fig A48b ln(OUR) graph for wastewater only batch test, 11-03, wastewater batch no. 21

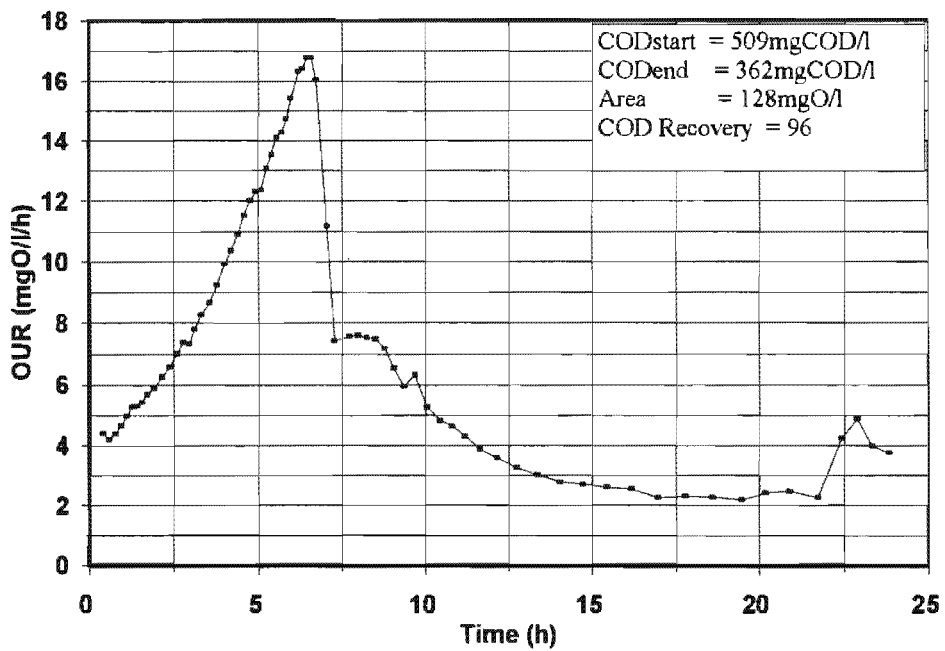


Fig A49a OUR graph for wastewater only batch test, 12-03, wastewater batch no. 21

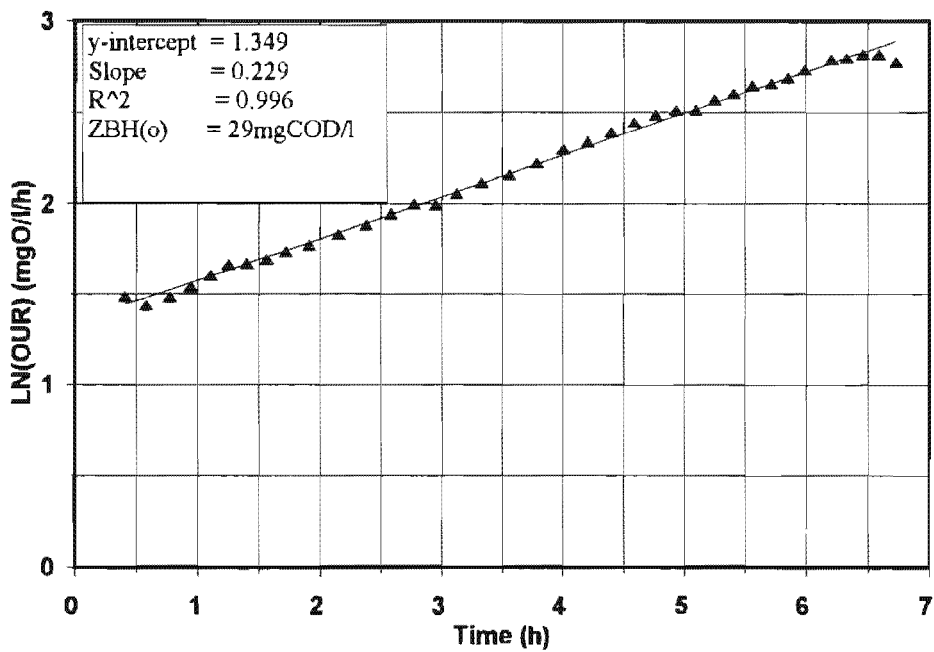


Fig A49b ln(OUR) graph for wastewater only batch test, 12-03, wastewater batch no. 21

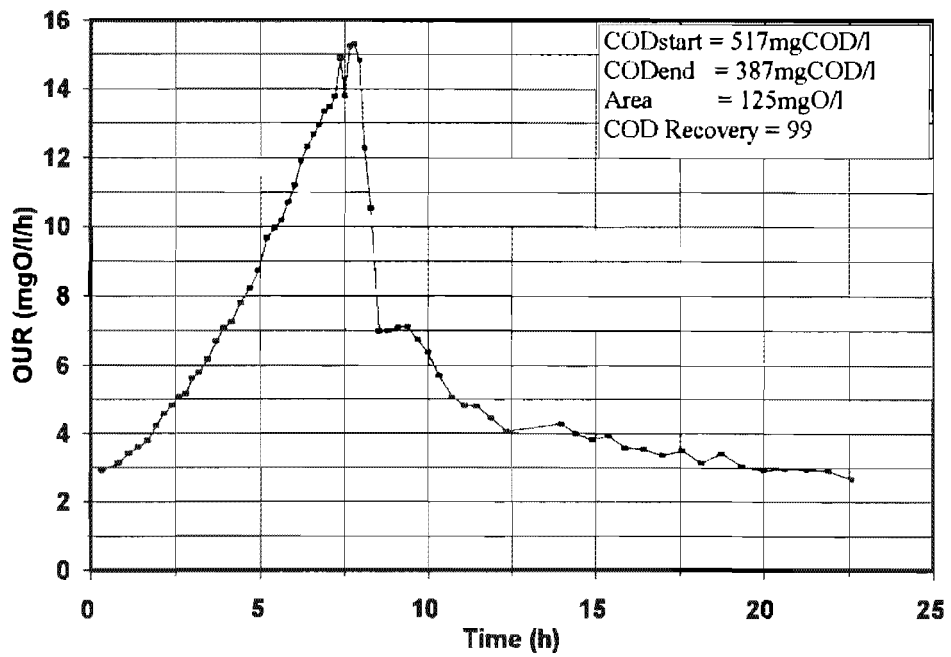


Fig A50a OUR graph for wastewater only batch test, 14-03, wastewater batch no. 21

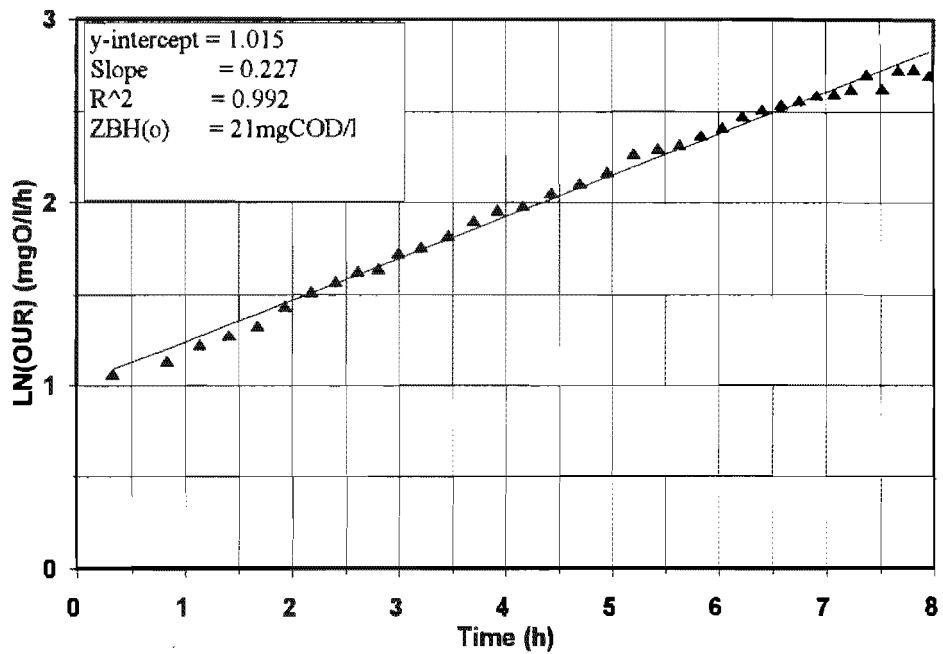


Fig A50b ln(OUR) graph for wastewater only batch test, 14-03, wastewater batch no.21

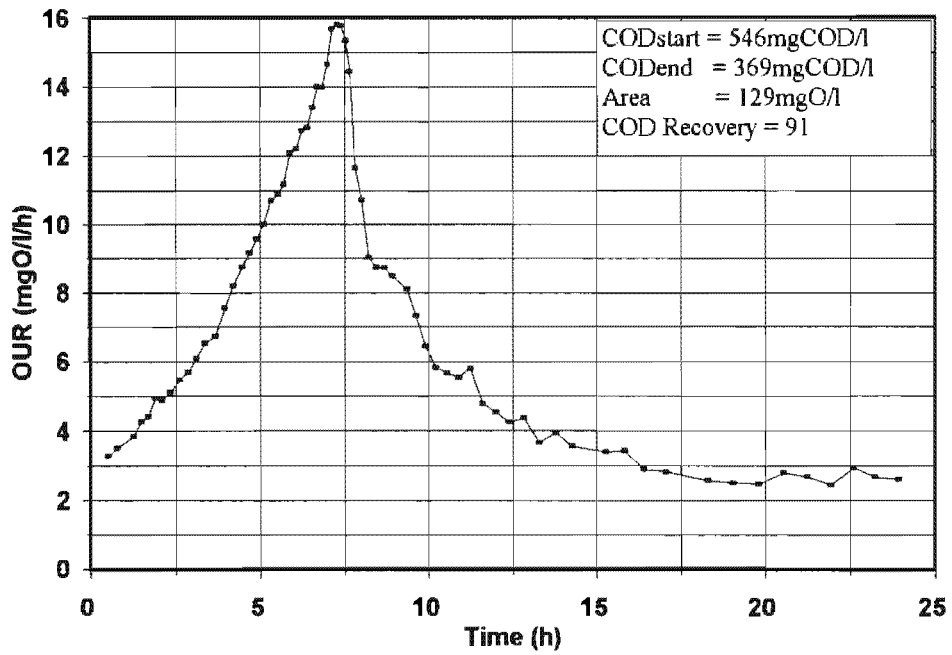


Fig A51a OUR graph for wastewater only batch test, 15-03, wastewater batch no. 21

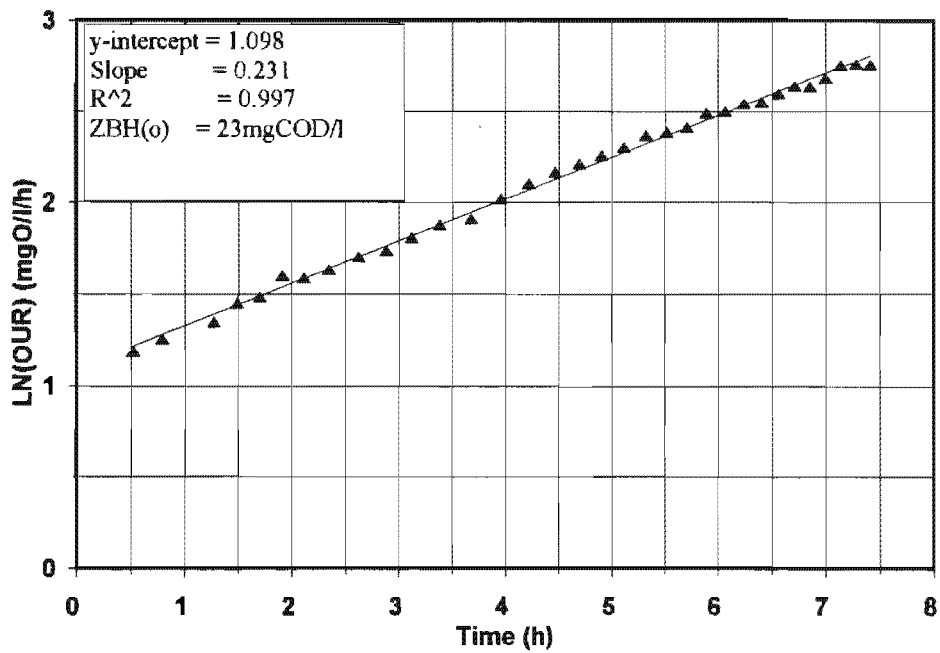


Fig A51b ln(OUR) graph for wastewater only batch test, 15-03, wastewater batch no.21

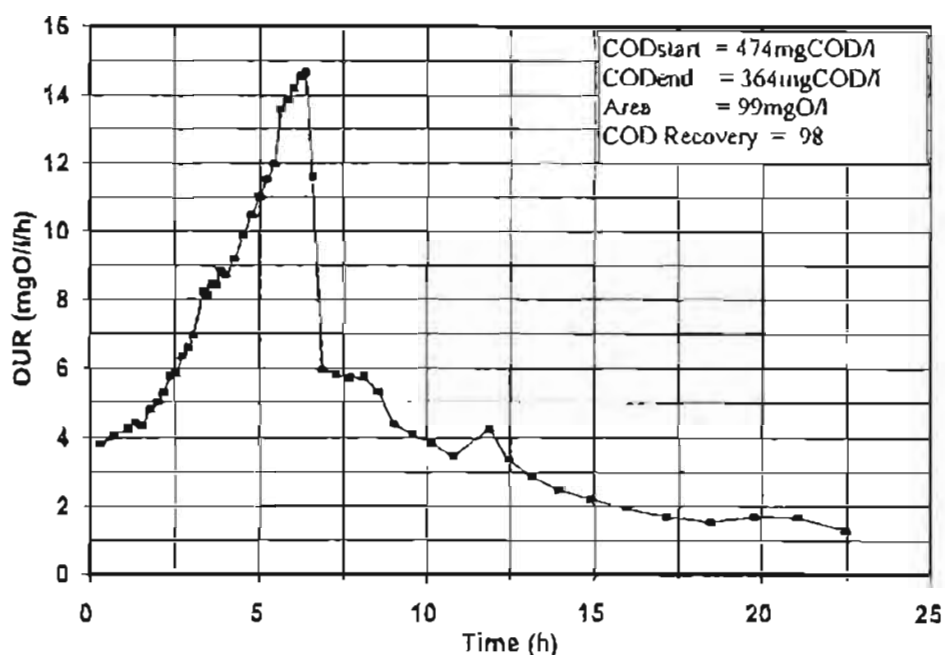


Fig A52a OUR graph for wastewater only batch test, 06-04, wastewater batch no. 22

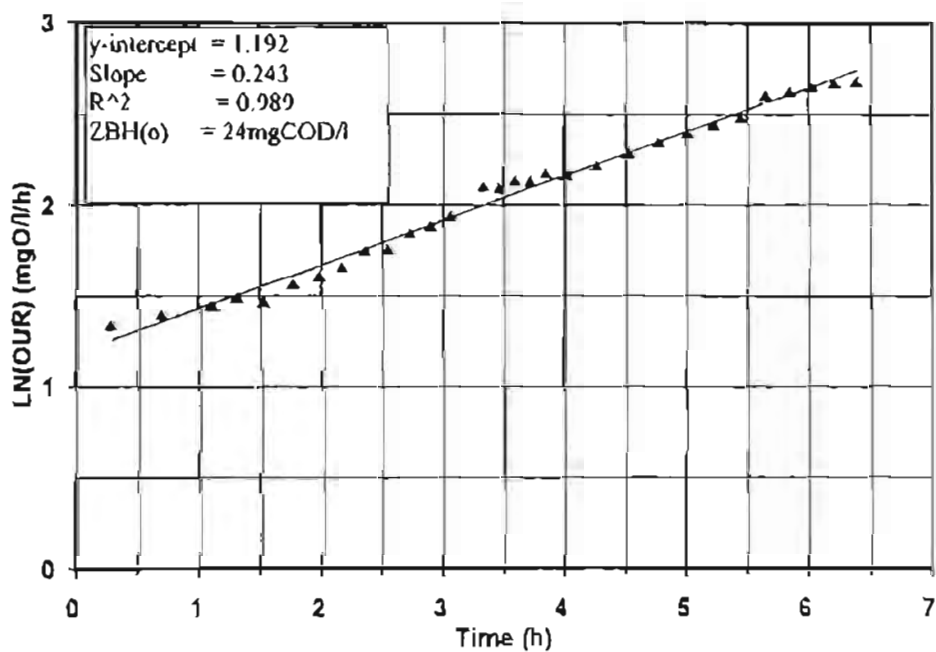


Fig A52b ln(OUR) graph for wastewater only batch test, 06-04, wastewater batch no. 22

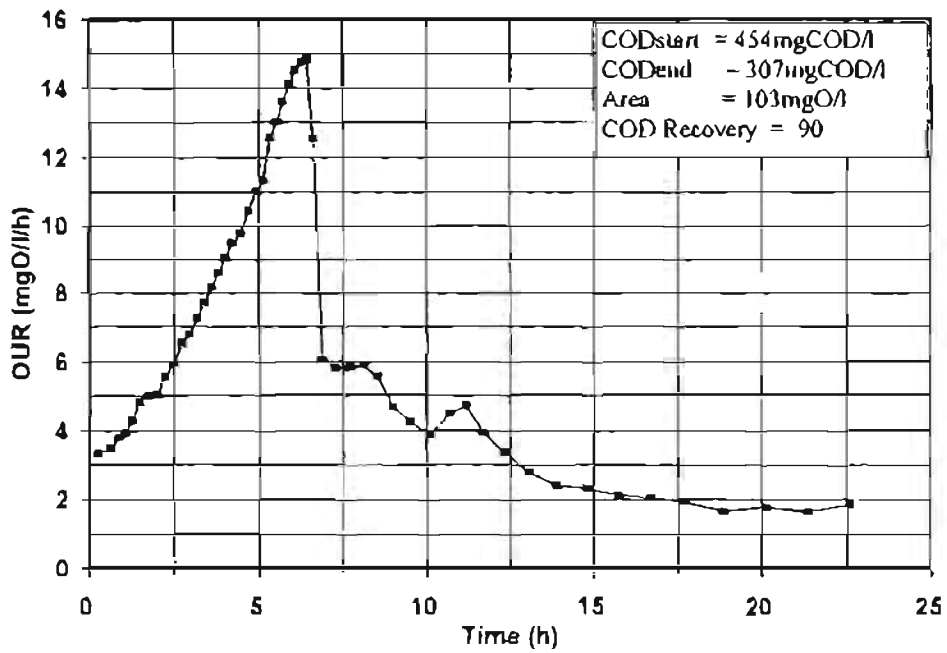


Fig A53a OUR graph for wastewater only batch test, 07-04, wastewater batch no. 22

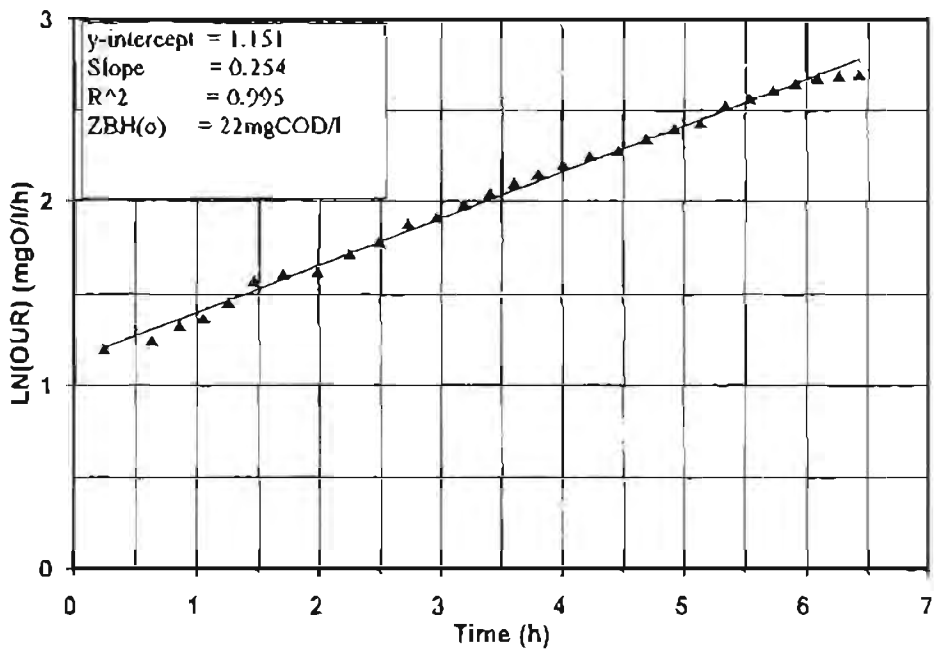


Fig A53b Ln(OUR) graph for wastewater only batch test, 07-04, wastewater batch no. 22

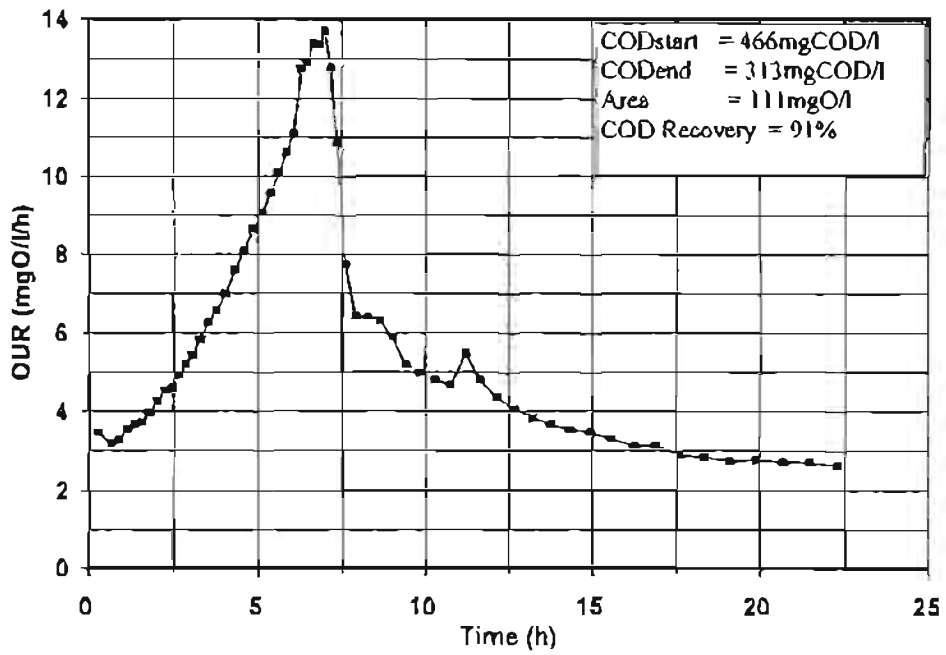


Fig A54a OUR graph for wastewater only batch test, 08-04, wastewater batch no. 22

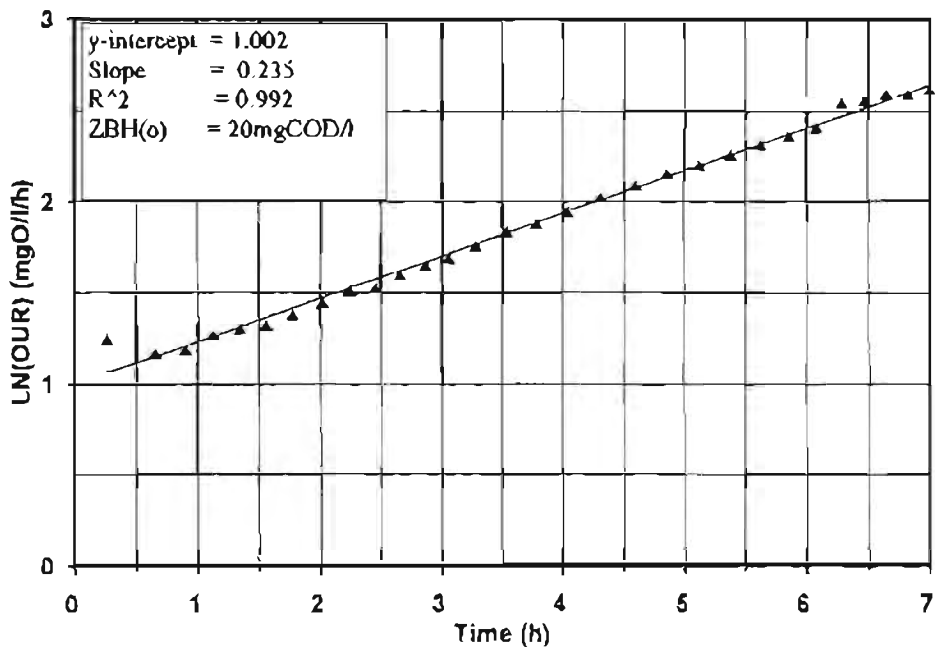


Fig A54b ln(OUR) graph for wastewater only batch test, 08-04, wastewater batch no.22

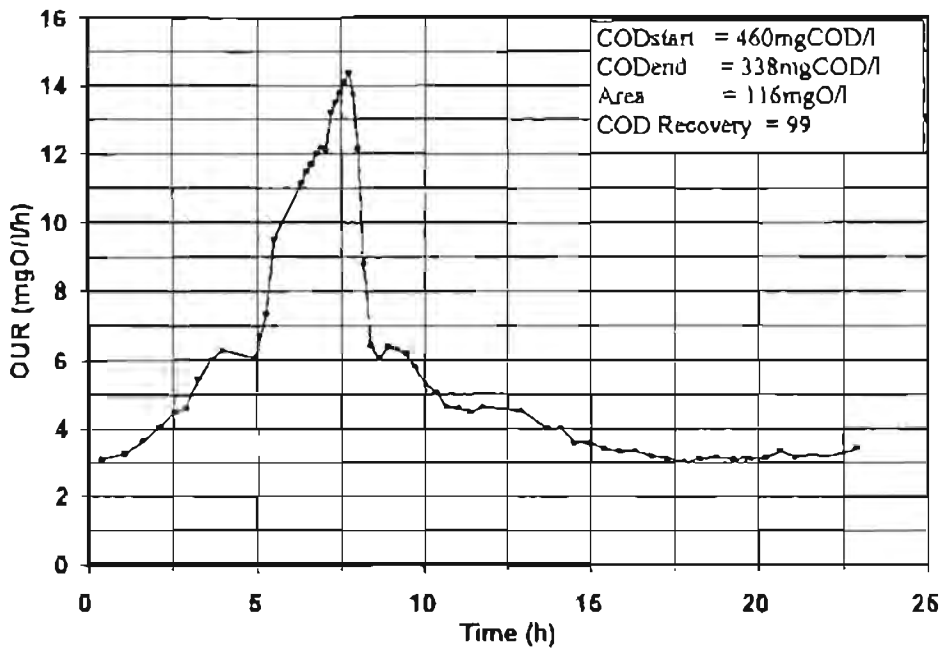


Fig A55a OUR graph for wastewater only batch test, 09-04, wastewater batch no. 22

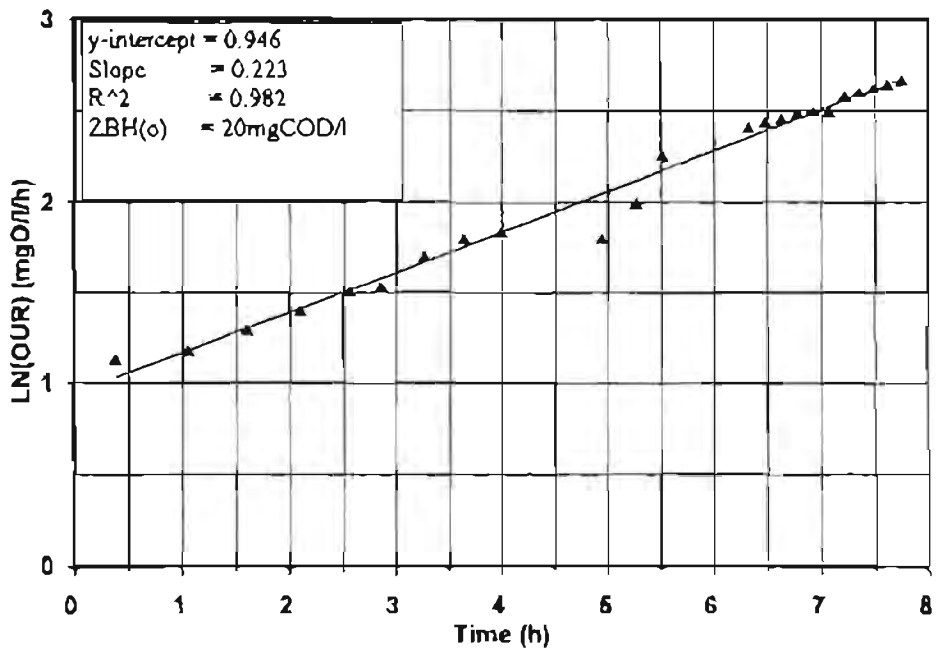


Fig A55b ln(OUR) graph for wastewater only batch test, 09-04, wastewater batch no. 22

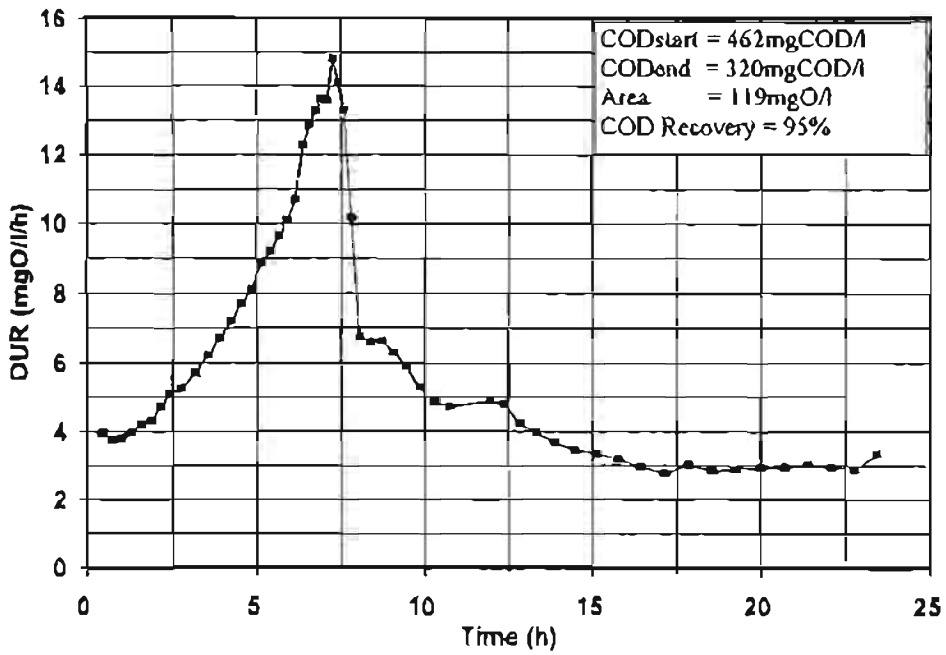


Fig A.56a OUR graph for wastewater only batch test, 10-04, wastewater batch no. 22

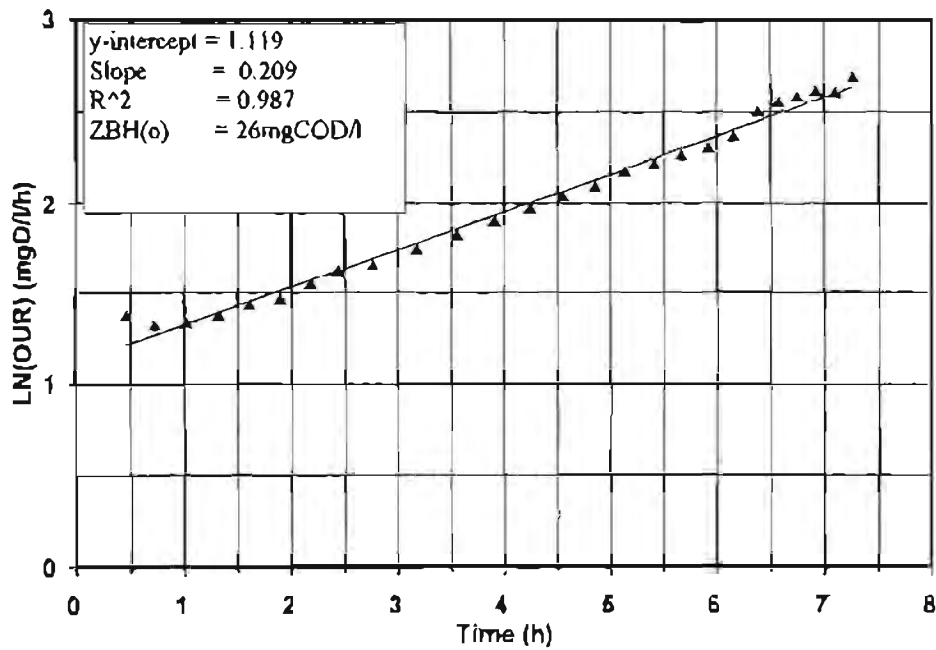


Fig A.56b LN(OUR) graph for wastewater only batch test, 10-04, wastewater batch no. 22

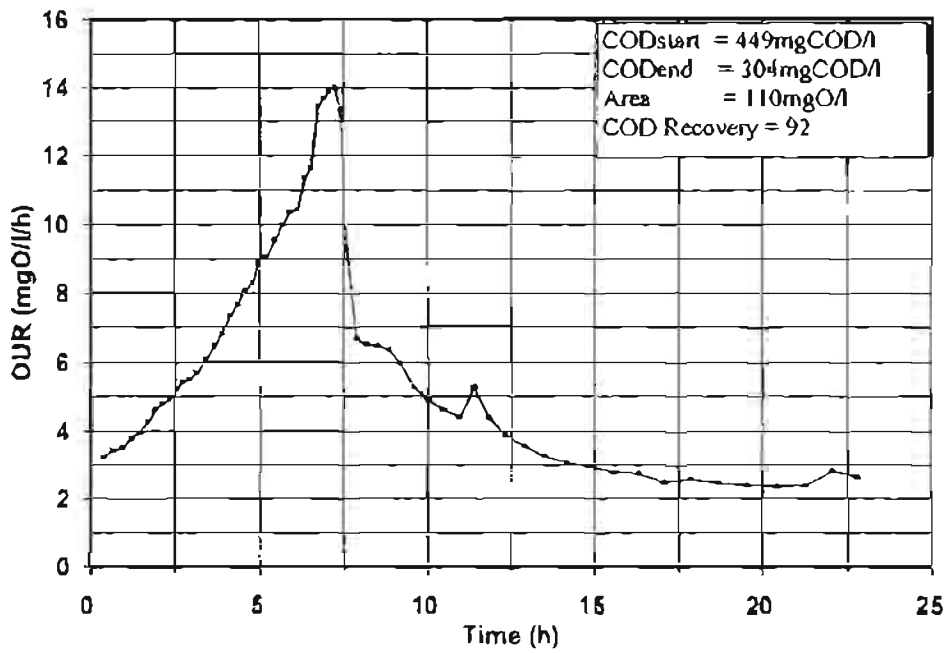


Fig A57a OUR graph for wastewater only batch test, 11-04, wastewater batch no. 22

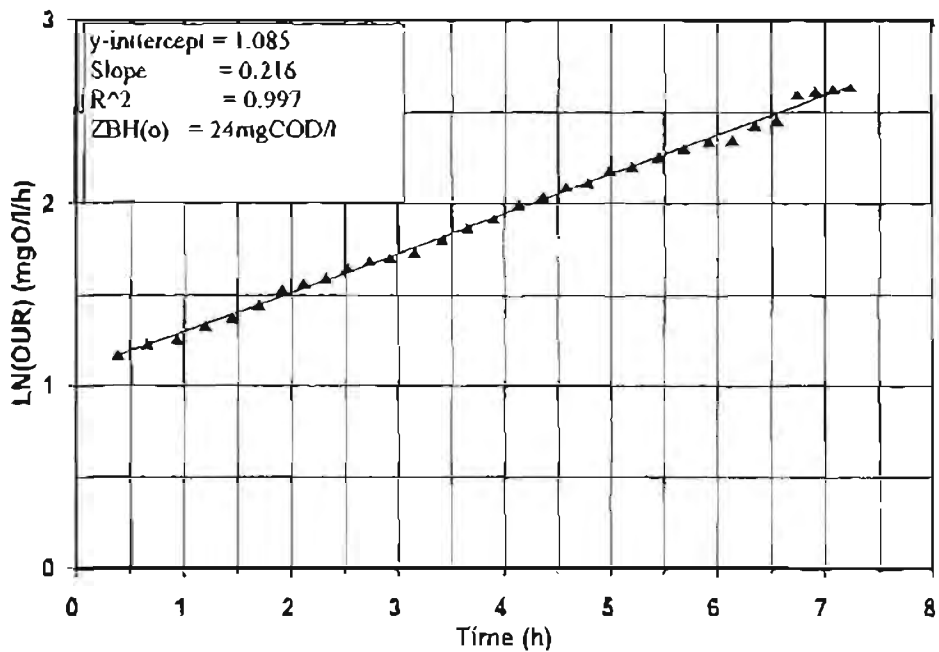


Fig A57b ln(OUR) graph for wastewater only batch test, 11-04, wastewater batch no. 22

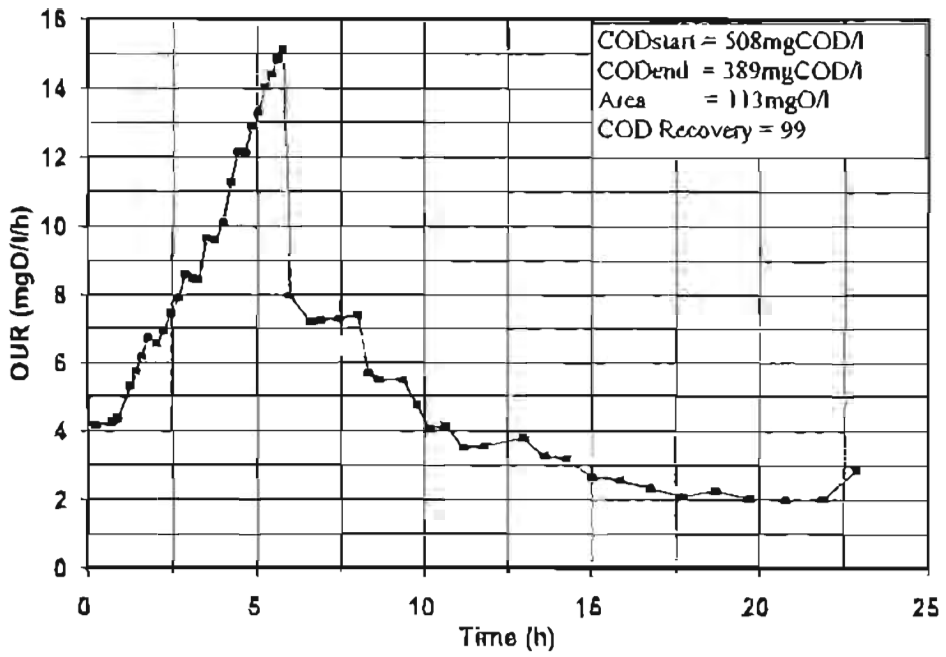


Fig A58a OUR graph for wastewater only batch test, 15-04, wastewater batch no. 23

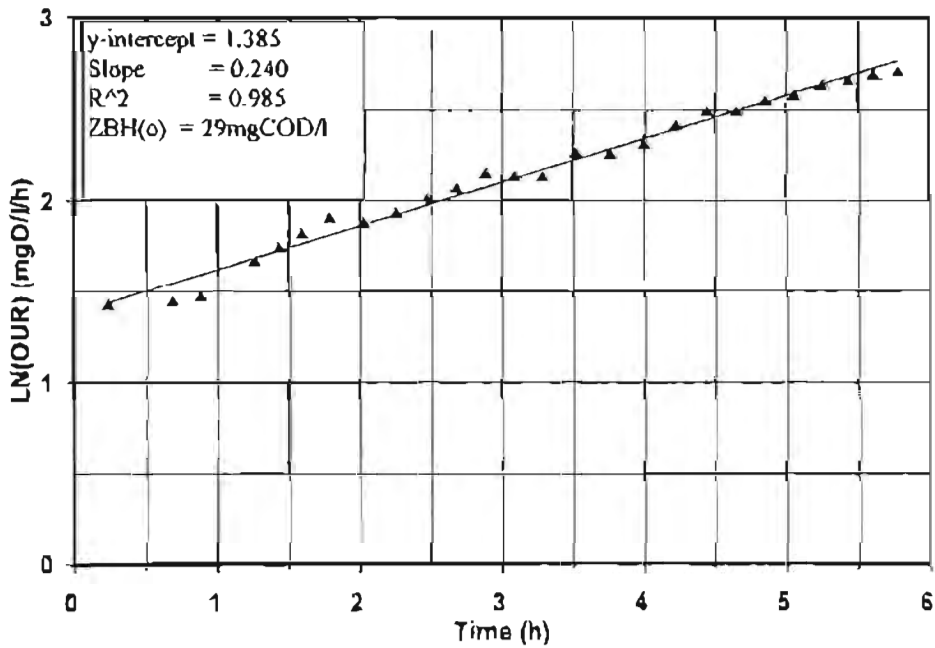


Fig A58b ln(OUR) graph for wastewater only batch test, 15-04, wastewater batch no. 23

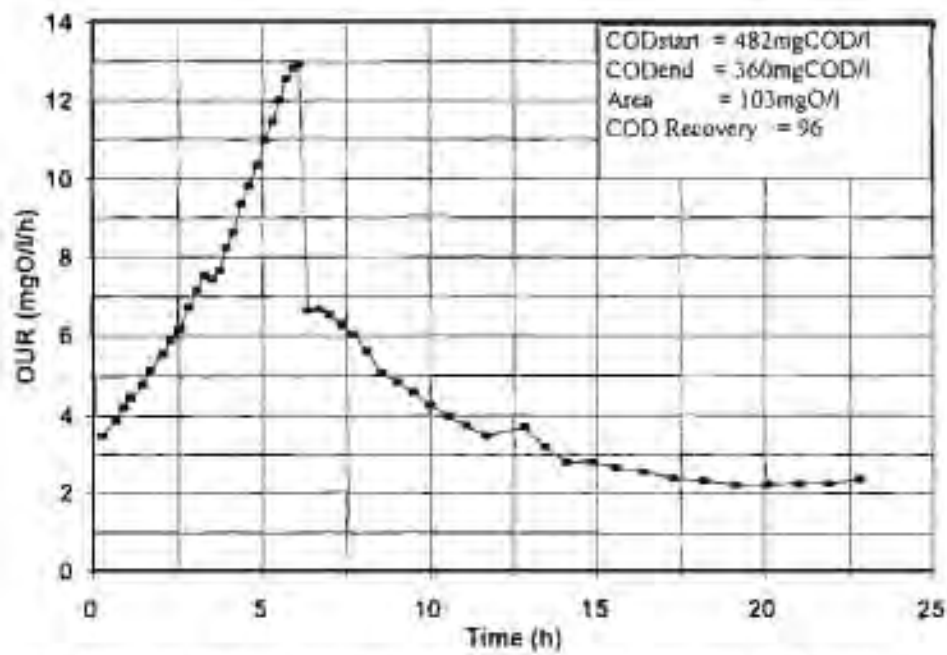


Fig A59a OUR graph for wastewater only batch test, 16-04, wastewater batch no.23

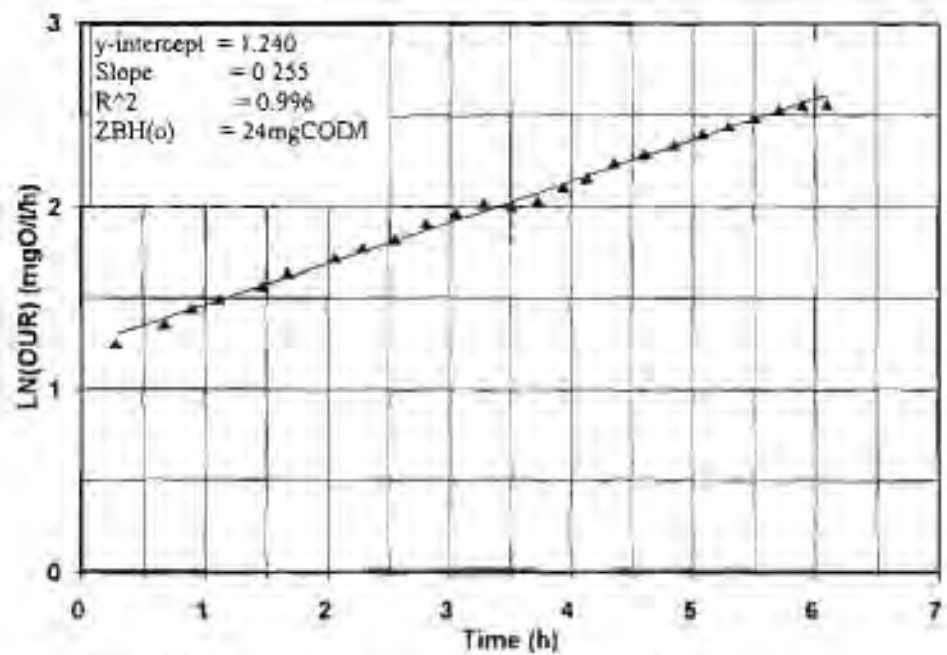


Fig A59b ln(OUR) graph for wastewater only batch test, 16-04, wastewater batch no. 23

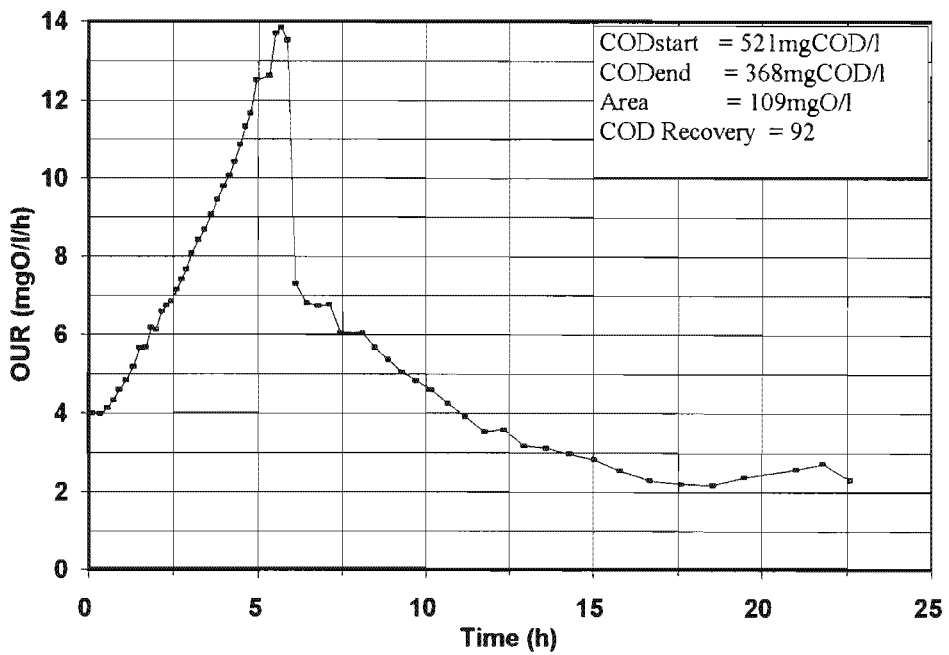


Fig A60a OUR graph for wastewater only batch test, 17-04, wastewater batch no. 23

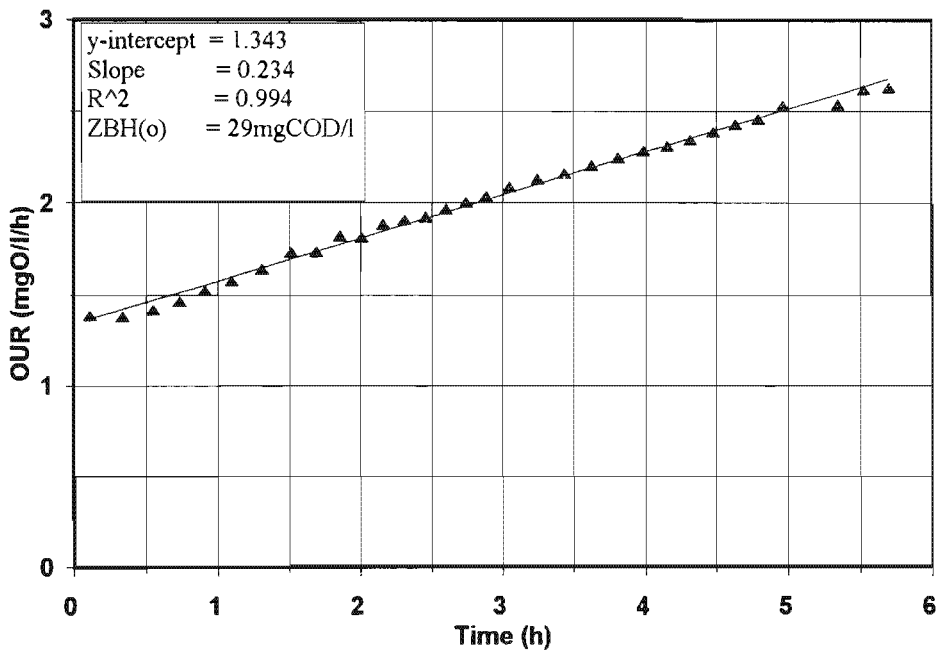


Fig A60b ln(OUR) graph for wastewater only batch test, 17-04, wastewater batch no.23

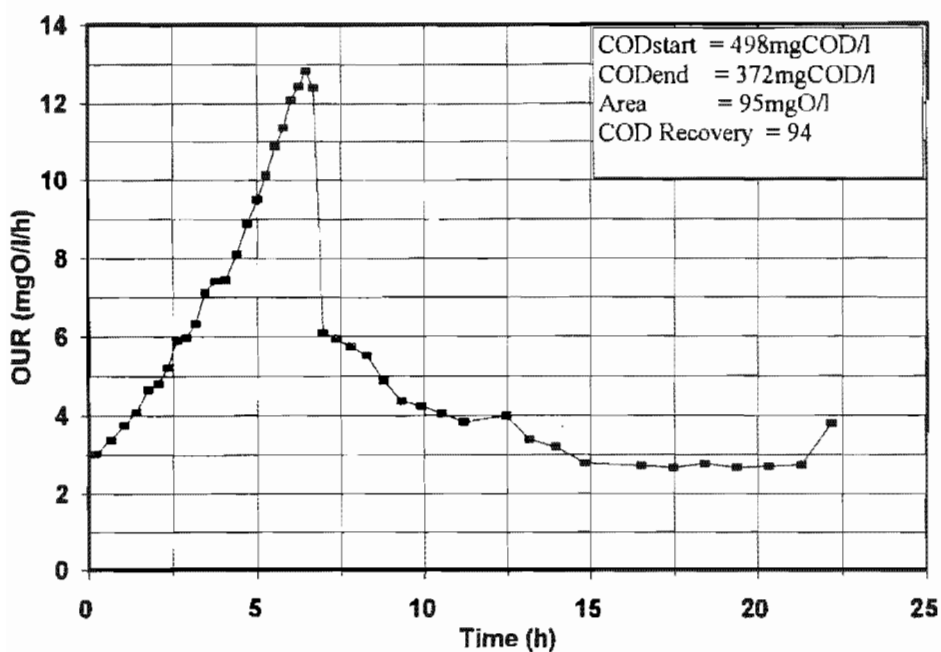


Fig A61a OUR graph for wastewater only batch test, 18-04, wastewater batch no.23

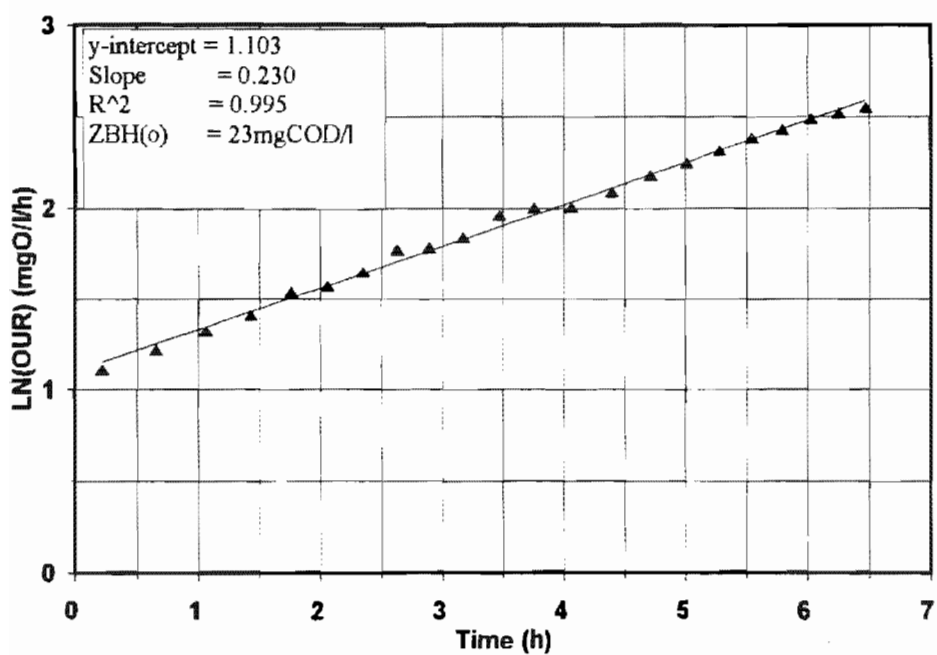


Fig A61b ln(OUR) graph for wastewater only batch test, 18-04, wastewater batch no. 23

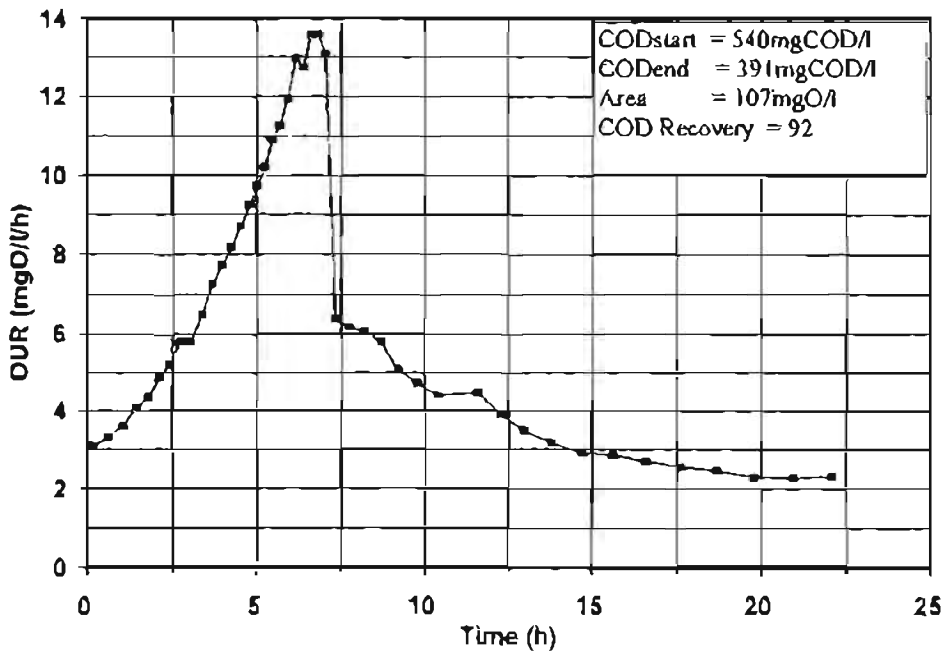


Fig A62a OUR graph for wastewater only batch test, 19-04, wastewater batch no.23

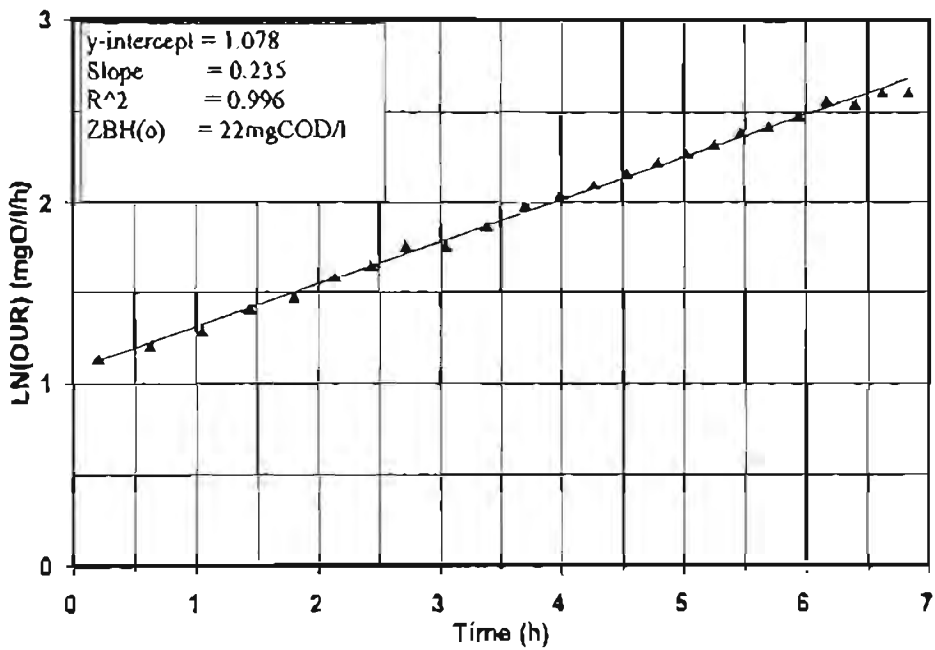


Fig A62b Ln(OUR) graph for wastewater only batch test, 19-04, wastewater batch no.23

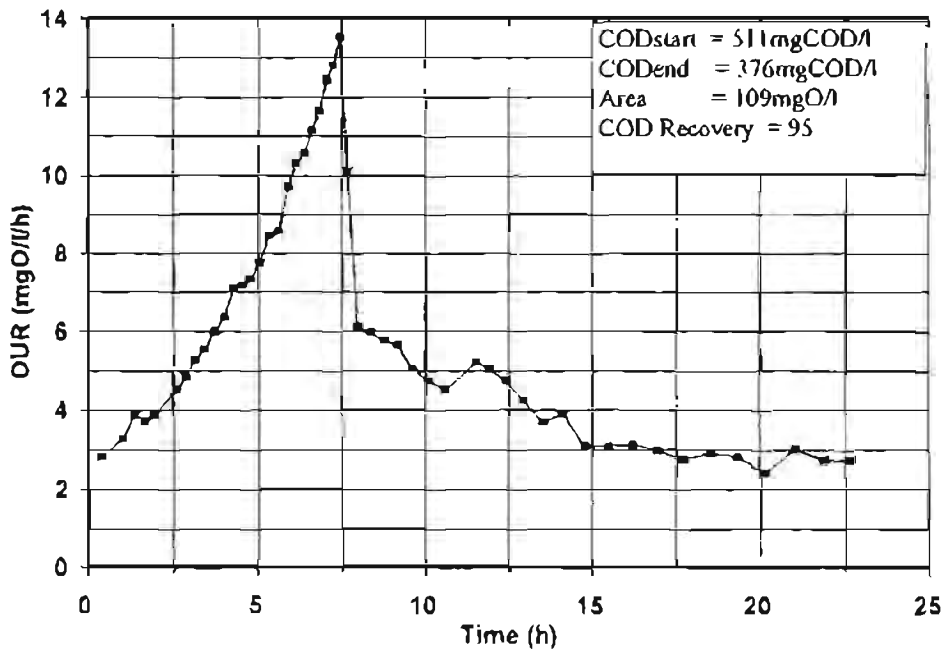


Fig A63a OUR graph for wastewater only batch test, 20-04, wastewater batch no. 23

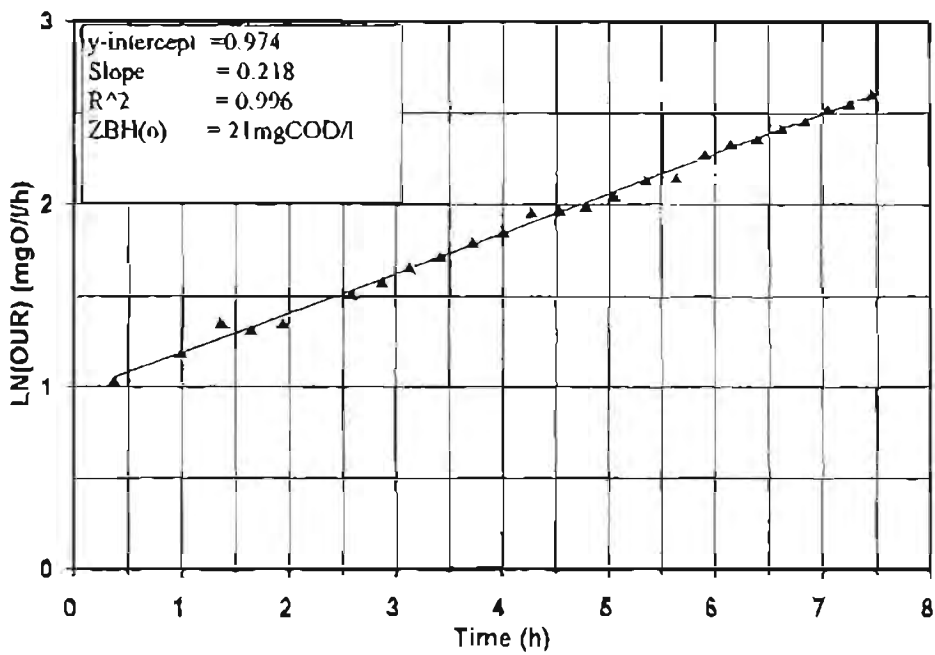


Fig A63b ln(OUR) graph for wastewater only batch test, 20-04, wastewater batch no. 23

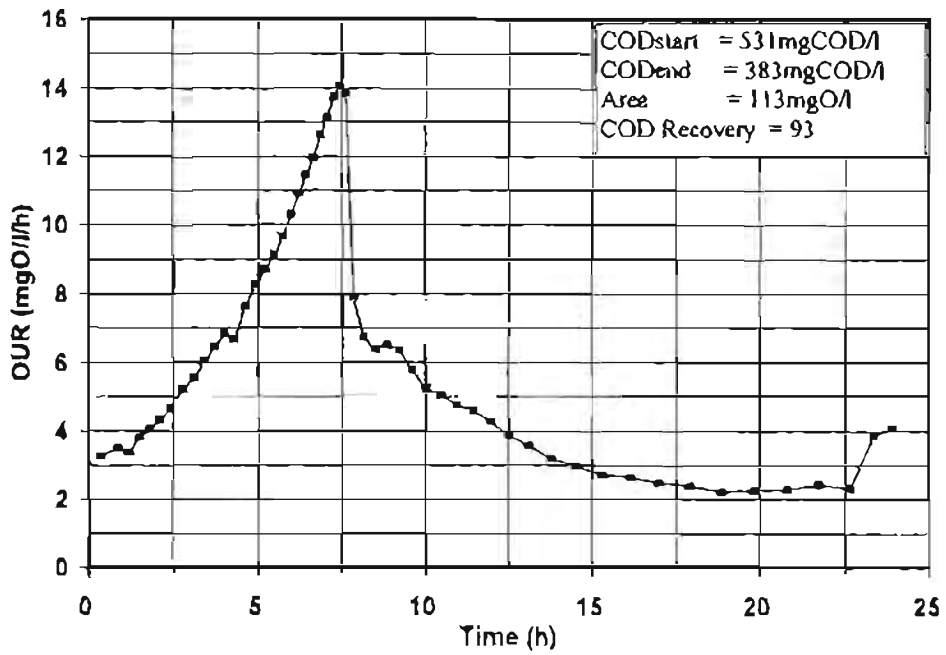


Fig A64a OUR graph for wastewater only batch test, 21-04, wastewater batch no. 23

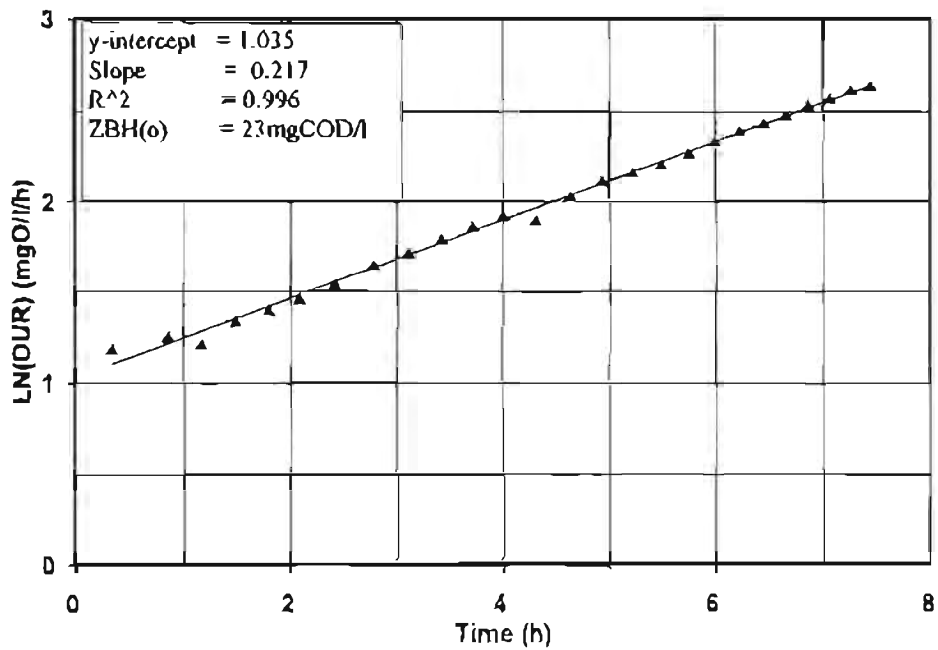


Fig A64b Ln(OUR) graph for wastewater only batch test, 21-04, wastewater batch no. 23

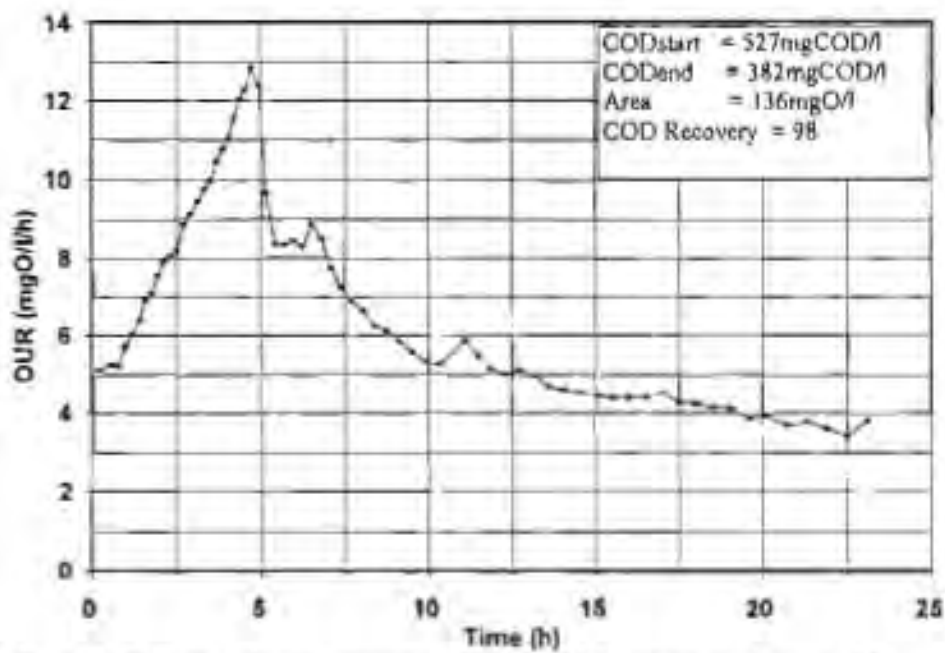


Fig. A65a OUR graph for wastewater only batch test, 21-04, wastewater batch no. 23

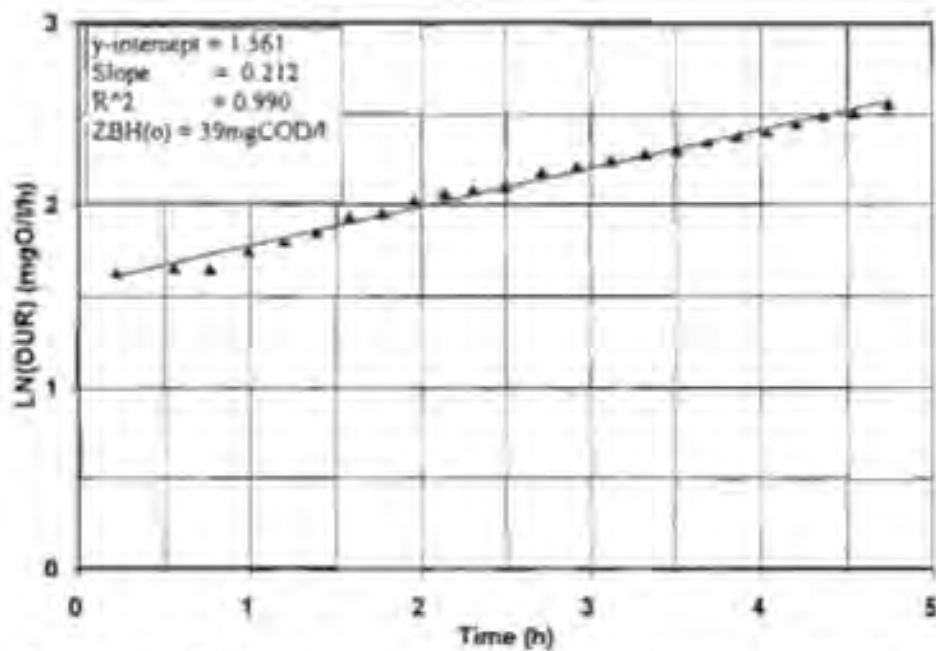


Fig. A65b Ln(OUR) graph for wastewater only batch test, 22-04, wastewater batch no. 23

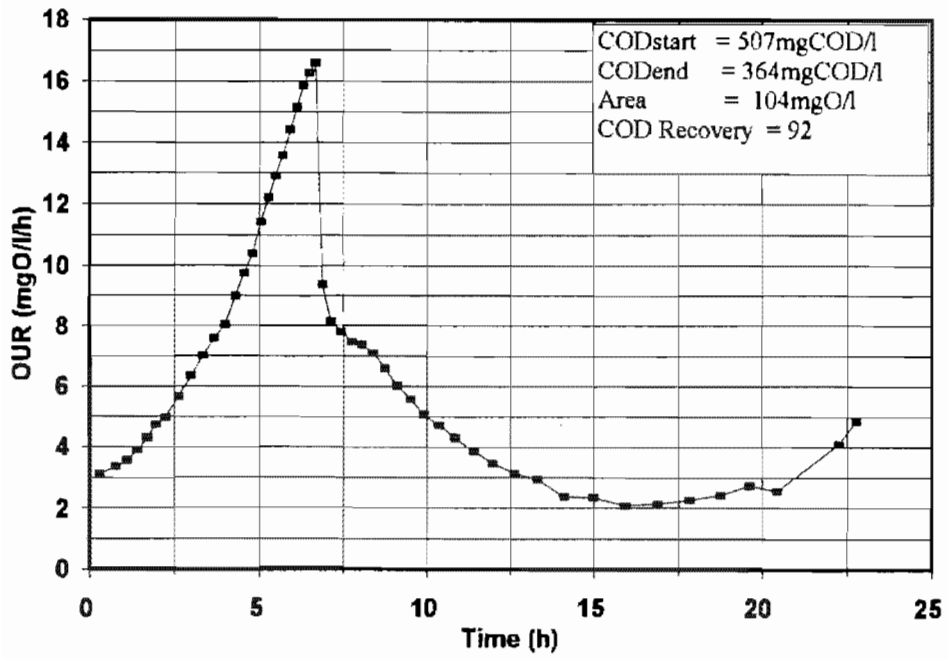


Fig A66a OUR graph for wastewater only batch test, 28-04, wastewater batch no. 24

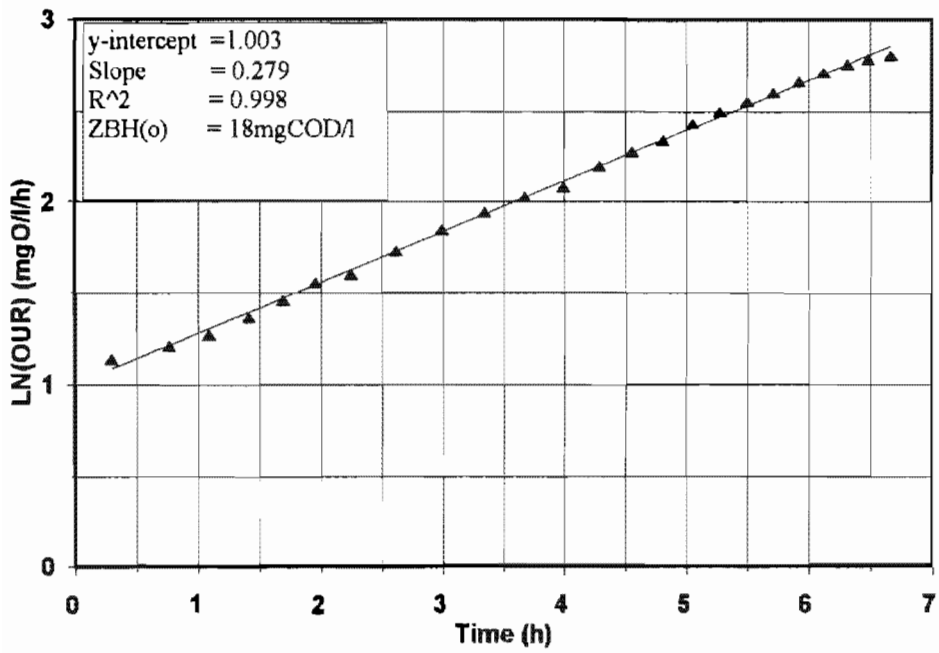


Fig A66b ln(OUR) graph for wastewater only batch test, 28-04, wastewater batch no. 24

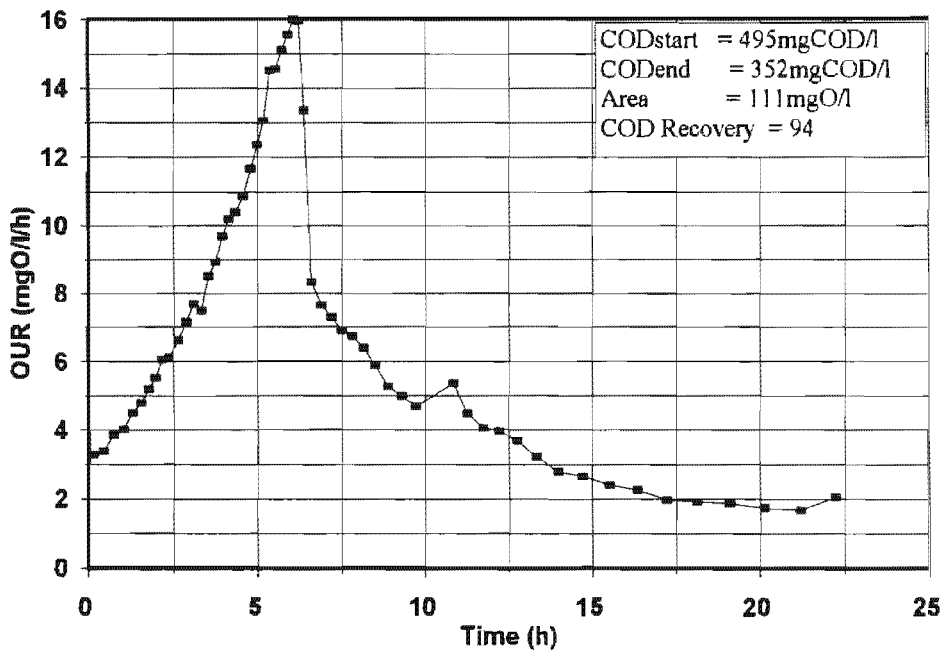


Fig A67a OUR graph for wastewater only batch test, 29-04, wastewater batch no.24

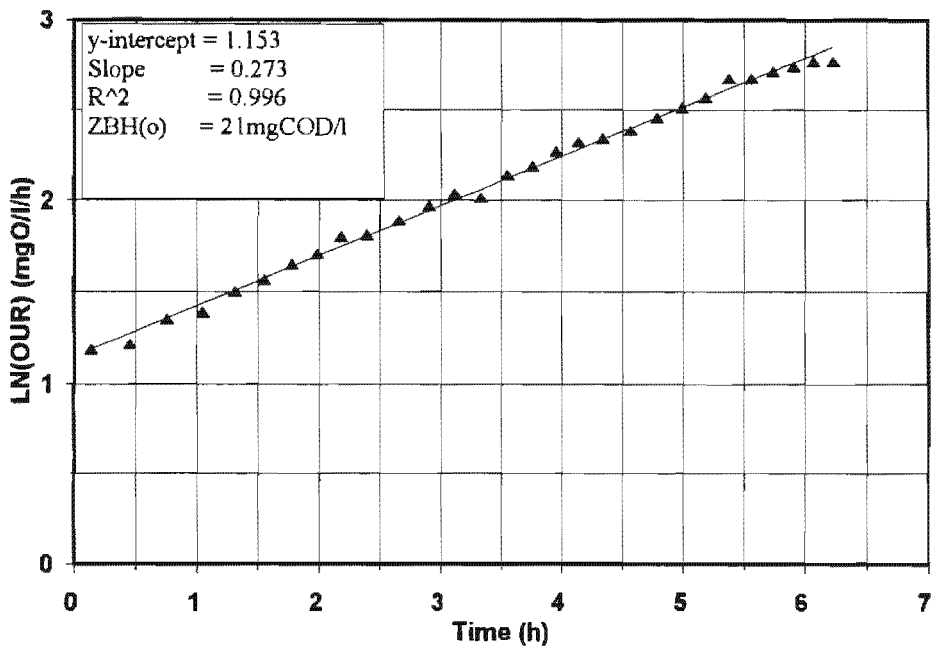


Fig A67b ln(OUR) graph for wastewater only batch test, 29-04, wastewater batch no. 24

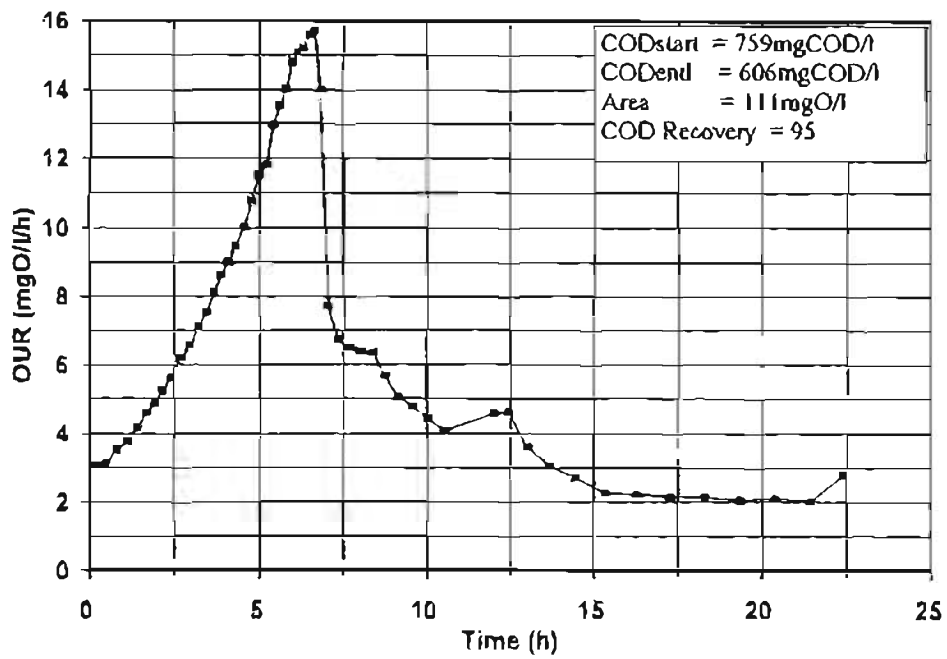


Fig A68a OUR graph for wastewater only batch test, 30-04, wastewater batch no. 24

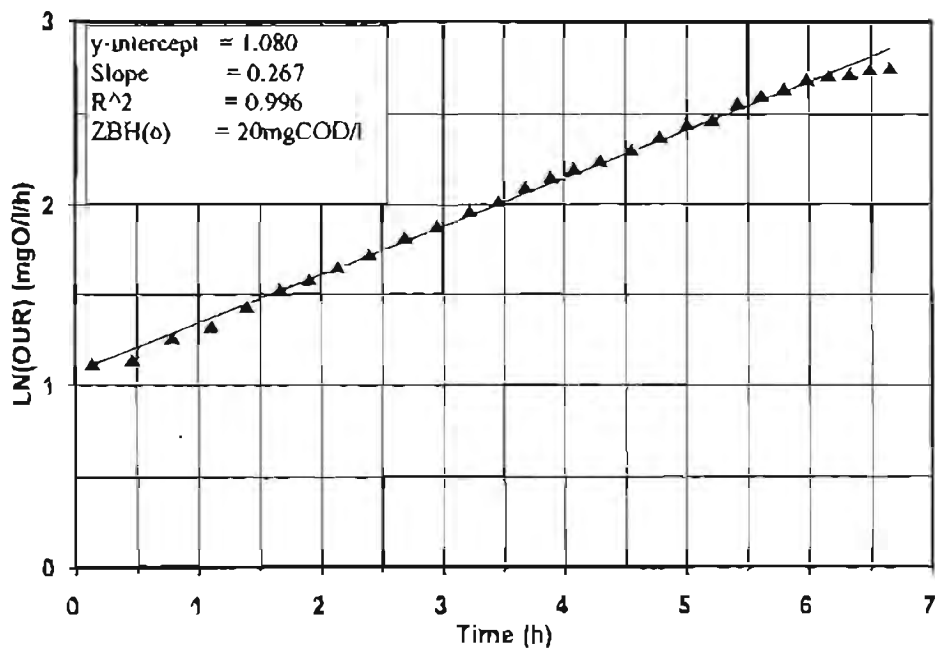


Fig A68b ln(OUR) graph for wastewater only batch test, 30-04, wastewater batch no. 24

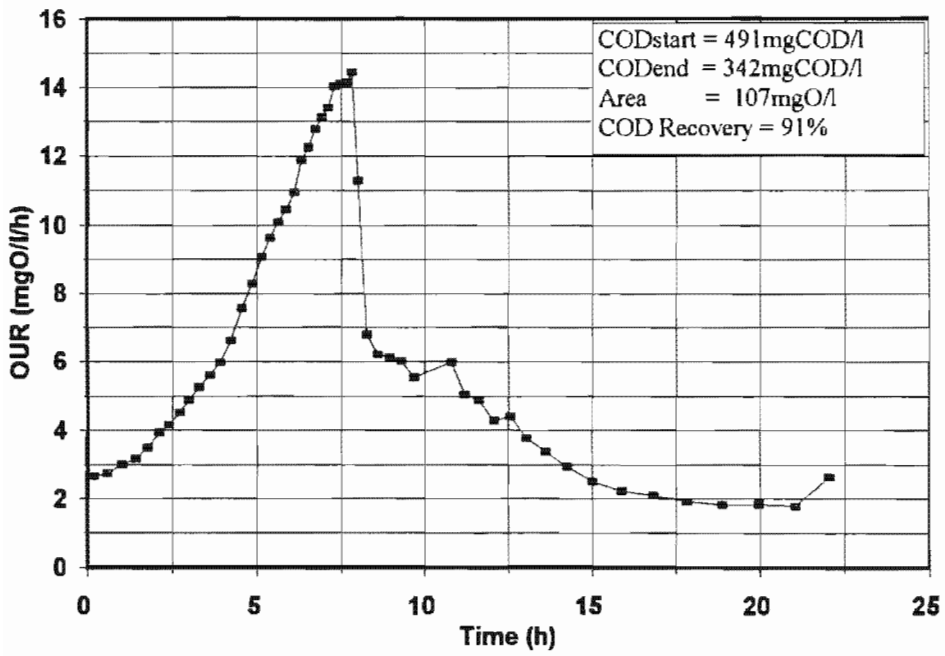


Fig A69a OUR graph for wastewater only batch test, 01-05, wastewater batch no. 24

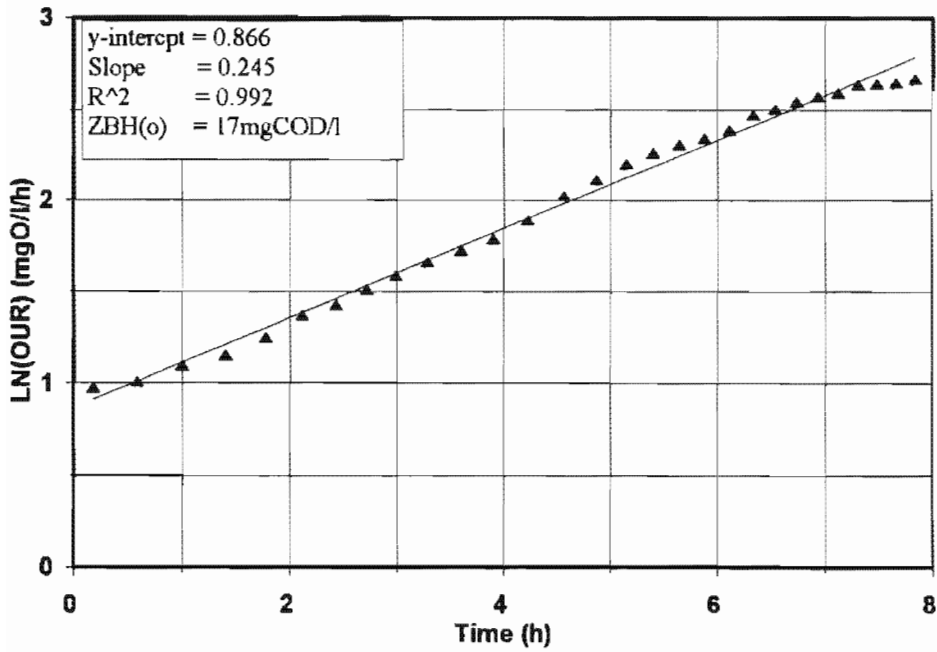


Fig A69b Ln(OUR) graph for wastewater only batch test, 01-05, wastewater batch no. 24

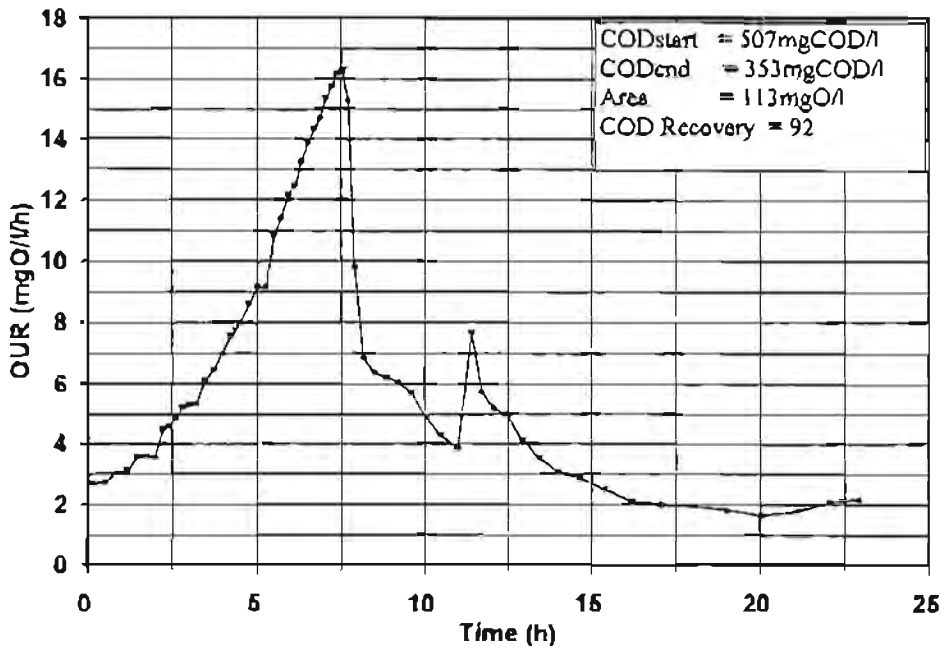


Fig A 70a OUR graph for wastewater only batch test, 02-05, wastewater batch no. 24

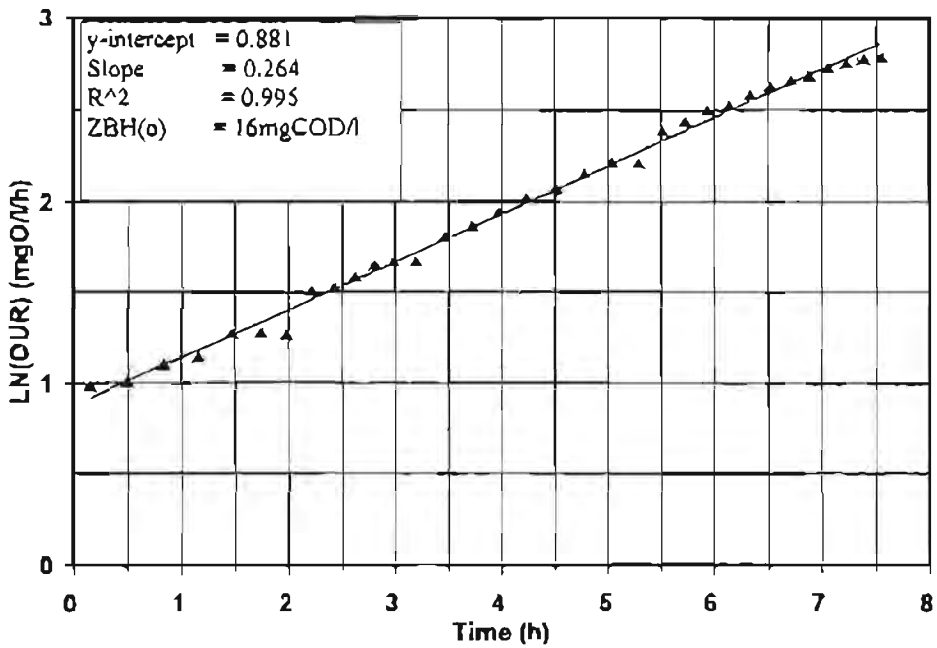


Fig A 70b ln(OUR) graph for wastewater only batch test, 02-05, wastewater batch no. 24

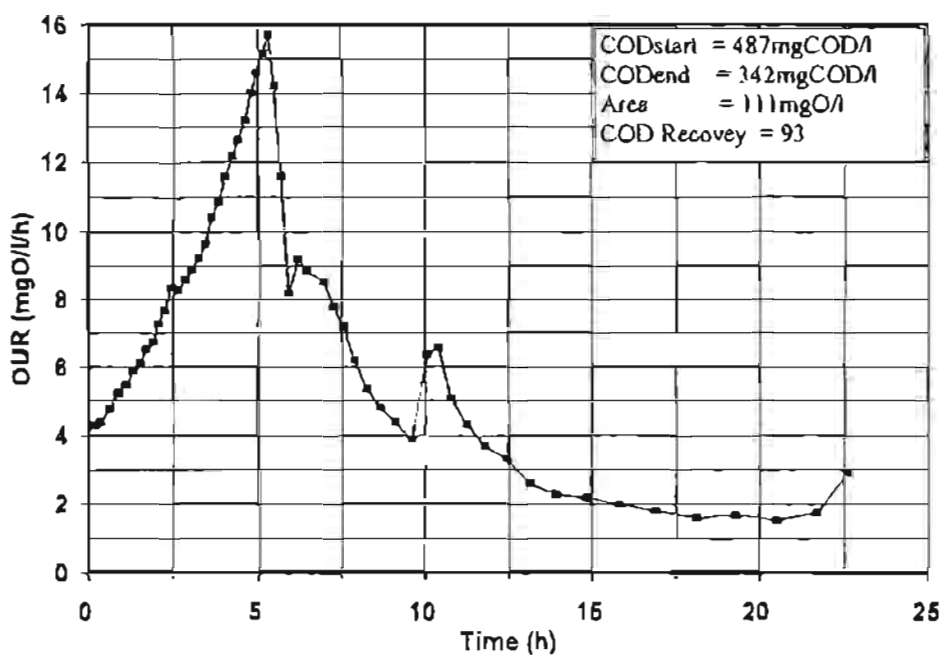


Fig A71a OUR graph for wastewater only batch test, 03-05, wastewater batch no. 24

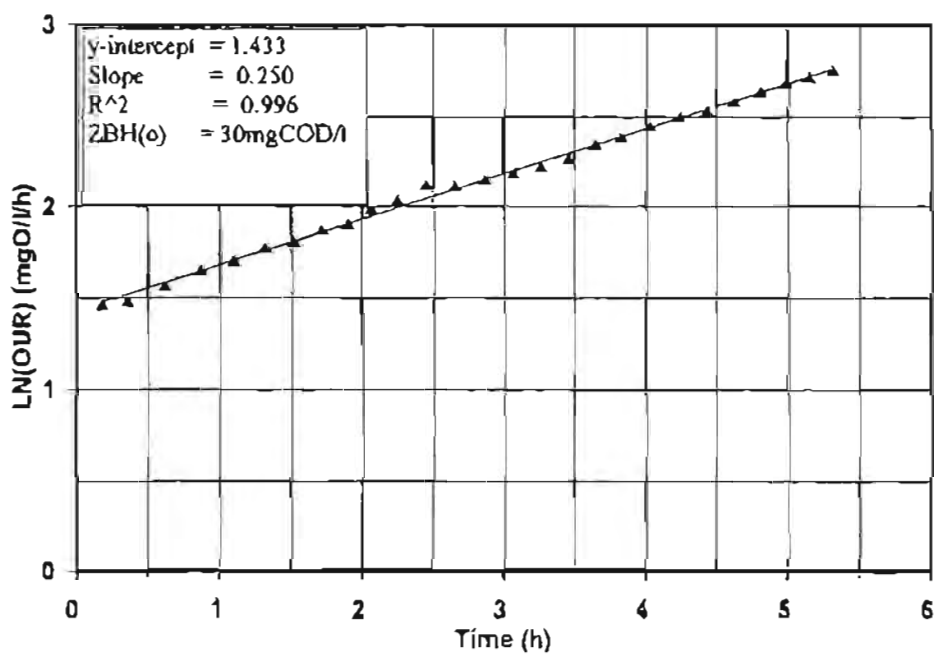


Fig A71b ln(OUR) graph for wastewater only batch test, 03-05, wastewater batch no. 24

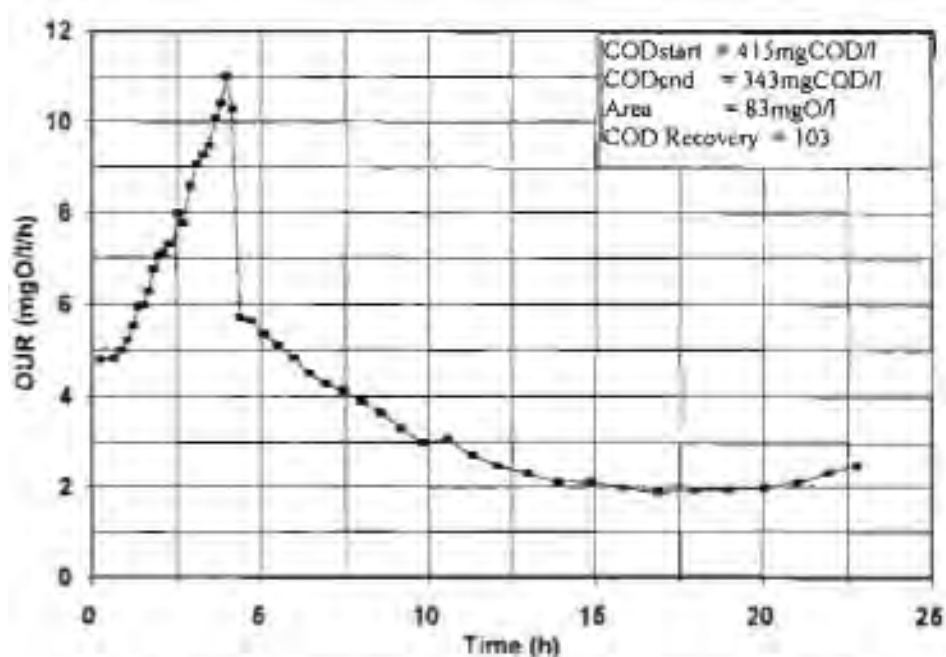


Fig A72a OUR graph for wastewater only batch test, 21-05, wastewater batch no. 26

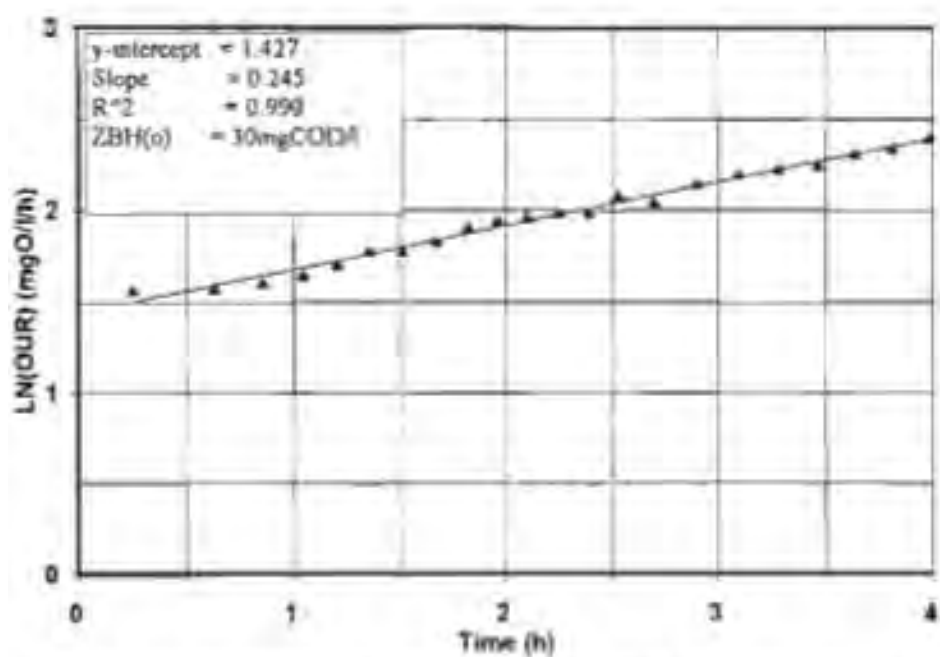


Fig A72b ln(OUR) graph for wastewater only batch test, 21-05, wastewater batch no. 26

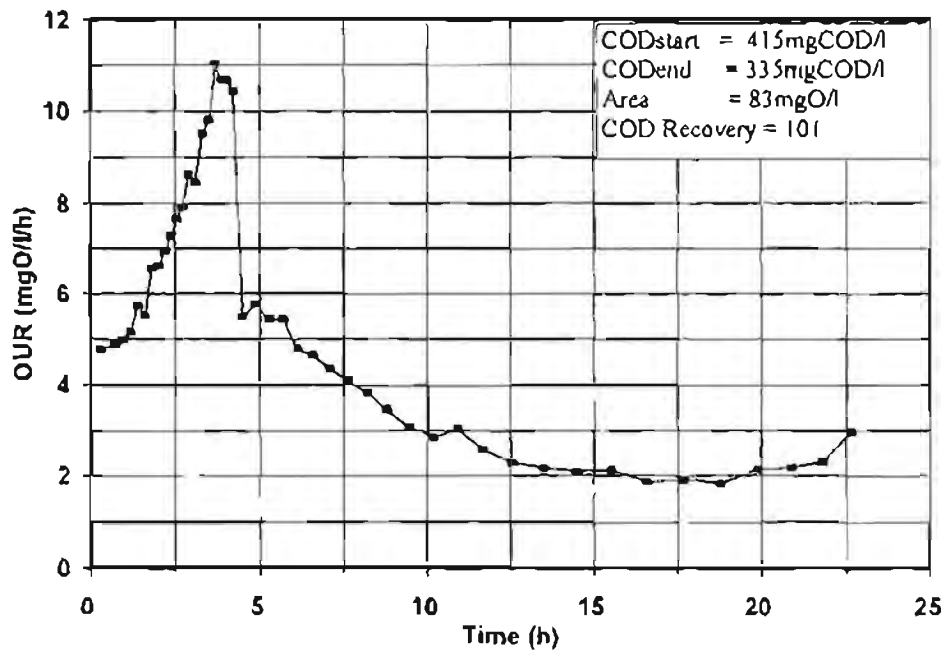


Fig A73a OUR graph for wastewater only batch test, 21-05, wastewater batch no.26

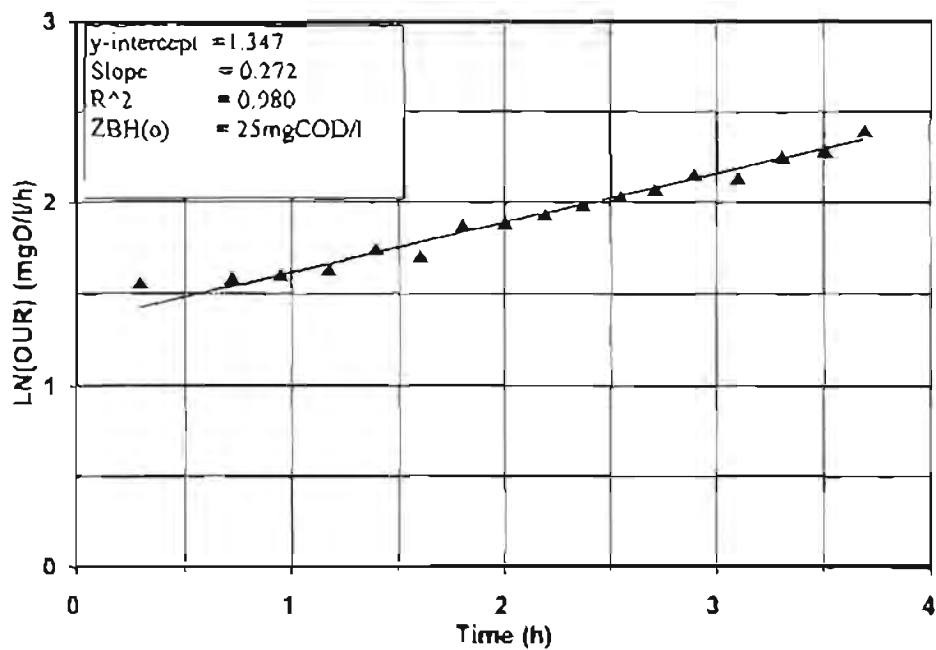


Fig A73b ln(OUR) graph for wastewater only batch test, 21-05, wastewater batch no. 26

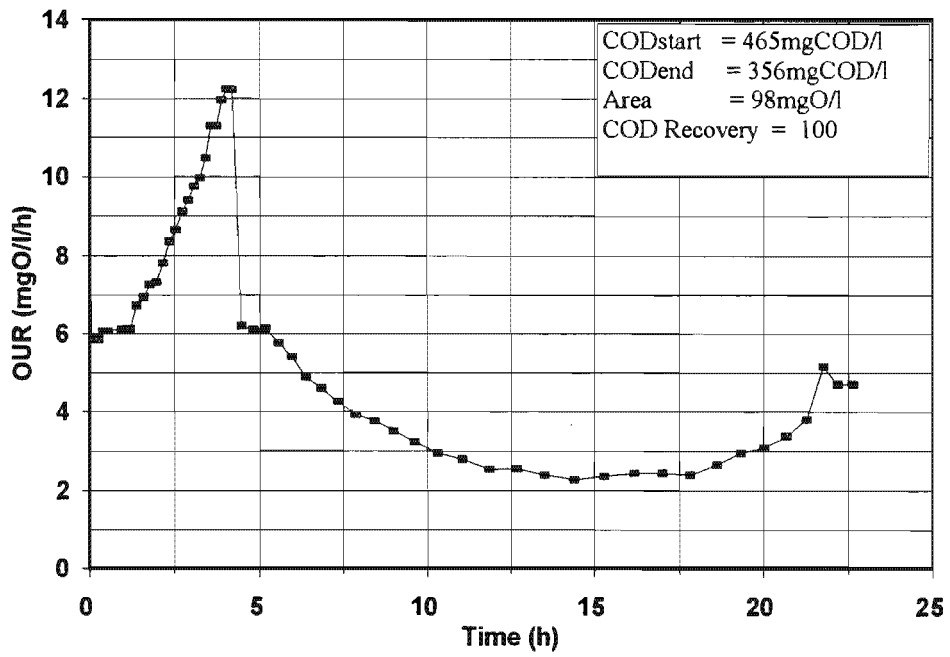


Fig A74a OUR graph for wastewater only batch test, 22-05, wastewater batch no. 26

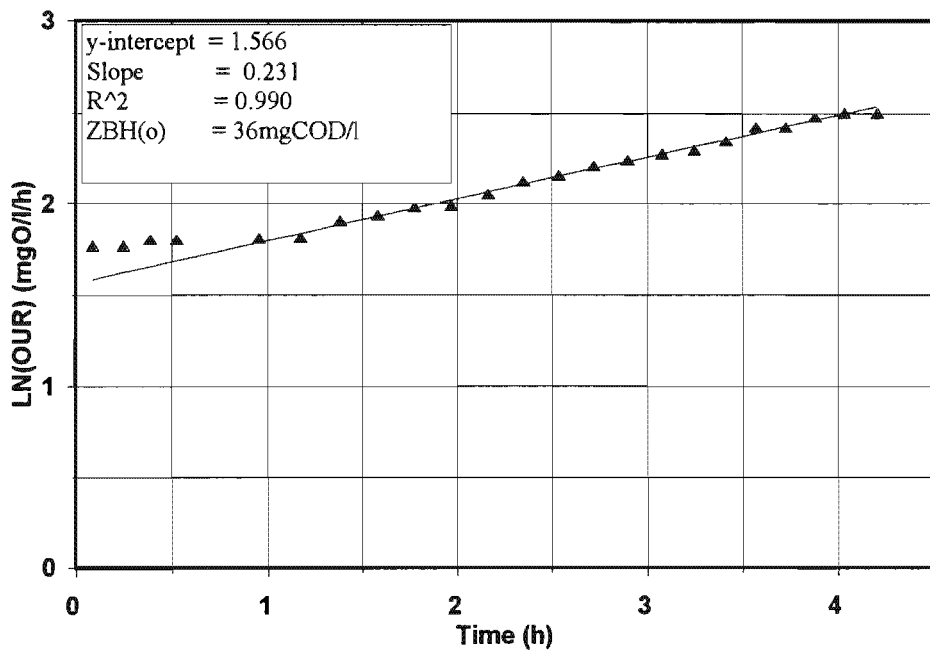


Fig A74b ln(OUR) graph for wastewater only batch test, 22-05, wastewater batch no. 26

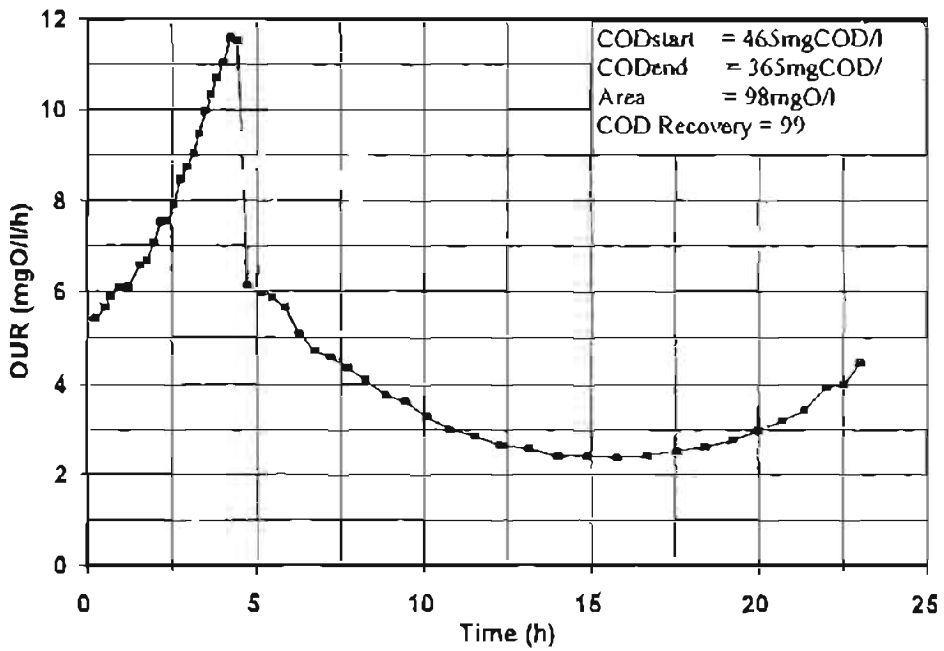


Fig A7Sa OUR graph for wastewater only batch test, 22-05, wastewater batch no. 26

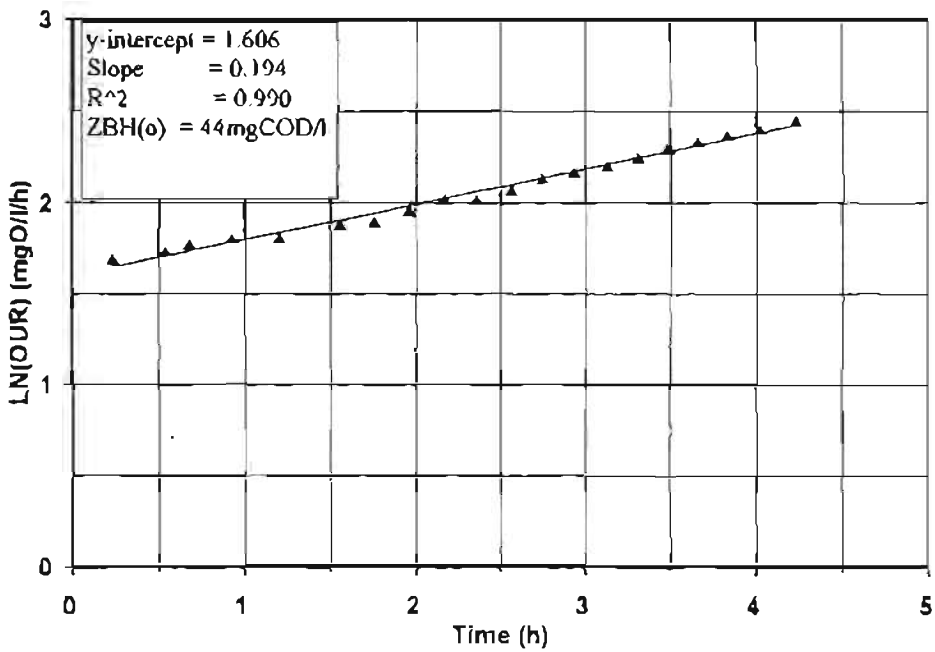


Fig A7Sb Ln(OUR) graph for wastewater only batch test, 22-05, wastewater batch no. 26

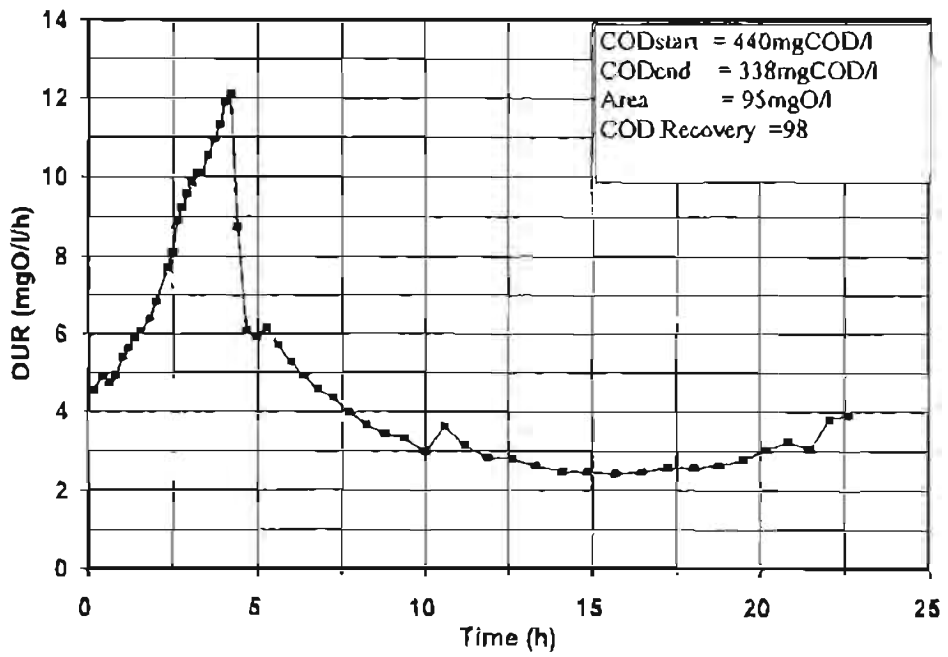


Fig A76a OUR graph for wastewater only batch test, 23-05, wastewater batch no. 26

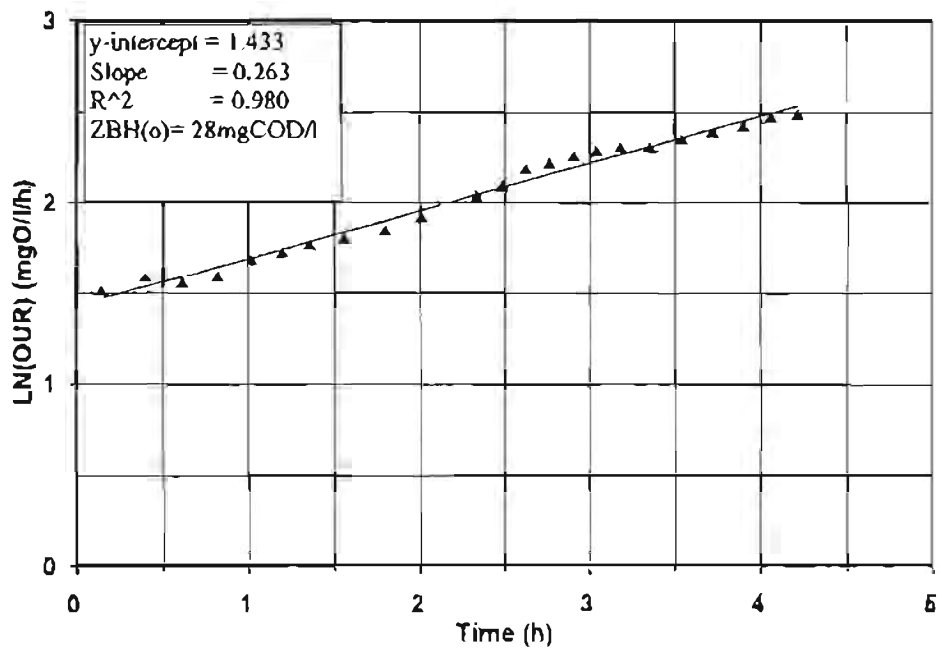


Fig A76b ln(OUR) graph for wastewater only batch test, 23-05, wastewater batch no. 26

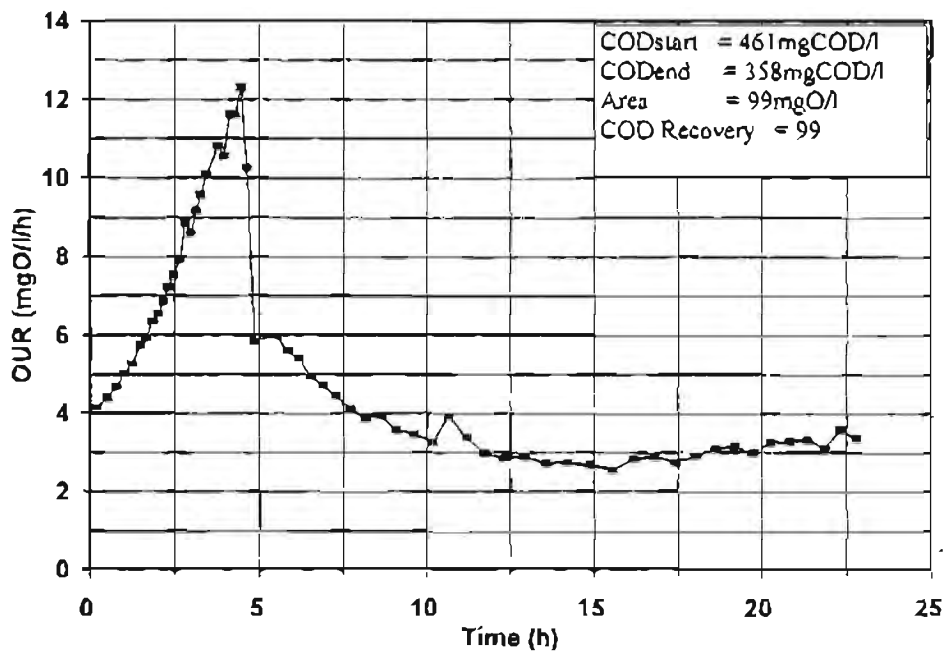


Fig A77a OUR graph for wastewater only batch test, 24-05, wastewater batch no. 26

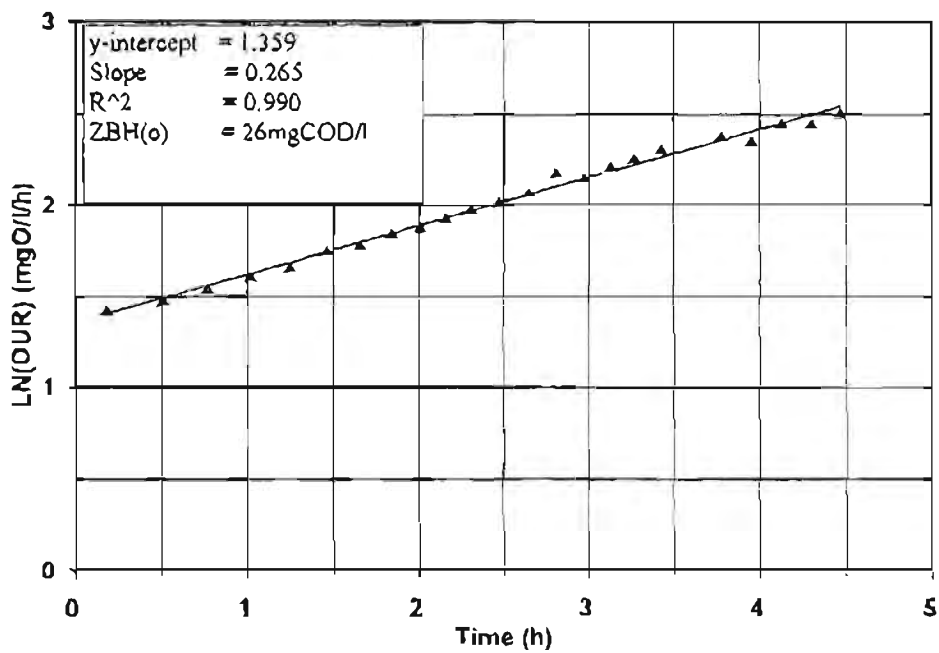


Fig A77b ln(OUR) graph for wastewater only batch test, 24-05, wastewater batch no. 26

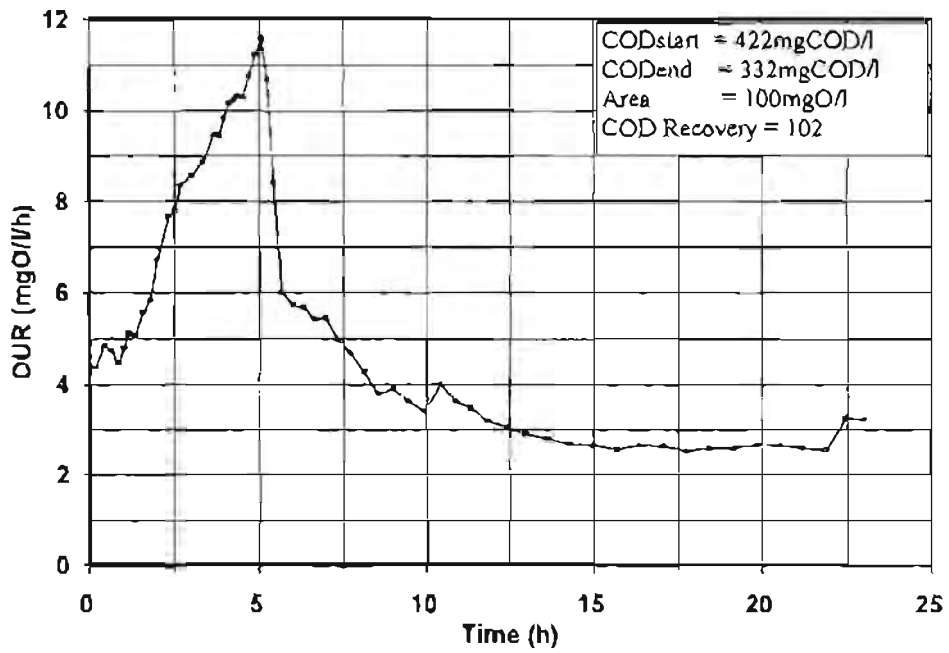


Fig A78a OUR graph for wastewater only batch test, 25-05, wastewater batch no 26

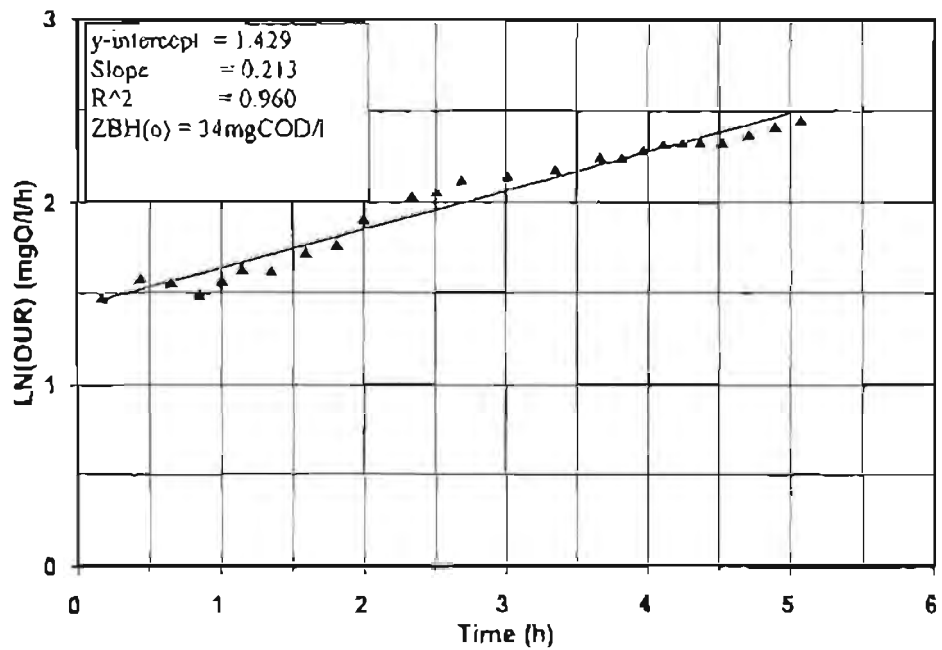


Fig A78b Ln(OUR) graph for wastewater only batch test, 25-05, wastewater batch no 26

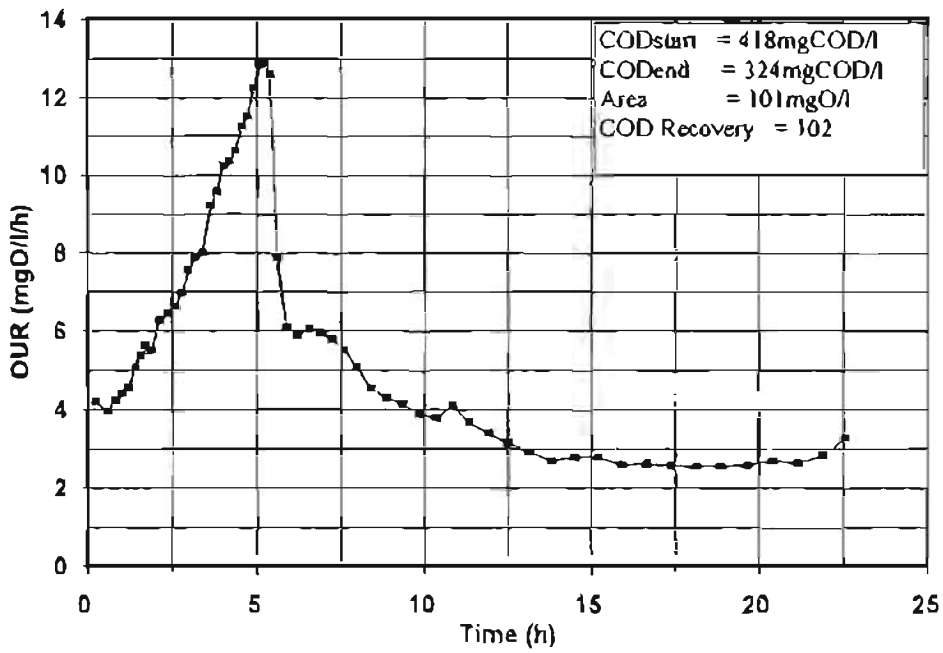


Fig A79a OUR graph for wastewater only batch test, 26-05, wastewater batch no. 26

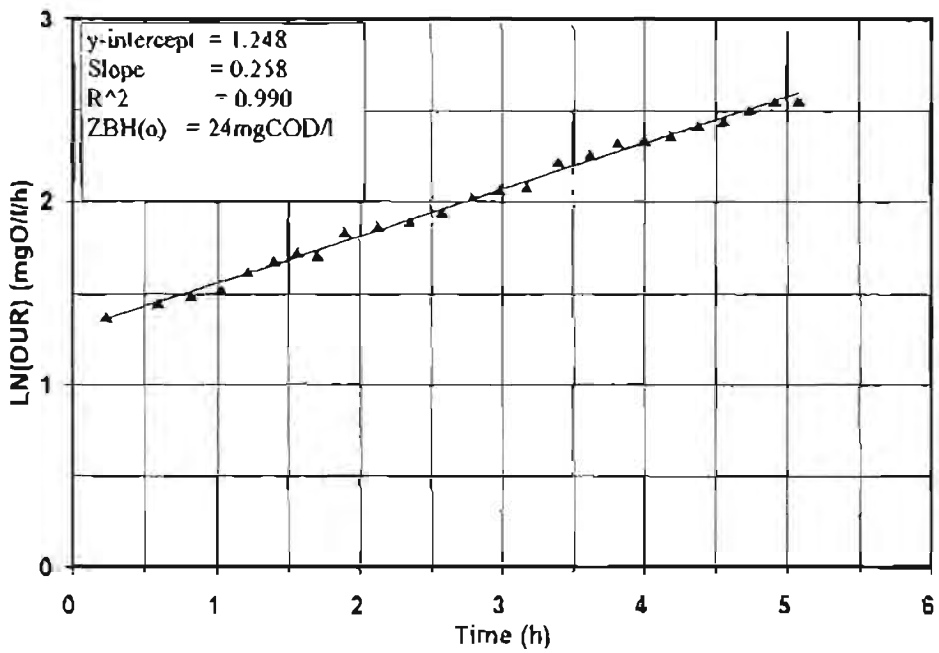


Fig A79b ln(OUR) graph for wastewater only batch test, 26-05, wastewater batch no. 26

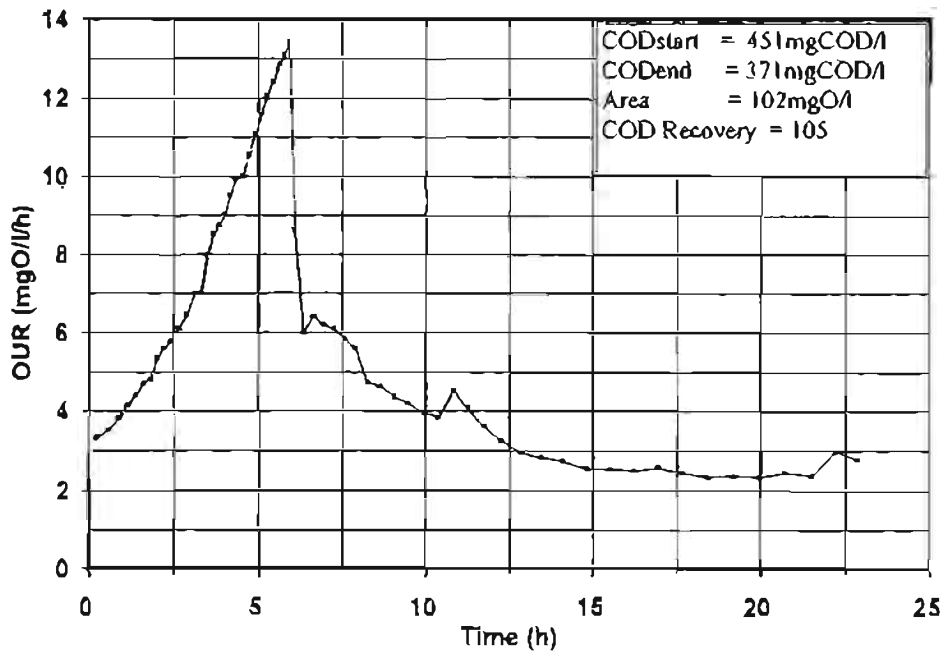


Fig A80a OUR graph for wastewater only batch test, 27-05, wastewater batch no. 26

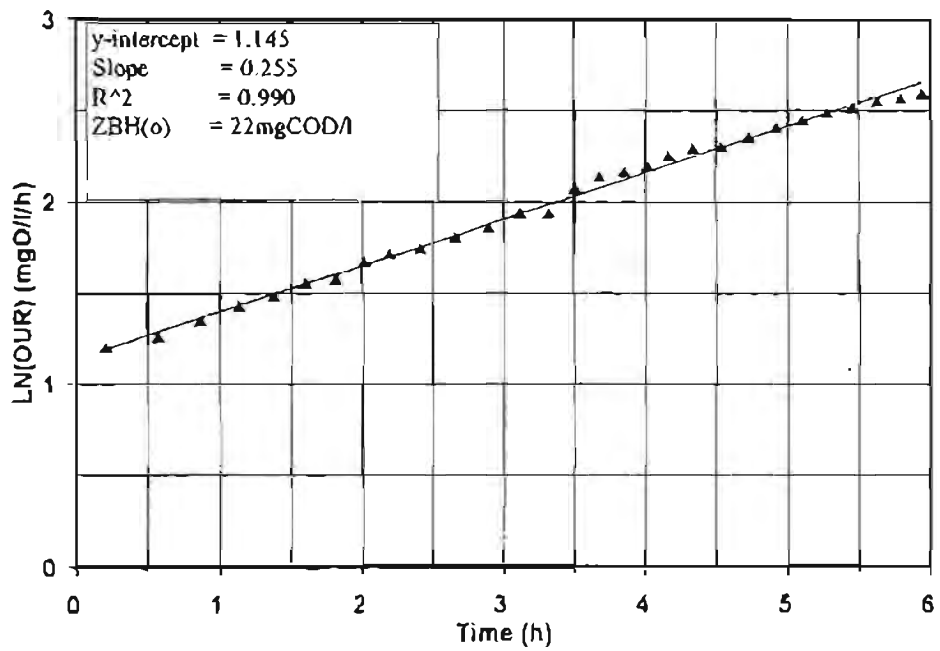


Fig A80b ln(OUR) graph for wastewater only batch test, 27-05, wastewater batch no. 26

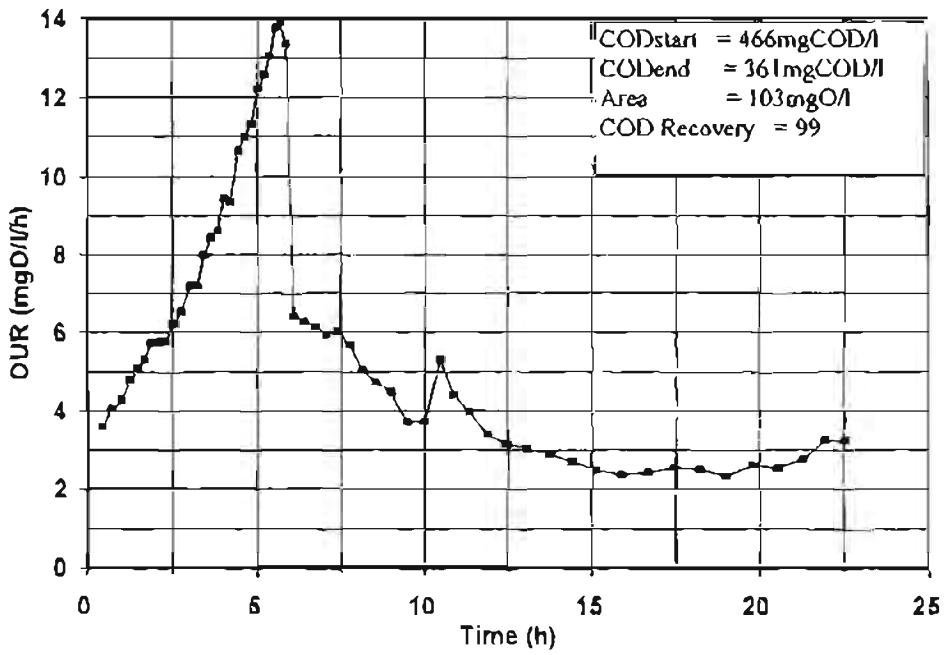


Fig A81a OUR graph for wastewater only batch test, 28-05, wastewater batch no. 26

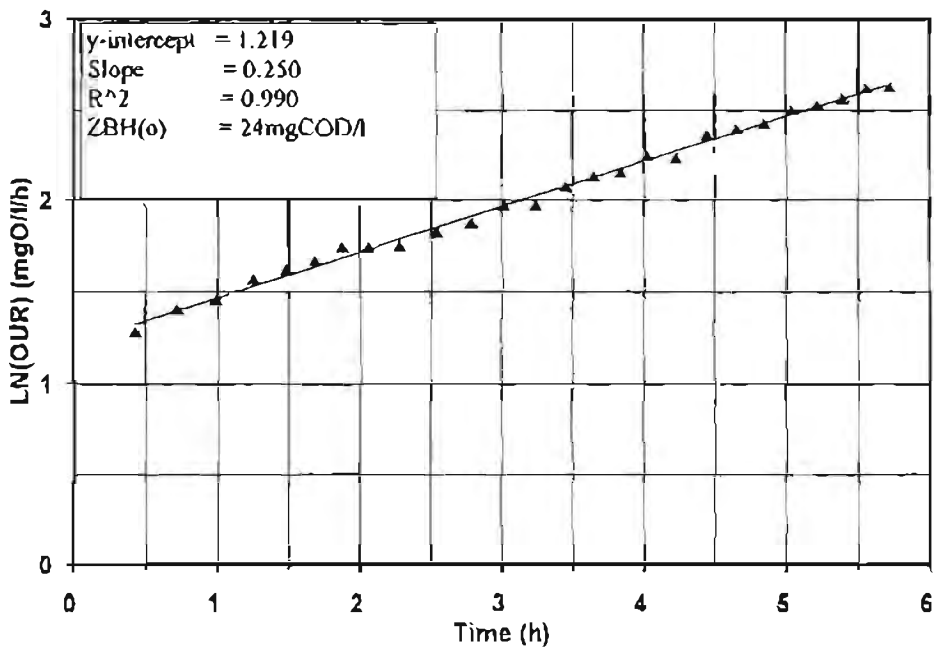


Fig A81b ln(OUR) graph for wastewater only batch test, 28-05, wastewater batch no. 26

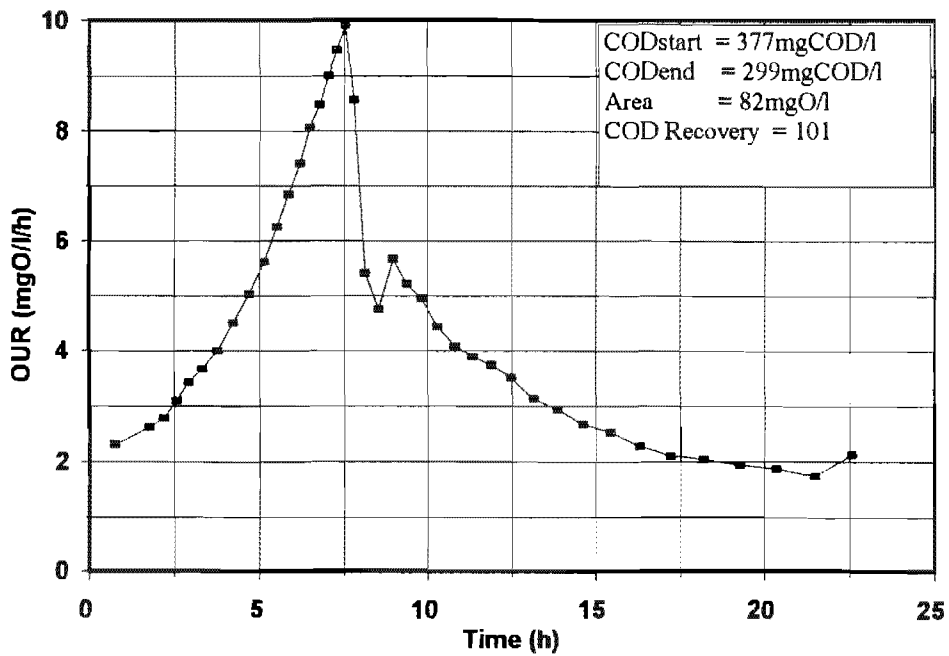


Fig A82a OUR graph for wastewater only batch test, 02-06, wastewater batch no. 27

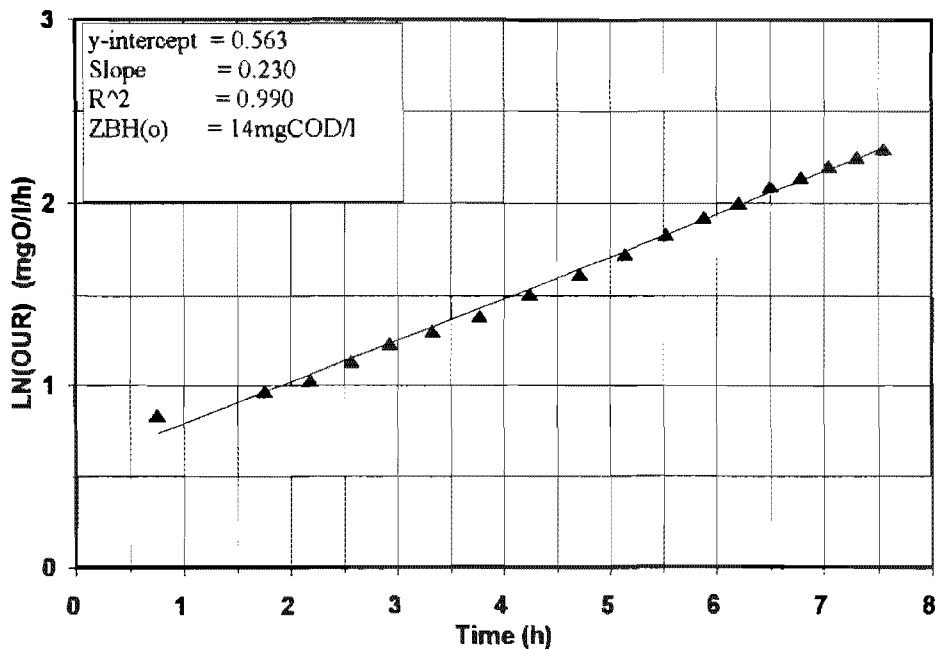


Fig A82b ln(OUR) graph for wastewater only batch test, 02-06, wastewater batch no. 27

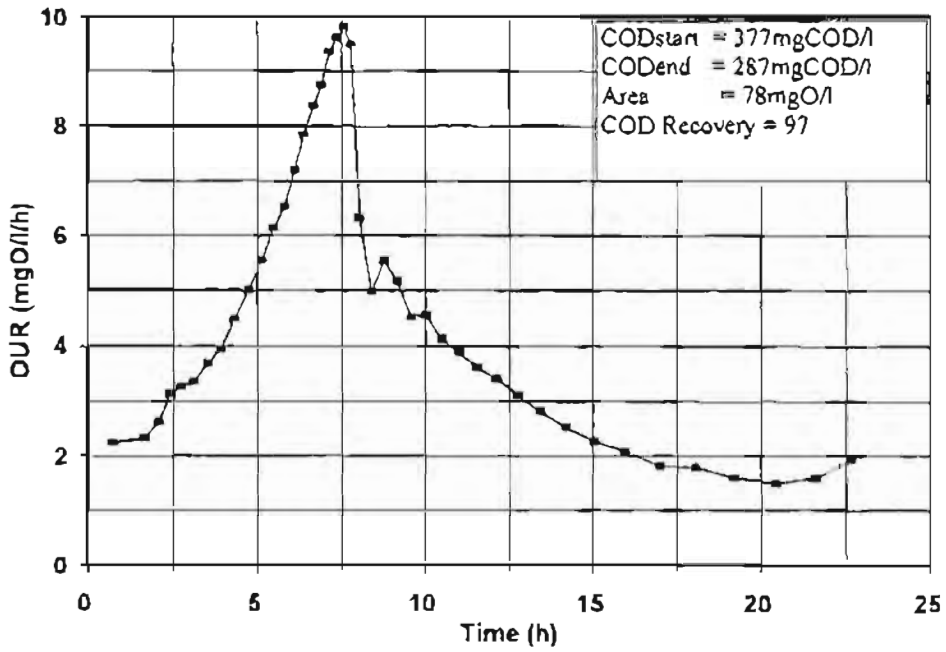


Fig A83a OUR graph for wastewater only batch test, 02-06, wastewater batch no. 27

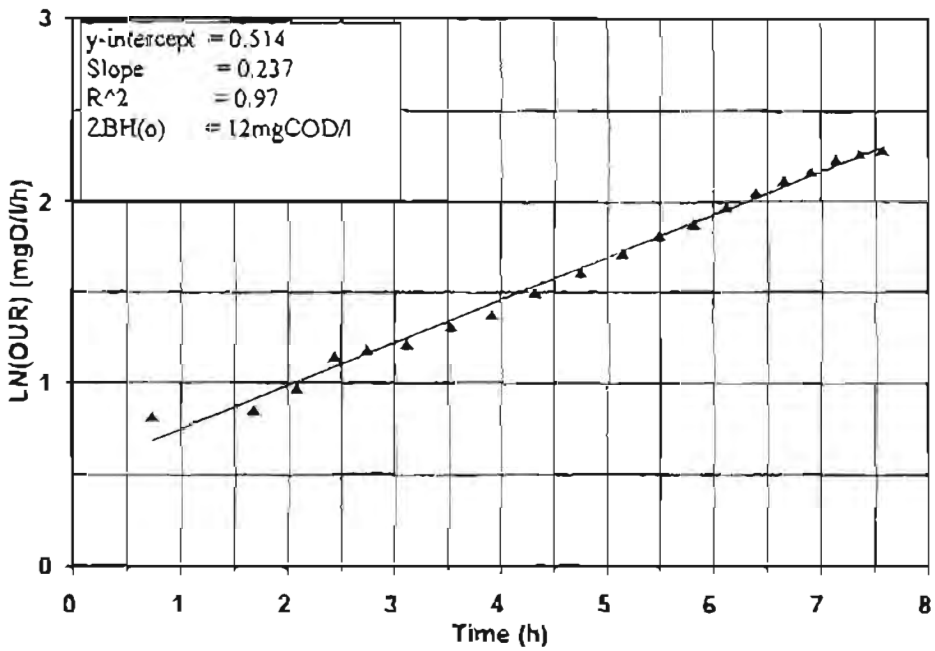


Fig A83b ln(OUR) graph for wastewater only batch test, 02-06, wastewater batch no. 27

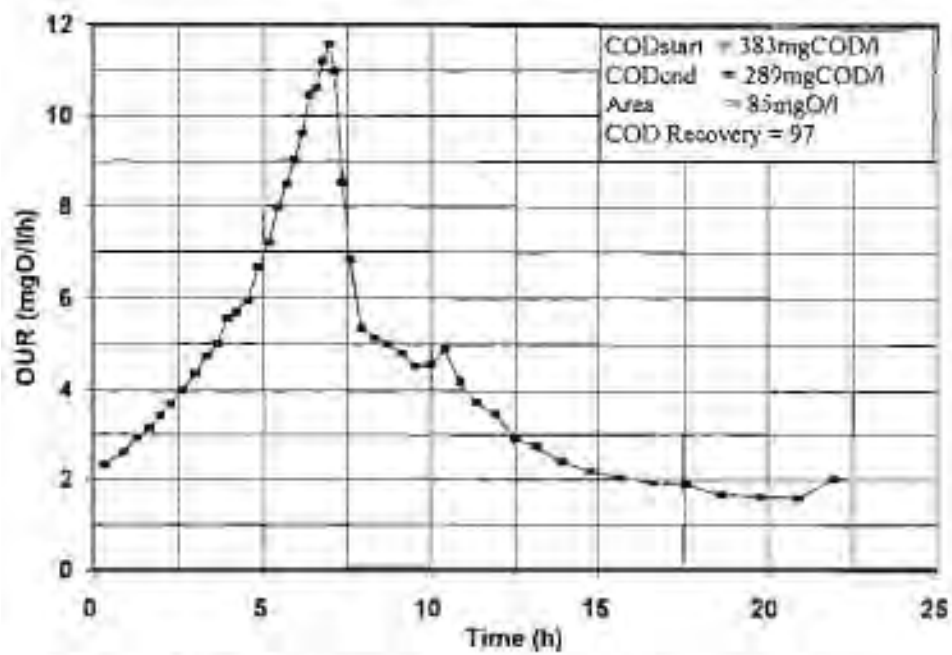


Fig A84a OUR graph for wastewater only batch test, 03-06, wastewater batch no. 27

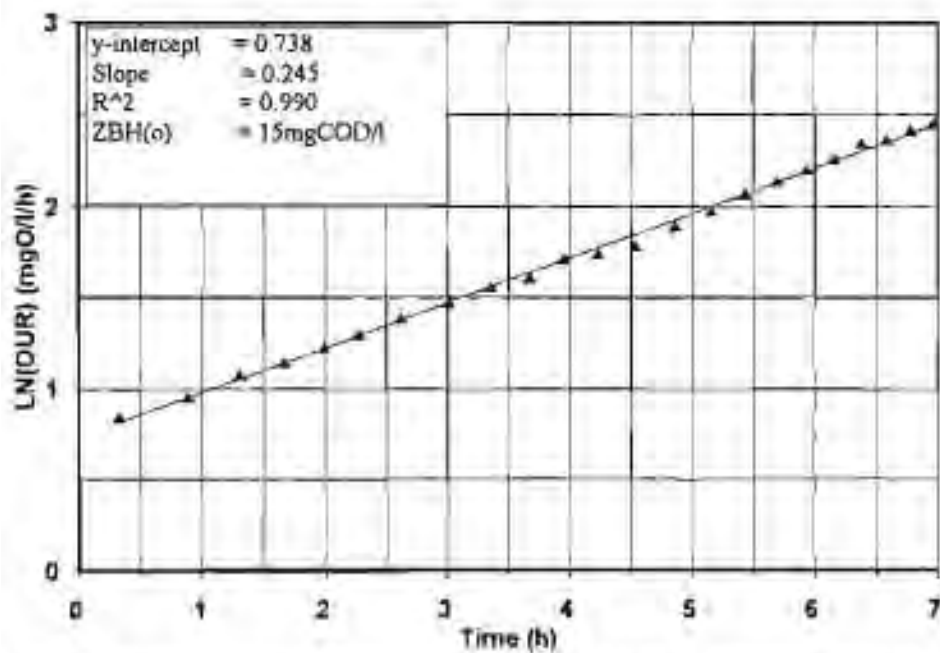


Fig A84b ln(OUR) graph for wastewater only batch test, 03-06, wastewater batch no. 27

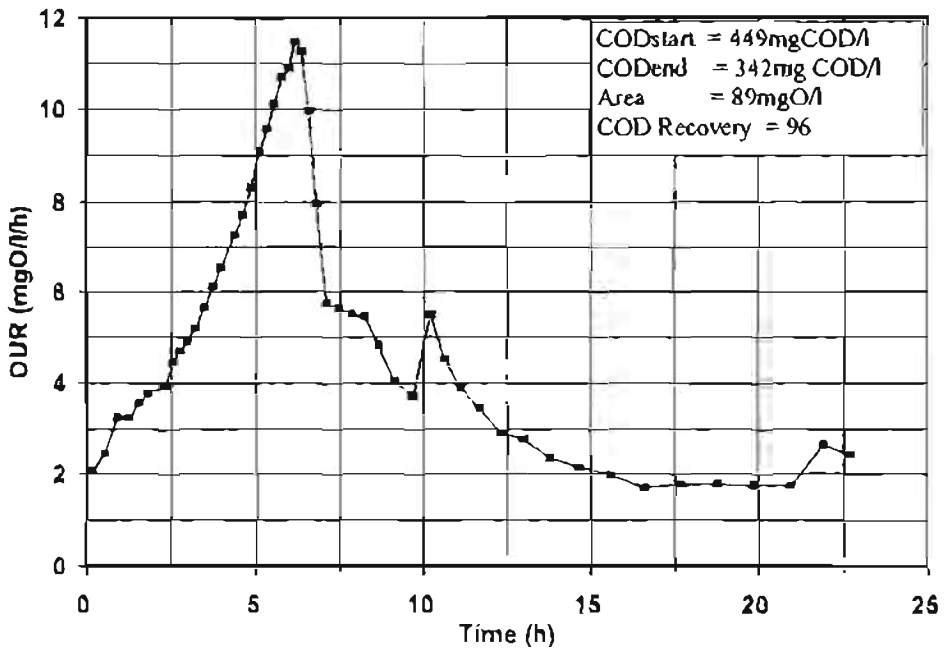


Fig A85a OUR graph for wastewater only batch test, 04-06, wastewater batch no 27

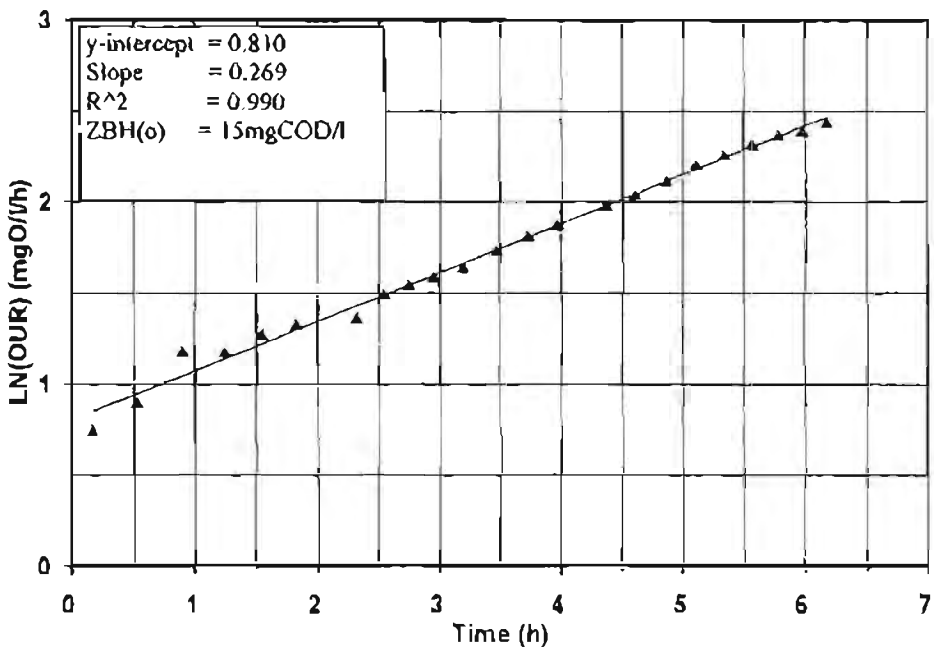


Fig A85b Ln(OUR) graph for wastewater only batch test, 04-06, wastewater batch no. 27

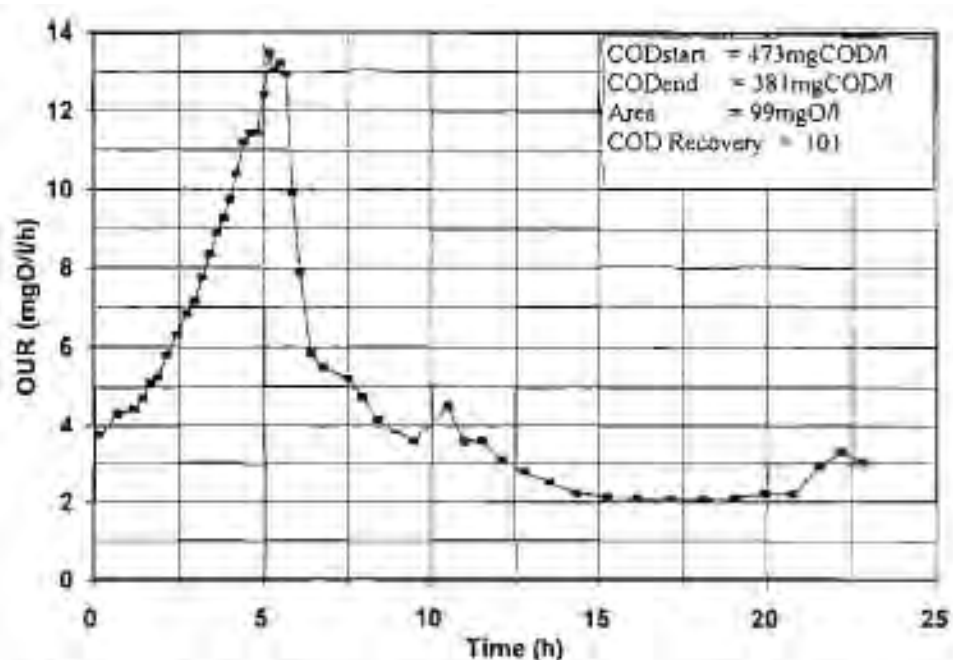


Fig A86a OUR graph for wastewater only batch test, 05-06, wastewater batch no: 27

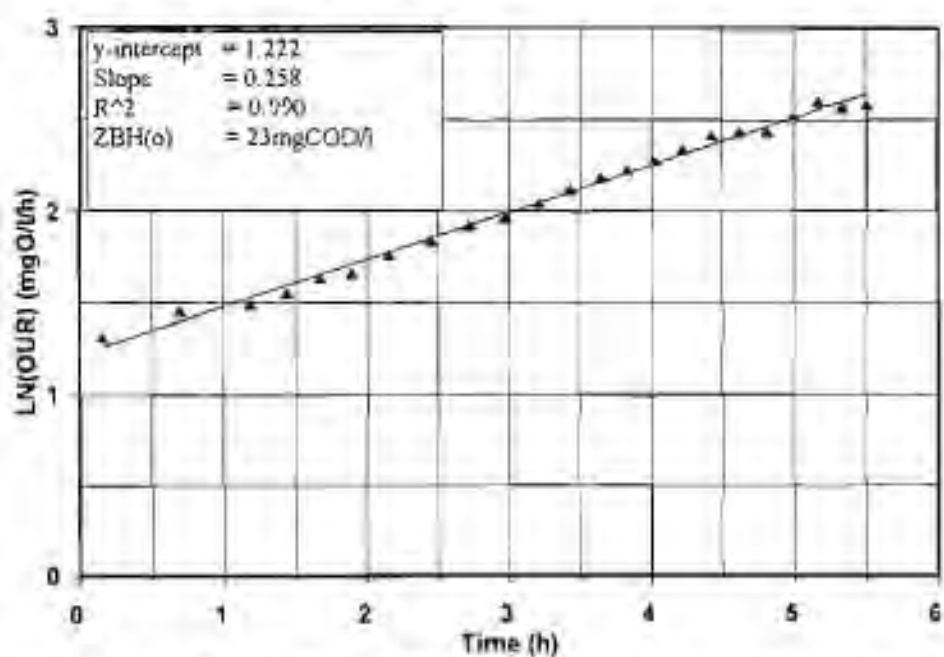


Fig A86b ln(OUR) graph for wastewater only batch test, 05-06, wastewater batch no: 27

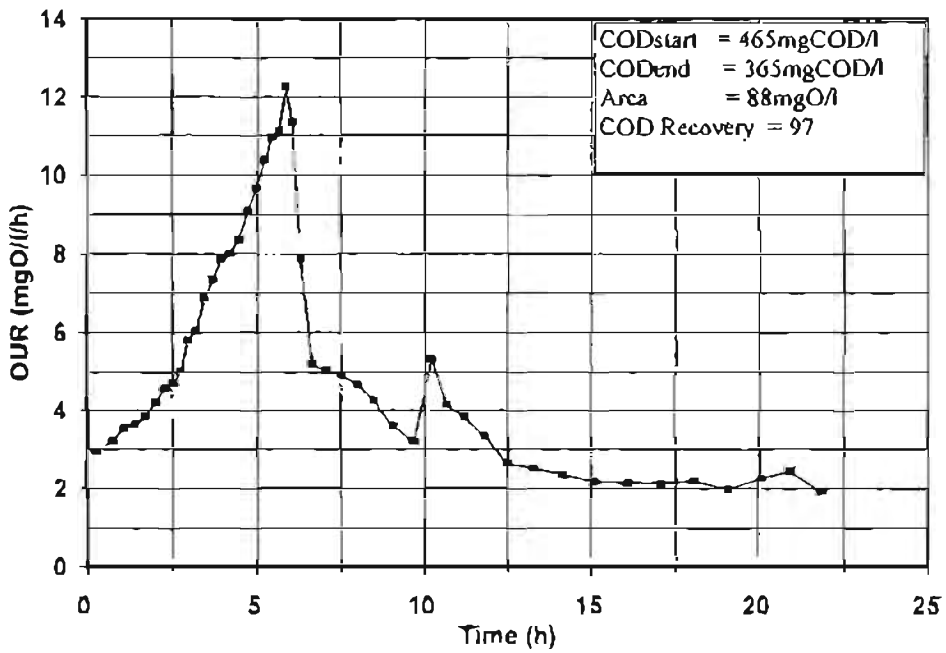


Fig A87a OUR graph for wastewater only batch test, 06-06, wastewater batch no. 27

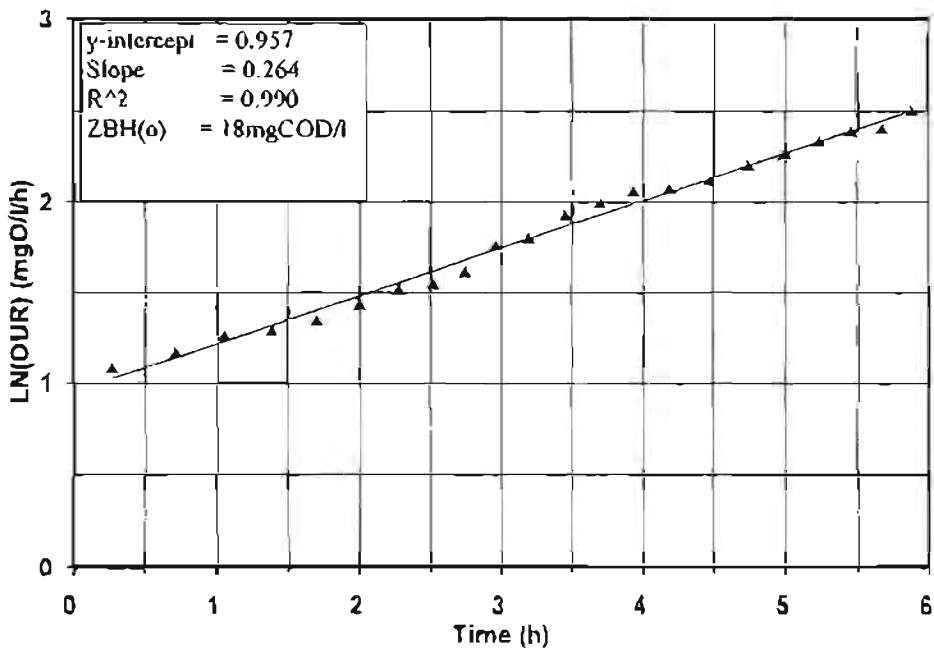


Fig A87b ln(OUR) graph for wastewater only batch test, 06-06, wastewater batch no. 27

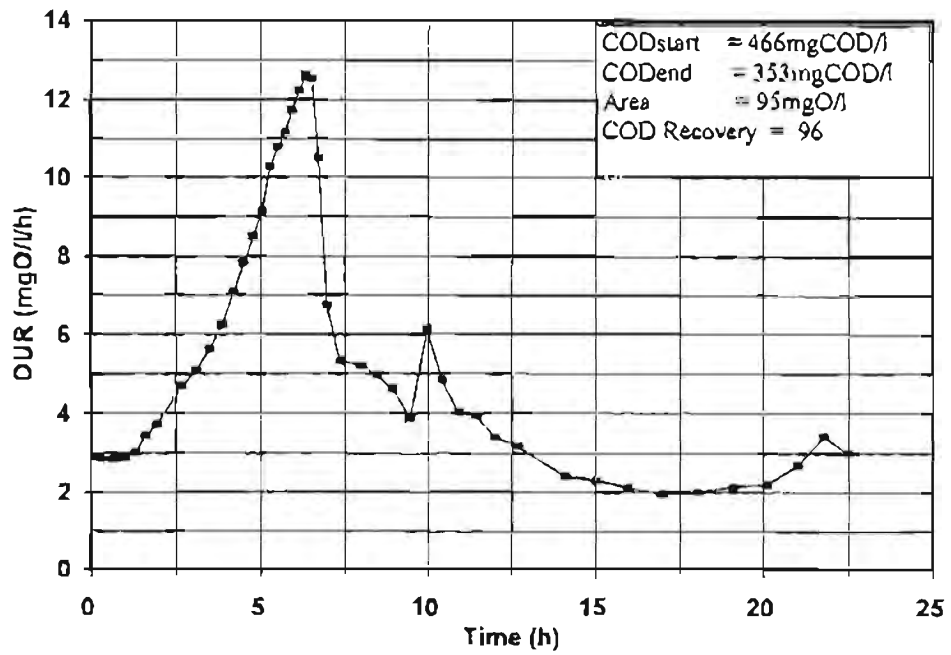


Fig A88a OUR graph for wastewater only batch test, 07-06, wastewater batch no. 27

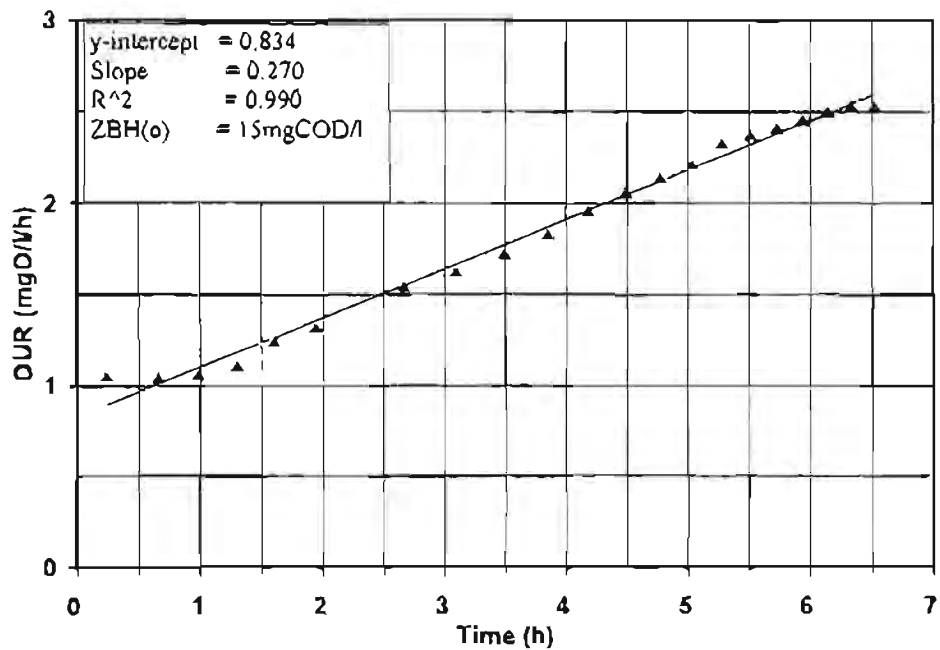


Fig A88b ln(OUR) graph for wastewater only batch test, 07-06, wastewater batch no. 27

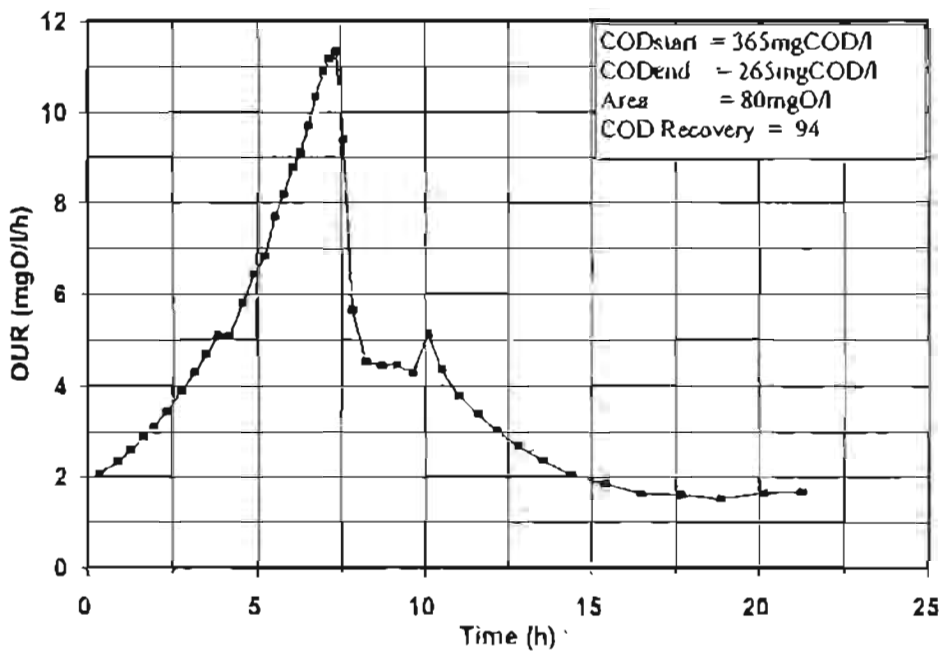


Fig A89a OUR graph for wastewater only batch test, 08-06, wastewater batch no. 27

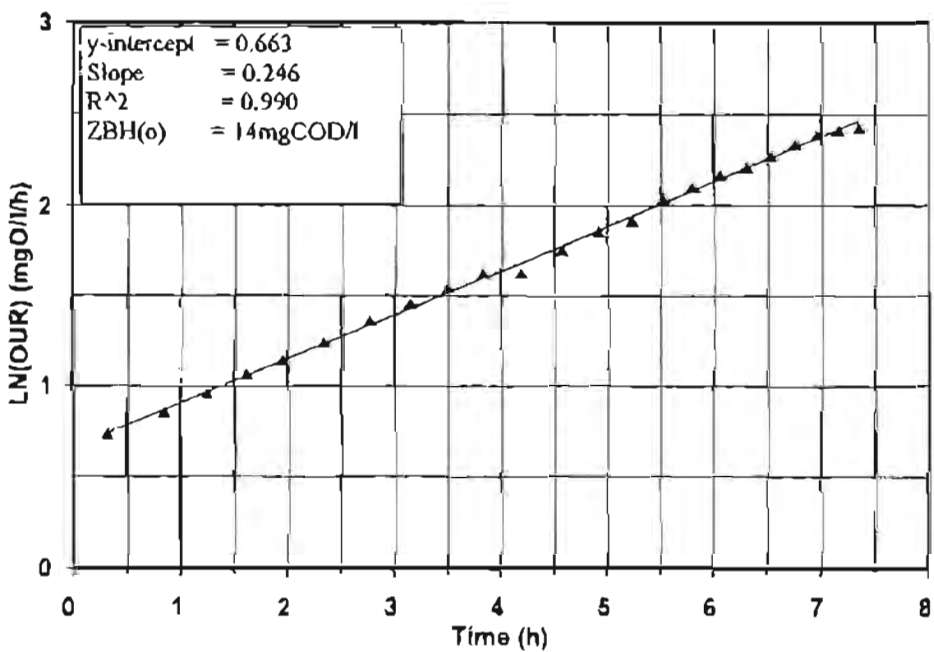


Fig A89b Ln(OUR) graph for wastewater only batch test, 08-06, wastewater batch no. 27

APPENDIX B

COMPREHENSIVE DATA AND OUR vs TIME PLOTS FOR THE WASTEWATER PLUS MIXED LIQUOR BATCH TESTS

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- Table B2 Daily wastewater plus mixed liquor batch test nitrification data, listing the y-intercept, slope and correlation coefficient of the nitrate concentration vs time plots and OUR for nitrification (OUR_N).
- Table B3 Daily measured heterotrophic active biomass data for wastewater plus mixed liquor and wastewater only batch tests in comparison with that calculated theoretically from steady state model.
- Fig B1a-B115b OUR vs time and $\ln(\text{OUR})$ vs time profiles for wastewater plus mixed liquor batch tests.
- Fig N1-N89 Nitrate concentration vs time profiles for the wastewater plus mixed liquor batch tests.

Table B1 Daily wastewater plus mixed liquor batch tests data with calculated COD recovery and heterotrophic active biomass

Sew. Batch No.	Batch Test No.	Date	COD (mgCOD/l)		Area (mgO/l)	Linear Regression data			%COD Recovery	ZBH(α) (mgCOD/l)
			Start	End		y-interc.	slope	R ²		
12	M1	20-Oct	670	506	174	2.209	0.143	0.972	102	108
	M2	22-Oct	740	559	155	2.389	0.092	0.960	96	186
	M3	23-Oct	851	691	161	2.267	0.113	0.907	100	139
	M4	24-Oct	748	600	155	2.31	0.113	0.962	101	145
	M5	26-Oct	804	698	172	2.262	0.076	0.993	96	188
	M6	27-Oct	756	577	158	2.266	0.138	0.969	97	119
	M7	28-Oct	704	538	156	2.199	0.16	0.990	99	97
	M8	29-Oct	631	496	102	1.049	0.137	0.987	95	50
93.8										
13	M9	01-Nov	548	395	134	1.696	0.235	0.990	97	42
	M10	04-Nov	729	406	185	2.104	0.145	0.949	81**	96
	M11	06-Nov	729	406	135	1.893	0.22	0.947	74**	54
	M12	07-Nov	729	406	202	2.207	0.116	0.941	83**	128
87										
17	M13	11-Jan	726	718	151	2.434	0.038	0.46*	120**	368
	M14	12-Jan	748	645	133	1.868	0.109	0.910	104	96
	M15	15-Jan	814	718	167	1.987	0.093	0.910	109	122
	M16	16-Jan	820	710	147	1.918	0.100	0.950	105	108
	M17	17-Jan	790	653	141	1.780	0.134	0.980	100	74
	M18	18-Jan	721	609	134	1.735	0.130	0.950	103	73
	M19	19-Jan	685	587	135	1.403	0.156	0.986	105	45
	M20	21-Jan	646	547	141	1.794	0.126	0.990	107	79
	M21	22-Jan	618	497	117	1.255	0.192	0.987	99	12
	M22	23-Jan	598	458	126	1.383	0.176	0.988	98	39
	M23	24-Jan	831	473	136	1.585	0.158	0.994	97	53
103										
18	M24	25-Jan	549	485	104	1.906	0.114	0.988	107	96
	M25	26-Jan	573	497	116	2.107	0.157	0.980	107	90
	M26	29-Jan	631	520	132	1.792	0.165	0.991	103	63
	M27	30-Jan	616	516	124	1.982	0.142	0.978	104	85
	M28	31-Jan	500	415	112	1.557	0.175	0.998	105	47
	M29	01-Feb	516	402	118	1.480	0.160	0.991	101	47
	M30	02-Feb	654	541	134	1.932	0.098	0.900	103	111
	M31	03-Feb	683	581	123	1.833	0.118	0.974	103	87
	M32	04-Feb	752	622	132	2.090	0.078	0.958	100	155
	M33	05-Feb	769	670	139	2.004	0.108	0.970	105	111
	M34	06-Feb	777	597	139	2.181	0.074	0.900	95	177
103										
19	M35	07-Feb	748	683	129	2.226	0.146	0.977	108	107
	M36	08-Feb	695	589	129	2.331	0.083	0.831*	103	188
	M37	09-Feb	752	552	166	2.190	0.149	0.927	95	102
	M38	11-Feb	617	491	134	1.866	0.151	0.988	101	73
	M39	12-Feb	654	540	120	1.811	0.184	0.982	101	58
	M40	13-Feb	647	537	126	1.750	0.180	0.989	102	56
	M41	14-Feb	639	487	118	1.409	0.225	0.997	95	33
	M42	15-Feb	604	482	127	1.504	0.190	0.991	102	42
	M43	16-Feb	618	528	110	0.783	0.270	0.896	103	15
	M44	17-Feb	528	406	123	1.311	0.237	0.997	100	28
	M45	18-Feb	516	369	126	1.410	0.240	0.997	100	31
	M46	19-Feb	501	373	133	1.503	0.221	0.992	101	36
	101									

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on COD < 90% or COD > 110%

Table B1-cont.

Daily wastewater plus mixed liquor batch tests data with calculated COD recovery and heterotrophic active biomass

Sew. Batch No.	Batch Test No.	Date	COD (mgCOD/l)		Area (mgO/l)	Linear Regression data			%COD Recovery	ZBH(o) (mgCOD/l)
			Start	End		y-interc.	slope	R ²		
20	M47	20-Feb	710	685	148	2.304	0.151	0.957	117**	113
	M48	21-Feb	669	558	155	2.341	0.071	0.878*	107	214
	M49	23-Feb	698	529	132	2.261	0.118	0.856	95	133
	M50	24-Feb	853	517	151	2.711	-0.034	0.160*	102	-3673
	M51	25-Feb	648	558	127	1.876	0.127	0.990	106	85
	M52	26-Feb	623	516	131	2.058	0.124	0.908	104	104
	M53	27-Feb	635	528	137	2.068	0.127	0.981	105	103
	M54	28-Feb	500	344	137	1.727	0.158	0.978	96	61
	M55	29-Feb	545	389	138	1.714	0.157	0.977	97	61
	M56	01-Mar	557	410	137	1.712	0.128	0.975	98	72
	M57	02-Mar	881	786	150	2.283	0.081	0.906	104	183
	M58	03-Mar	791	713	152	2.462	0.005	0.001*	109	758
M59	04-Mar	812	734	138	2.507	0.013	0.065*	107	630	
									102	
21	M60	11-Mar	851	677	131	2.292	0.124	0.982	96	132
	M61	12-Mar	818	660	135	2.339	0.086	0.976	97	185
	M62	14-Mar	839	502	129	1.588	0.172	0.994	99	48
	M63	15-Mar	689	548	137	1.661	0.169	0.991	99	54
	M64	17-Mar	776	661	122	1.973	0.116	0.952	101	101
	M65	18-Mar	558	431	129	1.396	0.225	0.992	100	32
	M66	19-Mar	529	382	122	1.370	0.217	0.987	96	32
									98	
22	M67	06-Apr	937	839	86	2.057	0.095	0.920	99	129
	M68	07-Apr	578	464	93	1.508	0.202	0.989	96	40
	M69	08-Apr	831	692	48	1.409	0.154	0.982	89**	45
	M70	09-Apr	698	578	62	0.874	0.265	0.971	92	13
	M71	10-Apr	818	713	96	1.641	0.126	0.982	99	68
	M72	11-Apr	692	583	101	1.814	0.114	0.936	99	87
									96	
23	M73	15-Apr	640	494	107	1.544	0.206	0.990	94	40
	M74	16-Apr	919	866	132	2.051	0.152	0.902	109	87
	M75	17-Apr	732	629	110	1.710	0.173	0.983	101	55
	M76	18-Apr	869	749	121	1.889	0.127	0.951	100	86
	M77	19-Apr	724	666	101	1.797	0.145	0.981	106	70
	M78	20-Apr	669	786	108	2.322	0.062	0.859*	103	231
	M79	21-Apr	976	819	127	2.130	0.098	0.933	97	135
	M80	22-Apr	607	525	130	1.696	0.187	0.980	108	51
									102	
24	M81	29-Apr	684	596	125	1.755	0.193	0.990	105	53
	M82	30-Apr	1091	1002	126	1.254	0.241	0.990	103	26
	M83	01-May	797	604	146	1.752	0.156	0.987	94	63
	M84	02-May	637	564	139	1.387	0.212	0.989	110	34
	M85	03-May	750	673	145	2.023	0.180	0.881*	109	81
	M86	04-May	621	548	119	1.220	0.211	0.996	107	29
	M87	05-May	531	466	116	1.839	0.147	0.836	110**	73
	M88	06-May	641	633	134	2.475	0.076	0.758*	120**	233
	M89	07-May	621	548	113	1.351	0.220	0.994	106	31
	M90	08-May	531	466	133	1.811	0.173	0.976	113	61
	M91	09-May	641	633	111	2.475	0.076	0.758*	116**	233
									108	

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on COD < 90% or COD > 110%

Table B1-cont.

Daily wastewater plus mixed liquor batch tests data with calculated COD recovery and heterotrophic active biomass.

Sew. Batch No.	Batch Test No.	Date	COD (mgCOD/l)		Area (mgO/l)	Linear Regression data			%COD Recovery	ZBH(a) (mgCOD/l)
			Start	End		y-interc.	slope	R ²		
26	M92	23-May	561	500	96	1.521	0.249	0.989	106	33
	M93	24-May	819	750	114	1.959	0.141	0.984	105	85
	M94	25-May	647	557	124	1.821	0.143	0.978	105	73
	M95	26-May	721	647	122	1.893	0.123	0.979	107	89
	M96	27-May	688	606	116	1.703	0.165	0.988	106	57
	M97	28-May	608	470	113	1.504	0.203	0.993	96	39
	M98	29-May c	669	548	121	1.684	0.172	0.993	100	54
	M99	29-May e	821	515	123	1.566	0.180	0.992	103	46
	M100	30-May c	718	596	133	1.854	0.147	0.993	102	74
	M101	30-May e	750	629	133	1.878	0.143	0.990	101	77
									103	
27	M102	03-Jun	496	418	102	1.280	0.174	0.986	105	36
	M103	04-Jun	656	770	118	1.866	0.099	0.974	104	103
	M104	05-Jun	750	664	116	1.810	0.149	0.960	104	70
	M105	06-Jun	901	721	122	2.021	0.081	0.869*	94	141
	M106	07-Jun	714	628	109	1.411	0.186	0.994	103	39
	M107	08-Jun	472	402	90	1.062	0.197	0.994	104	26
	M108	9-Jun c	632	546	104	1.509	0.162	0.978	103	48
	M109	9-Jun e	607	505	106	1.410	0.163	0.972	101	43
	M110	10-Jun c	763	698	110	1.660	0.142	0.987	106	64
	M111	10-Jun e	772	694	115	1.717	0.127	0.983	105	73
	M112	11-Jun c	644	554	106	1.437	0.194	0.994	102	38
	M113	11-Jun e	579	488	111	1.187	0.221	0.995	104	26
	M114	12-Jun c	813	731	110	1.896	0.148	0.984	103	63
	M115	12-Jun e	706	599	106	1.544	0.148	0.959	100	54
										108

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on COD < 90% or COD > 110%.

Table B2 Daily wastewater plus mixed liquor batch test nitrification data with the calculated OUR for nitrification.

Sewage Batch No	Batch Test No.	Date	y-intercept	slope	R²	OURn (mgO₂/l/h)
12	M1	20-Oct	0.547	0.129	0.983	0.59
	M2	22-Oct	0.572	0.257	0.962	1.17
	M3	23-Oct	0.426	0.506	0.923	2.31
	M4	24-Oct	0.541	0.296	0.987	1.35
	M5	26-Oct	0.739	0.326	0.966	1.49
	M6	27-Oct	0.845	0.191	0.913	0.87
	M7	28-Oct	0.557	0.211	0.882	0.96
	M8	29-Oct	0.343	0.075	0.989	0.34
13	M9	01-Nov	0.452	0.029	0.937	0.13
	M10	04-Nov	0.929	0.104	0.935	0.48
	M11	06-Nov	0.816	0.128	0.923	0.59
	M12	07-Nov	1.486	0.17	0.957	0.78
17	M13	11-Jan	0.565	0.279	0.994	1.28
	M14	12-Jan	0.845	0.265	0.993	1.21
	M15	15-Jan	0.711	0.435	0.937	1.99
	M16	16-Jan	0.776	0.201	0.952	0.92
	M17	17-Jan	0.609	0.322	0.931	1.47
	M18	18-Jan	0.612	0.106	0.902	0.48
	M19	19-Jan	0.560	0.109	0.908	0.50
	M20	21-Jan	0.514	0.123	0.967	0.56
	M21	22-Jan	0.359	0.025	0.930	0.11
	M22	23-Jan	0.362	0.021	0.934	0.10
18	M23	24-Jan	0.381	0.034	0.943	0.16
	M24	25-Jan	0.531	0.159	0.994	0.73
	M25	26-Jan	0.605	0.146	0.998	0.67
	M26	29-Jan	0.455	0.084	0.921	0.38
	M27	30-Jan	0.377	0.105	0.977	0.48
	M28	31-Jan	0.272	0.031	0.943	0.14
	M29	01-Feb	0.275	0.031	0.945	0.14
	M30	02-Feb	0.390	0.299	0.960	1.37
	M31	03-Feb	0.523	0.103	0.964	0.47
	M32	04-Feb	0.688	0.188	0.921	0.86
	M33	05-Feb	0.559	0.247	0.934	1.13
	M34	06-Feb	0.613	0.269	0.973	1.23
19	M35	07-Feb	0.615	0.312	0.910	1.43
	M36	08-Feb	0.740	0.293	0.953	1.34
	M37	09-Feb	0.696	0.350	0.940	1.60
	M38	11-Feb	0.664	0.206	0.954	0.94
	M39	12-Feb	0.499	0.336	0.960	1.54
	M40	13-Feb	0.462	0.372	0.944	1.70
	M41	14-Feb	0.338	0.282	0.968	1.29
	M42	15-Feb	0.396	0.254	0.980	1.16
	M43	16-Feb	0.390	0.210	0.942	0.96
	M44	17-Feb	0.336	0.132	0.975	0.60
	M45	18-Feb	0.265	0.128	0.996	0.58
	M46	19-Feb	0.348	0.138	0.931	0.63

Table B2-cont.

Daily wastewater plus mixed liquor batch test nitrification data with the calculated OUR for nitrification.

Sewage Batch No	Batch Test No.	Date	y-intercept	slope	R²	OURn (mgO₂/l/h)
20	M47	20-Feb	0.730	0.222	0.927	1.01
	M48	21-Feb	0.678	0.584	0.942	2.67
	M49	23-Feb	0.979	0.409	0.900	1.87
	M50	24-Feb	1.039	0.325	0.994	1.49
	M51	25-Feb	0.720	0.181	0.982	0.83
	M52	26-Feb	0.804	0.311	0.987	1.42
	M53	27-Feb	0.909	0.322	0.932	1.47
	M54	28-Feb	0.333	0.145	0.935	0.66
	M55	29-Feb	0.370	0.150	0.900	0.69
	M56	01-Mar	0.477	0.125	0.982	0.57
	M57	02-Mar	0.891	0.865	0.933	3.95
	M58	03-Mar	0.964	0.815	0.921	3.72
M59	04-Mar	0.850	0.827	0.965	3.78	
21	M60	11-Mar	0.281	0.921	0.963	4.21
	M61	12-Mar	0.567	0.723	0.928	3.30
	M62	14-Mar	0.398	0.361	0.936	1.65
	M63	15-Mar	0.315	0.368	0.953	1.68
	M64	17-Mar	0.550	0.585	0.969	2.67
	M65	18-Mar	0.258	0.219	0.921	1.00
	M66	19-Mar	0.261	0.202	0.941	0.92
22	M67	06-Apr	1.858	1.200	0.952	5.48
	M68	07-Apr	0.851	0.096	0.700	0.44
	M69	08-Apr	1.188	0.908	0.971	4.15
	M70	09-Apr	0.924	0.581	0.936	2.66
	M71	10-Apr	1.808	0.826	0.967	3.77
	M72	11-Apr	1.087	0.560	0.984	2.56
23	M73	15-Apr	0.443	0.190	0.971	0.87
	M74	16-Apr	1.841	0.931	0.989	4.25
	M75	17-Apr	0.259	0.401	0.971	1.83
	M76	18-Apr	1.501	0.676	0.979	3.09
	M77	19-Apr	0.695	0.383	0.950	1.75
	M78	20-Apr	1.347	0.542	0.992	2.48
	M79	21-Apr	2.570	0.762	0.980	3.48
	M80	22-Apr	0.996	0.143	0.920	0.65
24	M81	29-Apr	0.589	0.023	0.920	0.11
	M82	30-Apr	0.351	0.097	0.956	0.44
	M83	01-May	1.168	0.226	0.901	1.03
	M84	02-May	0.705	0.226	0.986	1.03
	M85	03-May	1.272	0.281	0.918	1.28
	M86	04-May	0.756	0.110	0.900	0.50
	M87	05-May	0.791	0.118	0.906	0.54
	M88	06-May	0.733	0.295	0.925	1.35
	M89	07-May	1.457	0.266	0.984	1.22
	M90	08-May	1.557	0.295	0.984	1.35
	M91	09-May	1.436	0.266	0.966	1.22

Table B2-cont.

Daily wastewater plus mixed liquor batch test nitrification data with the calculated OUR for nitrification.

Sewage Batch No	Batch Test No.	Date	y-intercept	slope	R²	OURn (mgO/l/h)
26	M92	23-May	0.547	0.111	0.900	0.51
	M93	24-May	1.724	0.224	0.730	1.02
	M94	25-May	0.869	0.143	0.920	0.65
	M95	26-May	1.526	0.264	0.900	1.21
	M96	27-May	1.313	0.102	0.900	0.47
	M97	28-May	0.677	0.025	0.896	0.11
	M98	29-May c	1.266	0.022	0.958	0.10
	M99	29-May e	1.260	0.026	0.971	0.12
	M100	30-May c	1.672	0.059	0.958	0.27
	M101	30-May e	1.847	0.026	0.980	0.12
27	M102	03-Jun	0.291	0.008	0.900	0.04
	M103	04-Jun	0.627	0.014	0.979	0.06
	M104	05-Jun	0.314	0.065	0.971	0.30
	M105	06-Jun	0.614	0.143	0.975	0.65
	M106	07-Jun	0.308	0.039	0.964	0.18
	M107	08-Jun	0.314	0.015	0.961	0.07
	M108	9-Jun c	0.482	0.003	0.962	0.01
	M109	9-Jun e	0.514	0.003	0.962	0.01
	M110	10-Jun c	0.701	0.102	0.974	0.47
	M111	10-Jun e	0.740	0.081	0.974	0.37
	M112	11-Jun c	0.489	0.002	0.958	0.01
	M113	11-Jun e	0.377	0.040	0.902	0.18
	M114	12-Jun c	0.750	0.051	0.959	0.23
	M115	12-Jun e	0.551	0.013	0.957	0.06

Table B3 Daily heterotrophic active biomass data measured in wastewater plus mixed liquor and wastewater only batch tests compared to theoretical values calculated from steady state model.

Sew. Batch No.	Batch Test No.	Date	Wastewater + Mixed liquor Volumes (litres)		Measured ZBH(o) (mgCOD/l)			Theoretical ZBH(ML) (mgCOD/l)
			ML	WW	ML+WW	(WW)D	ML	
12	1	20-Oct	0.2	2.8	108	17.5	90	80
	2	22-Oct	0.4	2.6	186	16.3	168	159
	3	23-Oct	0.3	2.7	139	16.9	122	119
	4	24-Oct	0.3	2.7	145	16.9	128	119
	5	26-Oct	0.4	2.6	188	16.3	172	159
	6	27-Oct	0.3	2.7	119	16.9	102	119
	7	28-Oct	0.2	2.8	97	17.5	79	80
	8	29-Oct	0.1	2.9	50	18	32	40
13+	9	01-Nov	0.1	2.9	42	8.7	33	36
	10	04-Nov	0.3	2.7	96	8.1	88**	109
	11	06-Nov	0.2	2.8	54	8.4	45**	72
	12	07-Nov	0.4	2.6	128	7.4	120**	145
17	13	11-Jan	0.3	2.7	368	16.2	352 ⁺	109
	14	12-Jan	0.3	2.7	96	16.2	80	109
	15	15-Jan	0.3	2.7	122	16.2	106	109
	16	16-Jan	0.3	2.7	108	16.2	91	109
	17	17-Jan	0.2	2.8	74	16.8	57	73
	18	18-Jan	0.2	2.8	73	16.8	56	73
	19	19-Jan	0.2	2.8	45	16.8	-28***	73
	20	21-Jan	0.2	2.8	79	16.8	62	73
	21	22-Jan	0.1	2.9	32	17.4	15	36
	22	23-Jan	0.1	2.9	39	17.4	22	36
18	23	24-Jan	0.1	2.9	53	17.4	36	36
	24	25-Jan	0.2	2.8	96	26.9	69	67
	25	26-Jan	0.2	2.8	90	26.9	63	67
	26	29-Jan	0.1	2.9	63	27.8	36	33
	27	30-Jan	0.2	2.8	85	26.9	58	67
	28	31-Jan	0.1	2.9	47	27.8	19	33
	28	01-Feb	0.1	2.9	47	27.8	19	33
	30	02-Feb	0.3	2.7	111	25.9	85	100
	31	03-Feb	0.2	2.8	87	26.9	60	67
	32	04-Feb	0.4	2.6	155	25.0	130	133
	33	05-Feb	0.3	2.7	111	25.9	85	100
	34	06-Feb	0.4	2.6	177	25.0	152	133
19	35	07-Feb	0.4	2.6	107	20.5	87	163
	36	08-Feb	0.4	2.6	188	20.5	168 ⁺	163
	37	09-Feb	0.4	2.6	102	20.5	81	163
	38	11-Feb	0.3	2.7	73	21.2	52	122
	39	12-Feb	0.3	2.7	58	21.2	37	122
	40	13-Feb	0.3	2.7	56	21.2	35	122
	41	14-Feb	0.2	2.8	33	22.0	11	81
	42	15-Feb	0.2	2.8	42	22.0	20	81
	43	16-Feb	0.2	2.8	15	22.0	-7***	81
	44	17-Feb	0.1	2.9	28	22.0	5	41
	45	18-Feb	0.1	2.9	31	22.8	8	41
	46	19-Feb	0.1	2.9	38	22.8	14	41

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on COD < 90% or COD > 110%

*** test rejected as negative result

+ sewage batch rejected on parent system N and COD mass balance

Table B3- cont

Daily heterotrophic active biomass data measured in wastewater plus mixed liquor and wastewater only batch tests compared to theoretical values calculated from steady state model.

Sew. Batch No.	Batch Test No.	Date	Wastewater + Mixed liquor Volumes (litres)		Measured ML+WW	ZBH(o) (mgCOD/l)		Theoretical ZBH(ML) (mgCOD/l)
			ML	WW		(WW)D	ML	
20	47	20-Feb	0.3	2.7	113	20.4	92*	118
	48	21-Feb	0.3	2.7	214	20.4	194*	118
	49	23-Feb	0.3	2.7	133	20.4	113	118
	50	24-Feb	0.3	2.7	-3673	20.4	-3694***	118
	51	25-Feb	0.2	2.8	85	21.2	64	78
	52	26-Feb	0.2	2.8	104	21.2	83	78
	53	27-Feb	0.2	2.8	103	21.2	82	78
	54	28-Feb	0.1	2.9	61	21.9	39	39
	55	29-Feb	0.1	2.9	61	21.9	39	39
	56	01-Mar	0.1	2.9	72	21.9	50	39
	57	02-Mar	0.4	2.6	183	19.7	163	157
58	03-Mar	0.4	2.6	758	19.7	739*	157	
59	04-Mar	0.4	2.6	630	19.7	610*	157	
21+	60	11-Mar	0.4	2.6	132	21.7	110	171
	61	12-Mar	0.4	2.6	185	21.7	163	171
	62	14-Mar	0.2	2.8	48	23.4	25	85
	63	15-Mar	0.2	2.8	54	23.4	31	85
	64	17-Mar	0.3	2.7	101	22.6	79	128
	65	18-Mar	0.1	2.9	32	24.3	8	43
	66	19-Mar	0.1	2.9	32	24.3	8	43
22	67	06-Apr	0.4	2.6	129	19.7	109	189
	68	07-Apr	0.1	2.9	40	21.9	18	47
	69	08-Apr	0.3	2.7	45	20.4	25**	142
	70	09-Apr	0.2	2.8	13	21.2	-8***	94
	71	10-Apr	0.2	2.8	68	20.4	47	94
	72	11-Apr	0.3	2.7	87	21.2	66	142
23	73	15-Apr	0.1	2.9	40	23.6	17	52
	74	16-Apr	0.4	2.6	87	21.1	66	207
	75	17-Apr	0.2	2.8	55	22.8	33	104
	76	18-Apr	0.3	2.7	86	22.0	64	155
	77	19-Apr	0.2	2.8	70	22.8	48	104
	78	20-Apr	0.3	2.7	231	22.0	210*	155
	79	21-Apr	0.4	2.6	135	21.1	114	207
	80	22-Apr	0.1	2.9	51	23.6	27	52
24	81	29-Apr	0.2	2.8	53	17.2	36	92
	82	30-Apr	0.1	2.9	26	17.8	8	46
	83	01-May	0.3	2.7	63	16.6	46	138
	84	02-May	0.2	2.8	34	17.2	16	92
	85	03-May	0.3	2.7	81	16.6	65*	138
	86	04-May	0.15	2.85	29	17.5	11	69
	87	05-May	0.1	2.9	73	17.8	55**	46
	88	06-May	0.25	2.75	233	16.9	216*	115
	89	07-May	0.15	2.85	31	17.5	14	69
	90	08-May	0.3	2.7	61	16.6	45	138
	91	09-May	0.25	2.75	233	16.9	216*	115

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on COD < 90% or COD > 110%

*** test rejected as negative result

+ sewage batch rejected on parent system N and COD mass balance

Table B3-cont.

Daily heterotrophic active biomass data measured in wastewater plus mixed liquor and wastewater only batch tests compared to theoretical values calculated from steady state model.

Sew. Batch No.	Batch Test No.	Date	Wastewater + Mixed liquor Volumes (litres)		Measured ML+WW	ZBH(o) (mgCOD/l)		Theoretical ZBH(ML) (mgCOD/l)
			ML	WW		(WW)D	ML	
26	92	23-May	0.1	2.9	33	26.8	6	40
	93	24-May	0.3	2.7	85	24.9	60	120
	94	25-May	0.2	2.8	73	25.9	47	80
	95	26-May	0.3	2.7	89	24.9	64	120
	96	27-May	0.2	2.8	57	25.9	32	80
	97	28-May	0.1	2.9	39	26.8	12	40
	98	29-May c	0.15	2.85	54	26.3	28	60
	99	29-May e	0.15	2.85	46	26.3	20	60
	100	30-May c	0.25	2.75	74	25.4	48	100
	101	30-May e	0.25	2.75	77	25.4	52	100
27	102	03-Jun	0.1	2.9	36	14.2	21	42
	103	04-Jun	0.3	2.7	103	13.3	90	126
	104	05-Jun	0.2	2.8	70	13.7	56	84
	105	06-Jun	0.3	2.7	141	13.2	127*	126
	106	07-Jun	0.2	2.8	39	13.7	25	84
	107	08-Jun	0.1	2.9	26	14.2	12	42
	108	09-Jun c	0.15	2.85	48	14.0	34	63
	109	09-Jun e	0.15	2.85	43	14.0	29	63
	110	10-Jun c	0.25	2.75	64	13.5	50	105
	111	10-Jun e	0.25	2.75	73	13.5	59	105
	112	11-Jun c	0.15	2.85	38	14.0	24	63
	113	11-Jun e	0.1	2.9	26	14.2	12	42
	114	12-Jun c	0.25	2.75	63	13.5	49	105
	115	12-Jun e	0.2	2.8	54	13.7	40	84

* test rejected on $R^2 < 0.9$

** test rejected as an outlier on COD < 90% or COD > 110%

*** test rejected as negative result

+ sewage batch rejected on parent system N and COD mass balance

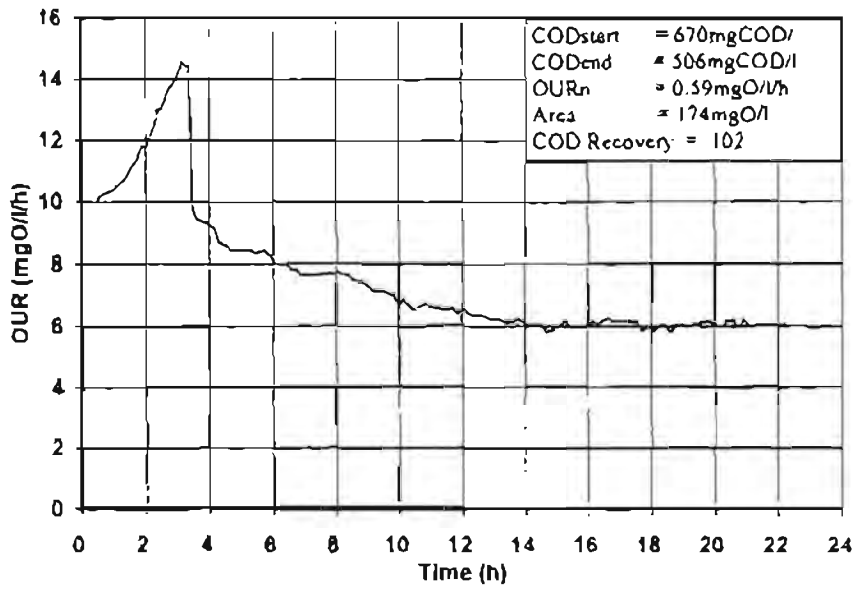


Fig B 1a OUR graph for wastewater plus mixed liquor batch test, 20-10, batch no. 12

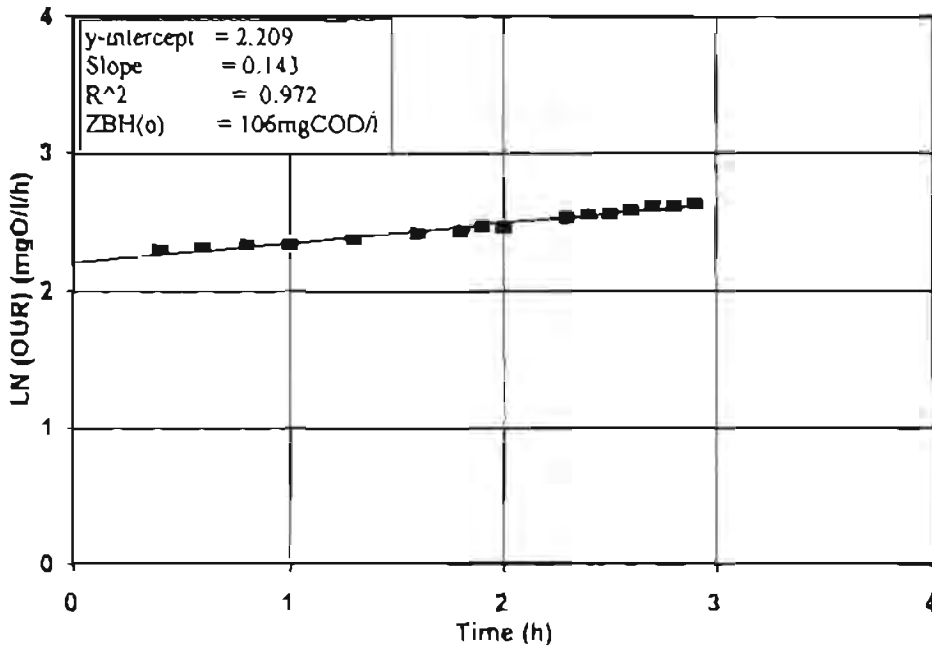


Fig B 1b ln(OUR) graph for wastewater plus mixed liquor batch test, 20-10, batch no. 12

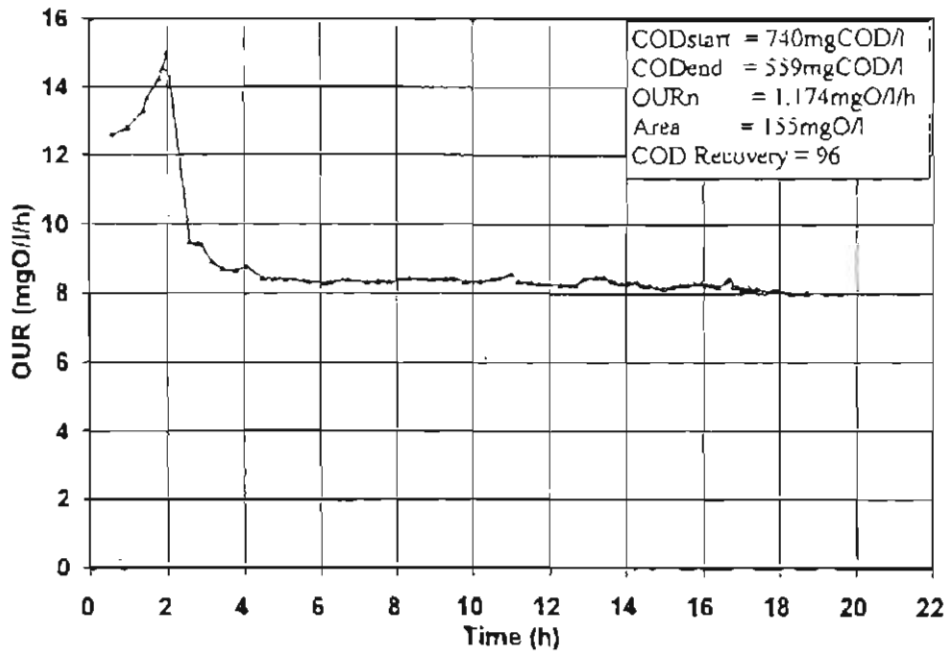


Fig B2a OUR graph for wastewater plus mixed liquor batch test, 22-10, batch no. 12

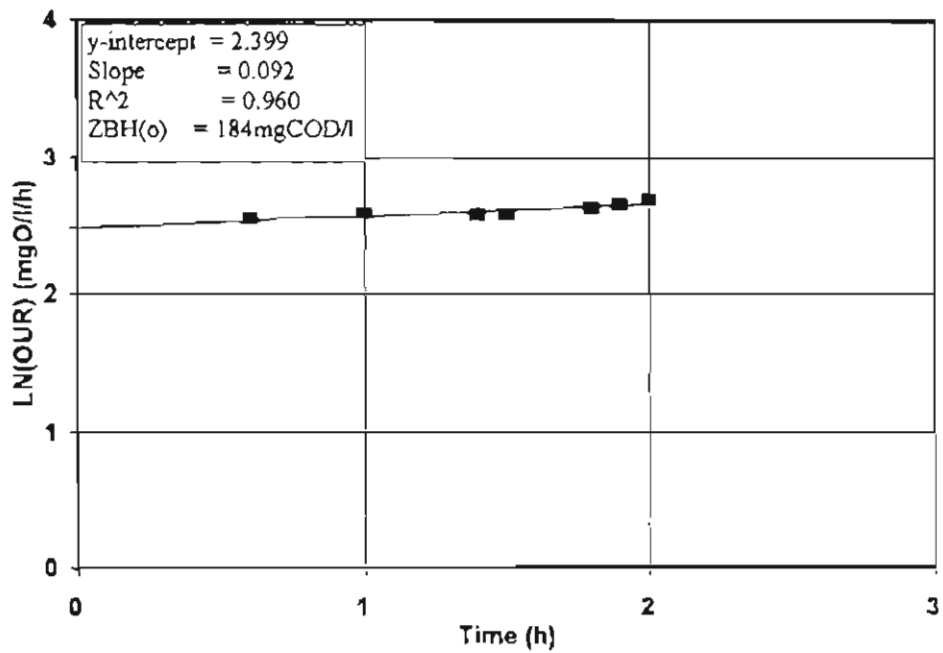


Fig B2b ln(OUR) graph for wastewater plus mixed liquor batch test, 22-10, batch no. 12

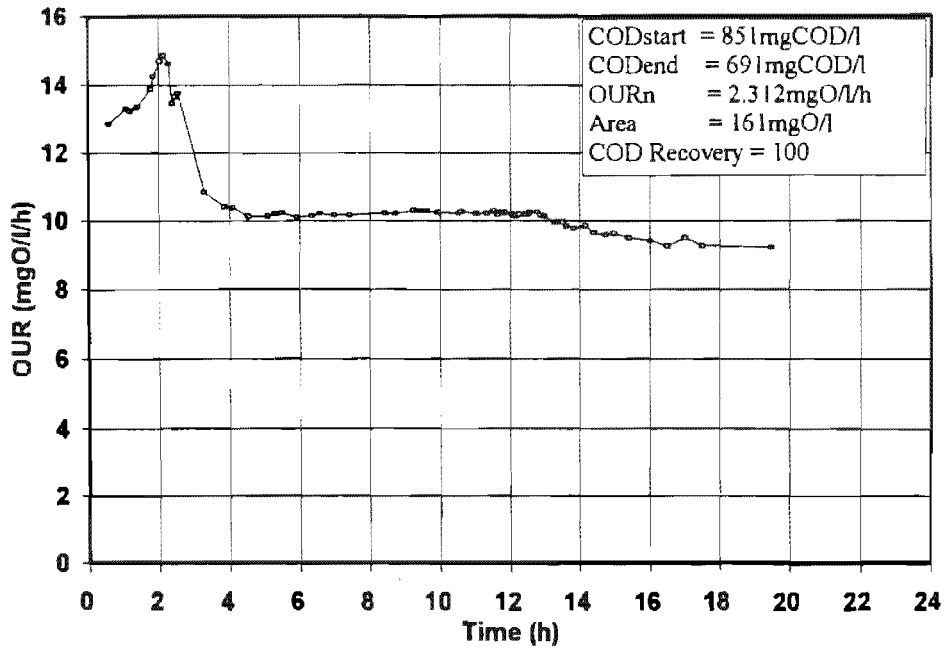


Fig B3a OUR graph for wastewater plus mixed liquor batch test, 23-10, batch no. 12

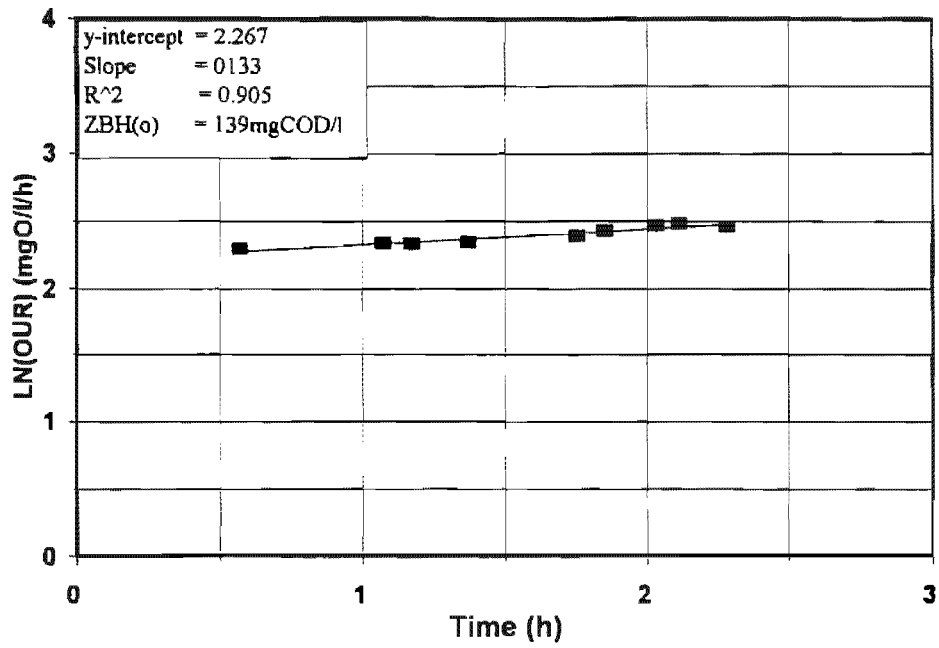


Fig B3b Ln(OUR) graph for wastewater plus mixed liquor batch test, 23-10, batch no. 12

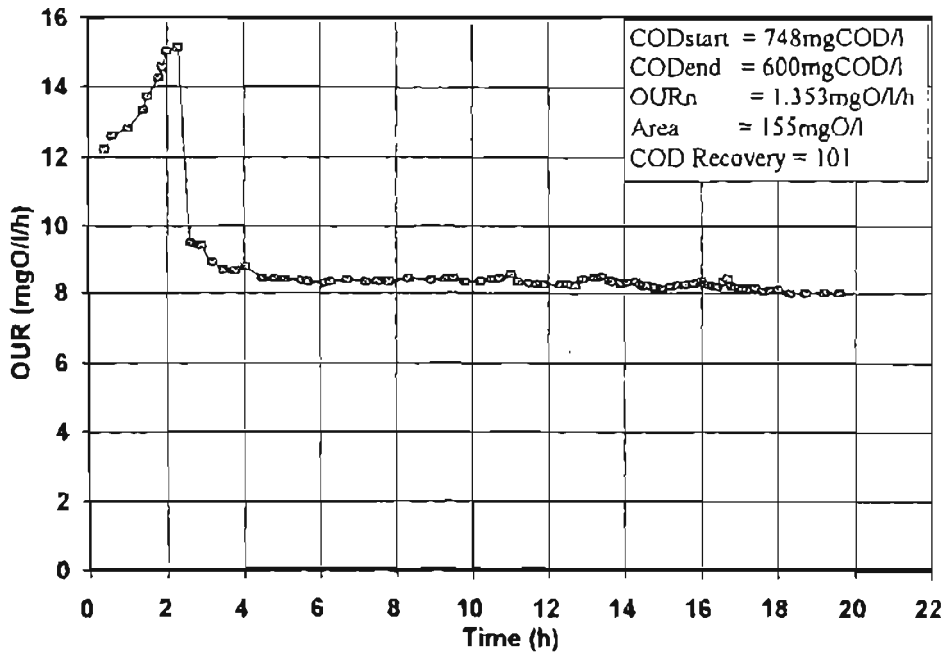


Fig B4a OUR graph for wastewater plus mixed liquor batch test, 24-10, batch no. 12

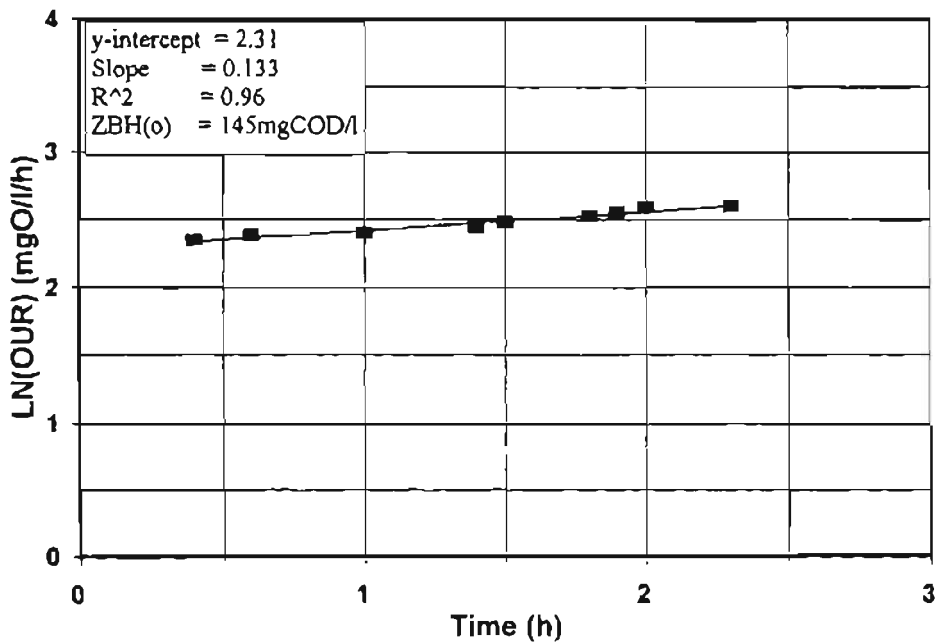


Fig B4b ln(OUR) graph for wastewater plus mixed liquor batch test, 24-10, batch no. 12

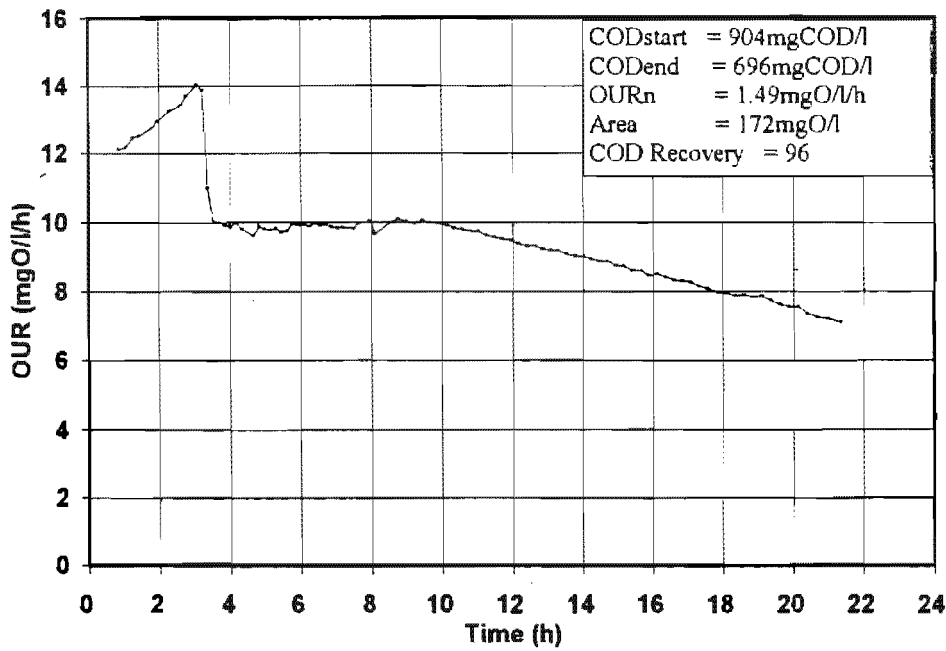


Fig B5a OUR graph for wastewater plus mixed liquor batch test, 26-10, batch no. 12

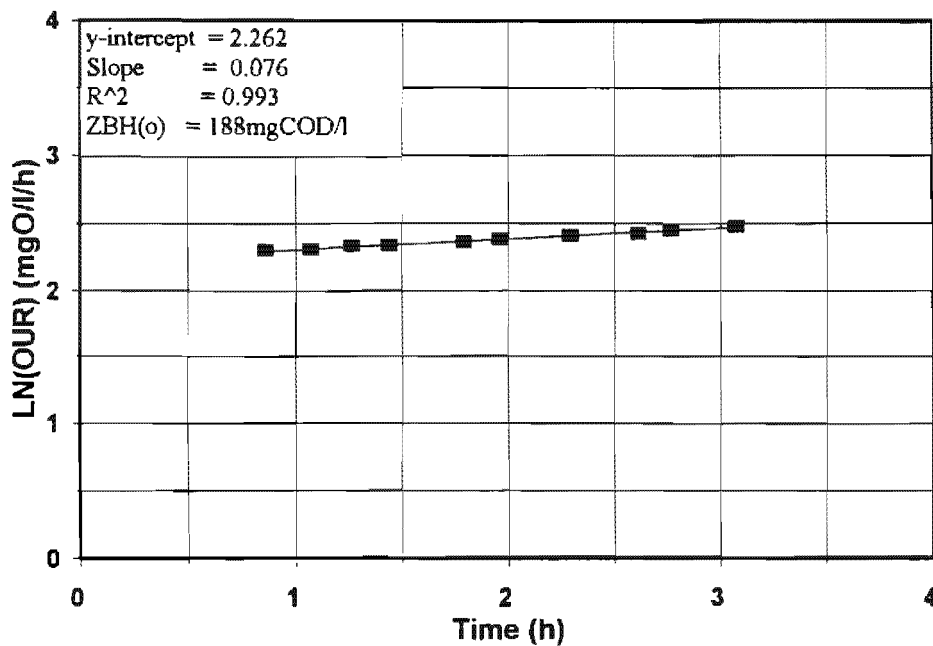


Fig B5b ln(OUR) graph for wastewater plus mixed liquor batch test, 26-10, batch no. 12

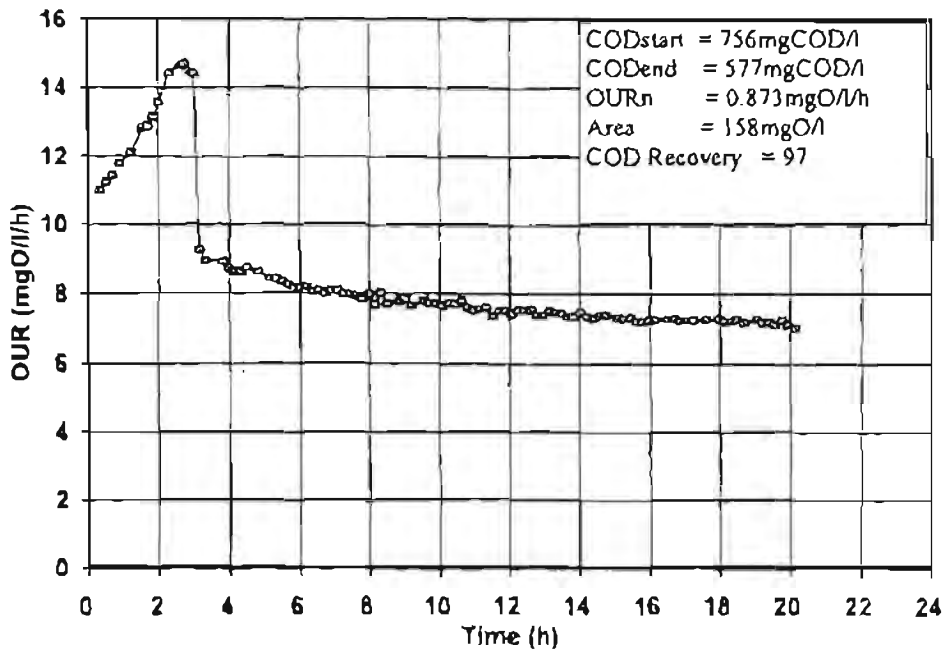


Fig B6a OUR graph for wastewater plus mixed liquor batch test, 27-10, batch no. 12

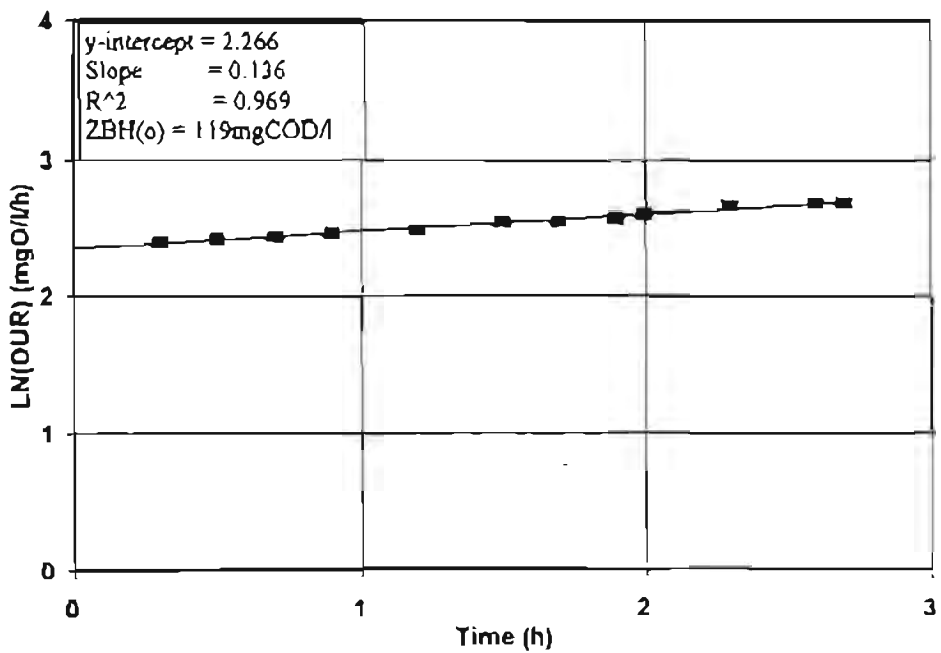


Fig B6b ln(OUR) graph for wastewater plus mixed liquor batch test, 27-10, batch no. 12

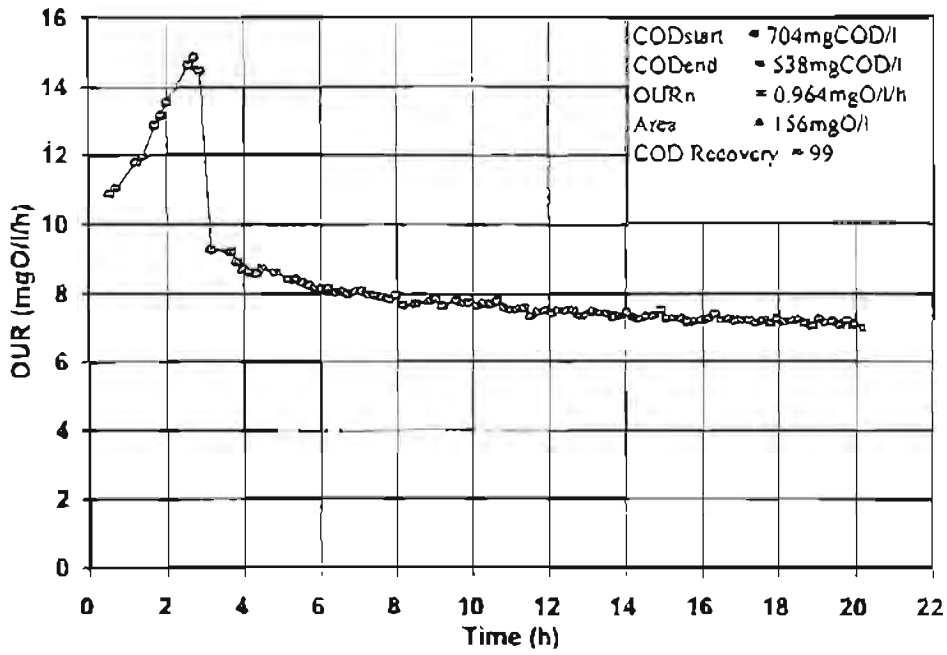


Fig B7a OUR graph for wastewater plus mixed liquor batch test, 28-10, batch no. 12

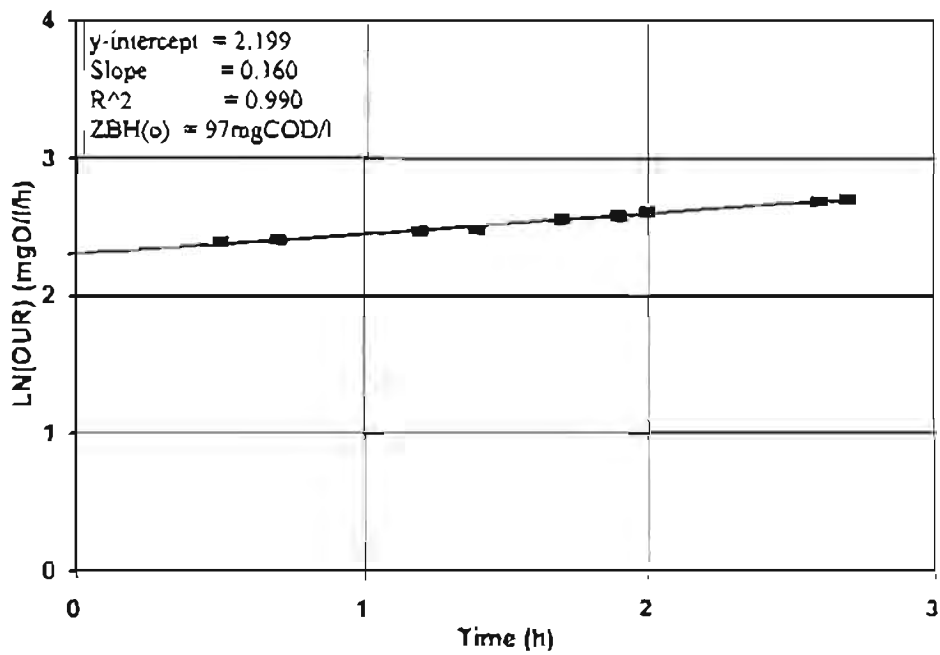


Fig B7b ln(OUR) graph for wastewater plus mixed liquor batch test, 28-10, batch no. 12

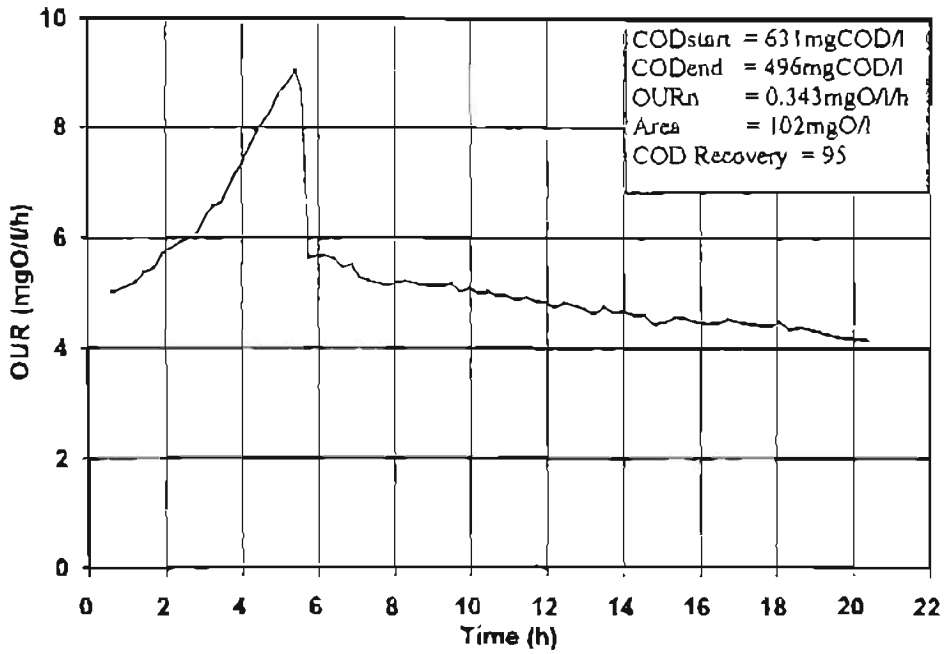


Fig B8a OUR graph for wastewater plus mixed liquor batch test, 29-10, batch no. 12

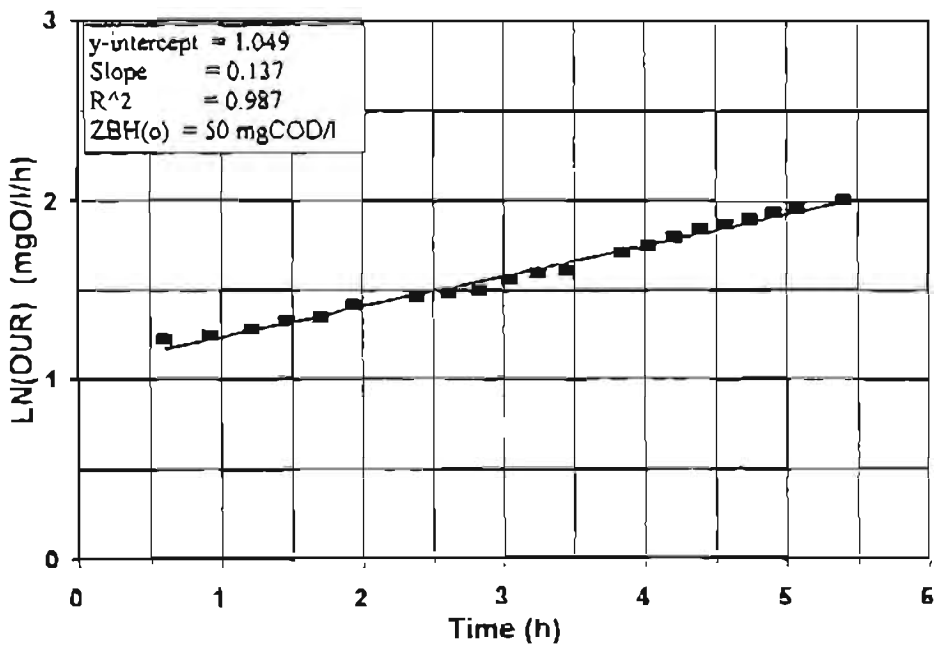


Fig B8b ln(OUR) graph for wastewater plus mixed liquor batch test, 29-10, batch no. 12

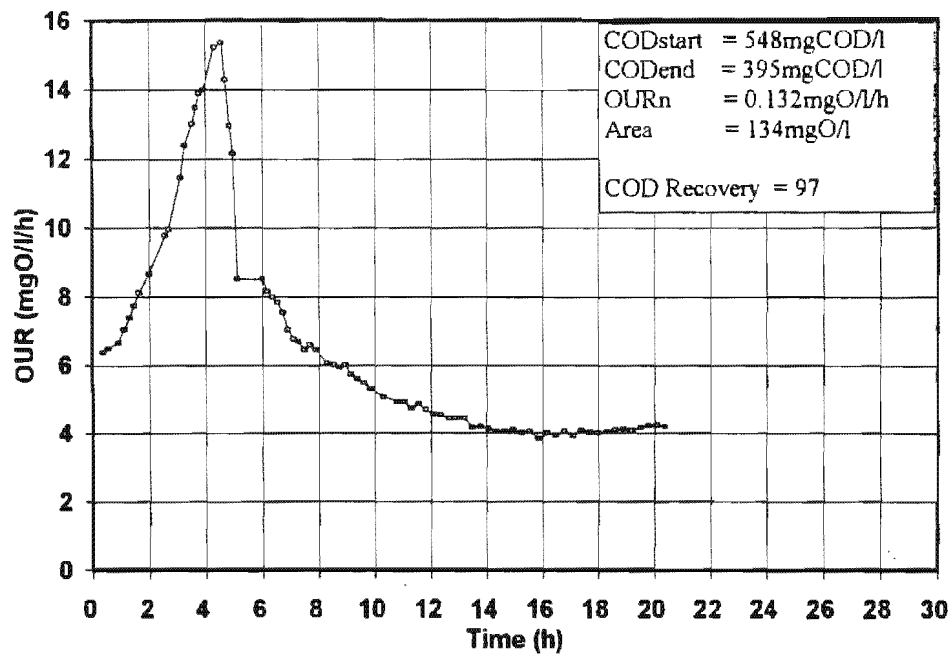


Fig B9a OUR graph for wastewater plus mixed liquor batch test, 01-11, batch no. 13

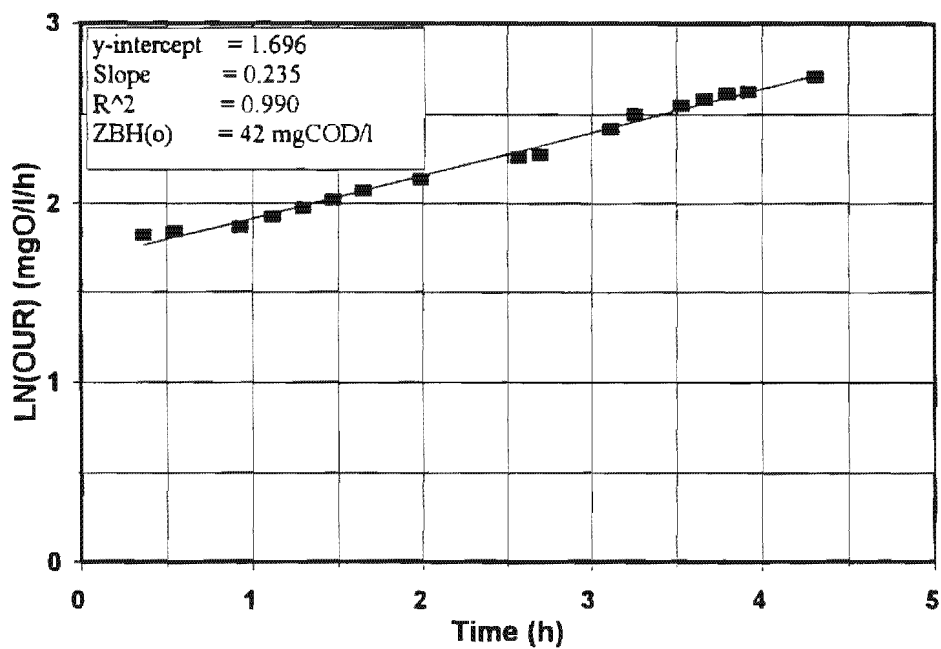


Fig B9b ln(OUR) graph for wastewater plus mixed liquor batch test, 01-11, batch no. 13

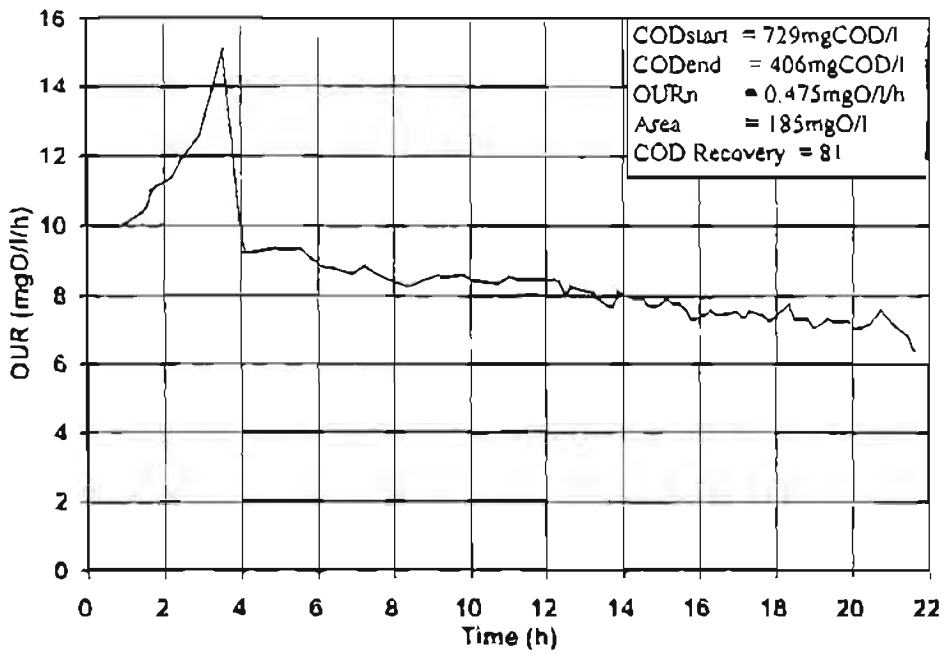


Fig B10a OUR graph for wastewater plus mixed liquor batch test, 04-11, batch no. 13

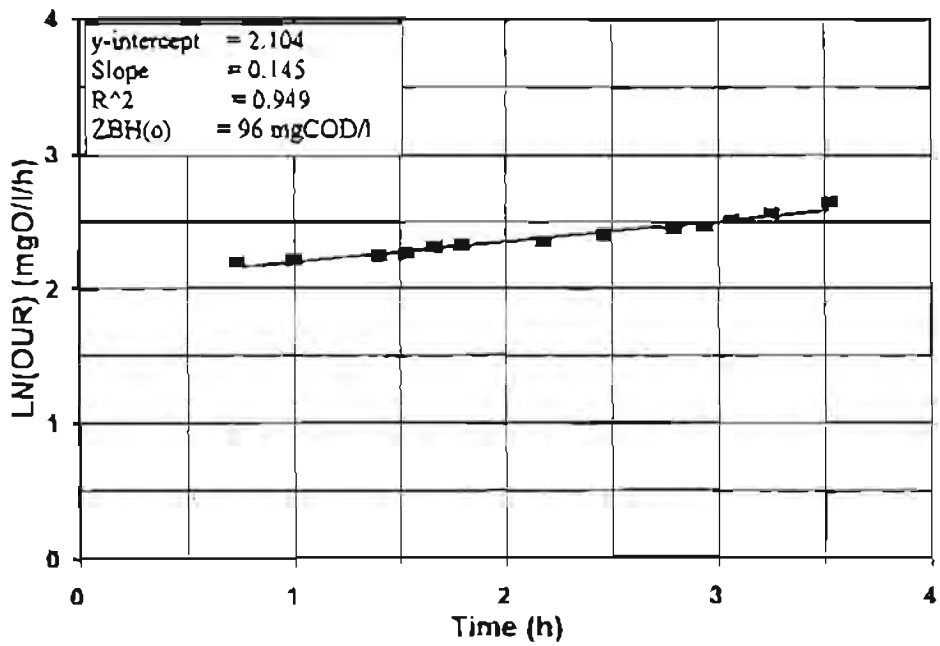


Fig B10b ln(OUR) graph for wastewater plus mixed liquor batch test, 04-11, batch no. 13

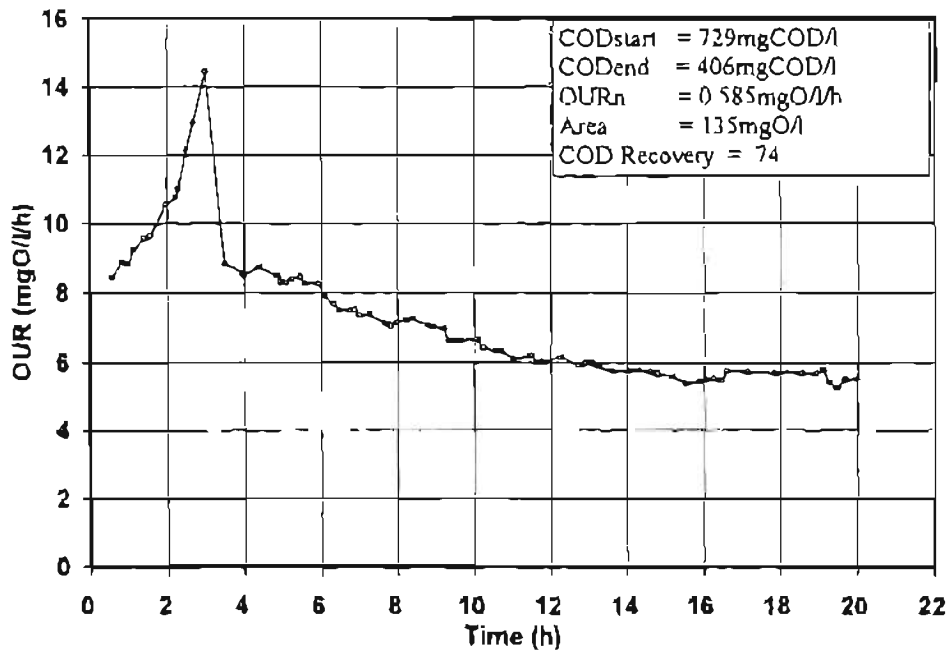


Fig B11a OUR graph for wastewater plus mixed liquor batch test, 06-11, batch no. 13

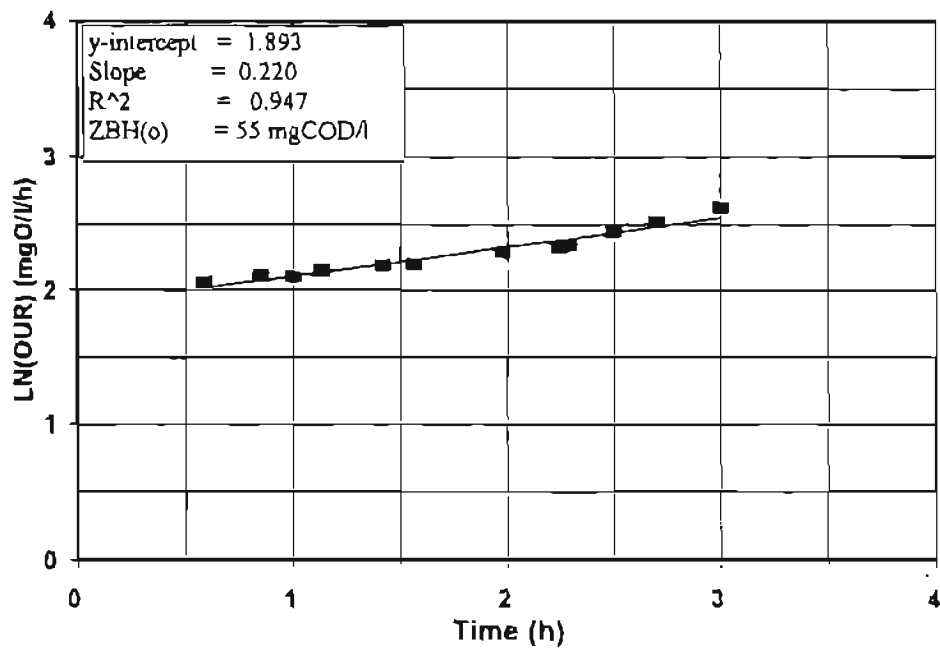


Fig B11b ln(OUR) graph for wastewater plus mixed liquor batch test, 06-11, batch no. 13

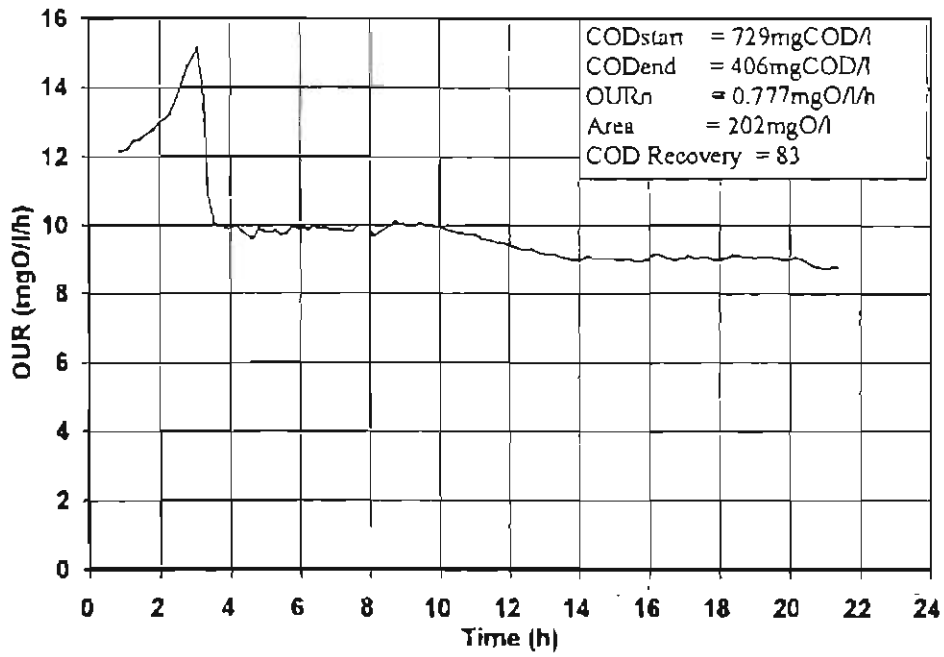


Fig B12a OUR graph for wastewater plus mixed liquor batch test, 07-11, batch no. 13

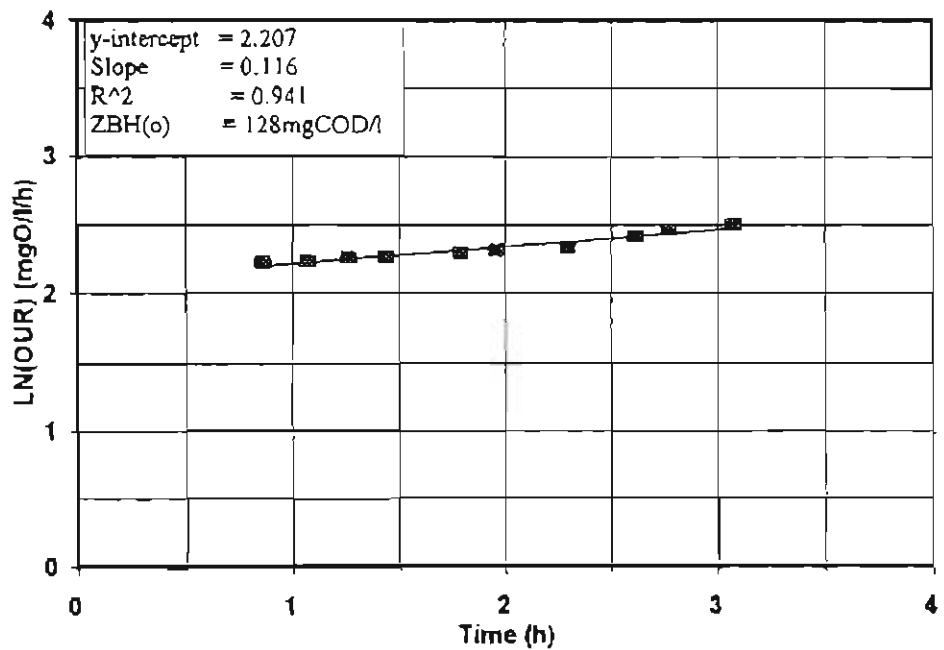


Fig B12b ln(OUR) graph for wastewater plus mixed liquor batch test, 07-11, batch no. 13

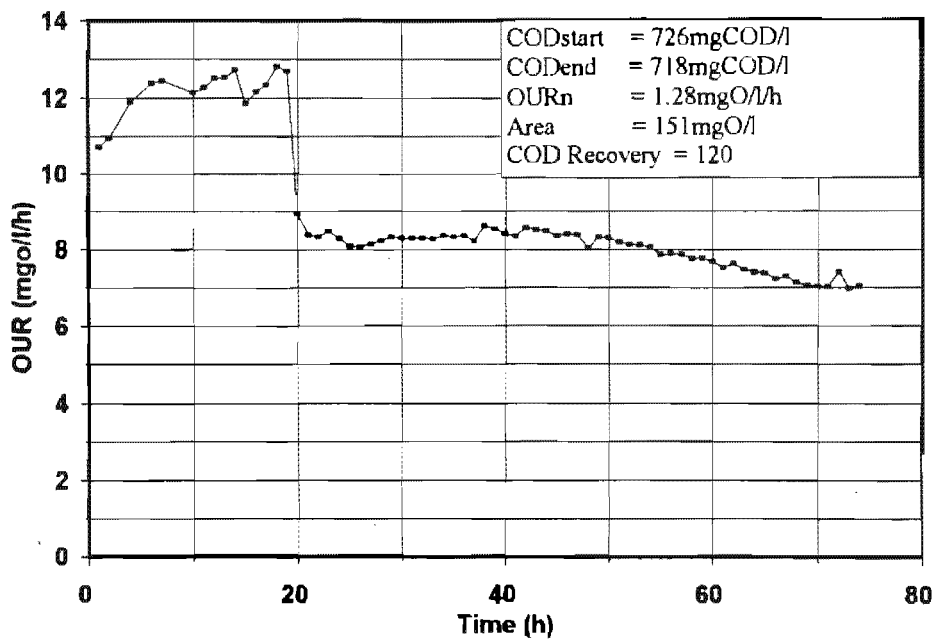


Fig B13a OUR graph for wastewater plus mixed liquor batch test, 11-01, batch no. 17

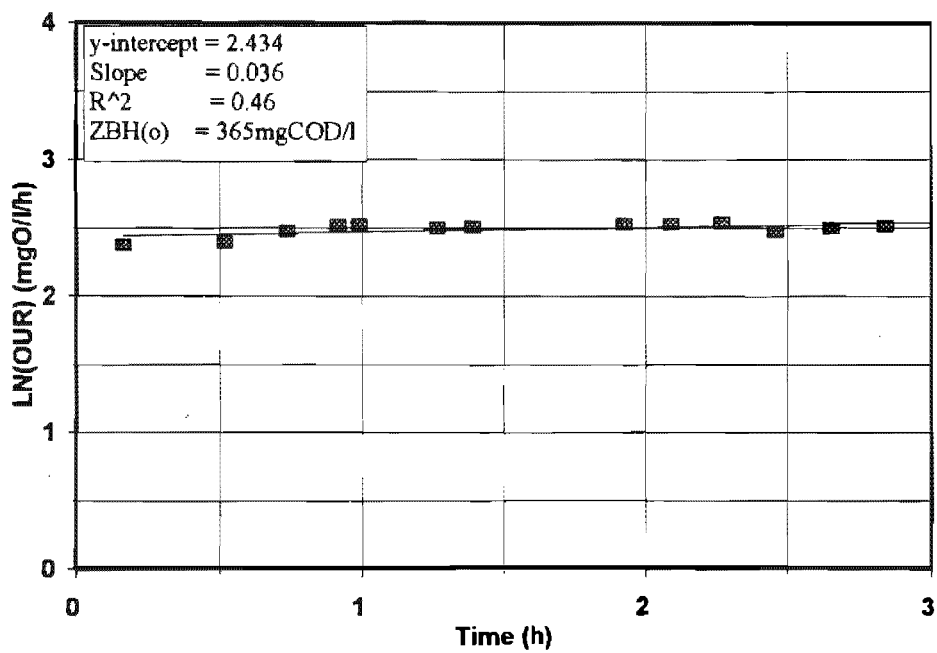


Fig B13b ln(OUR) graph for wastewater plus mixed liquor batch test, 11-01, batch no. 17

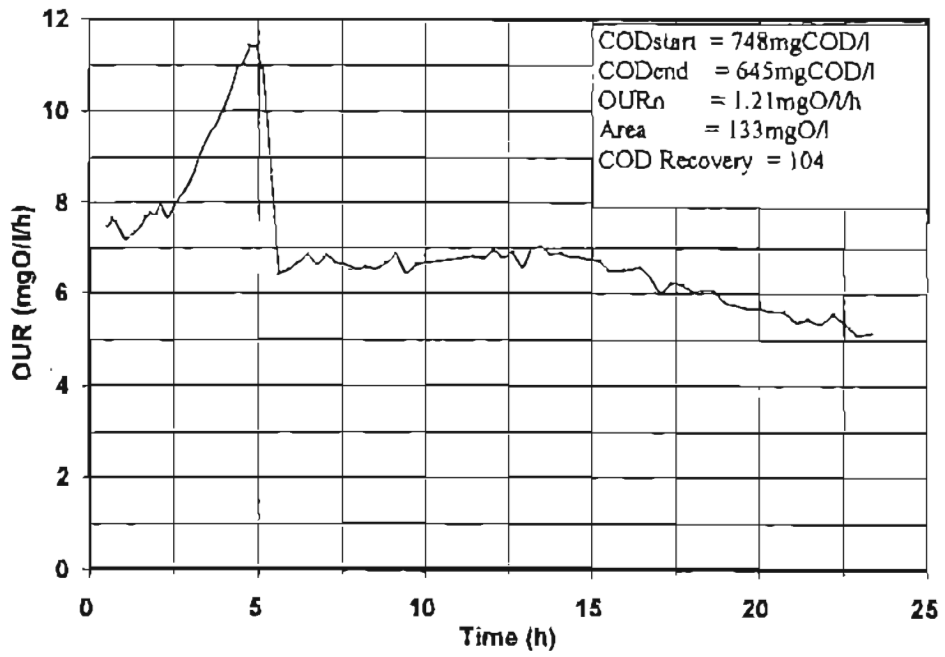


Fig B14a OUR graph for wastewater plus mixed liquor batch test, 12-01, batch no. 17

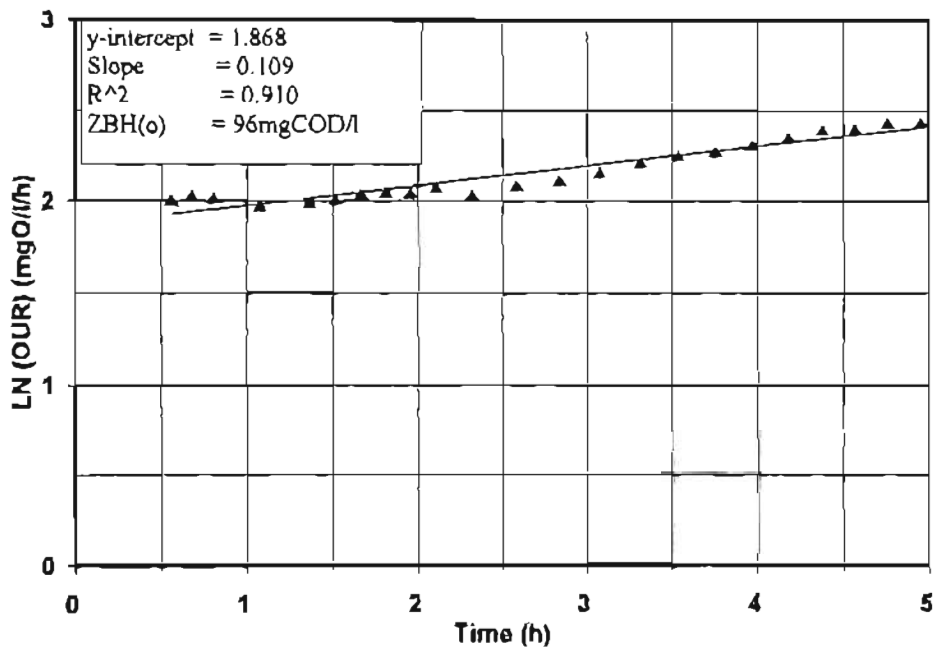


Fig B14b ln(OUR) graph for wastewater plus mixed liquor batch test, 12-01, batch no. 17

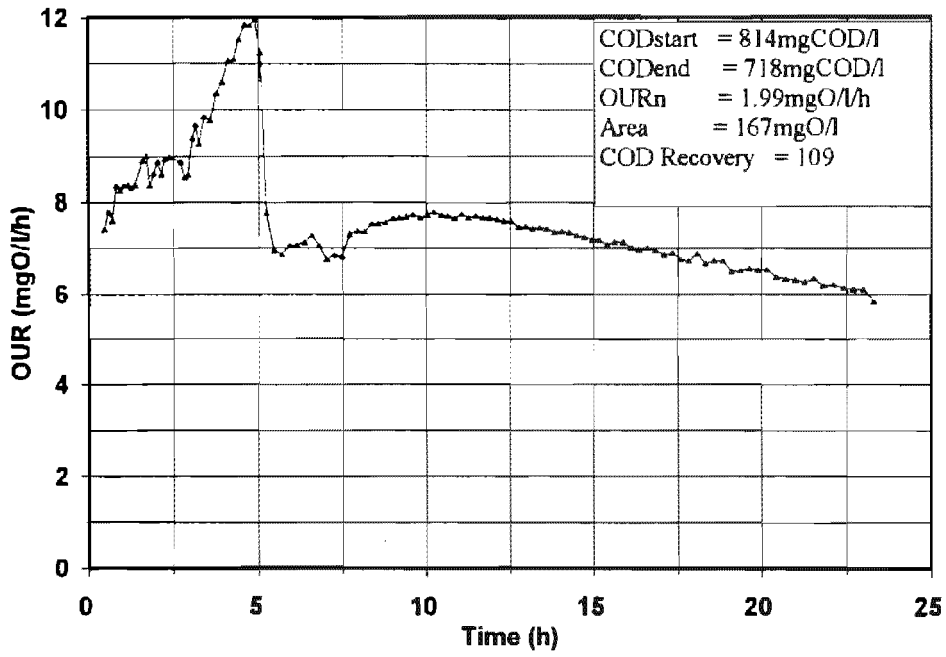


Fig B15a OUR graph for wastewater plus mixed liquor batch test, 15-01, batch no. 17

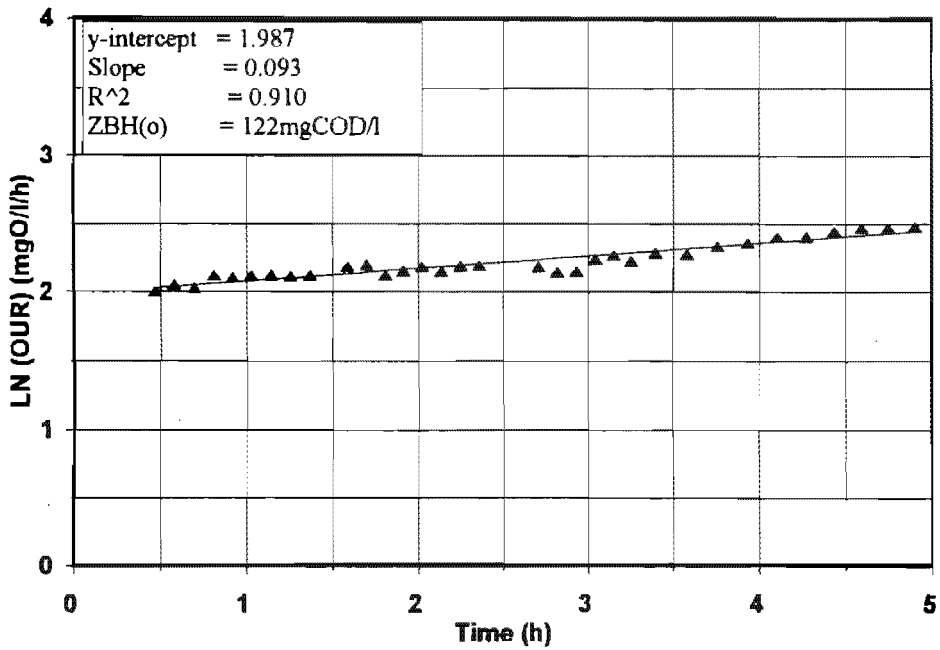


Fig B15b ln(OUR) graph for wastewater plus mixed liquor, 15-01, batch no. 17

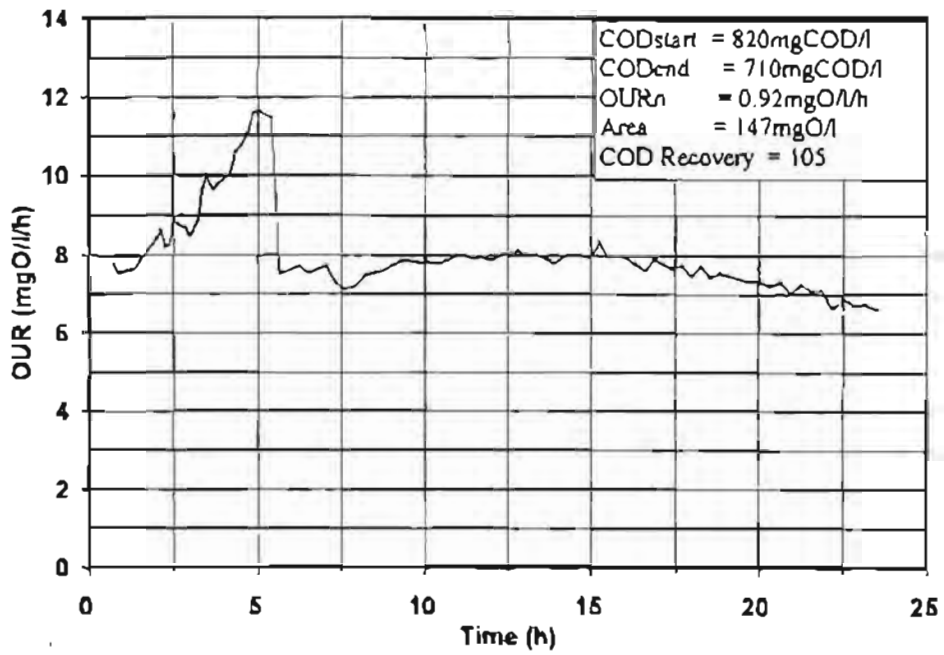


Fig B16a OUR graph for wastewater plus mixed liquor batch test, 16-01, batch no. 17

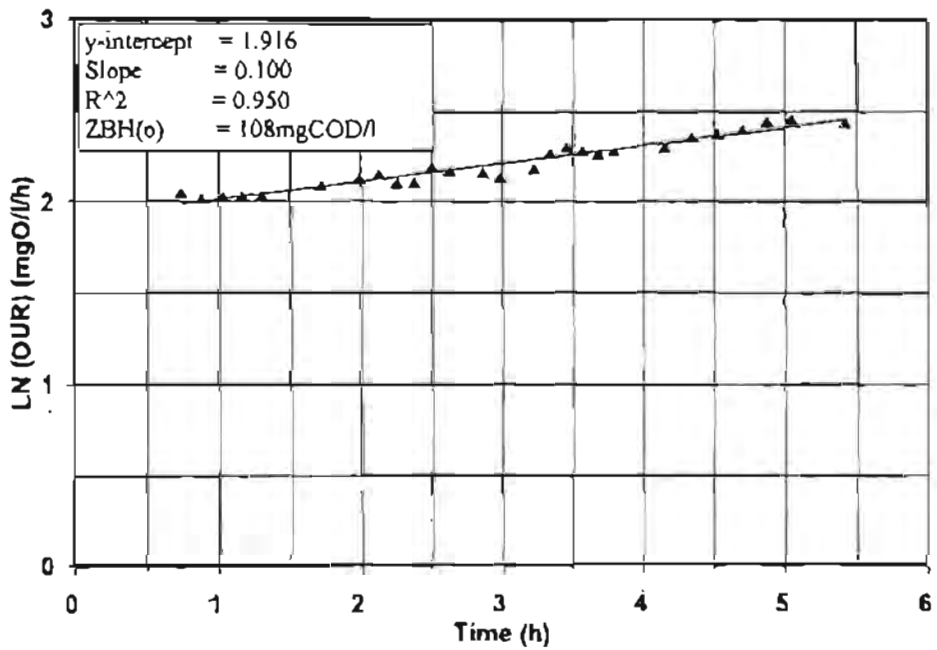


Fig B16b Ln(OUR) graph for wastewater plus mixed liquor batch test, 16-01, batch no. 17

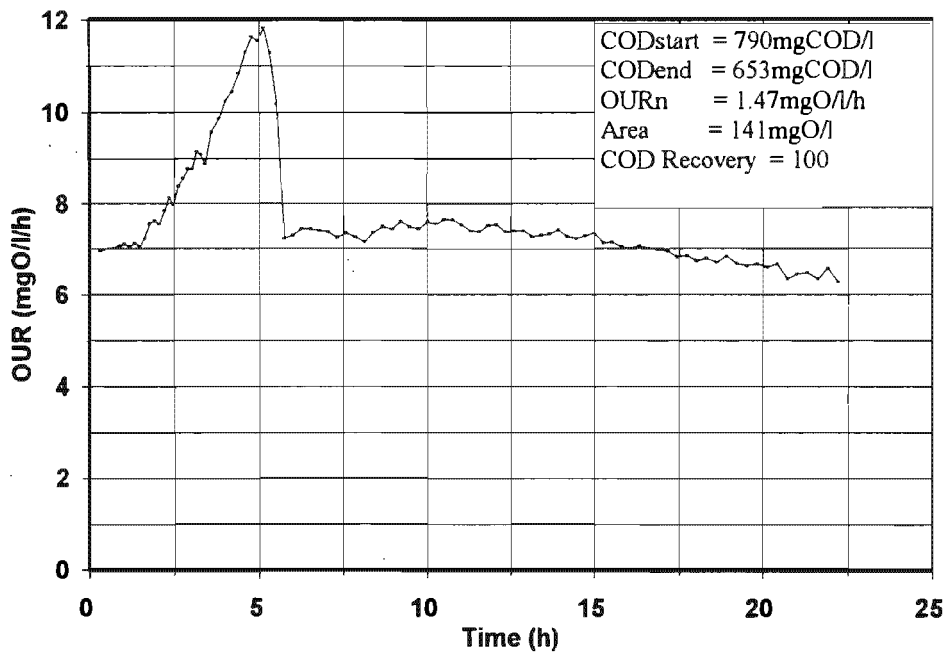


Fig b17a OUR graph for wastewater plus mixed liquor batch test, 17-01, batch no. 17

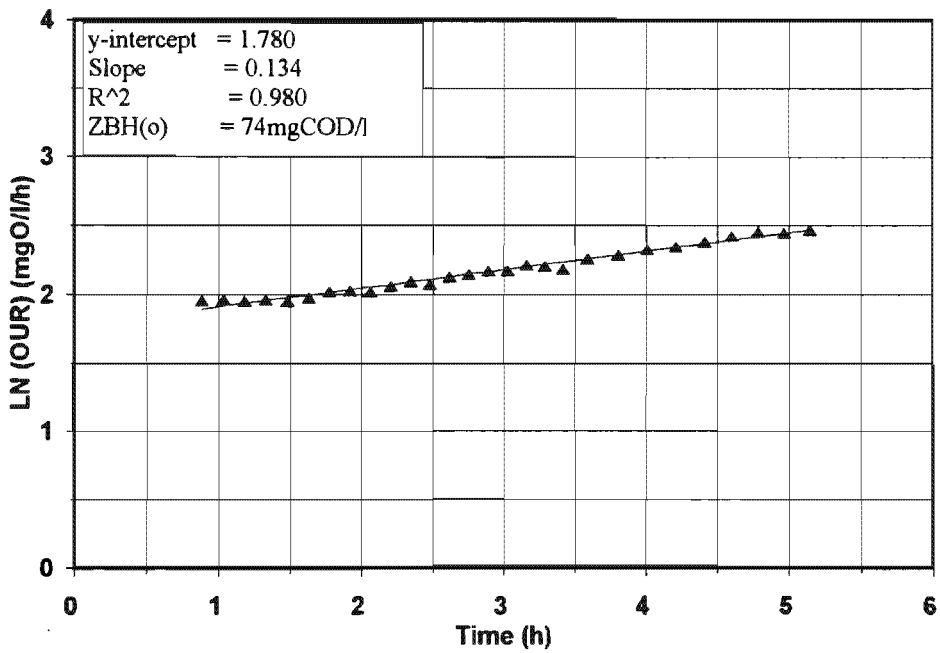


Fig B17b ln(OUR) graph for wastewater plus mixed liquor batch test, 17-01, batch no. 17

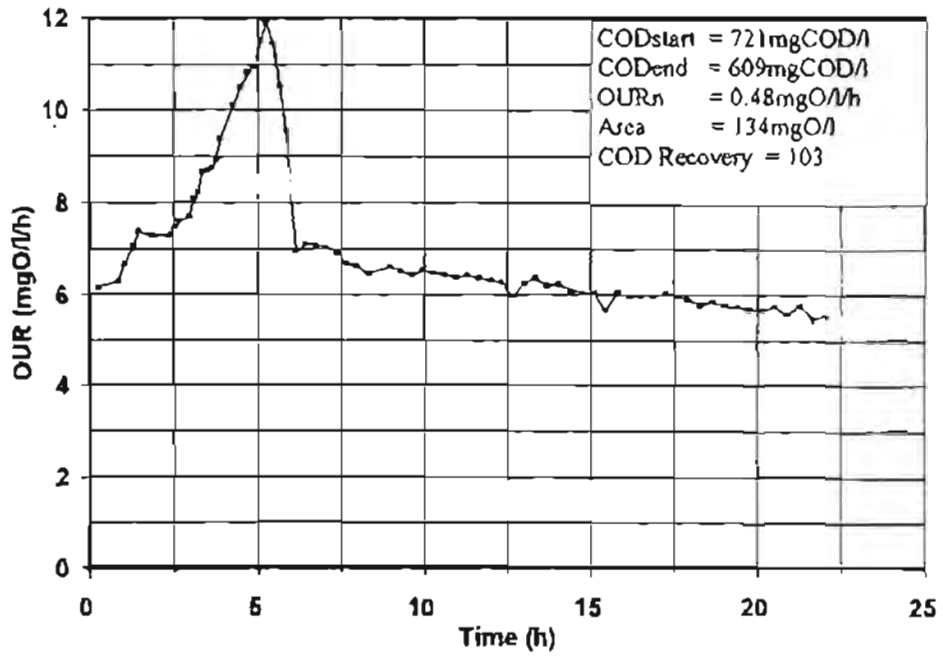


Fig B18a OUR graph for wastewater only batch test, 18-01, batch no. 17

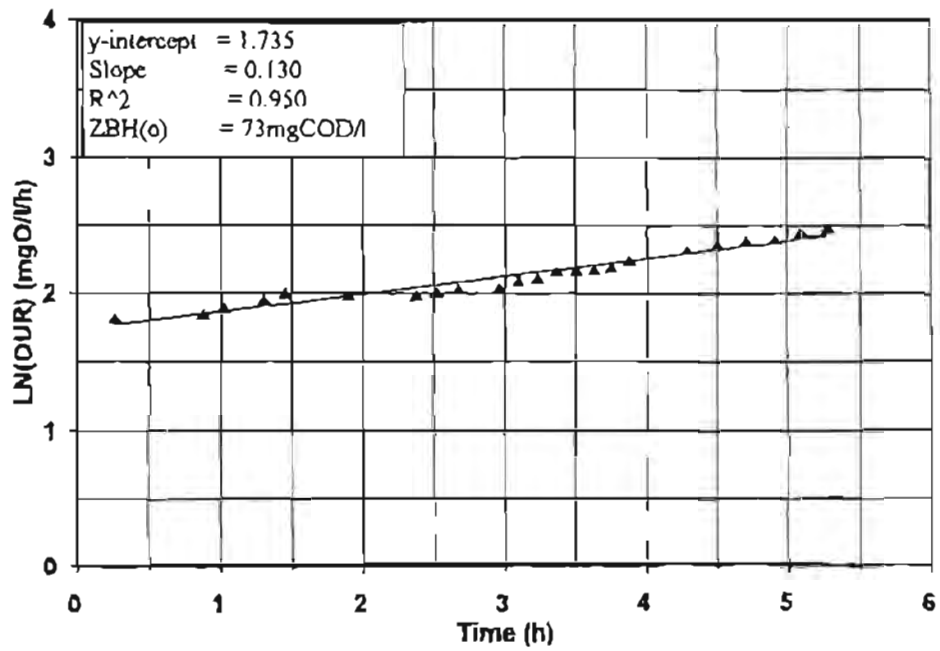


Fig B18b ln(OUR) graph for wastewater plus mixed liquor batch test, 18-01, batch no. 17

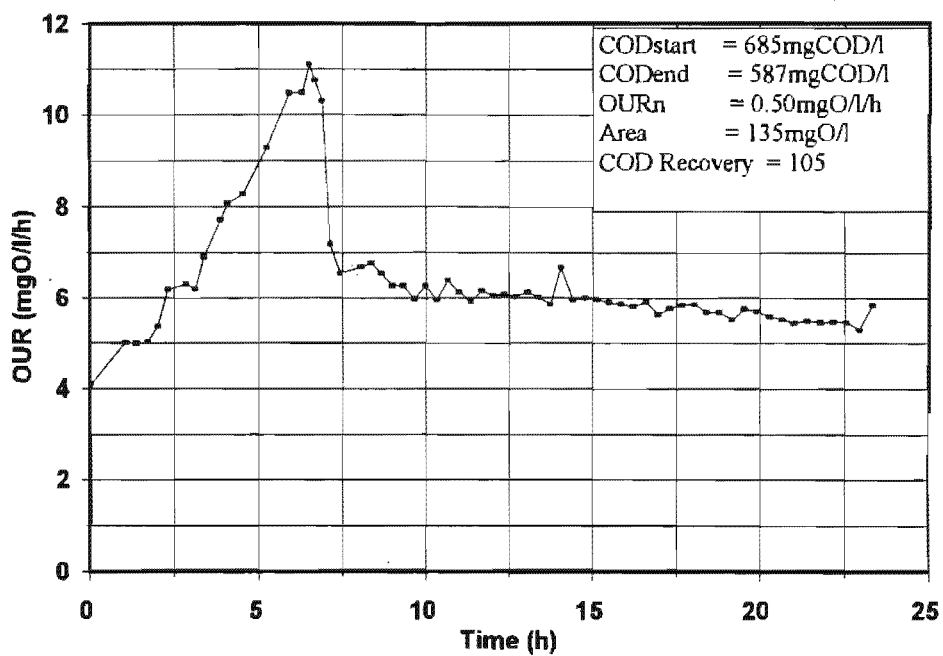


Fig B19a OUR graph for wastewater plus mixed liquor batch test, 19-01, batch no. 17

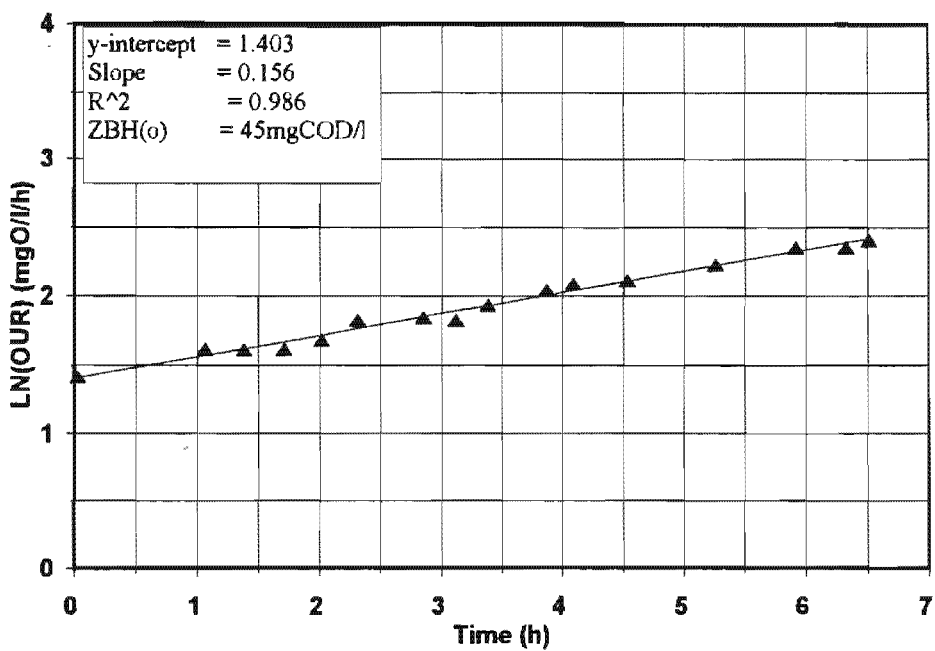


Fig B19b ln(OUR) graph wastewater plus mixed liquor batch test, 19-01, batch no. 17

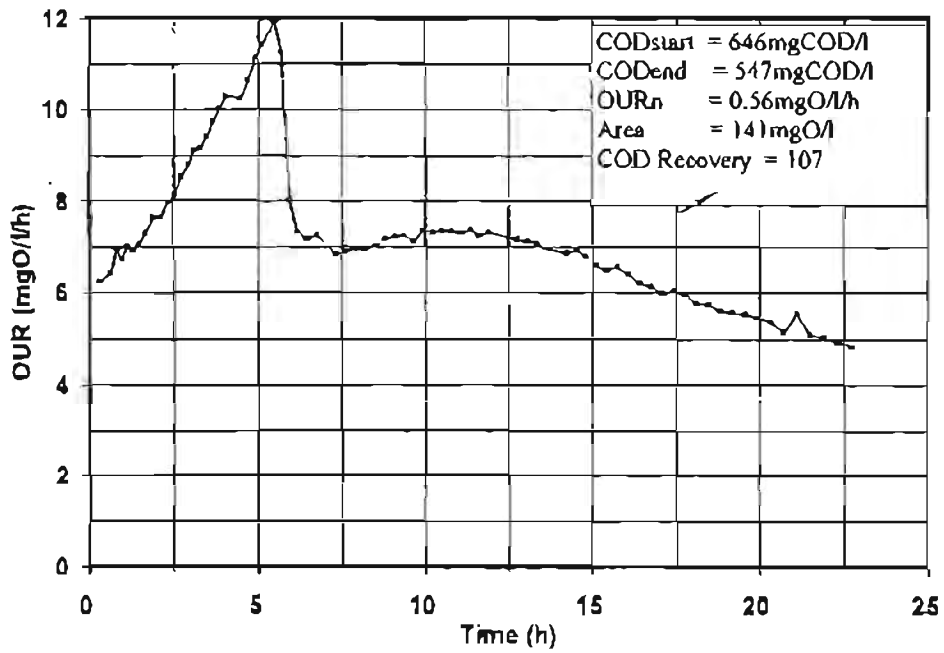


Fig B20a OUR graph for wastewater plus mixed liquor batch test, 21-01, batch no. 17

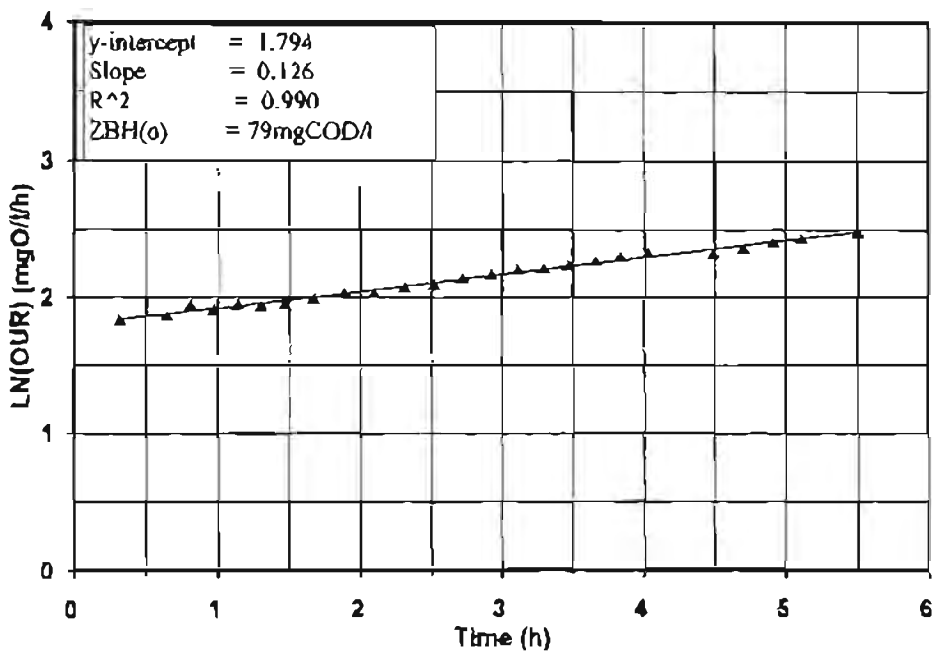


Fig B20b ln(OUR) graph for wastewater plus mixed liquor batch test, 21-01, batch no. 17

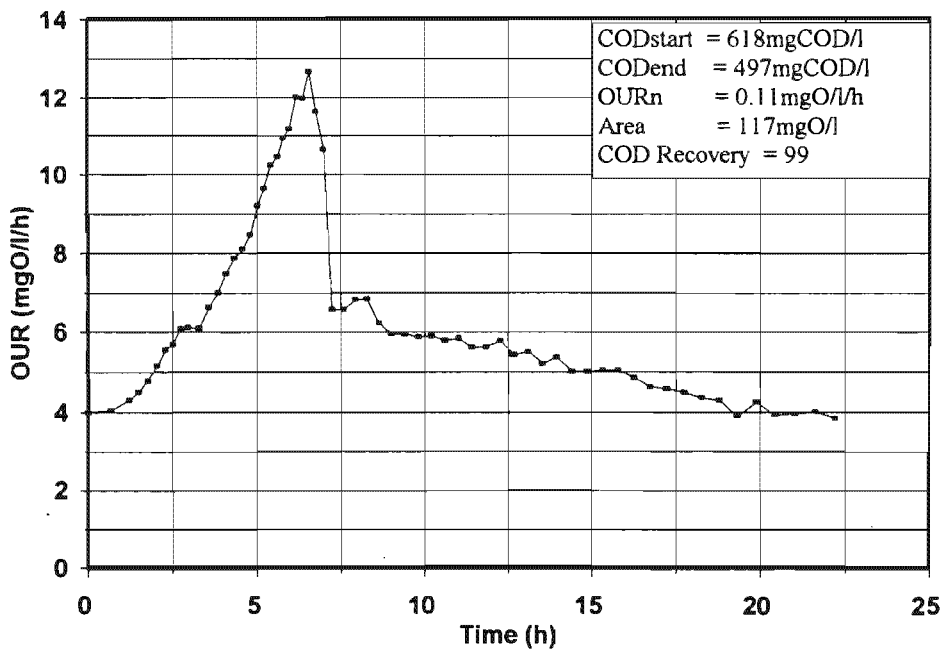


Fig B21a OUR graph for wastewater plus mixed liquor batch test, 22-01, batch no. 17

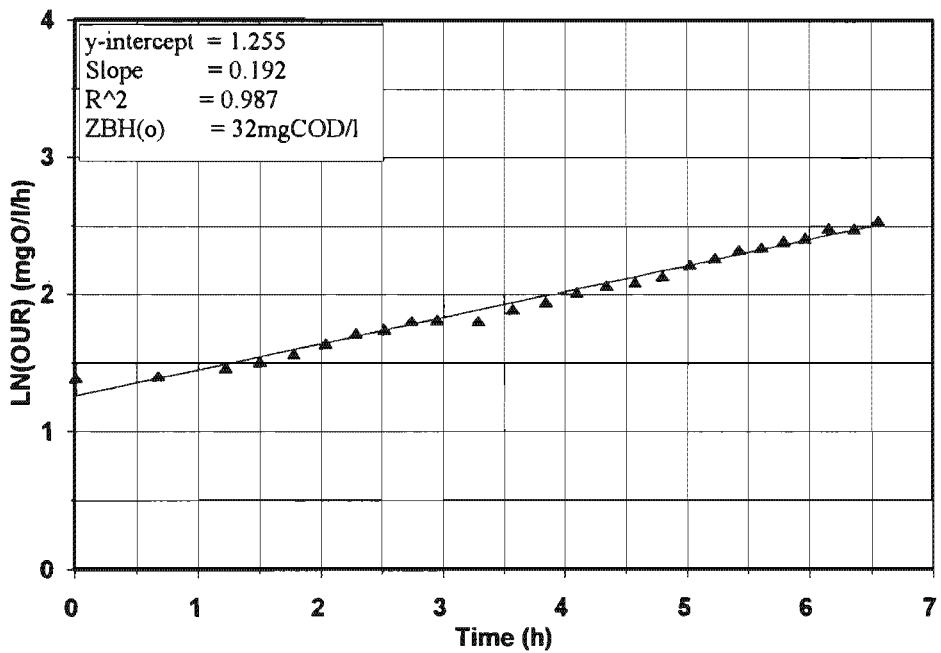


fig B21b ln(OUR) graph for wastewater plus mixed liquor batch test, 22-01, batch no. 17

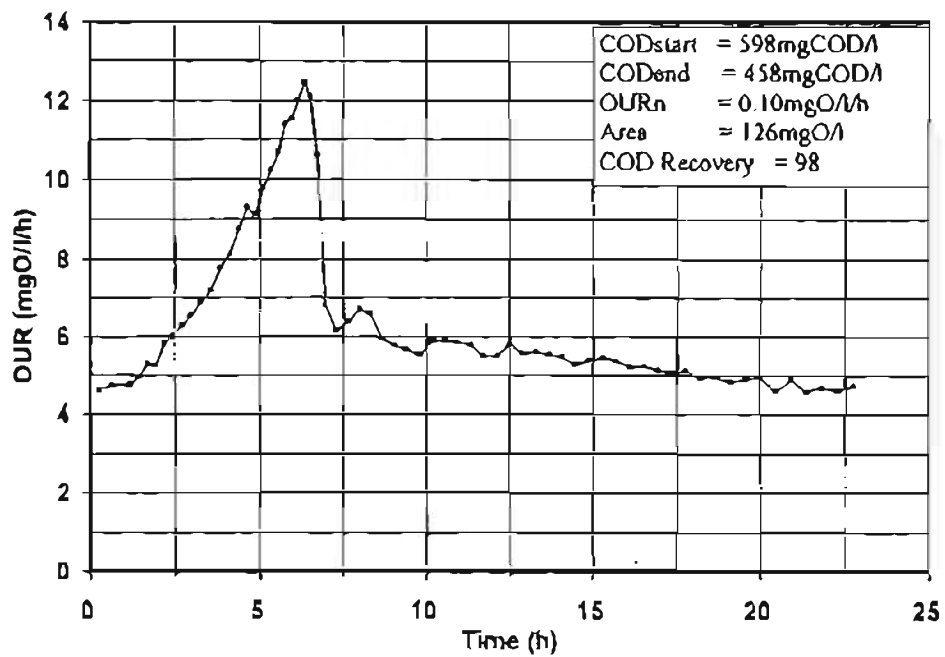


Fig B22a OUR graph for wastewater plus mixed liquor batch test, 23-01, batch no. 17

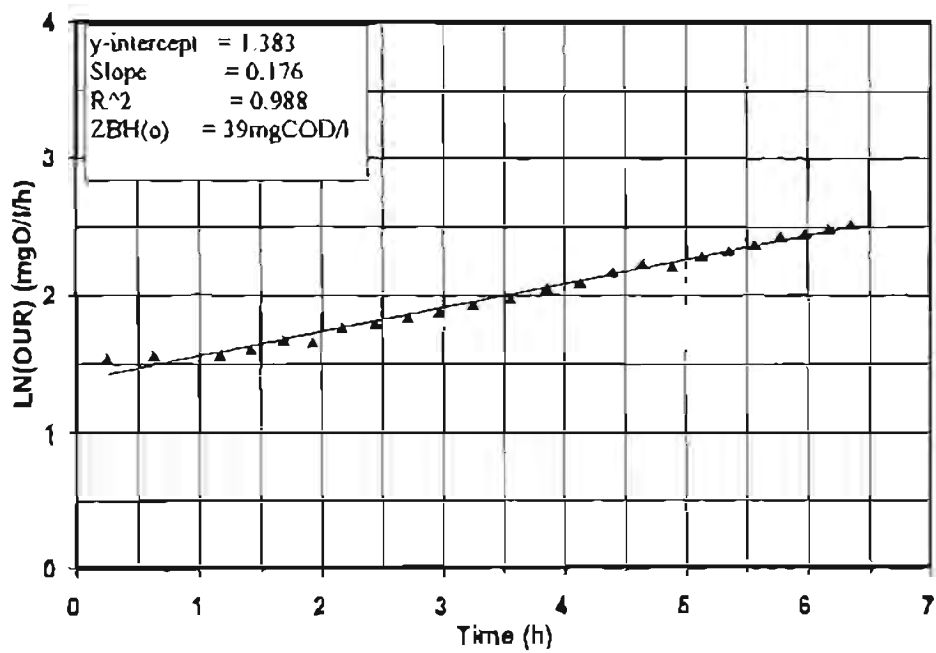


Fig B22b Ln(OUR) graph for wastewater plus mixed liquor batch test, 23-01, batch no. 17

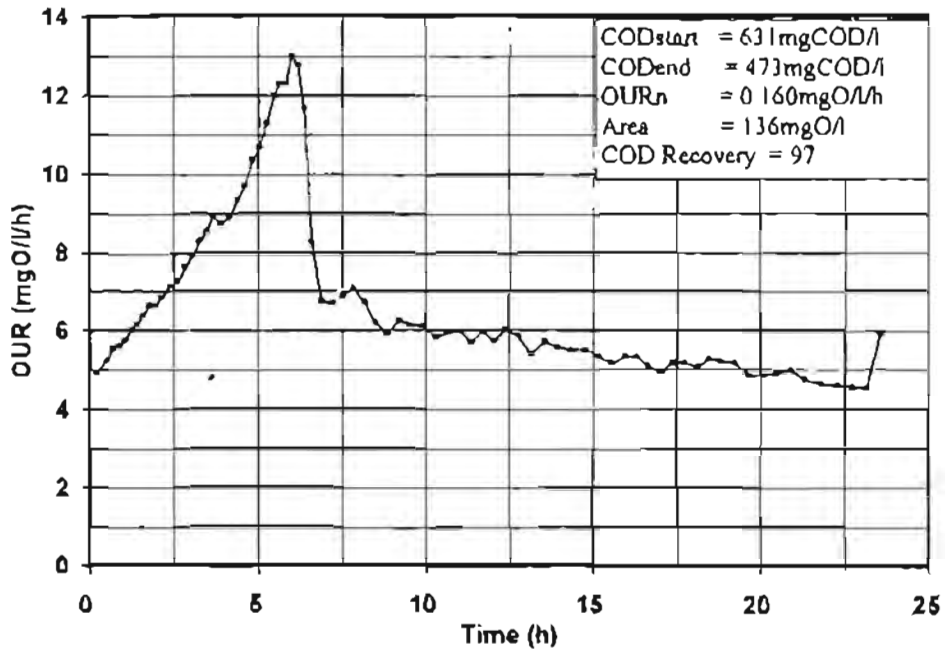


Fig B23a OUR graph for wastewater plus mixed liquor batch test, 24-01, batch no. 17

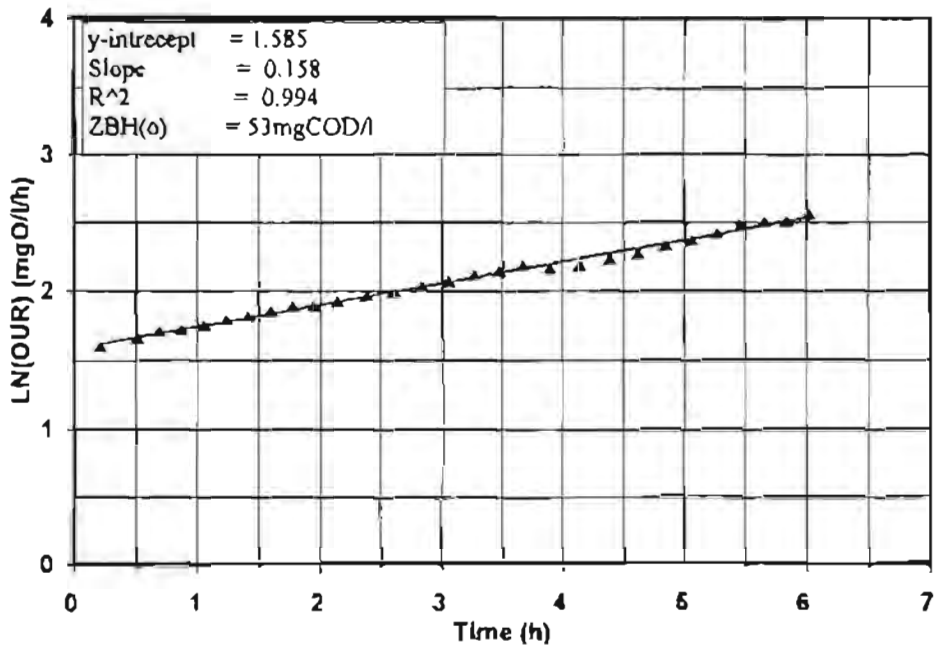


Fig B23b ln(OUR) graph for wastewater plus mixed liquor batch test, 24-01, batch no. 17

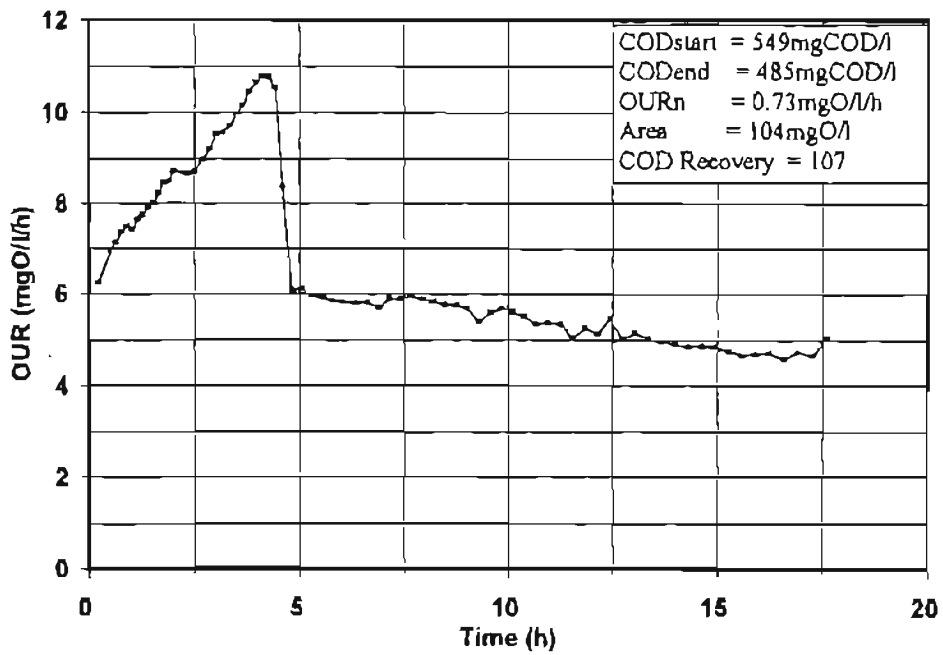


Fig B24a OUR graph for wastewater plus mixed liquor batch test, 25-01, batch no. 18

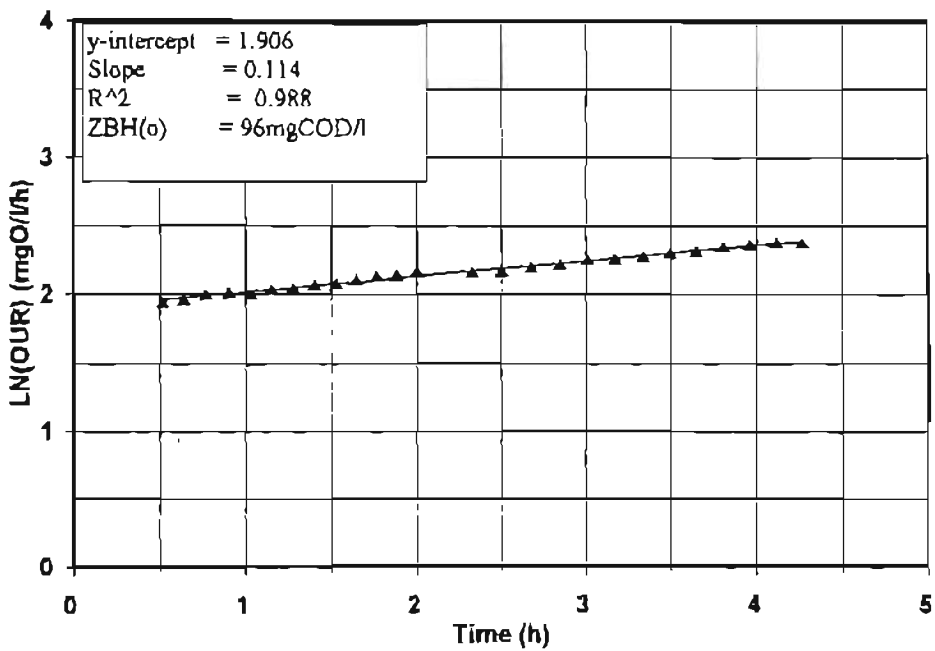


Fig B24b $\ln(\text{OUR})$ graph for wastewater plus mixed liquor batch test, 25-01, batch no. 18

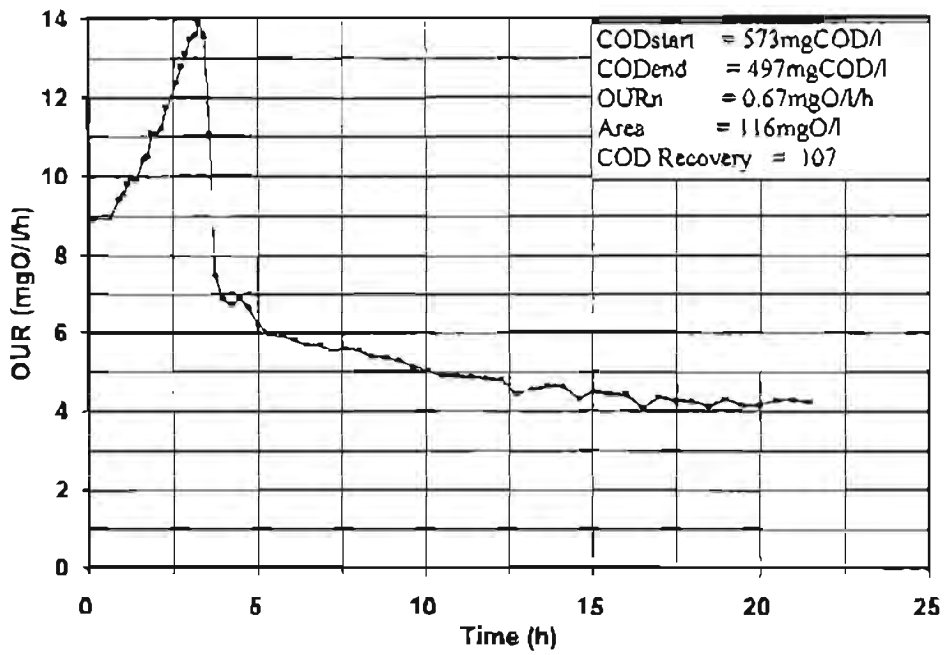


Fig B25a OUR graph for wastewater plus mixed liquor batch test, 26-01, batch no. 18

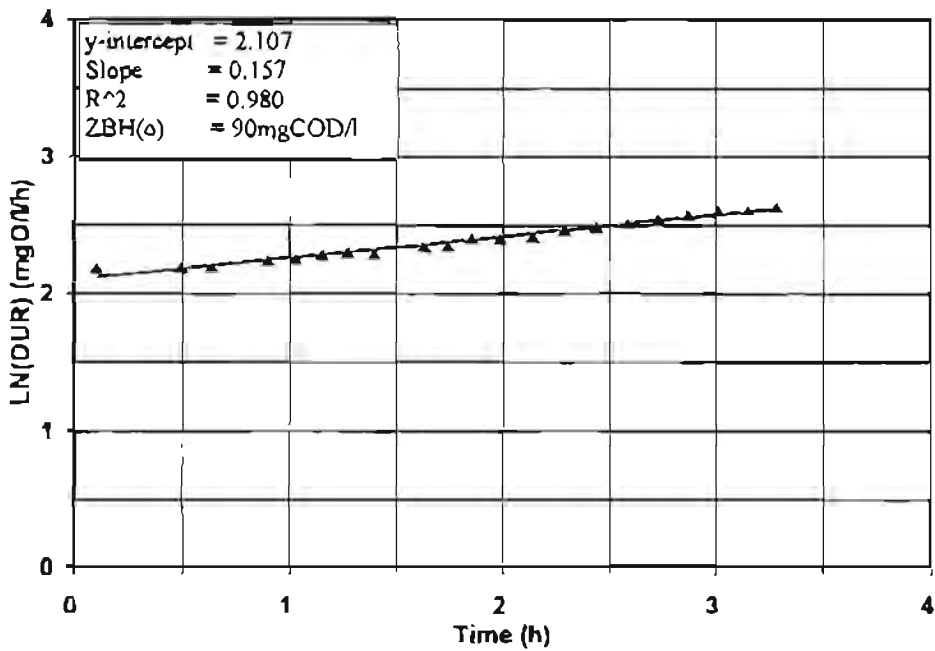


Fig B25b ln(OUR) graph for wastewater plus mixed liquor batch test, 26-01, batch no. 18

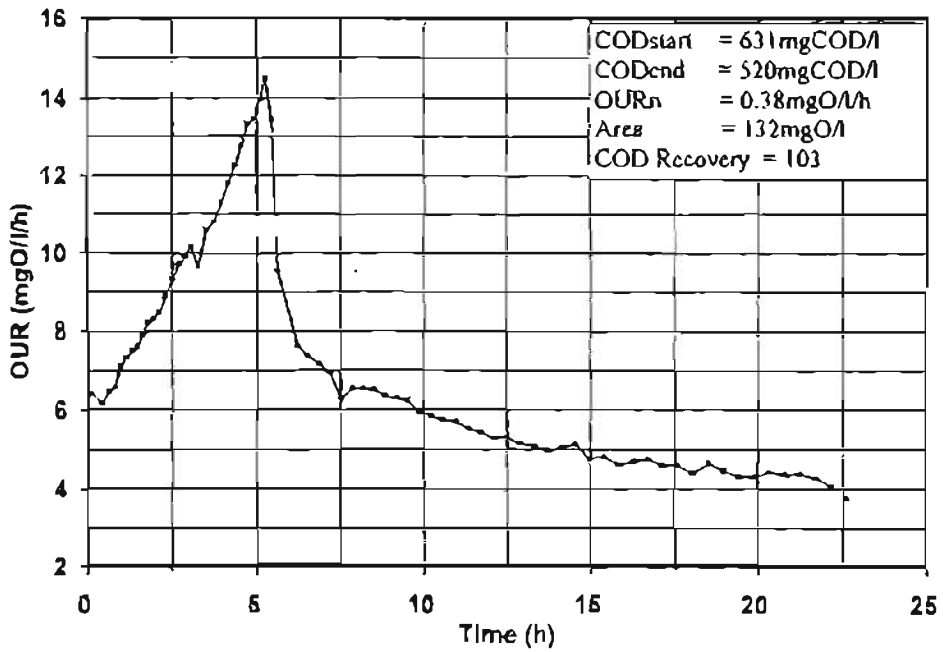


Fig B26a OUR graph for wastewater plus mixed liquor batch test, 29-01, batch no.18

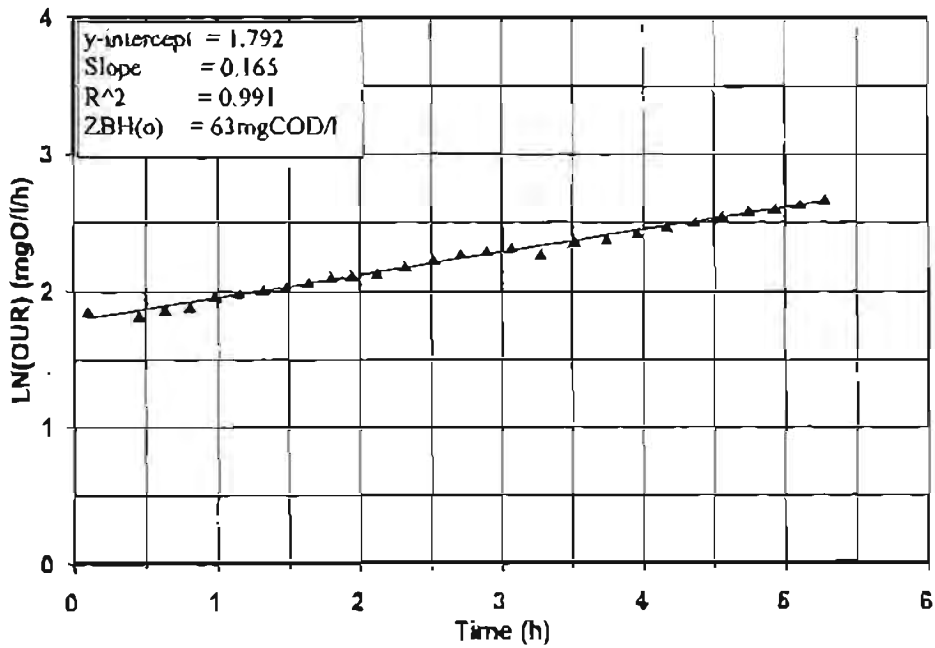


Fig B26b ln(OUR) graph for wastewater plus mixed liquor batch test, 29-01, batch no.18

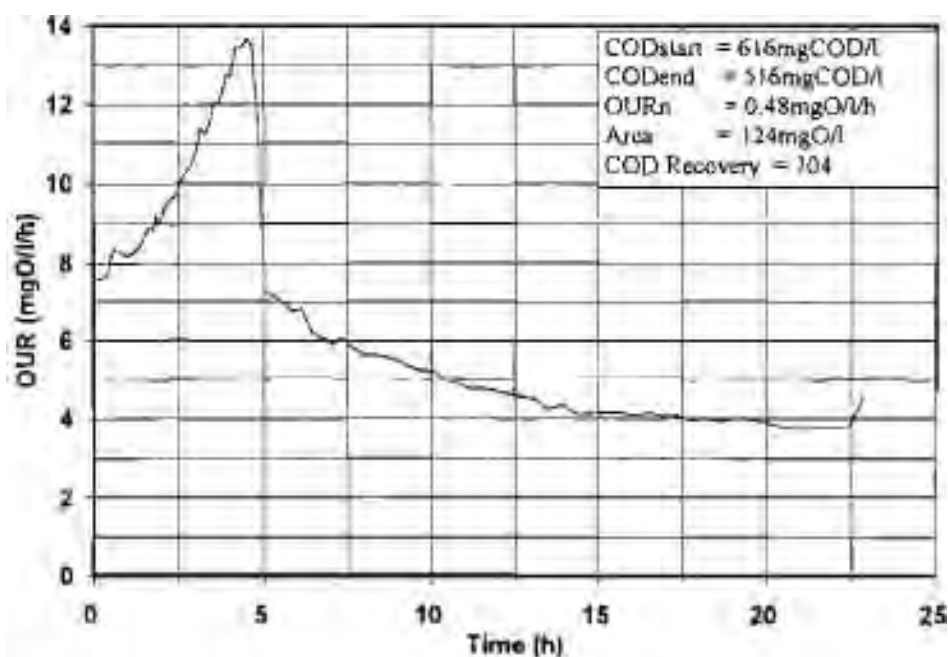


Fig B27a OUR graph for wastewater plus mixed liquor batch test, 30-01, batch no. 18

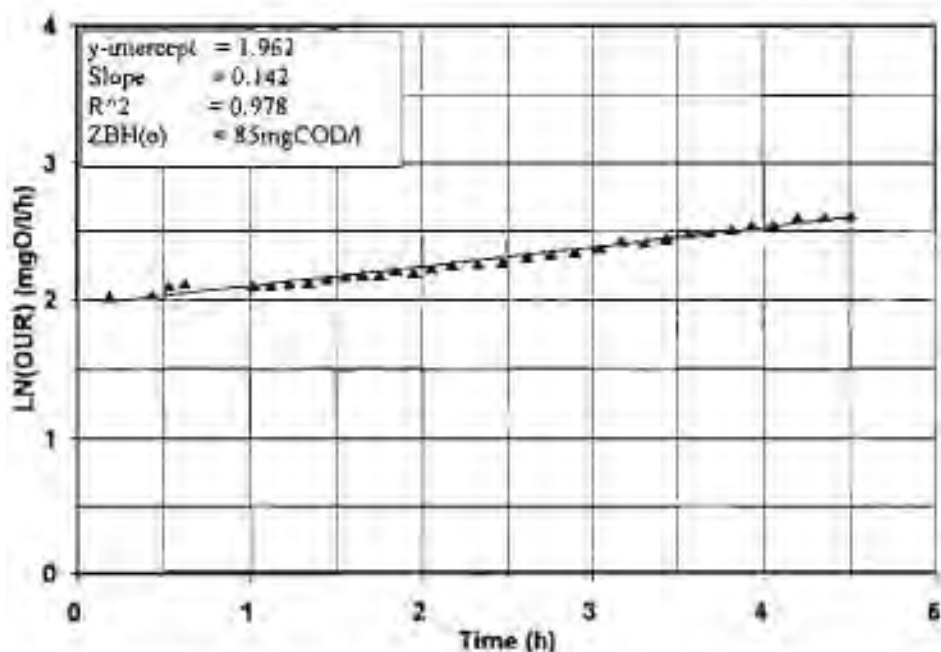


Fig B27b ln(OUR) graph for wastewater plus mixed liquor batch test, 30-01, batch no. 18

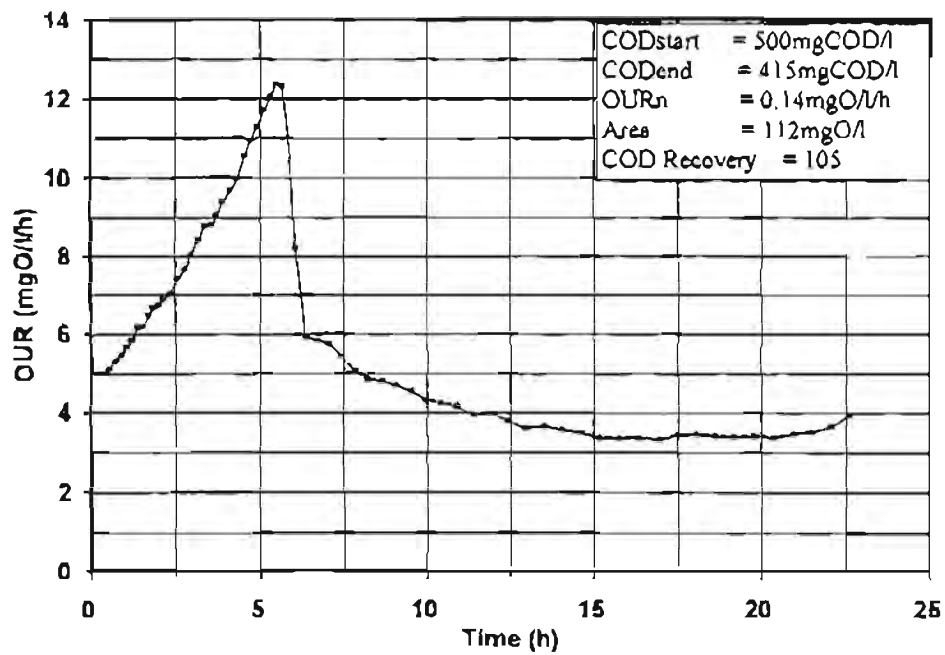


Fig B28a OUR graph for wastewater plus mixed liquor batch test, 31-01, batch no. 18

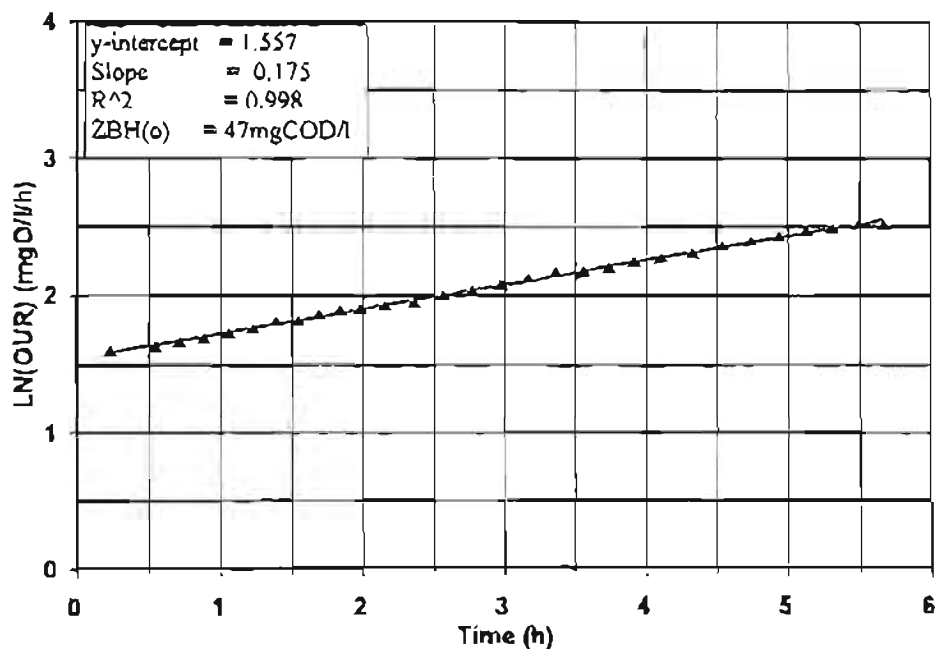


Fig B28b ln(OUR) graph for wastewater plus mixed liquor batch test, 31-01, batch no. 18

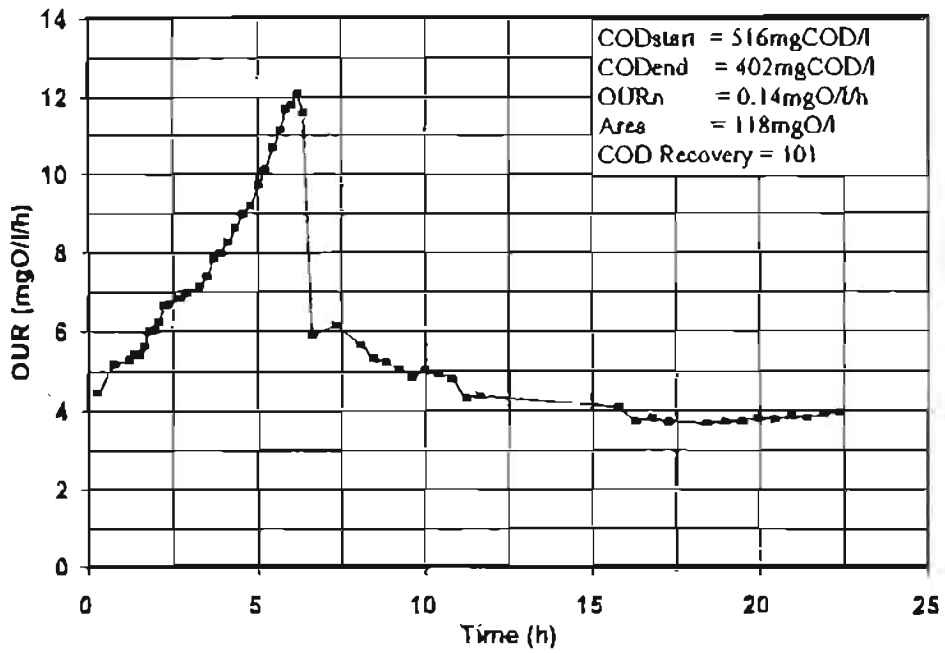


Fig B29a OUR graph wastewater plus mixed liquor batch test, 01-02, batch no. 18

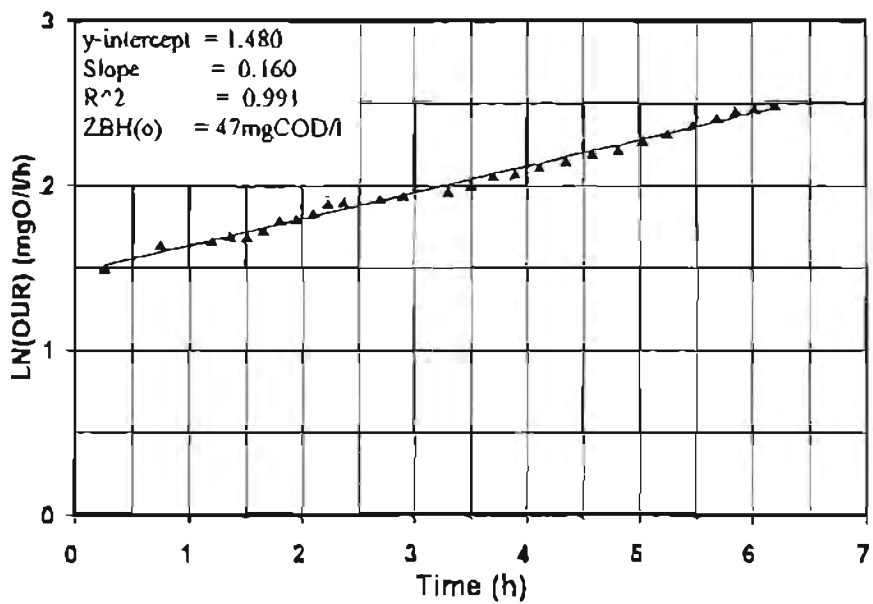


Fig B29b Ln(OUR) graph for wastewater plus mixed liquor batch test, 01-02, batch 18

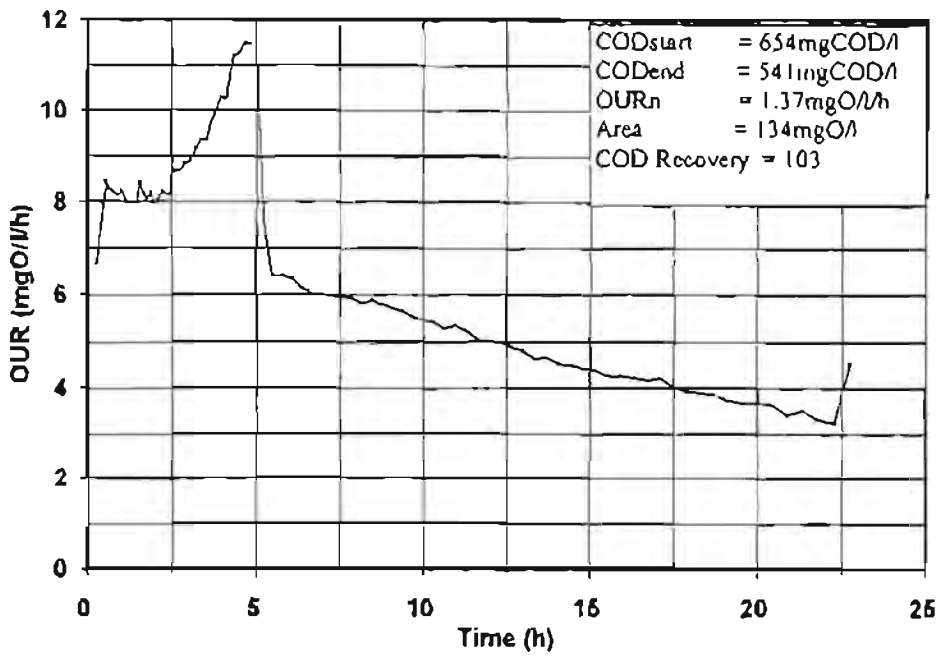


Fig B30a OUR graph for wastewater plus mixed liquor batch test, 02-02, batch no. 18

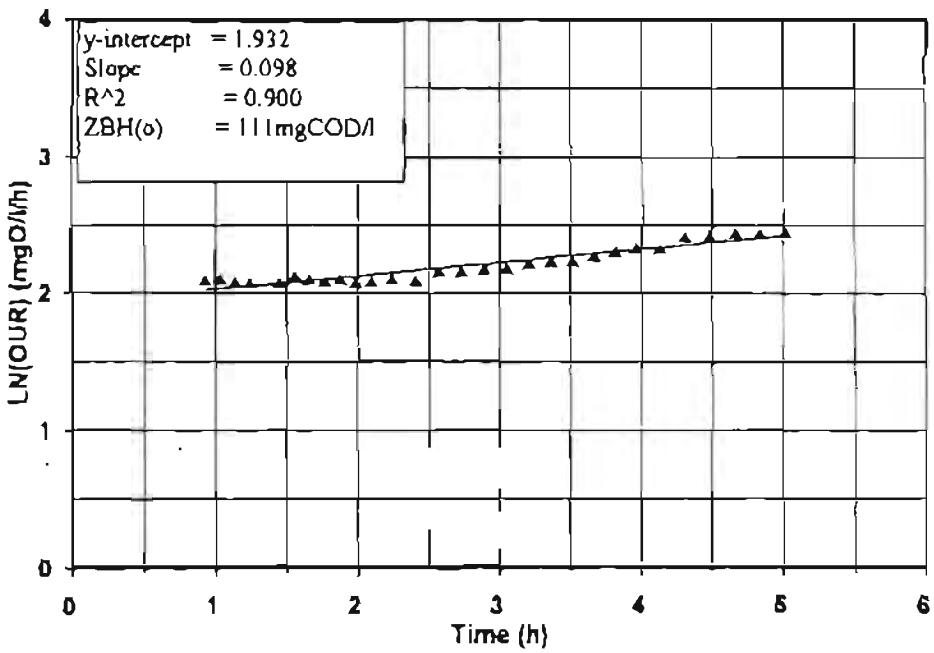


Fig B30b Ln(OUR) graph for wastewater plus mixed liquor batch test, 02-02, batch no. 18

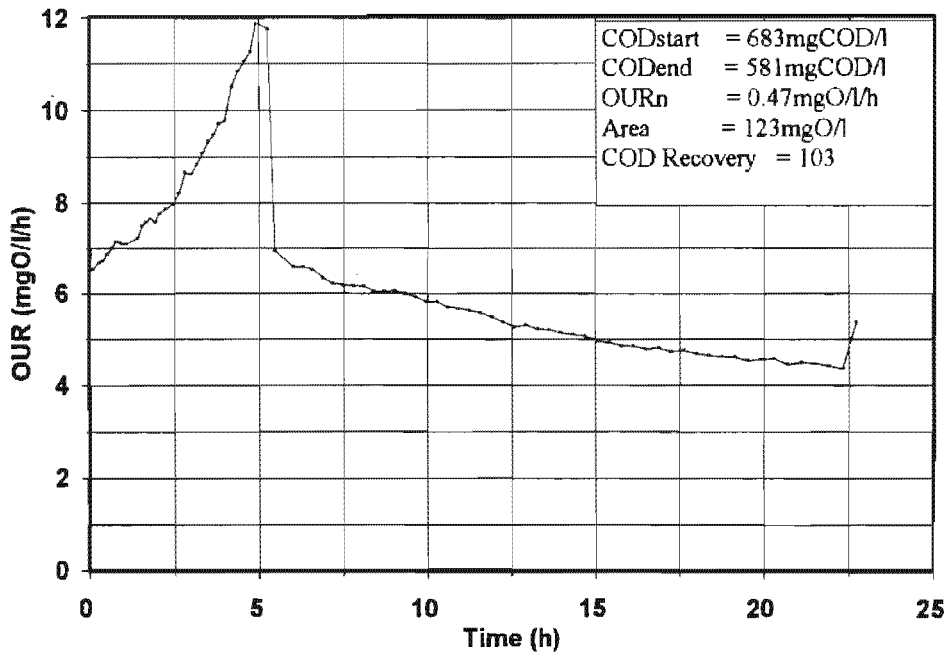


Fig B3 1a OUR graph for wastewater plus mixed liquor batch test, 03-02, batch no. 18

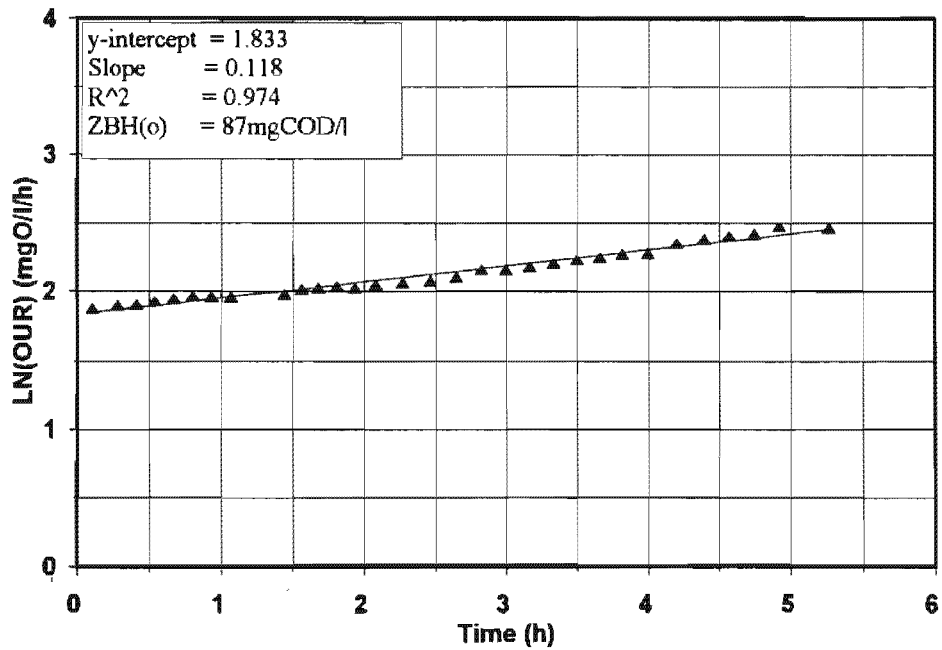


Fig B3 1b ln(OUR) graph for wastewater plus mixed liquor batch test, 03-02, batch no. 18

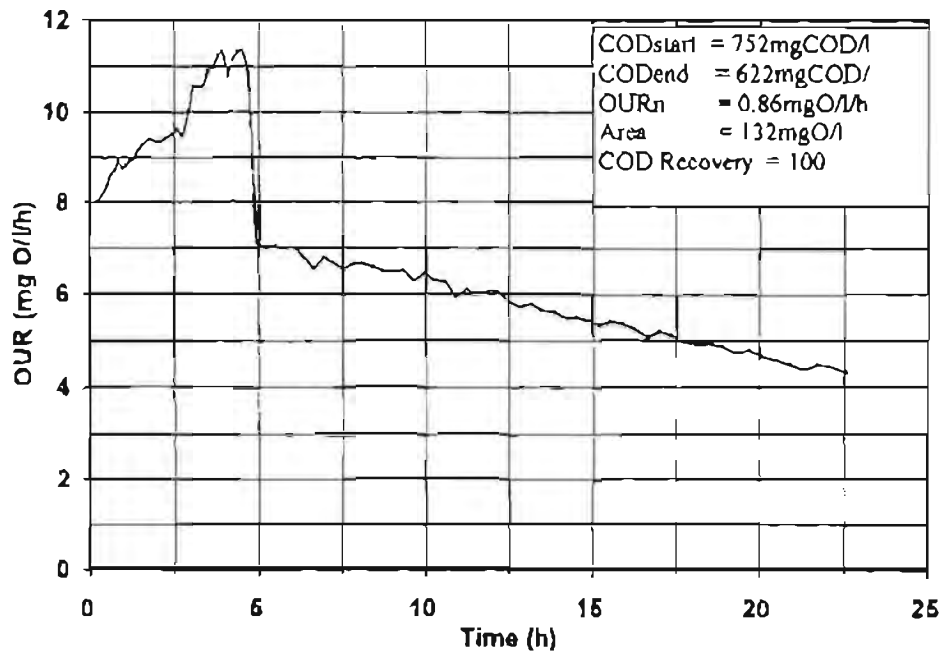


Fig B32a OUR graph for wastewater plus mixed liquor batch test, 04-02, batch no. 18

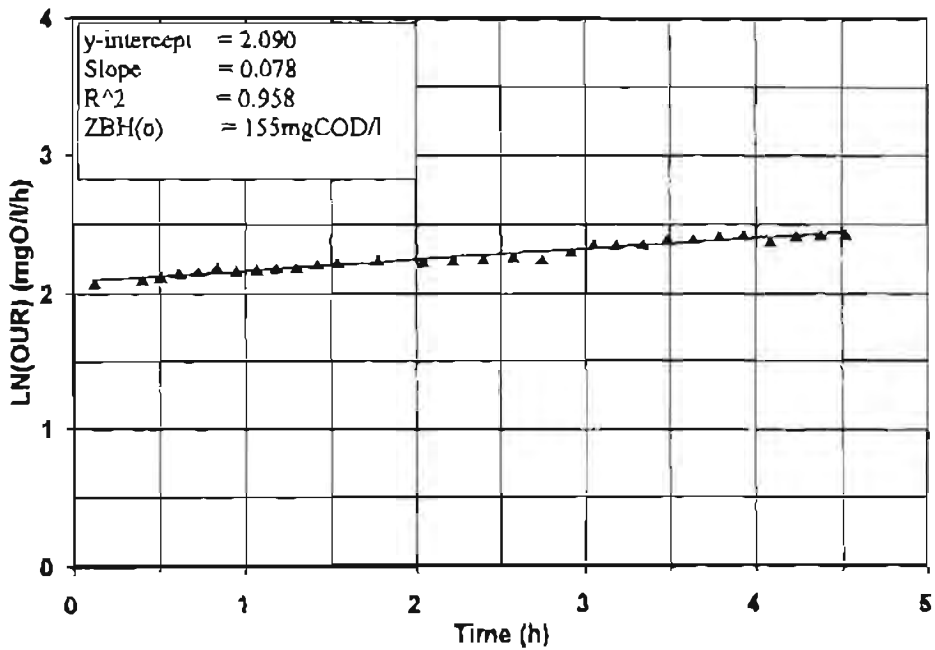


Fig B32b ln(OUR) graph for wastewater plus mixed liquor batch test, 04-02, batch no. 18

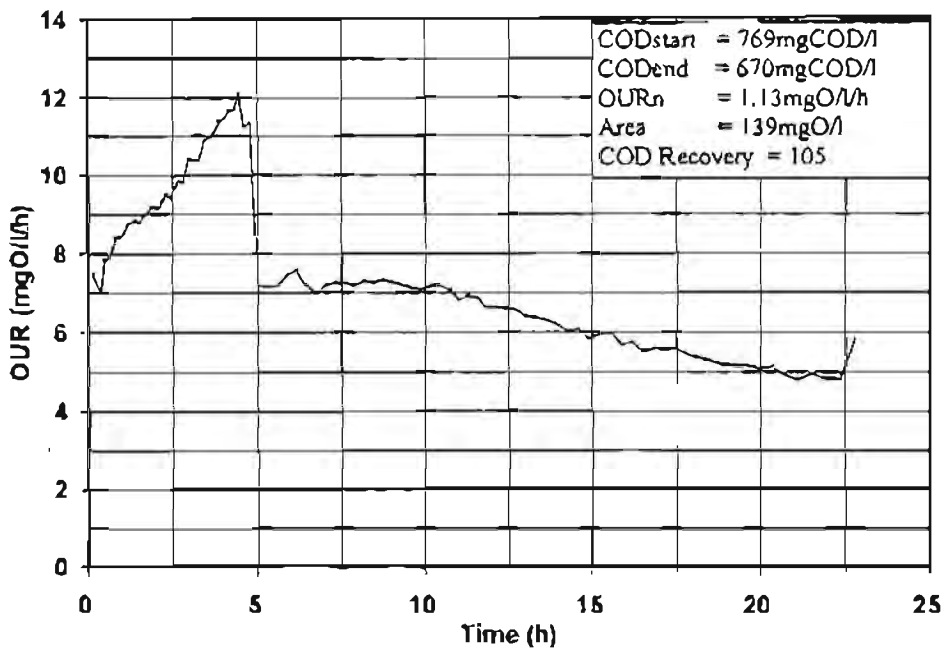


Fig B33a OUR graph for wastewater plus mixed liquor batch test, 05-02, batch no. 18

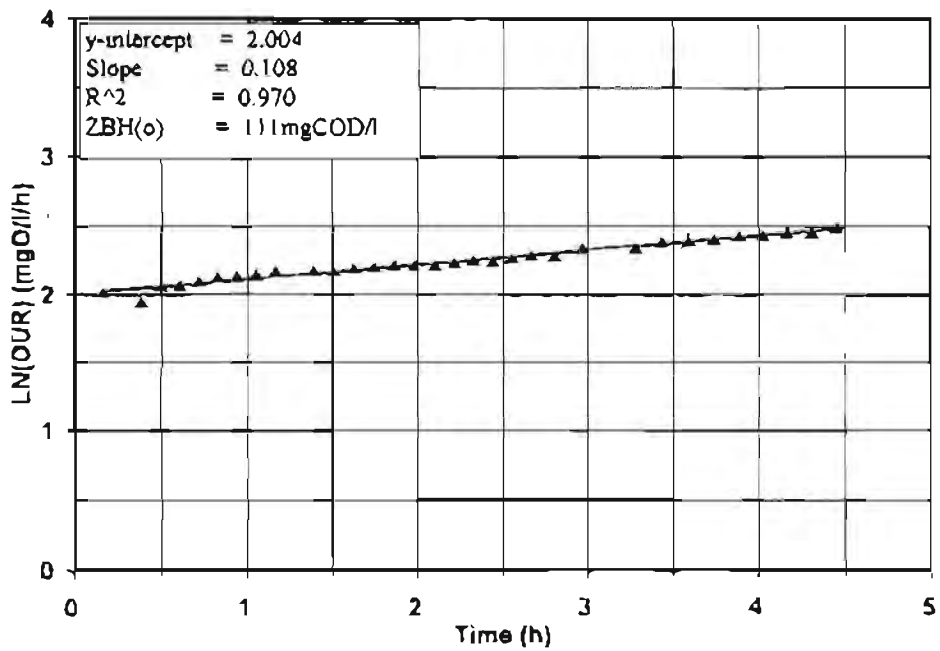


Fig B33b Ln(OUR) graph for wastewater plus mixed liquor batch test, 05-02, batch no. 18

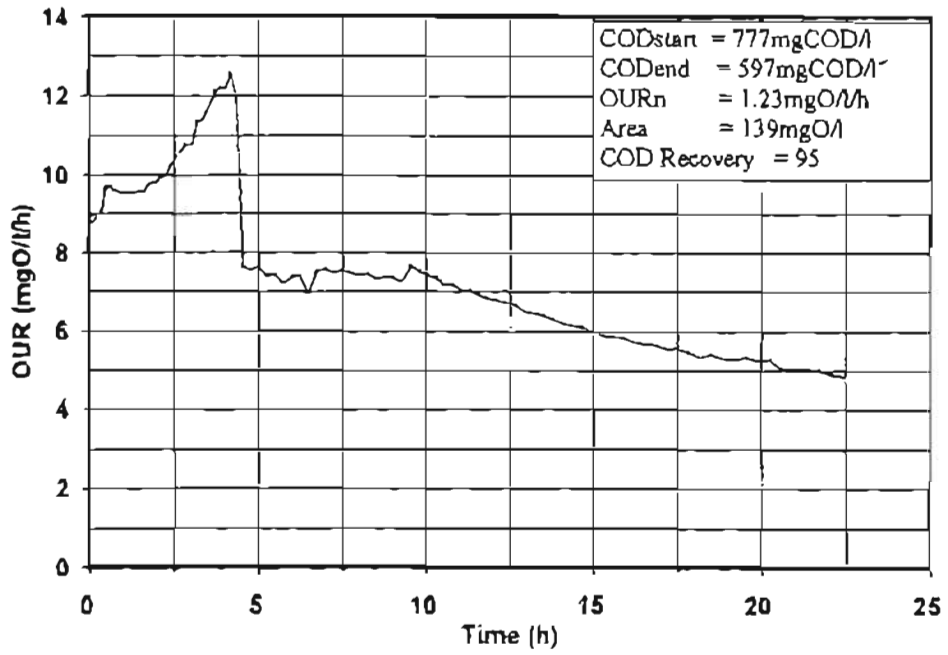


Fig B34a OUR graph for wastewater plus mixed liquor batch test, 06-02, batch no. 18

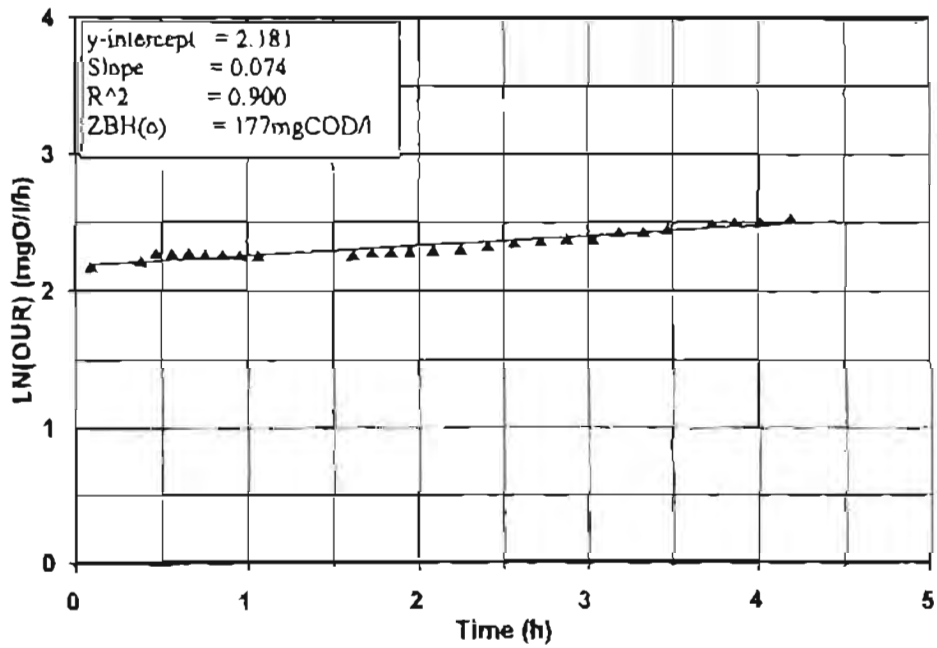


Fig B34b ln(OUR) graph for wastewater plus mixed liquor batch test, 06-02, batch no. 18

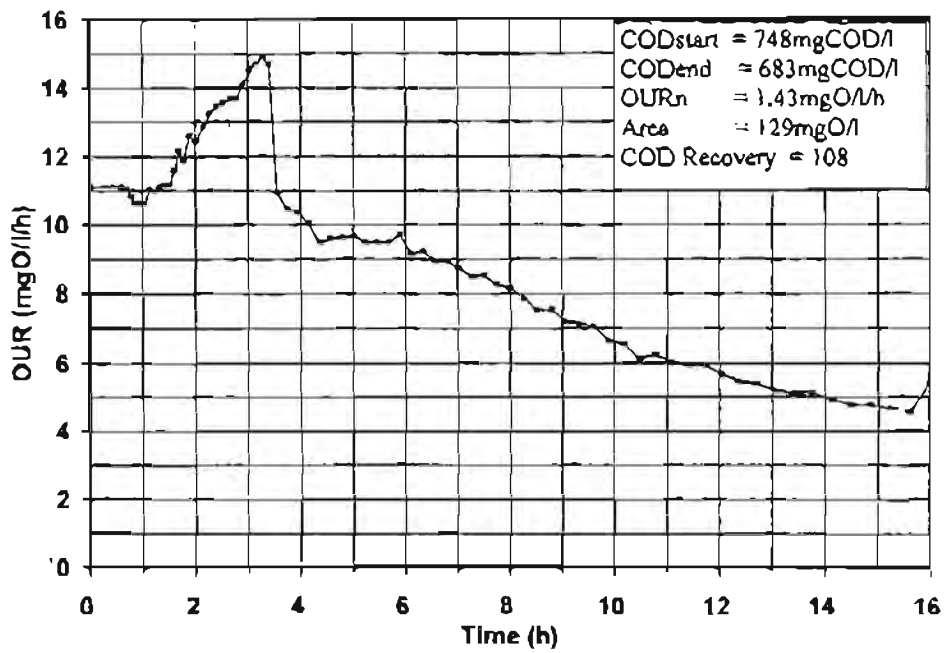


Fig B35a OUR graph for wastewater plus mixed liquor batch test, 07-02, batch no. 19

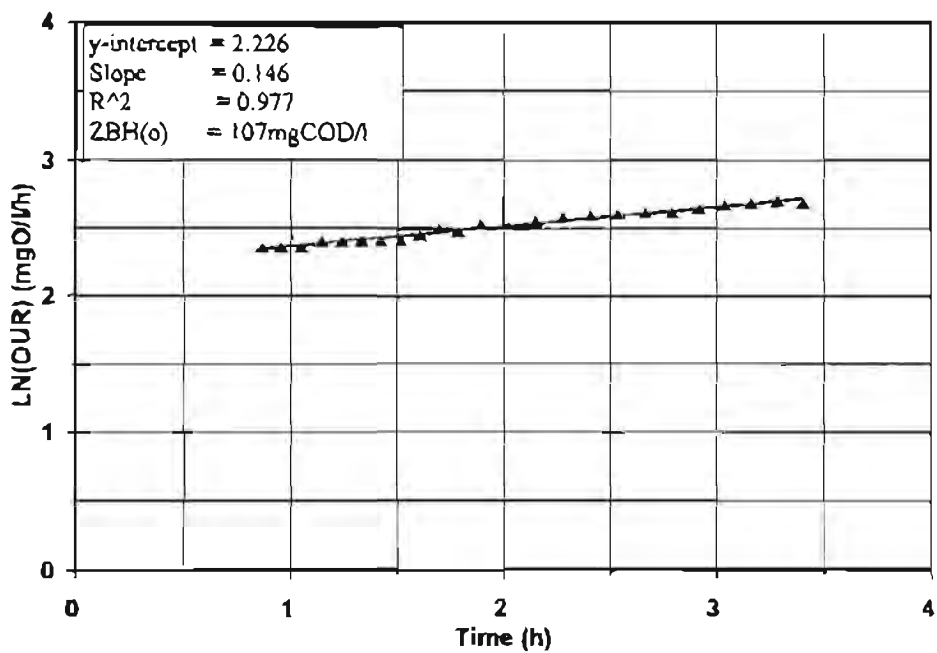


Fig B35b ln(OUR) graph for wastewater plus mixed liquor batch test, 07-02, batch no. 19

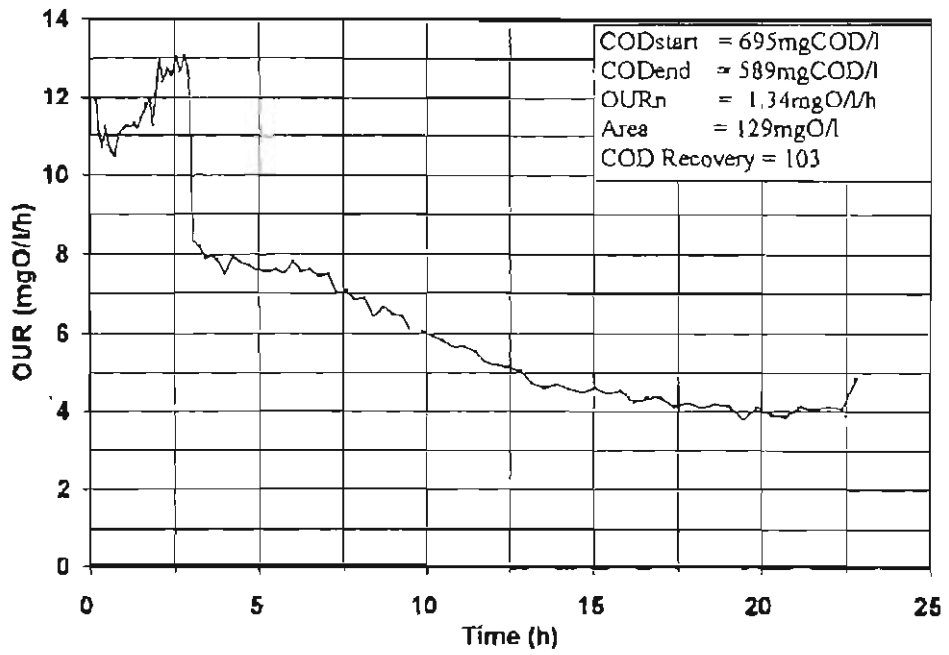


Fig B36a OUR graph for wastewater plus mixed liquor batch test, 08-02, batch no. 19

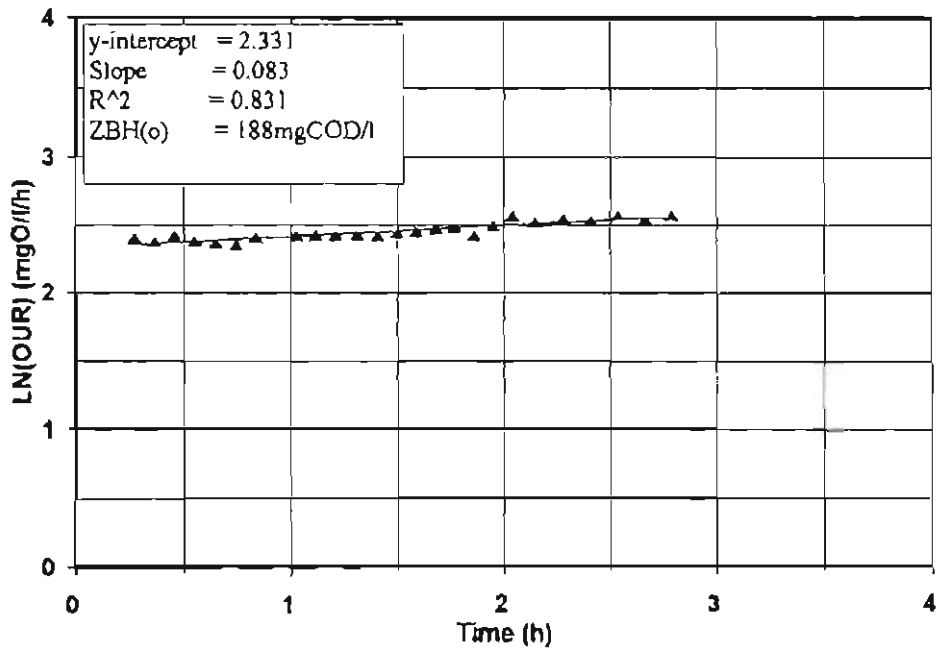


Fig B36b ln(OUR) graph for wastewater plus mixed liquor batch test, 08-02, batch no. 19

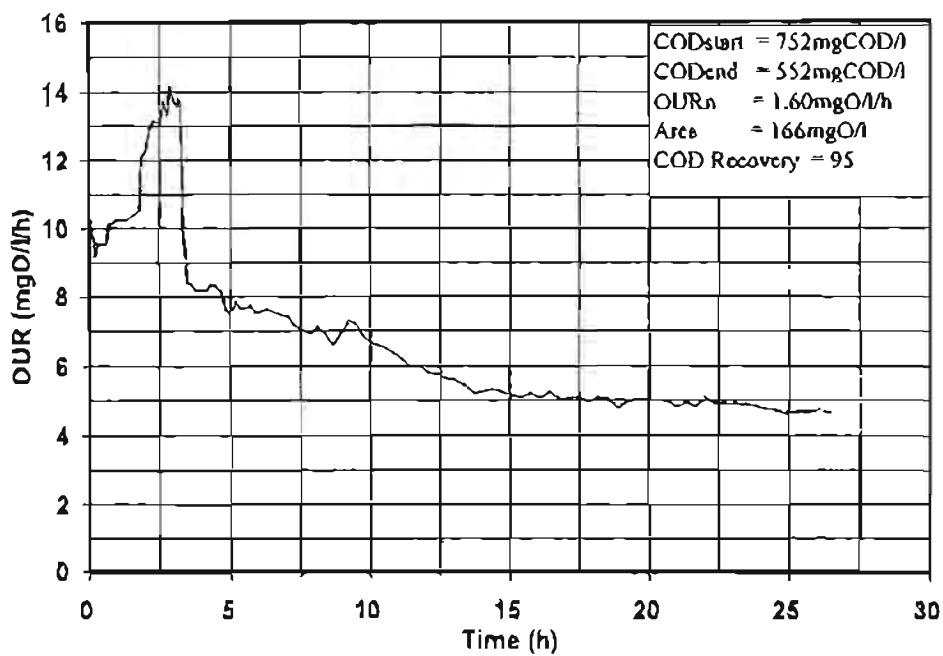


Fig B37a OUR graph for wastewater plus mixed liquor batch test, 09-02, batch no. 19

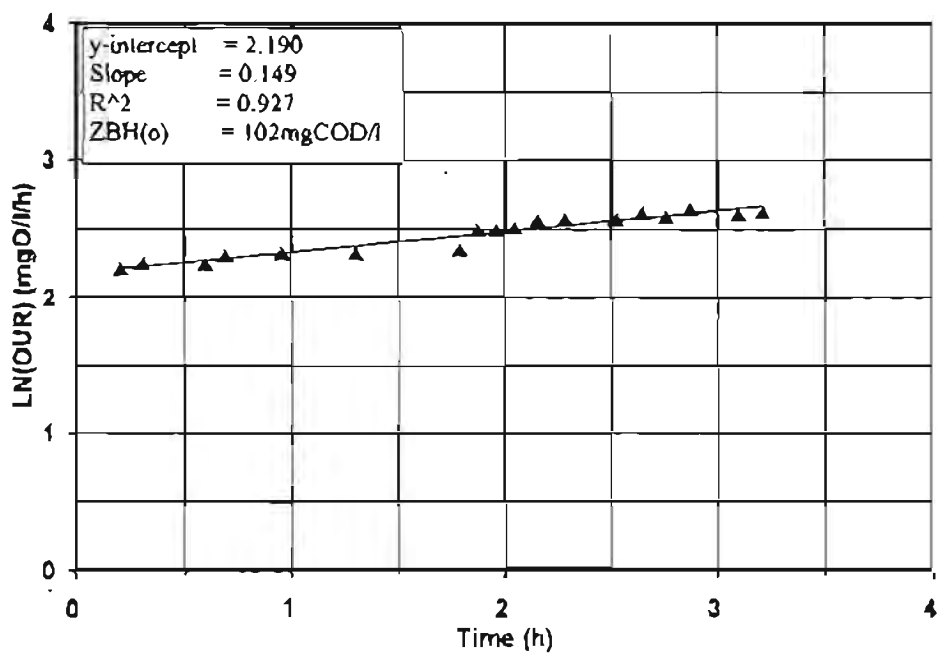


Fig B37b LN(OUR) graph for wastewater plus mixed liquor batch test, 09-02, batch no. 19

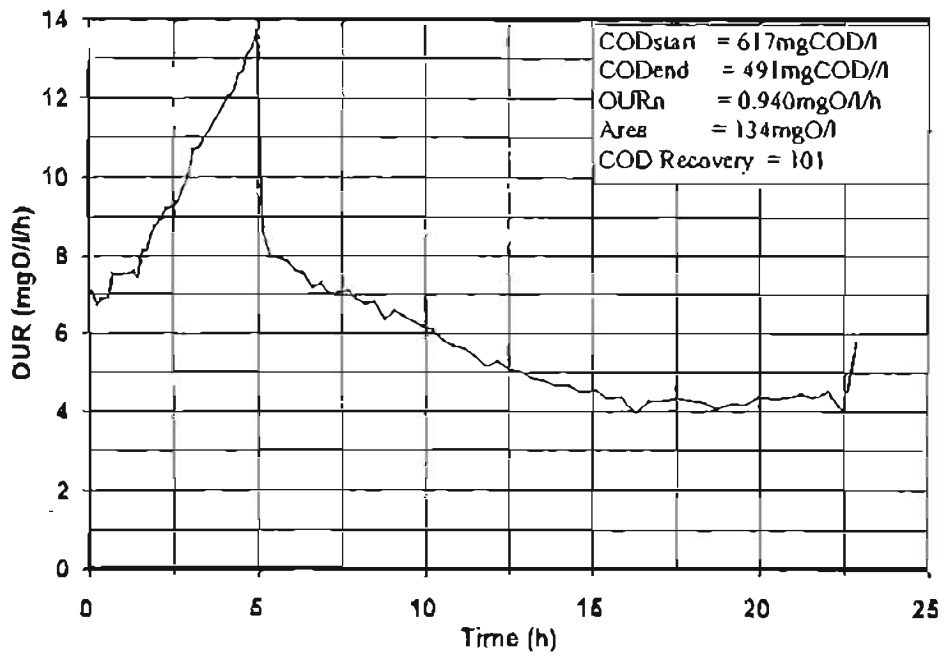


Fig B38a OUR graph for wastewater plus mixed liquor batch test, 11-02, batch no. 19

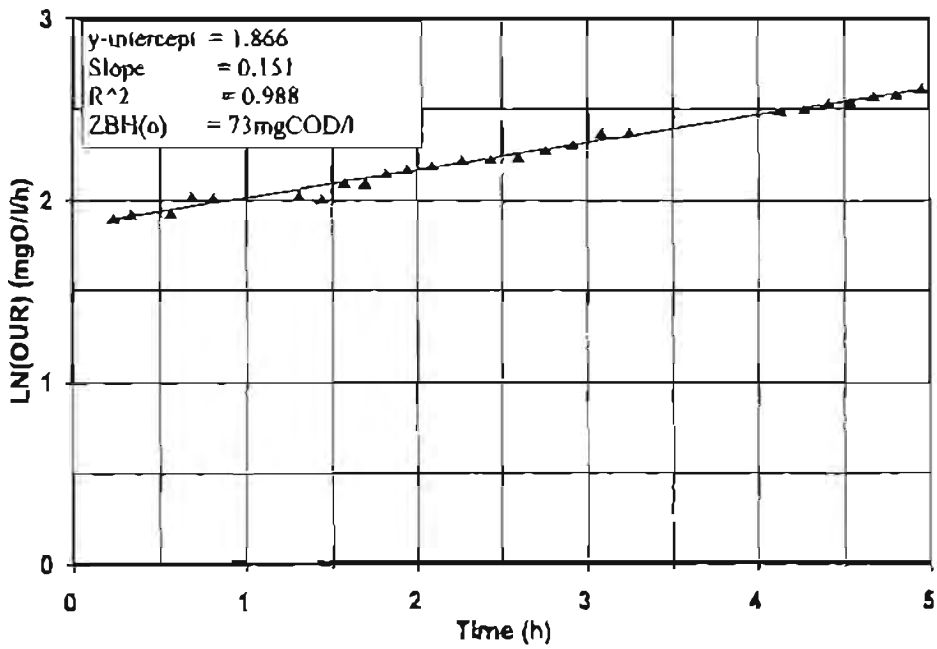


Fig B38b ln(OUR) graph for wastewater plus mixed liquor batch test, 11-02, batch no. 19

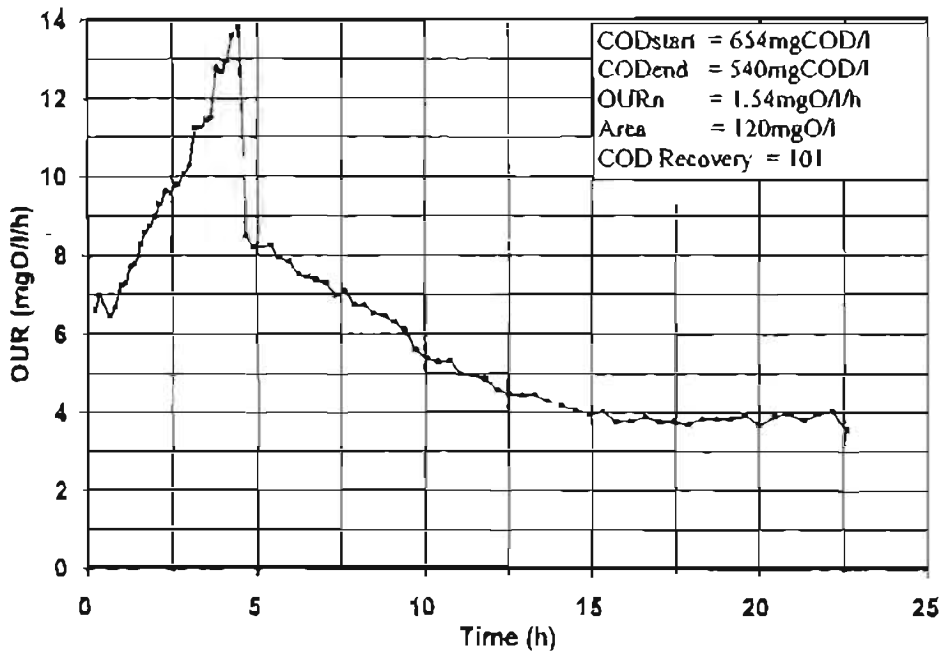


Fig B39a OUR graph for wastewater plus mixed liquor batch test, 12-02, batch no. 19

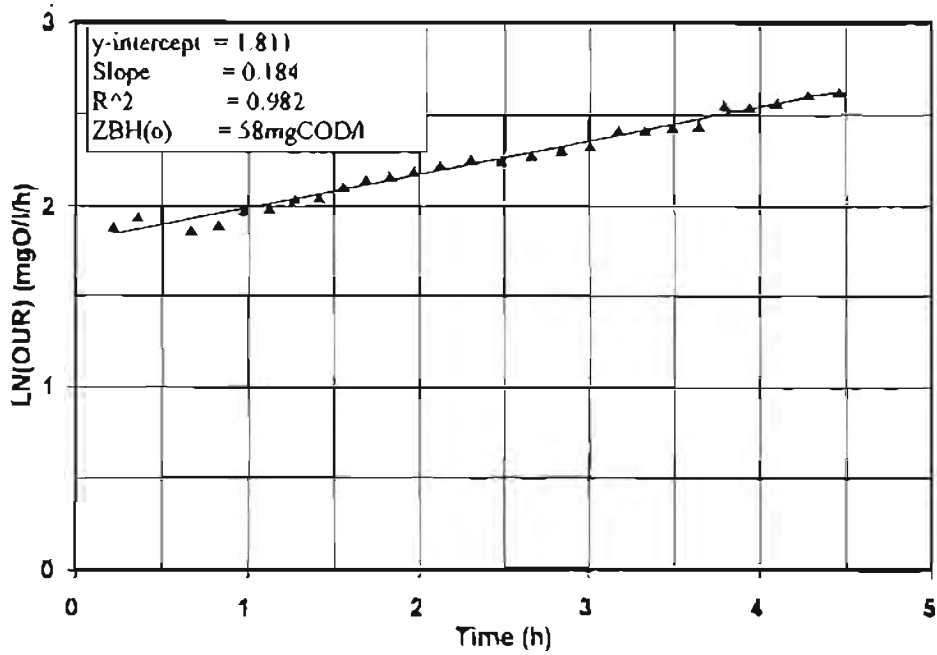


Fig B39b Ln(OUR) graph for wastewater plus mixed liquor batch test, 12-02, batch no. 19

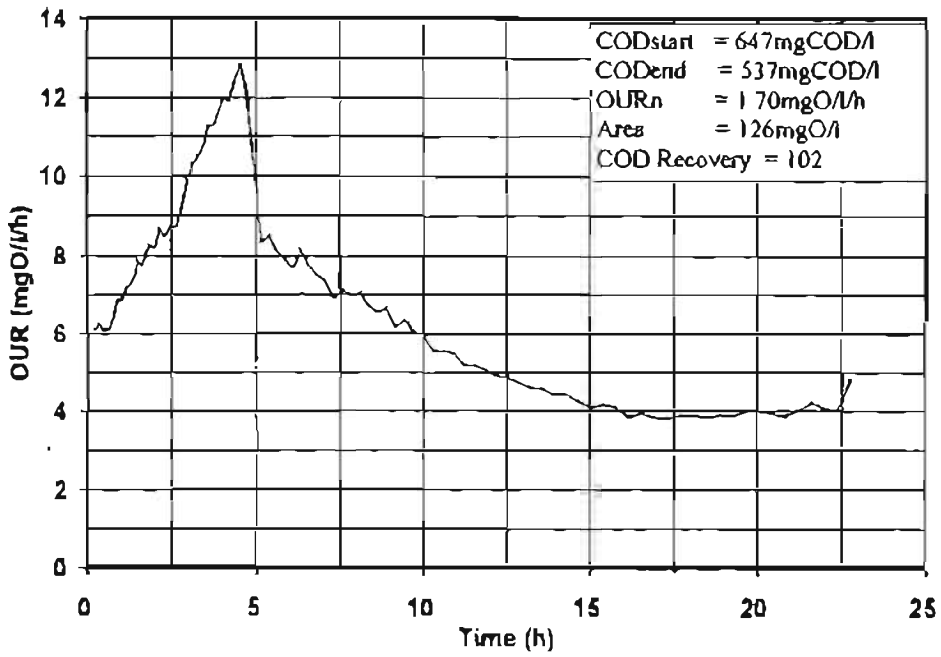


Fig B40a OUR graph for wastewater plus mixed liquor batch test, 13-02, batch no. 19

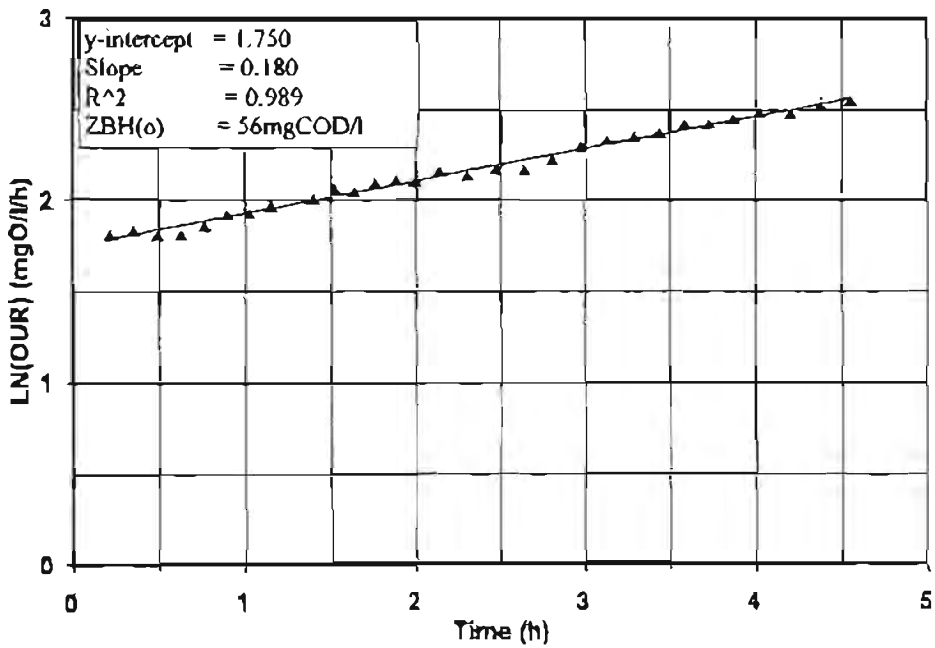


Fig B40b ln(OUR) graph for wastewater plus mixed liquor batch test, 13-02, batch no. 19

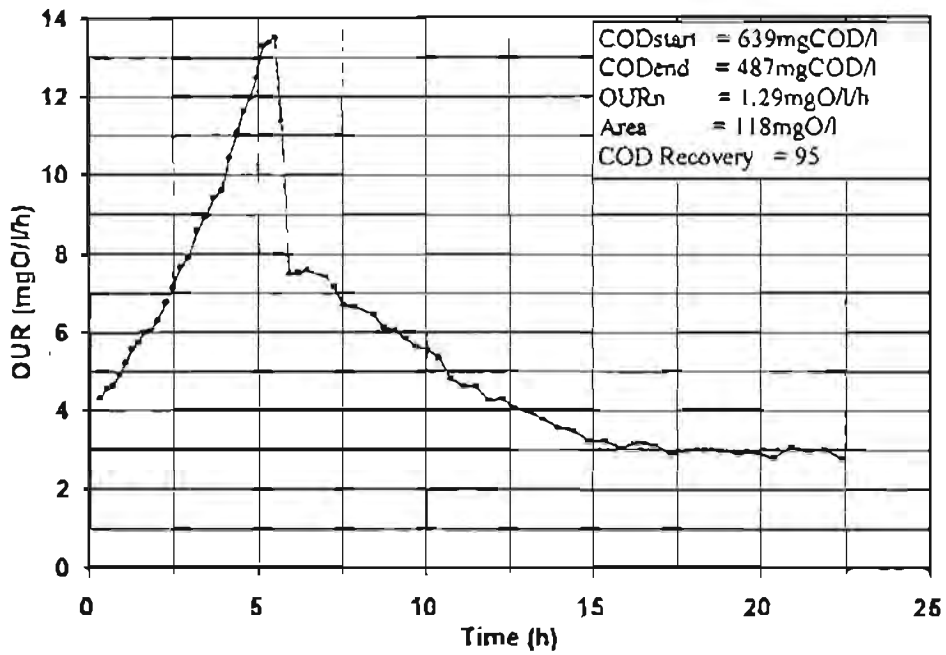


Fig B41a OUR graph for wastewater plus mixed liquor batch test, 14-02, batch no. 19

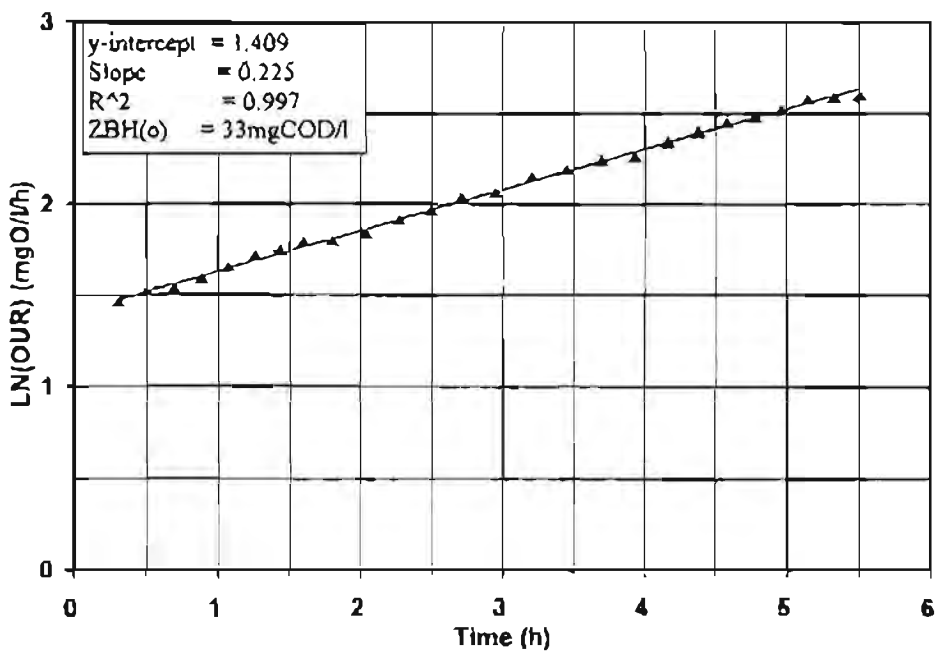


Fig B41b ln(OUR) graph for wastewater plus mixed liquor batch test, 14-02, batch no. 19

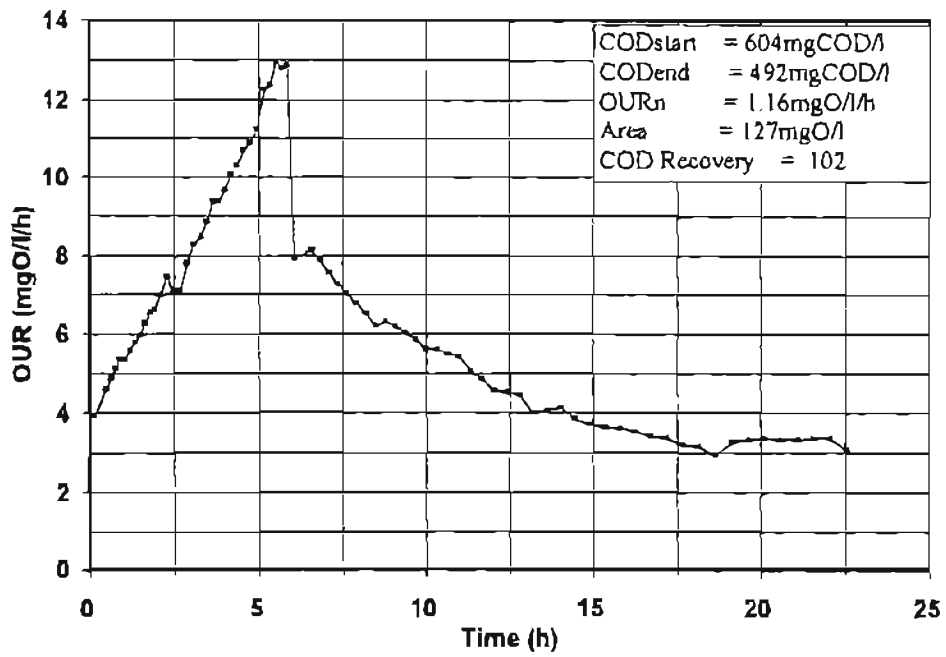


Fig B42a OUR graph for wastewater plus mixed liquor batch test, 15-02, batch no. 19

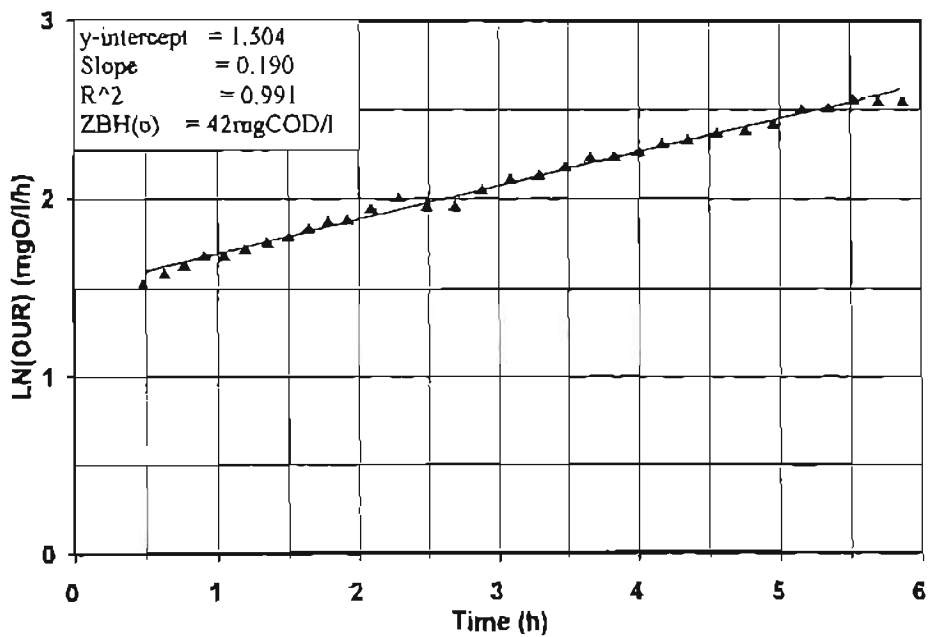


Fig B42b Ln(OUR) graph for wastewater plus mixed liquor batch test, 15-02, batch no. 19

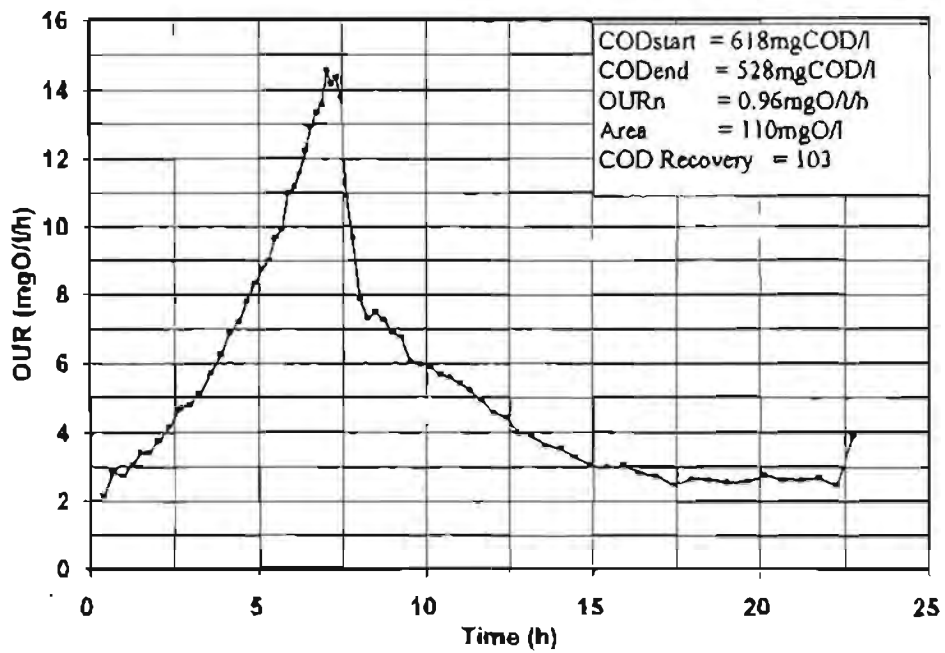


Fig B43a OUR graph for wastewater plus mixed liquor batch test, 16-02, batch no. 19

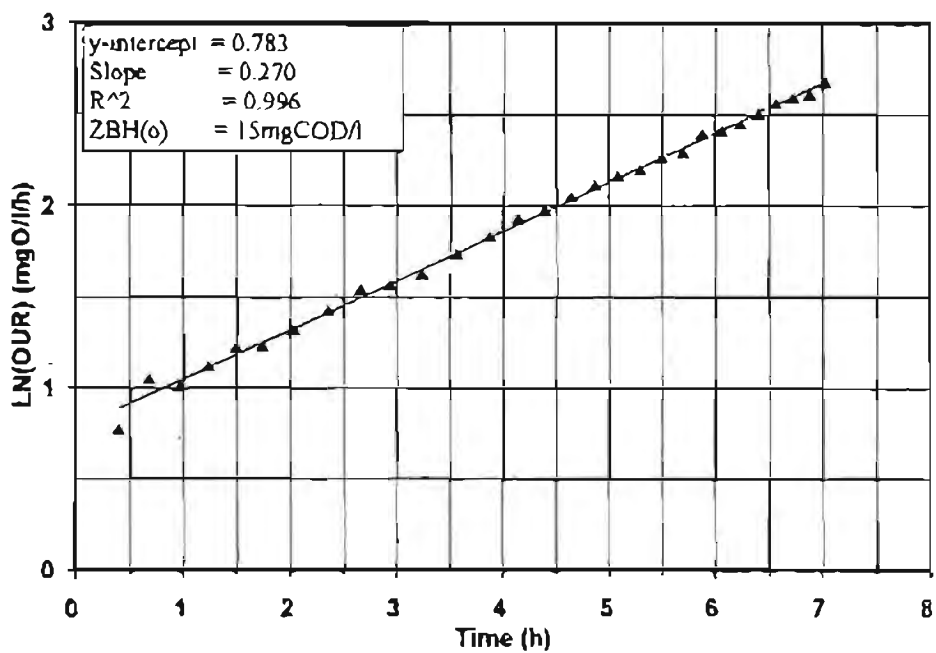


Fig B43b ln(OUR) graph for wastewater plus mixed liquor batch test, 16-02, batch no. 19

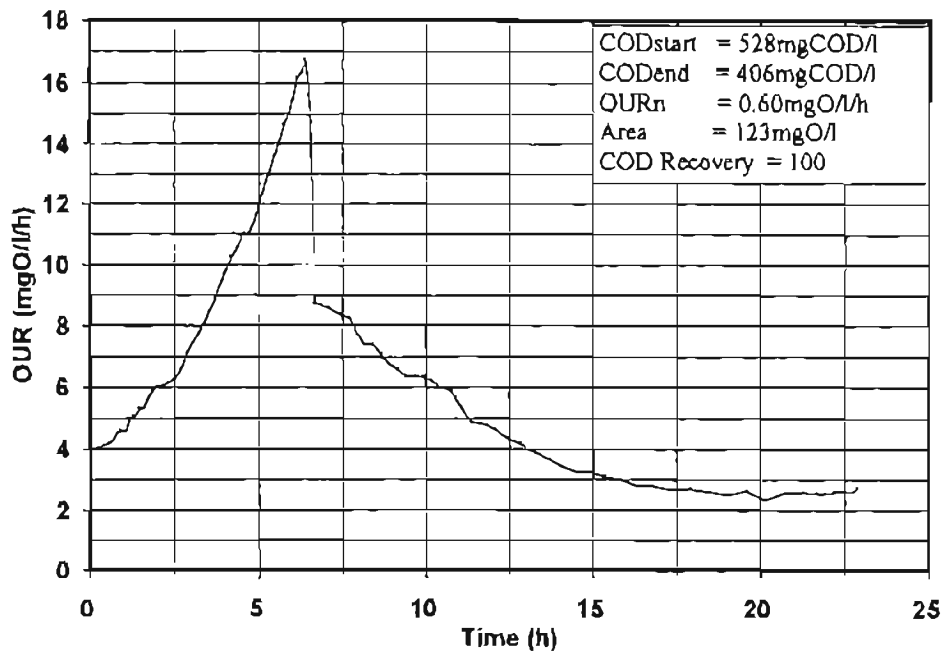


Fig B44a OUR graph for wastewater plus mixed liquor batch test, 17-02, batch no. 19

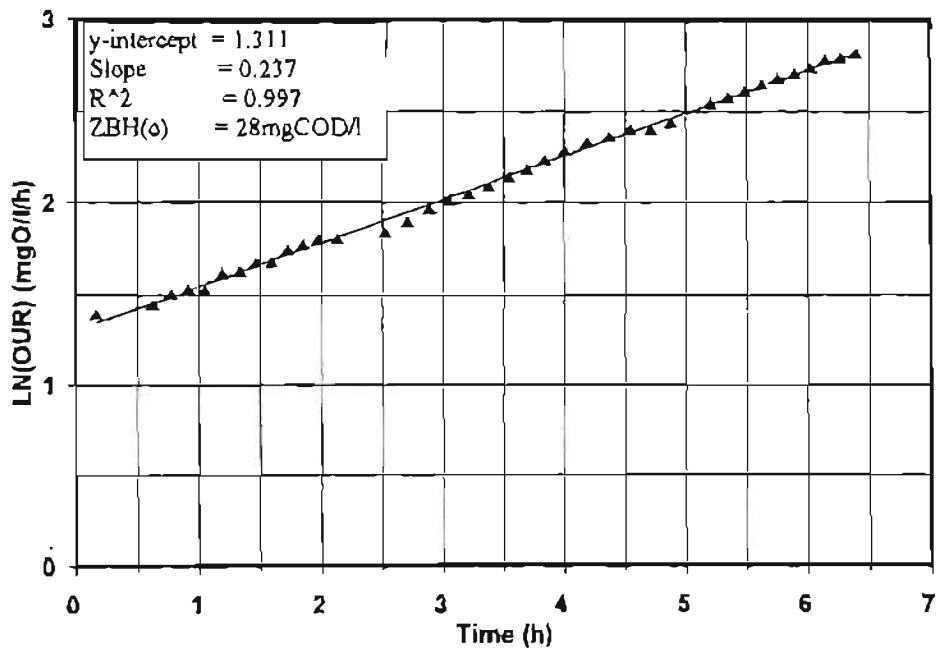


Fig B44b ln(OUR) graph for wastewater plus mixed liquor batch test, 17-02, batch no. 19

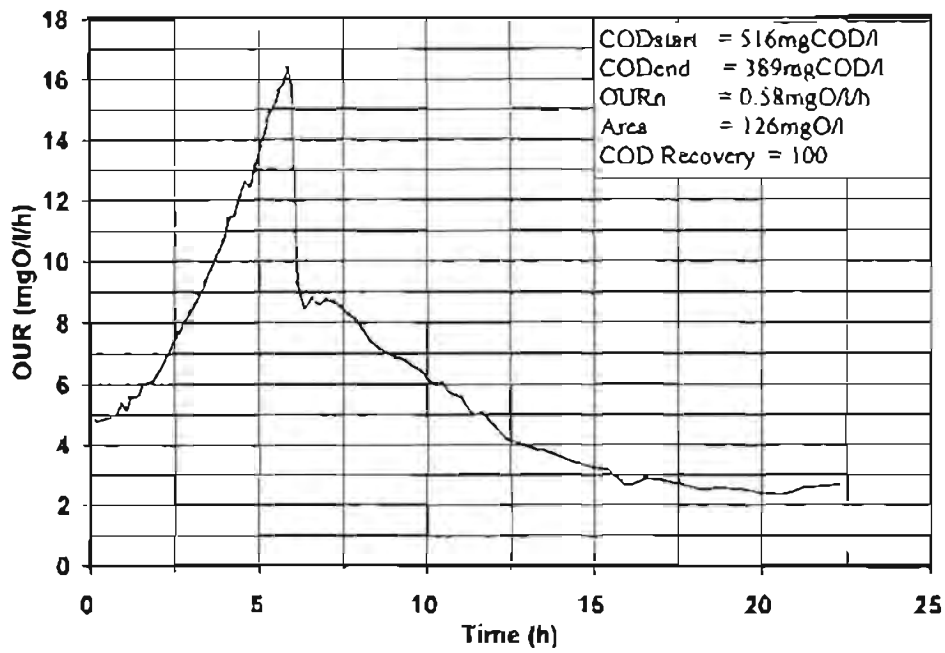


Fig B45a OUR graph for wastewater plus mixed liquor batch test, 18-02, batch no. 19

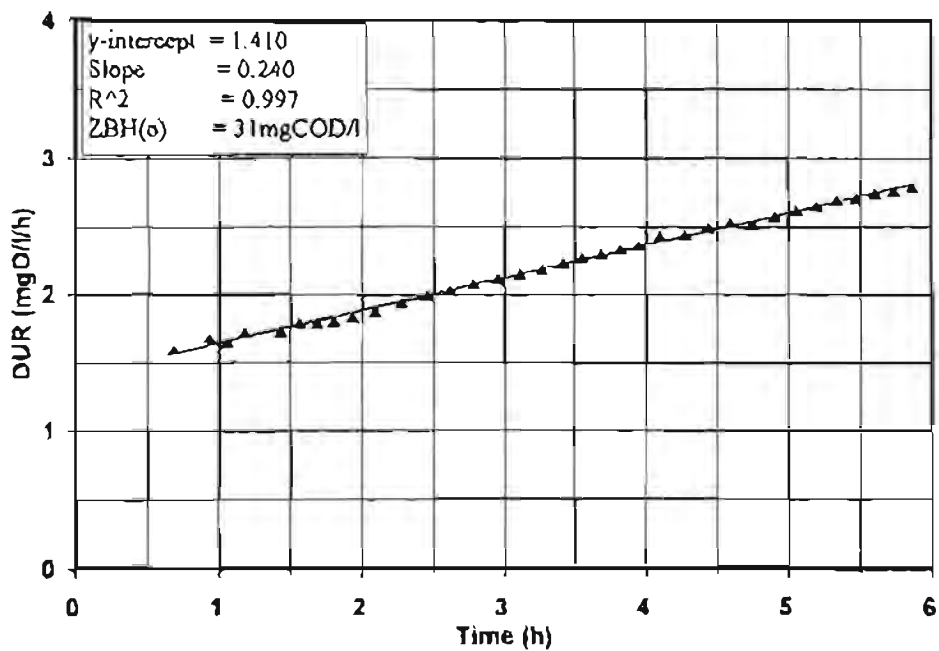


Fig B45b ln(OUR) graph for wastewater plus mixed liquor batch test, 18-02, batch no. 19

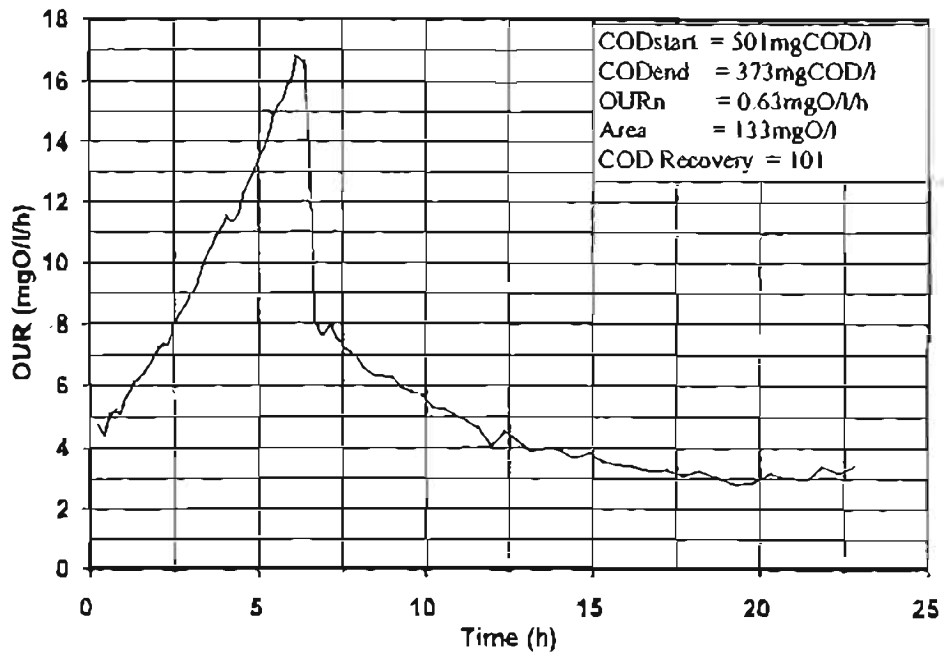


Fig B46a OUR graph for wastewater plus mixed liquor batch test, 19-02, batch no.19

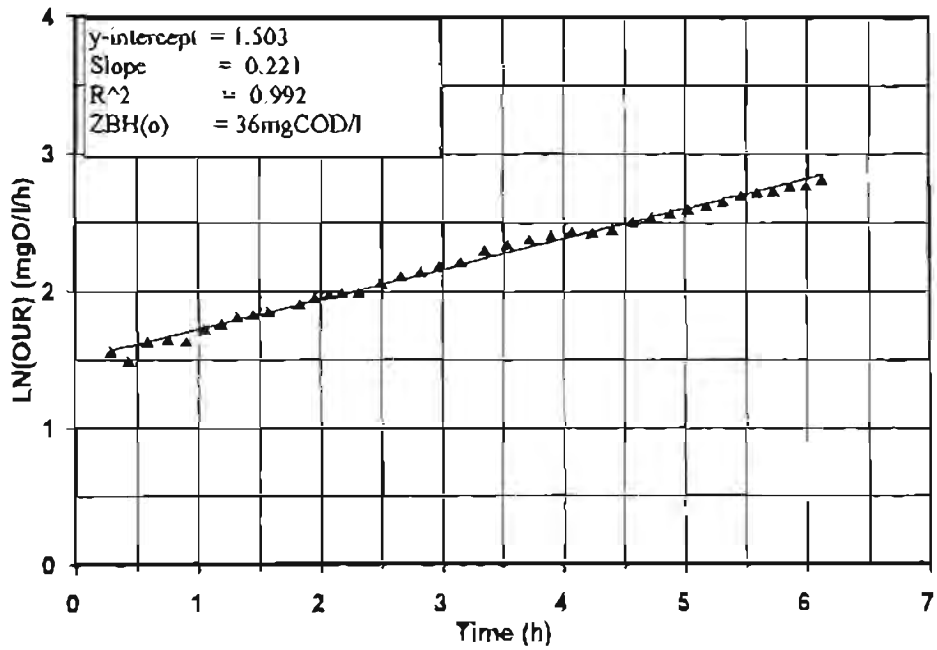


Fig B46b Ln(OUR) graph for wastewater plus mixed liquor batch test, 19-02, batch no. 19

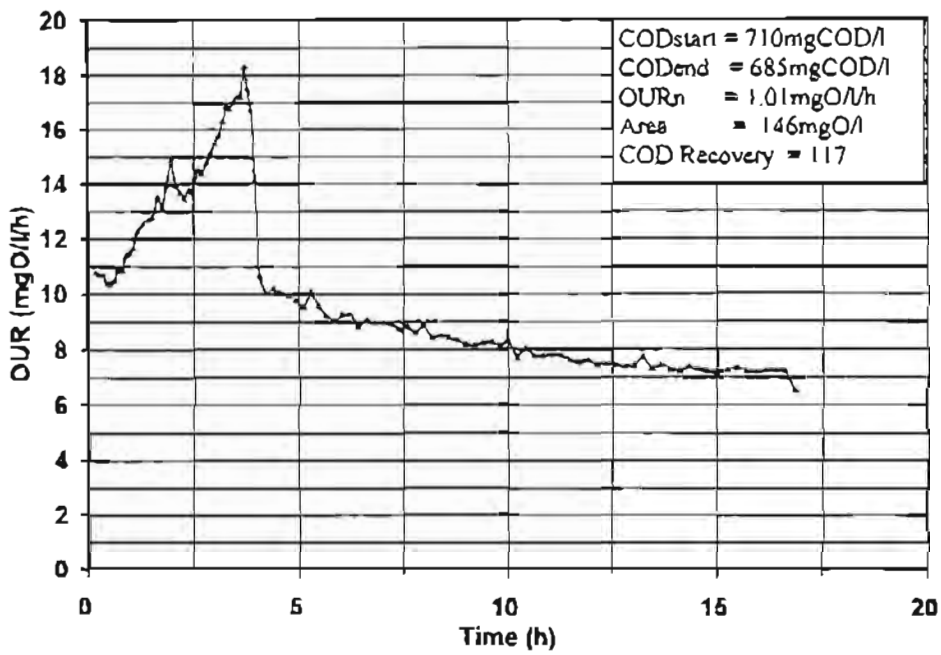


Fig B47a OUR graph for wastewater plus mixed liquor batch test, 20-02, batch no. 20

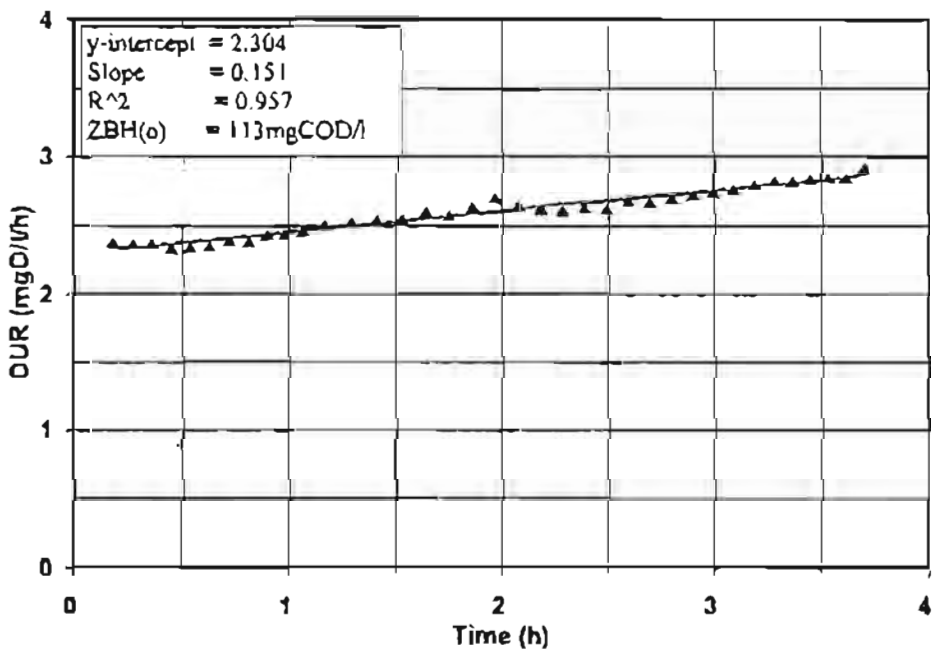


Fig B47b ln(OUR) graph for wastewater plus mixed liquor batch test, 20-02, batch no.20

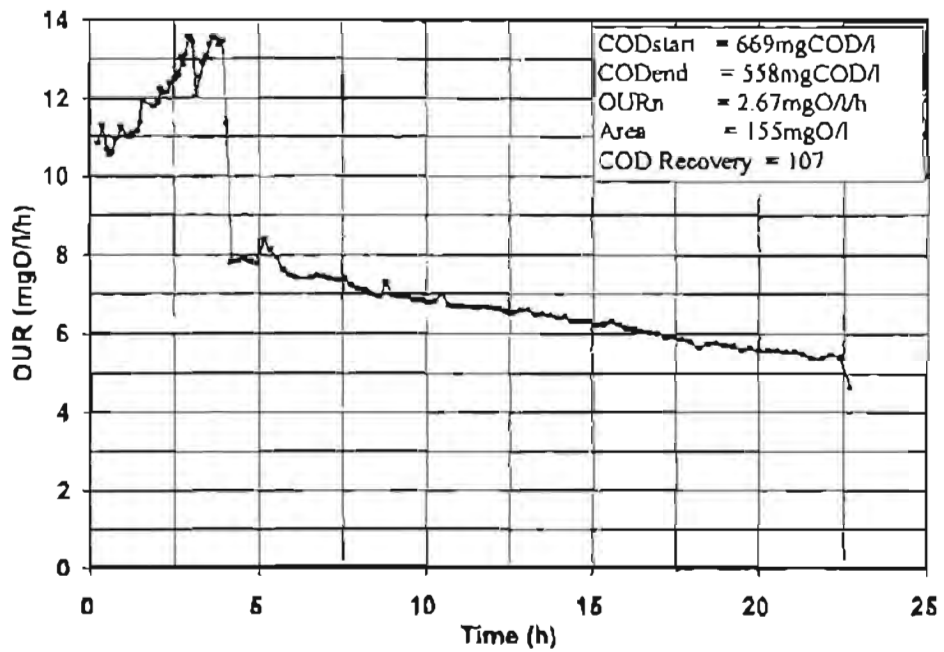


Fig B48a OUR graph for wastewater plus mixed liquor batch test, 21-02, batch no. 20

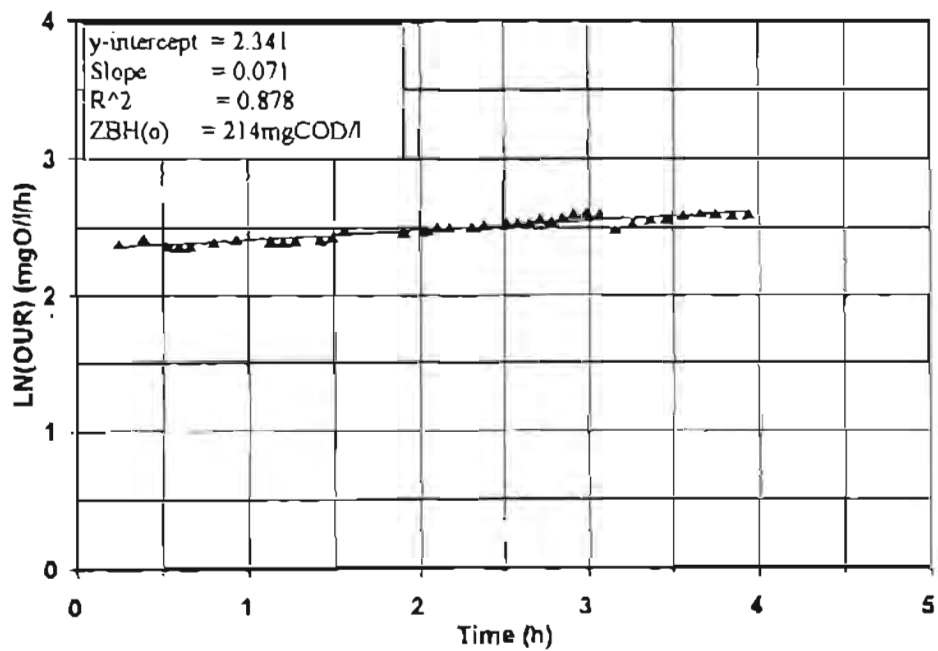


Fig B48b ln(OUR) graph for wastewater plus mixed liquor batch test, 21-02, batch no. 20

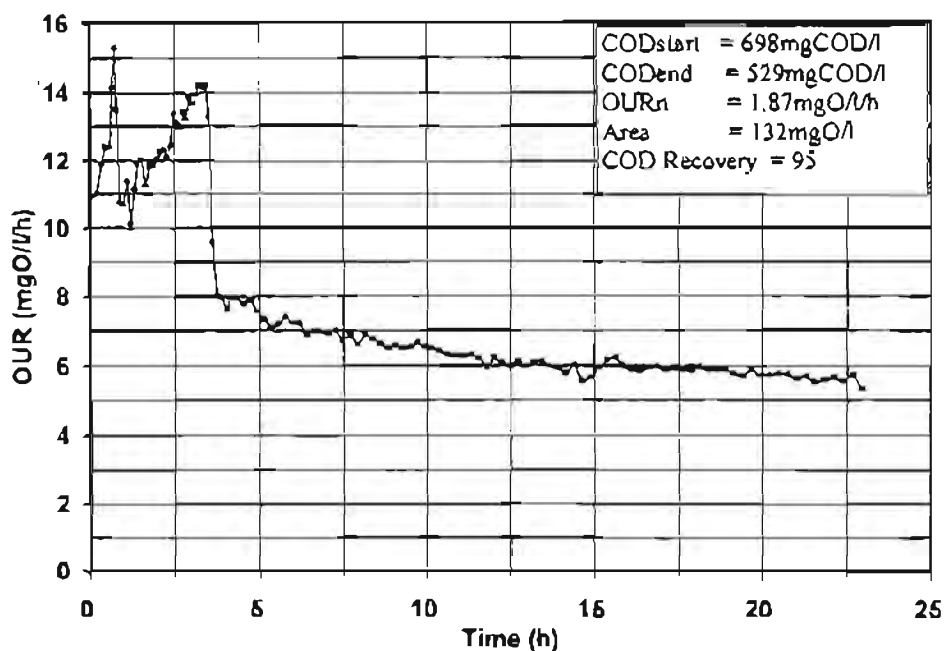


Fig B49a OUR graph for wastewater plus mixed liquor batch test, 23-02, batch no.20

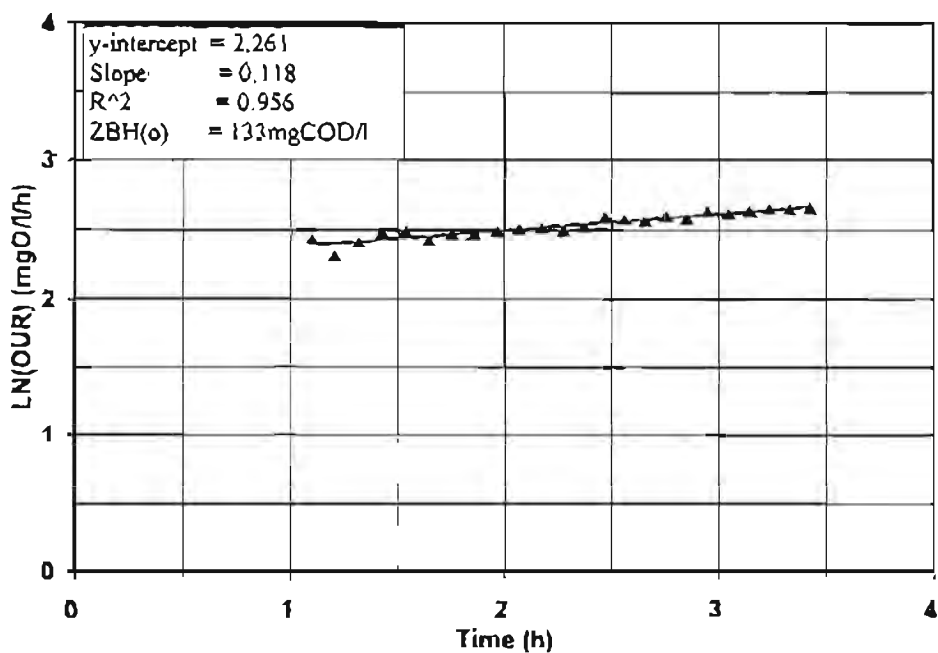


Fig B49b Ln(OUR) graph for wastewater plus mixed liquor batch test, 23-02, batch no.20

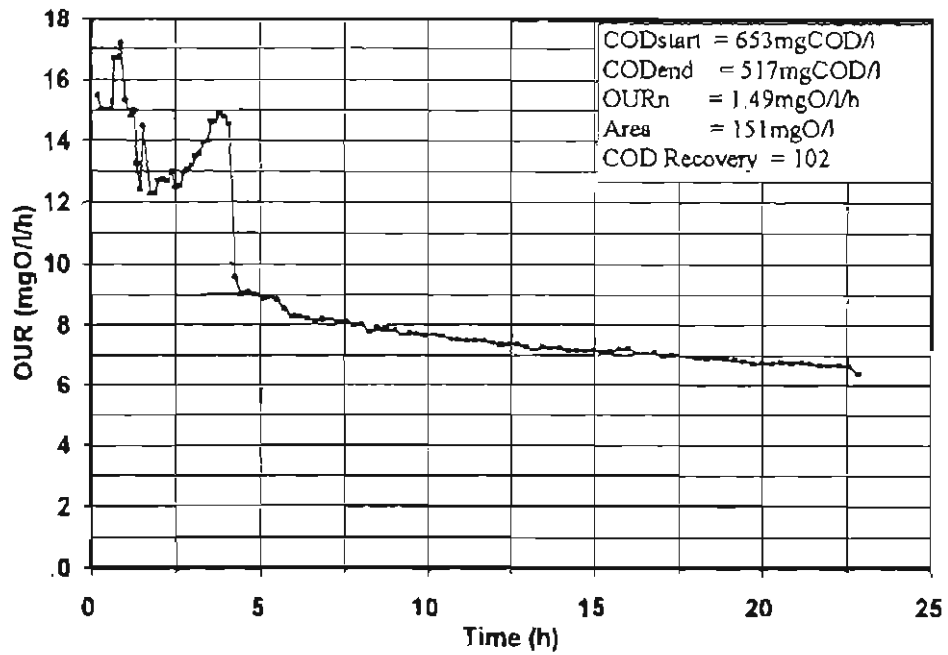


Fig B50a OUR graph for wastewater plus mixed liquor batch test, 24-02, batch no. 20

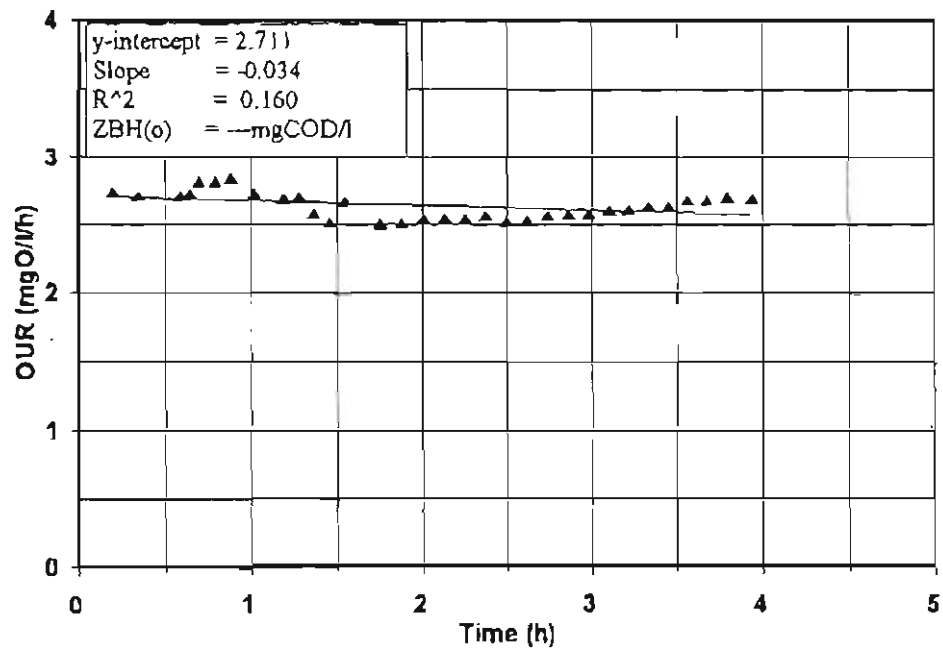


Fig B50b ln(OUR) graph for wastewater plus mixed liquor batch test, 24-02, batch no. 20

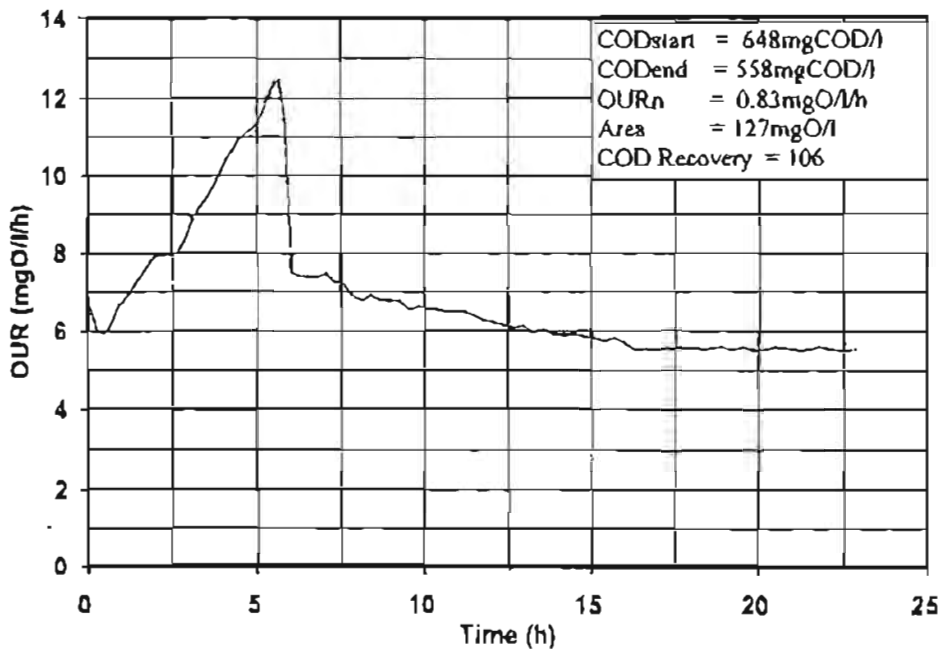


Fig B51a OUR graph for wastewater plus mixed liquor batch test, 25-02, batch no.20

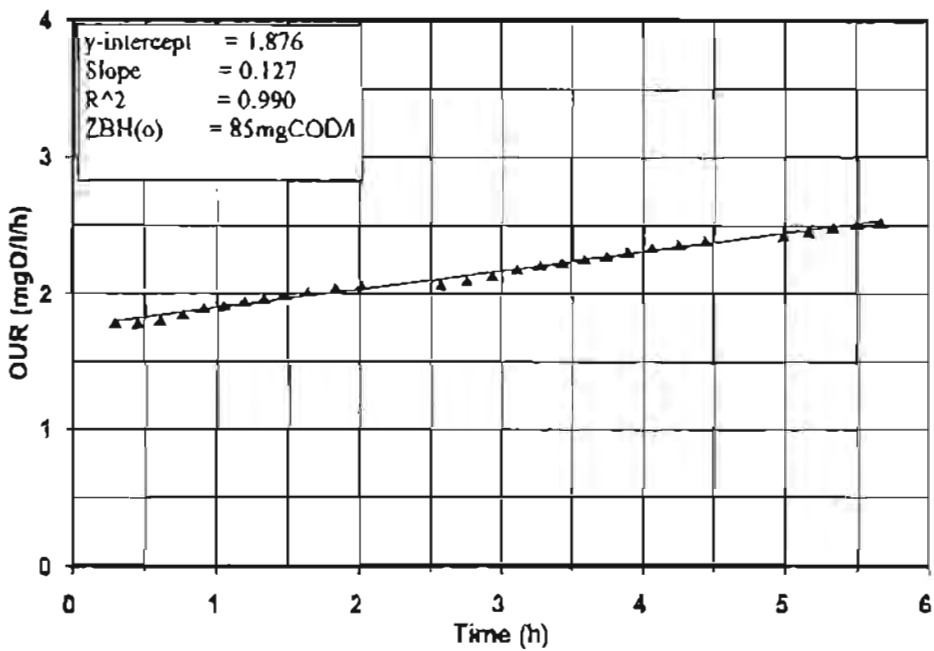


Fig B51b ln(OUR) graph for wastewater plus mixed liquor batch test, 25-02, batch no.20

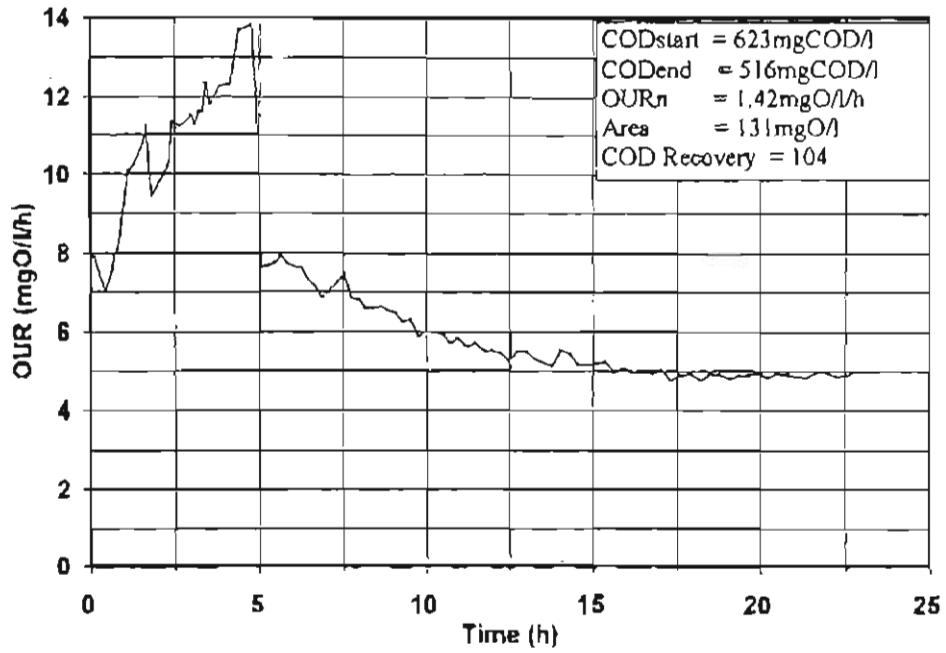


Fig B52a OUR graph for wastewater plus mixed liquor batch test, 26-02, batch no. 20

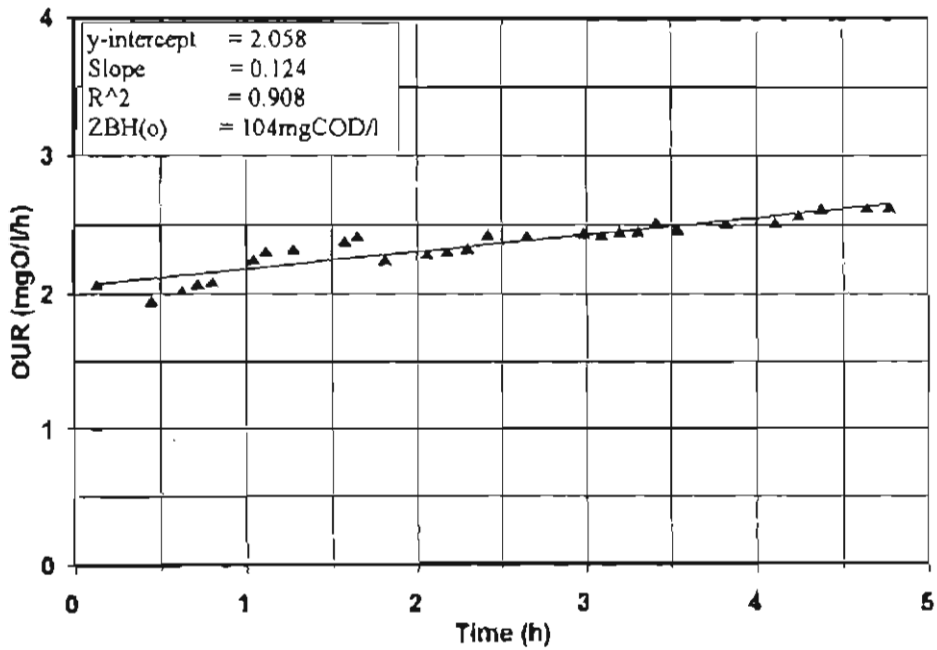


Fig B52b ln(OUR) graph for wastewater plus mixed liquor batch test, 26-02, batch no. 20

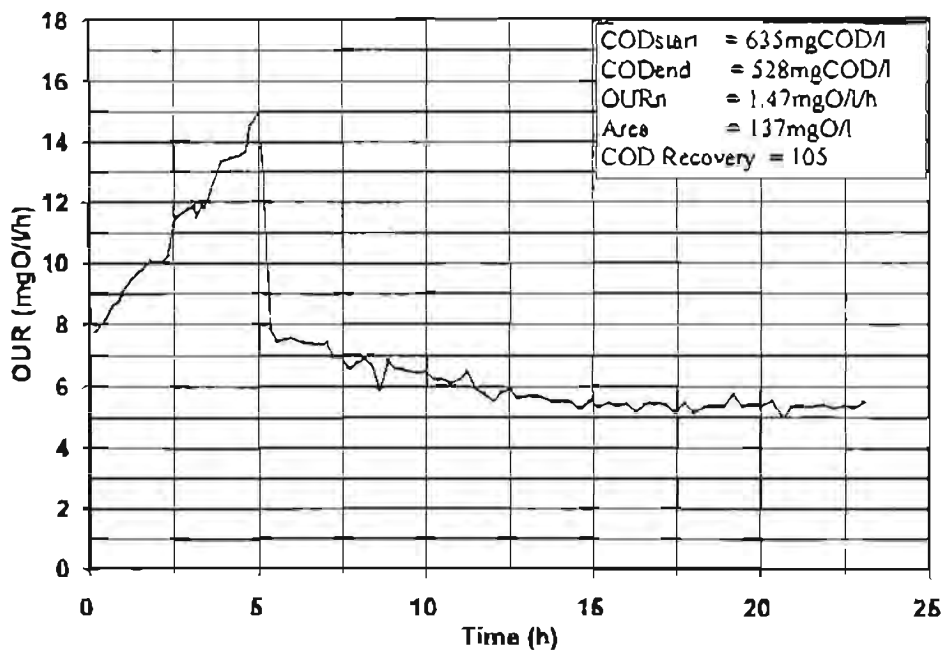


Fig B53a OUR graph for wastewater plus mixed liquor batch test, 27-02, batch no. 20

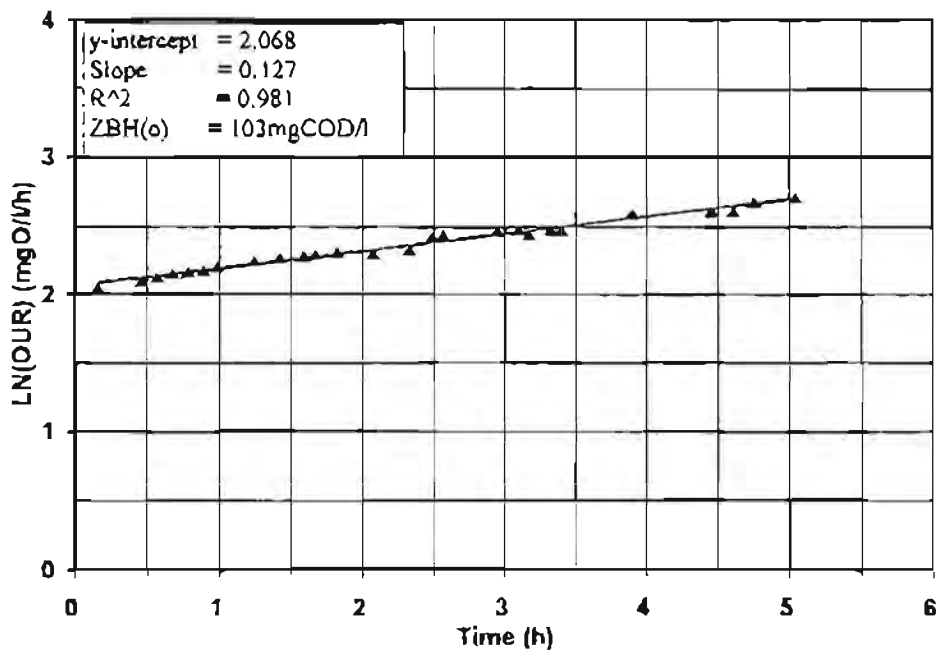


Fig B53b ln(OUR) graph for wastewater plus mixed liquor batch test, 27-02, batch no. 20

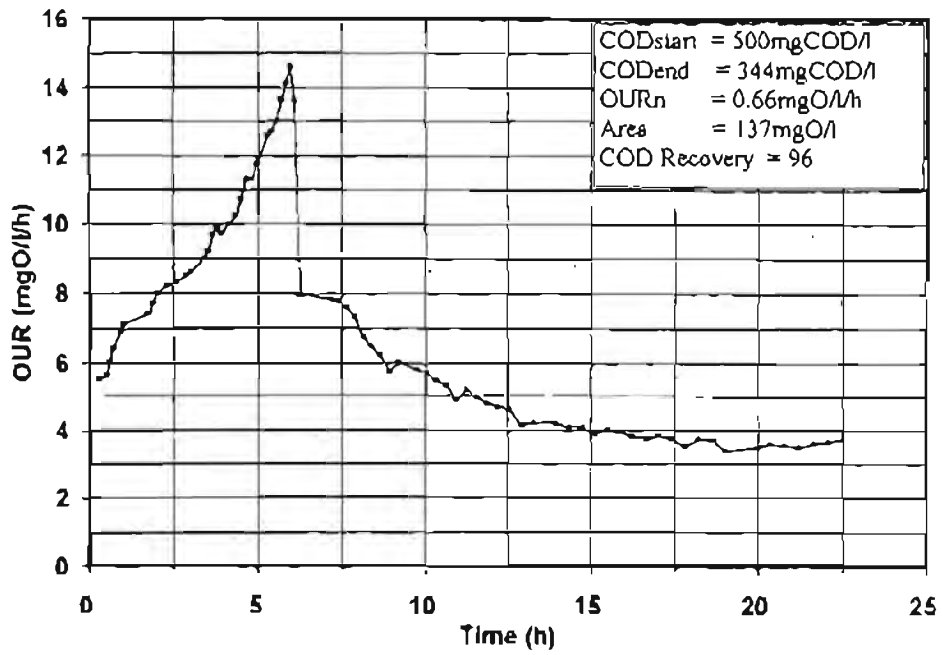


Fig B54a OUR graph for wastewater plus mixed liquor batch test, 28-02, batch no. 20

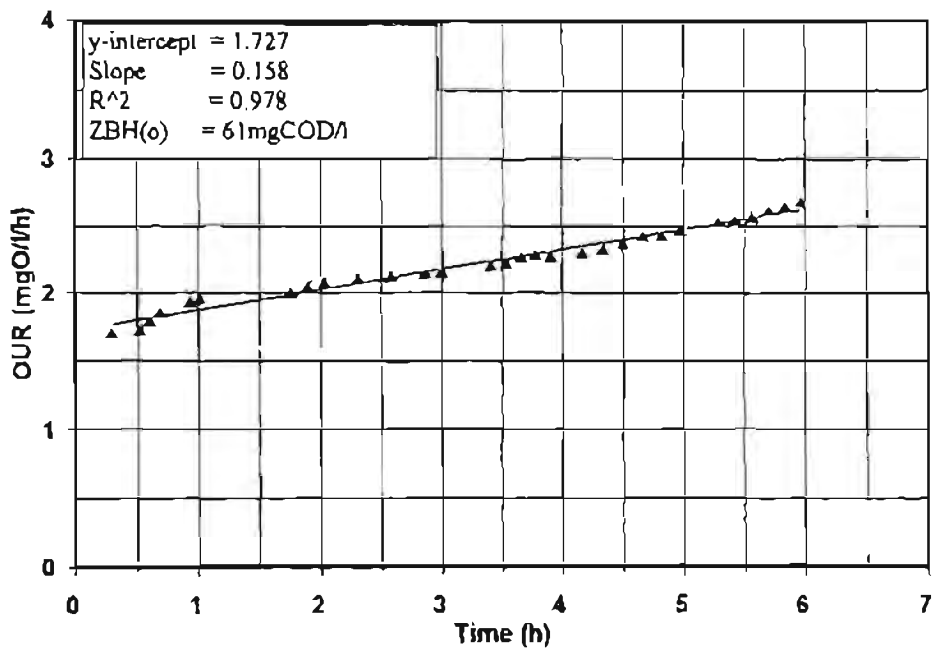


Fig B54b ln(OUR) graph for wastewater plus mixed liquor batch test, 28-02, batch no.20

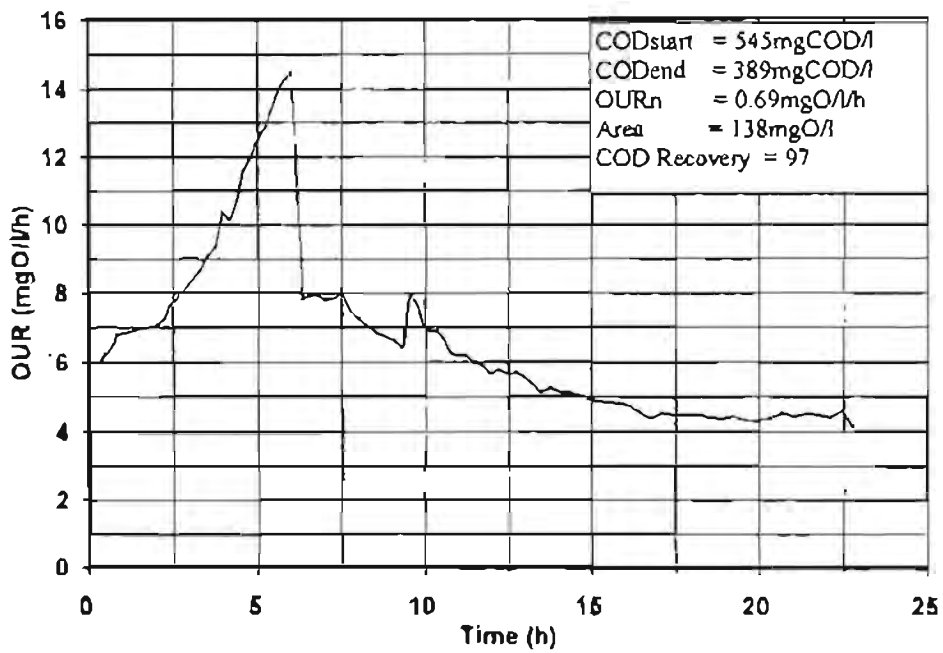


Fig B55a OUR graph for wastewater plus mixed liquor batch test, 29-02, batch no. 20

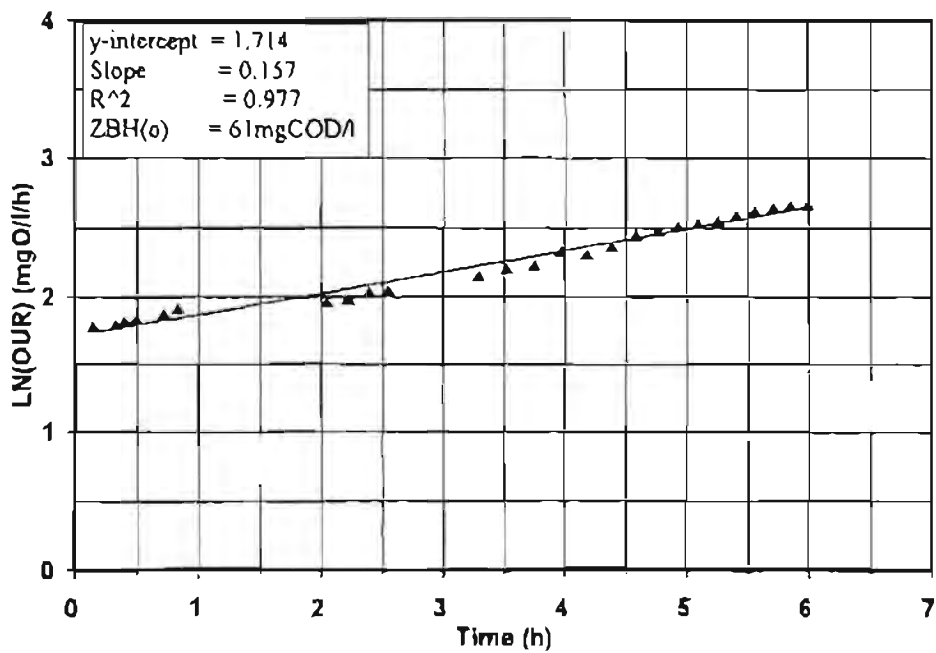


Fig B55b ln(OUR) graph for wastewater plus mixed liquor batch test, 29-02, batch no. 20

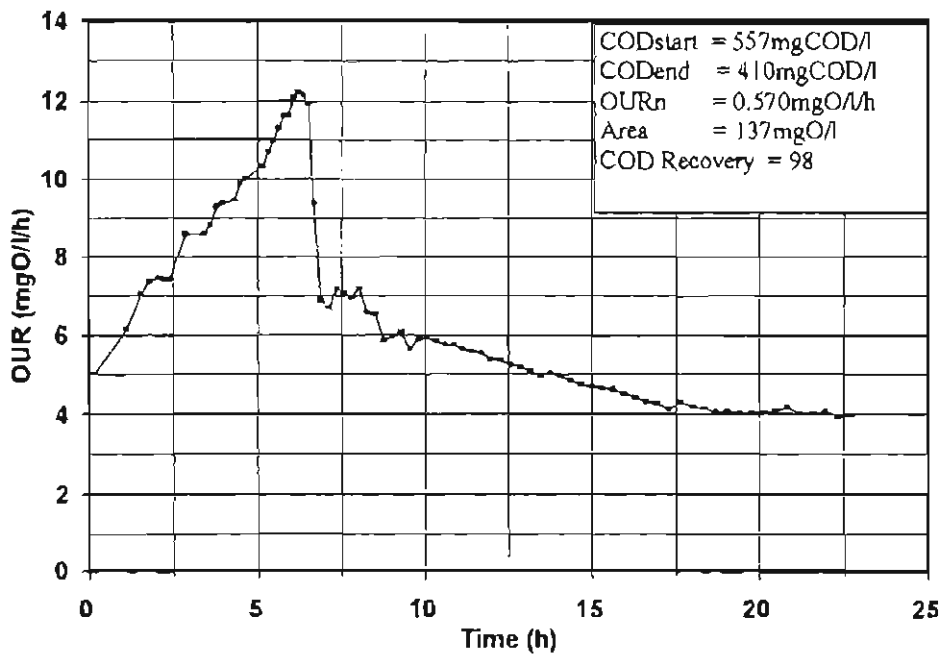


Fig B56a OUR graph for wastewater plus mixed liquor batch test, 01-03, batch no. 20

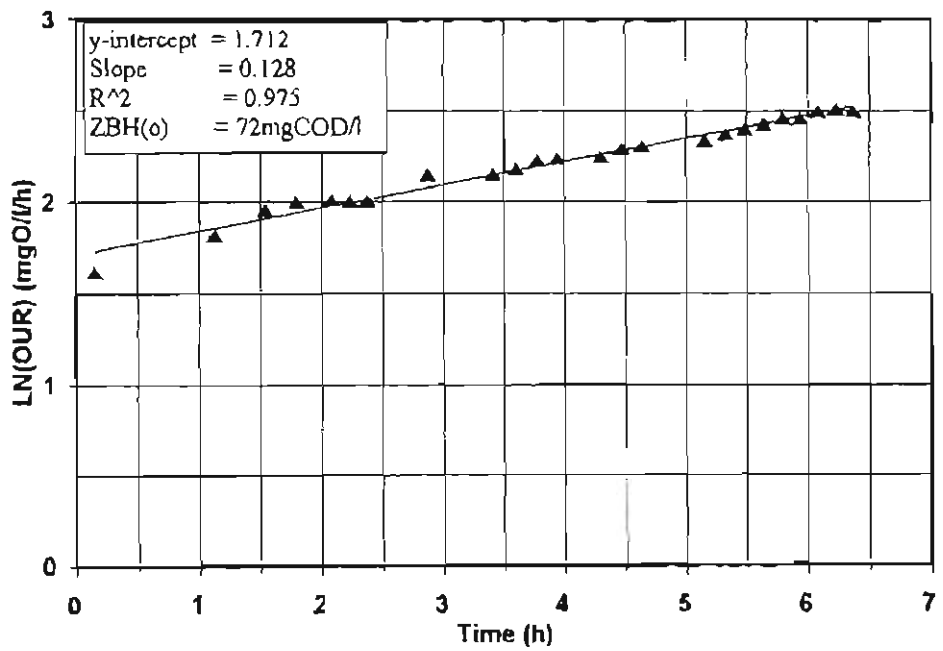


Fig B56b ln(OUR) graph for wastewater plus mixed liquor batch test, 01-03, batch no. 20

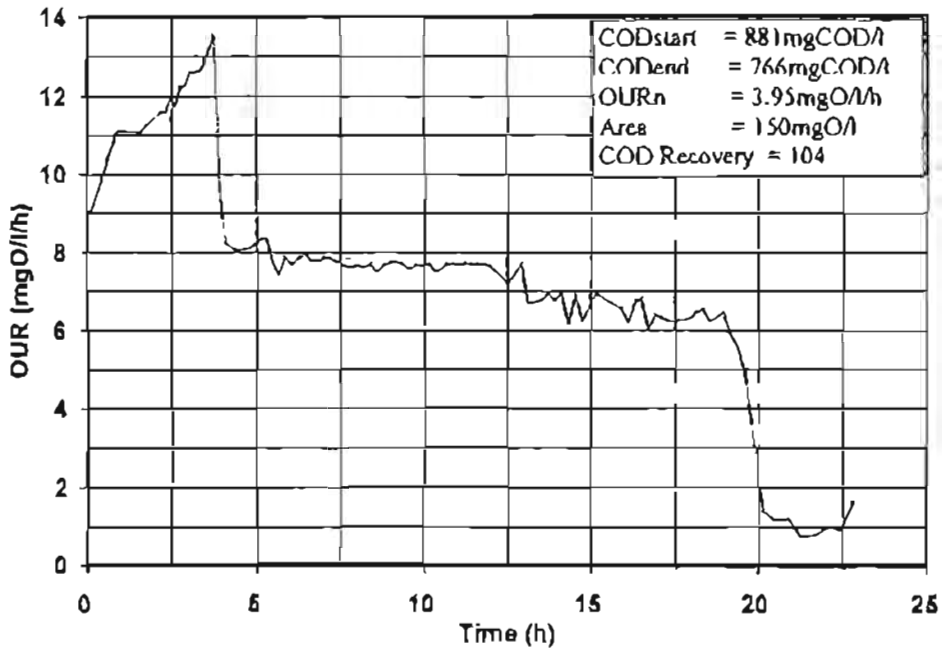


Fig B57a OUR graph for wastewater plus mixed liquor batch test, 02-03, batch no. 20

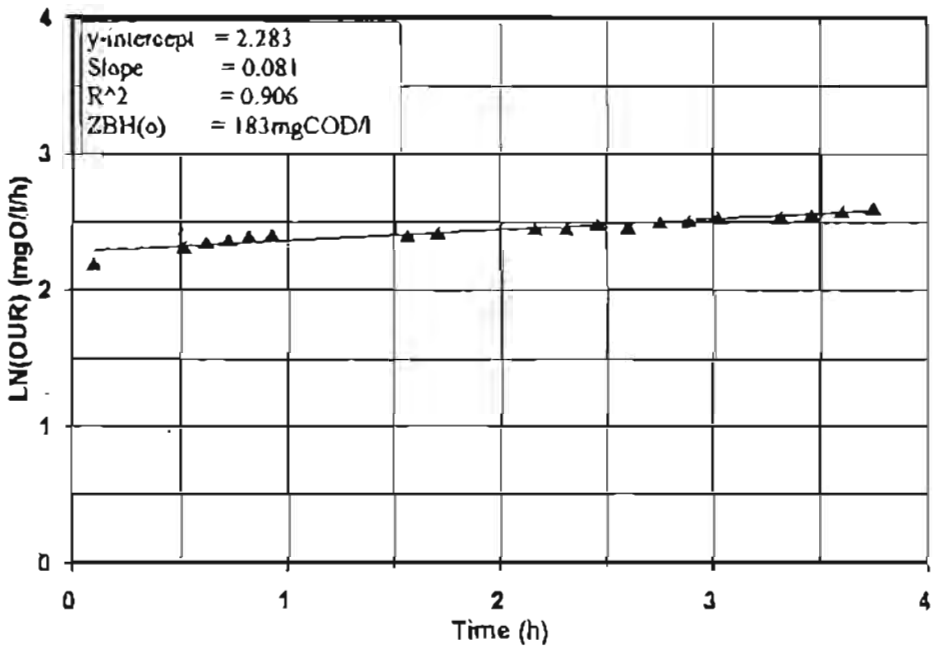


Fig B57b ln(OUR) graph for wastewater plus mixed liquor batch test, 02-03, batch no. 20

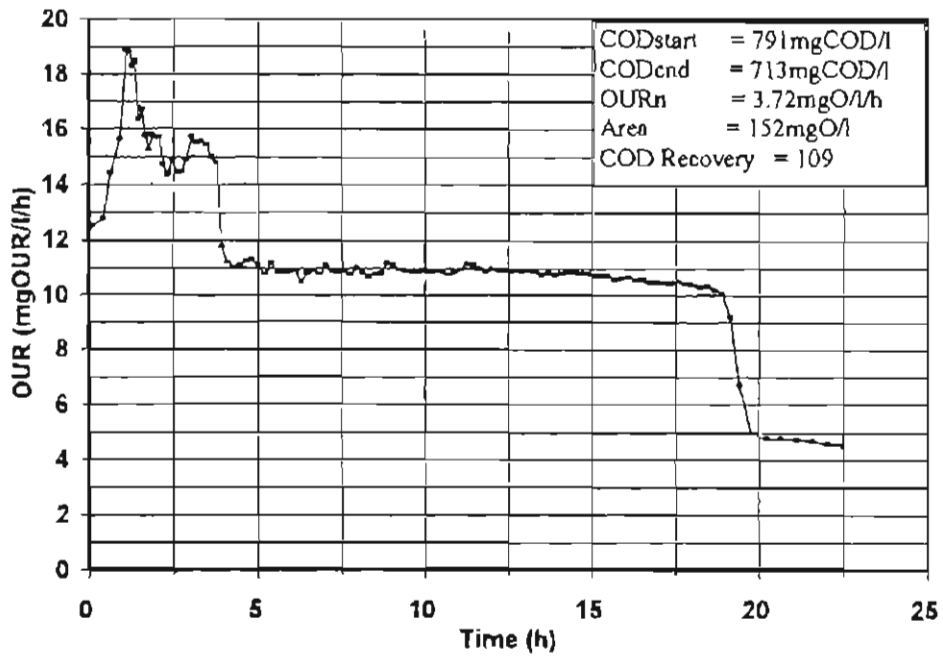


Fig B58a OUR graph for wastewater plus mixed liquor batch test, 03-03, batch no.20

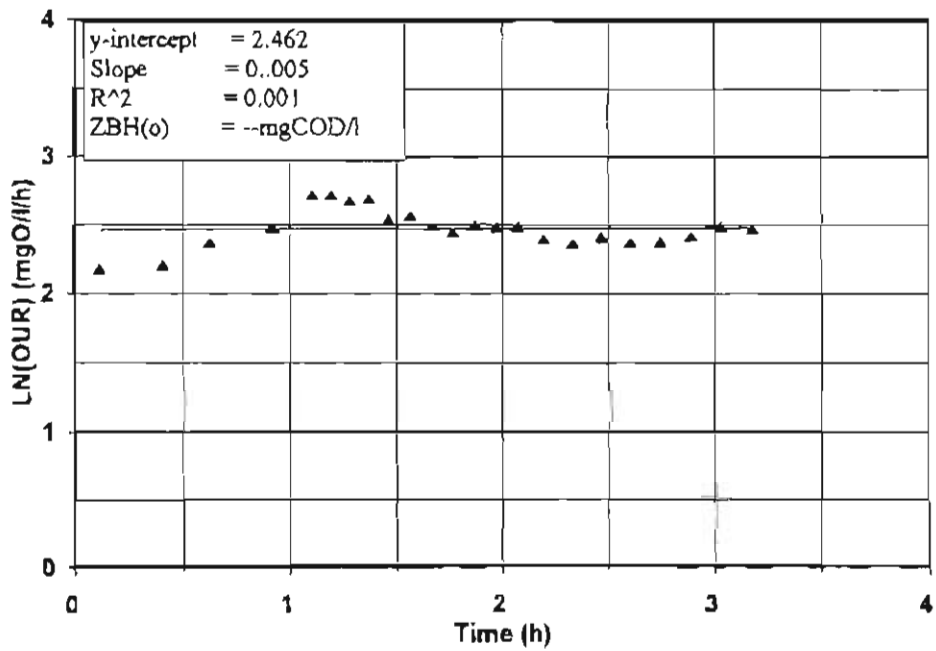


Fig B58b ln(OUR) graph for wastewater plus mixed liquor batch test, 03-03, batch no.20

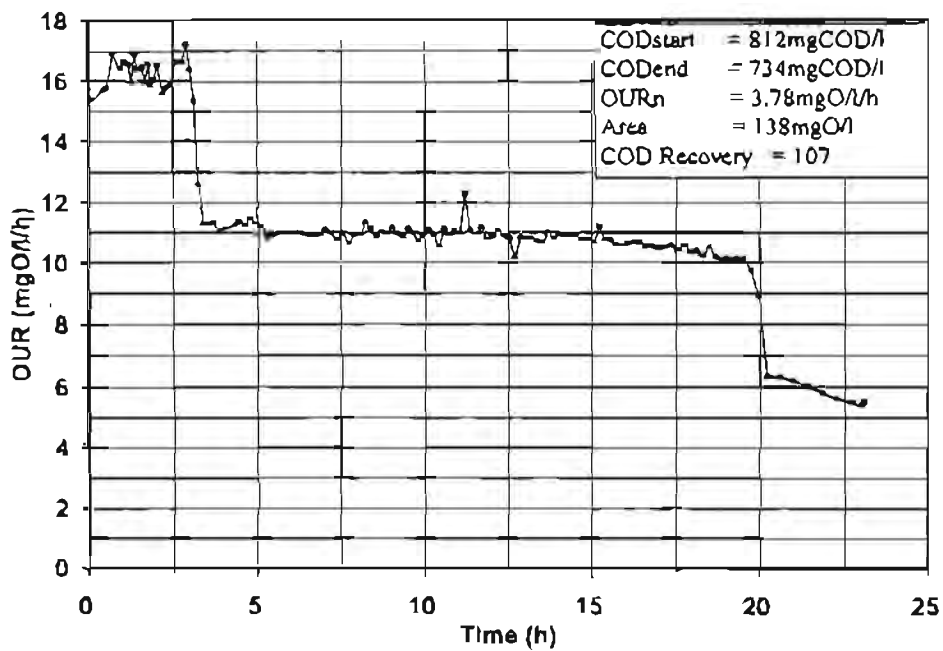


Fig B59a OUR graph for wastewater plus mixed liquor batch test, 04-03, batch no. 20

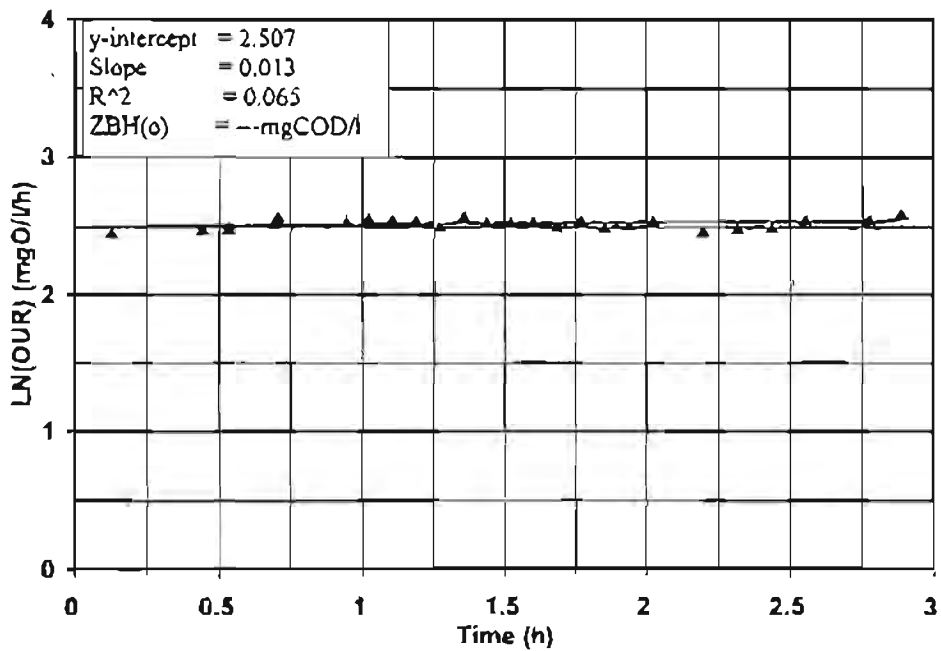


Fig B59b ln(OUR) graph for wastewater plus mixed liquor batch test, 04-03, batch no. 20

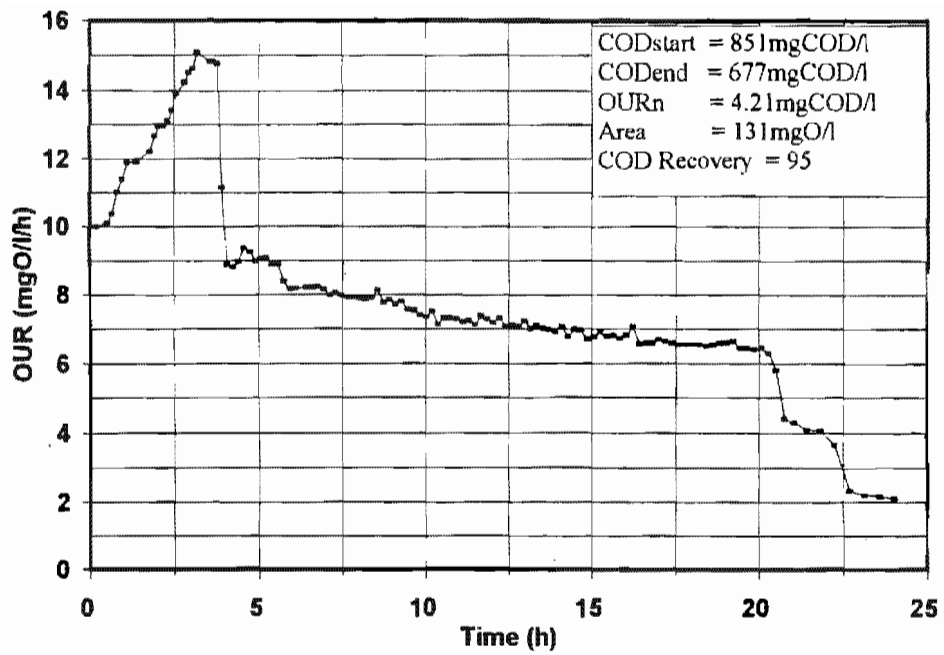


Fig B60a OUR graph for wastewater plus mixed liquor batch test, 11-03, batch no.21

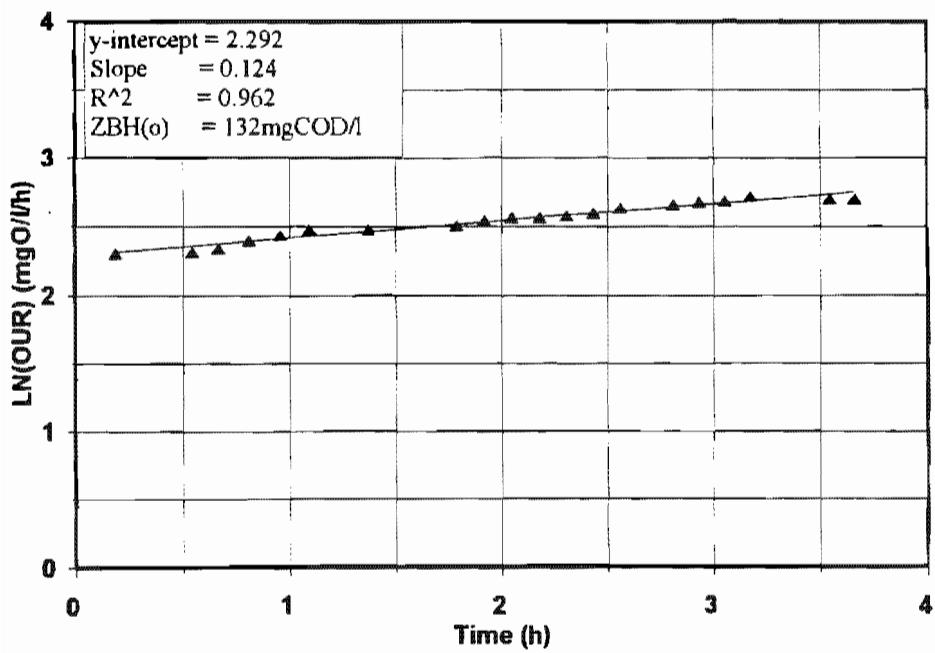


Fig B60b ln(OUR) graph for wastewater plus mixed liquor batch test, 11-03, batch n0.21

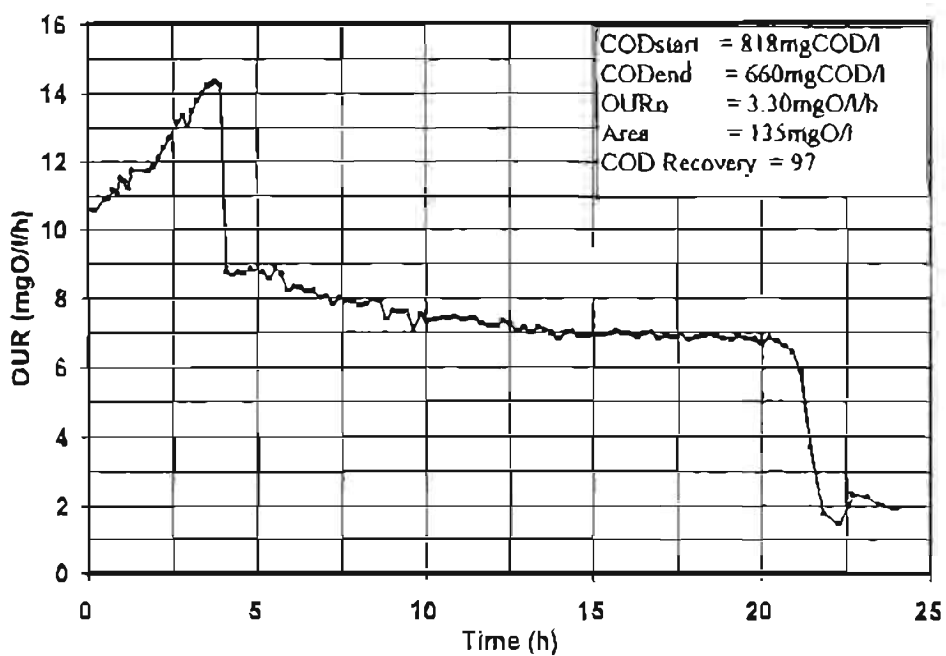


Fig B6 1a OUR graph for wastewater plus mixed liquor batch test, 12-03, batch no. 22

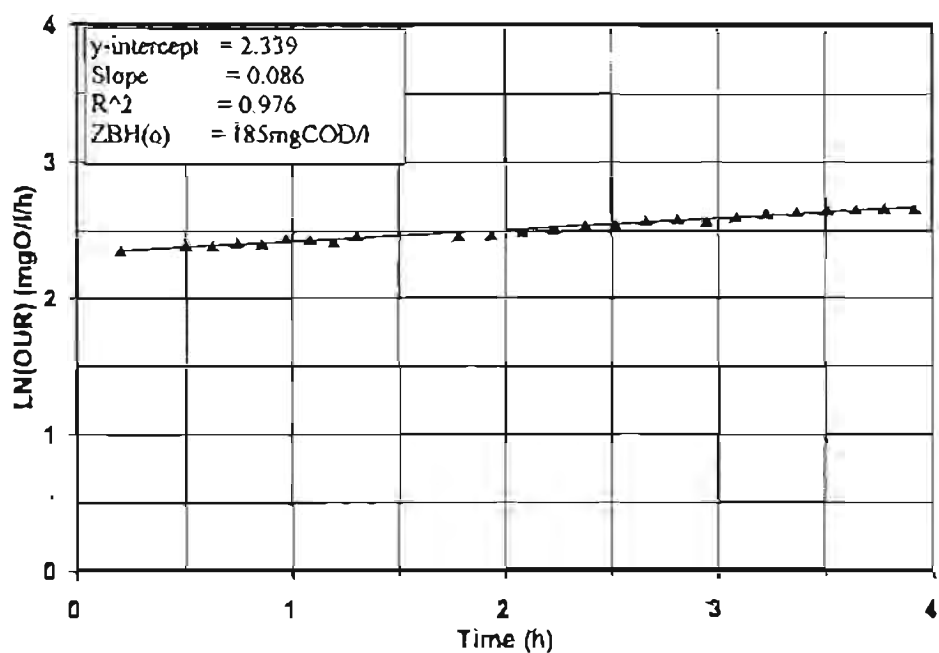


Fig B6 1b Ln(OUR) graph for wastewater plus mixed liquor batch test, 12-03, batch no. 21

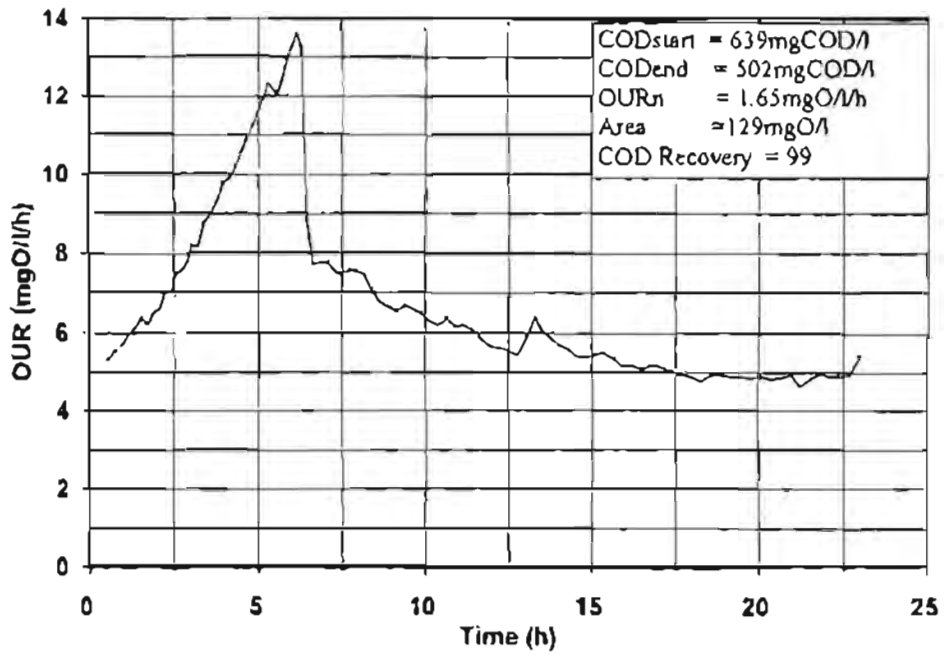


Fig B62a OUR graph for wastewater plus mixed liquor batch test, 14-03, batch no.21

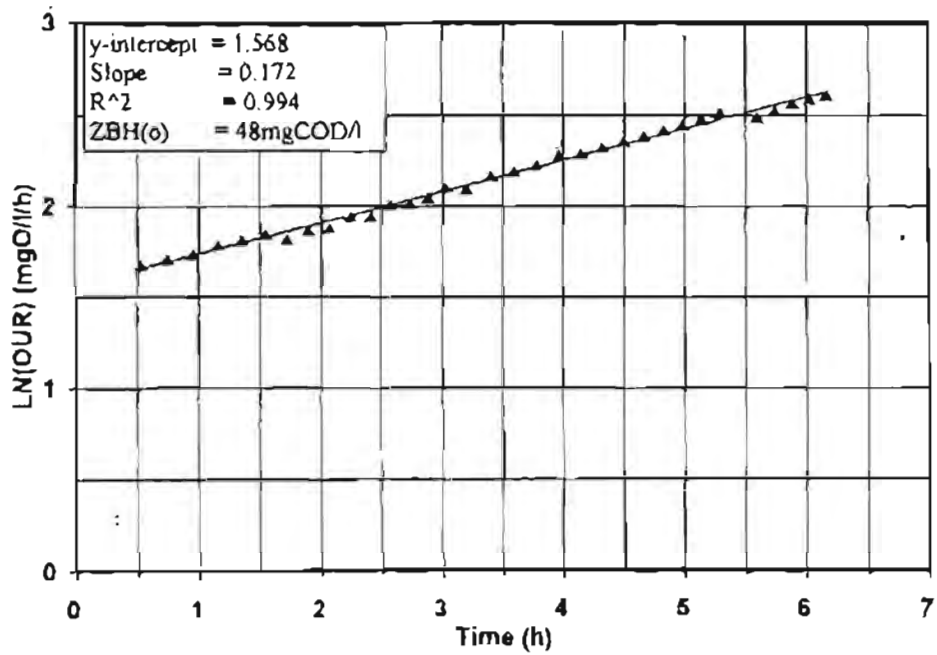


Fig B62b ln(OUR) graph for wastewater plus mixed liquor batch test, 14-03, batch no. 21

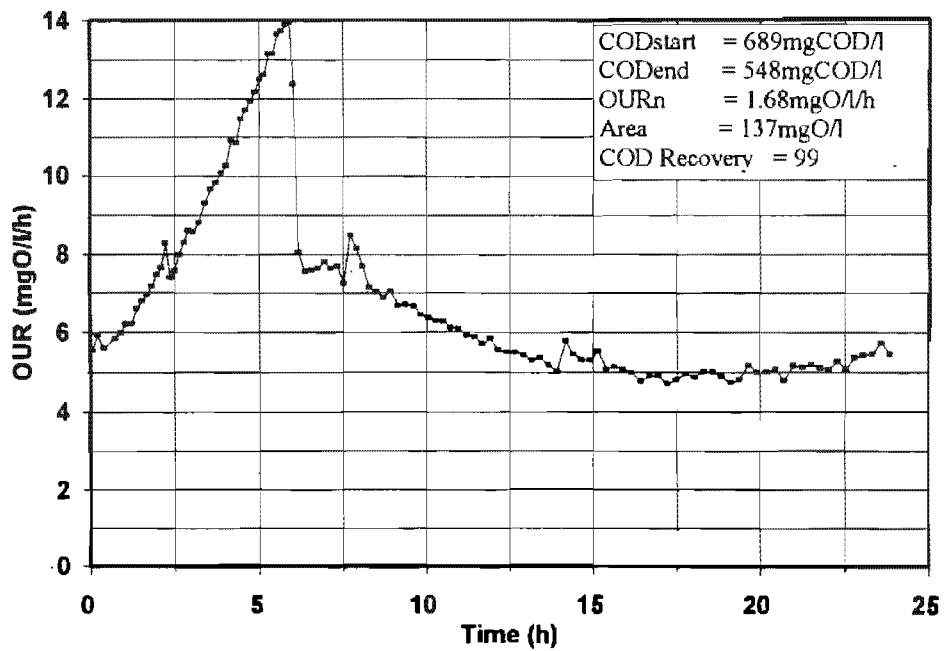


Fig B63a OUR graph for wastewater plus mixed liquor batch test, 15-03, batch no.21

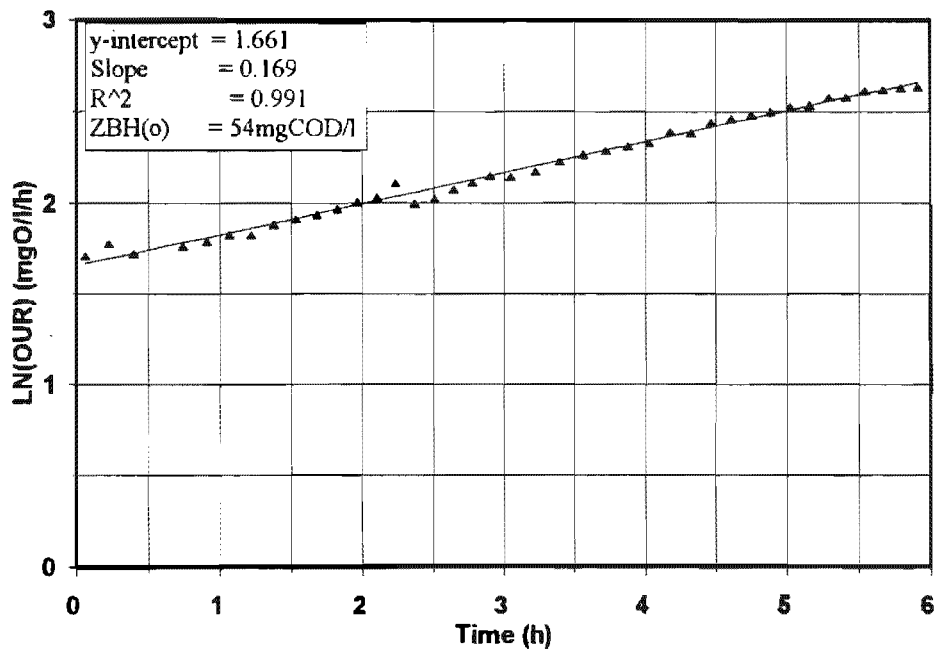


Fig B63b ln(OUR) graph for wastewater plus mixed liquor batch test, 15-03, batch no.21

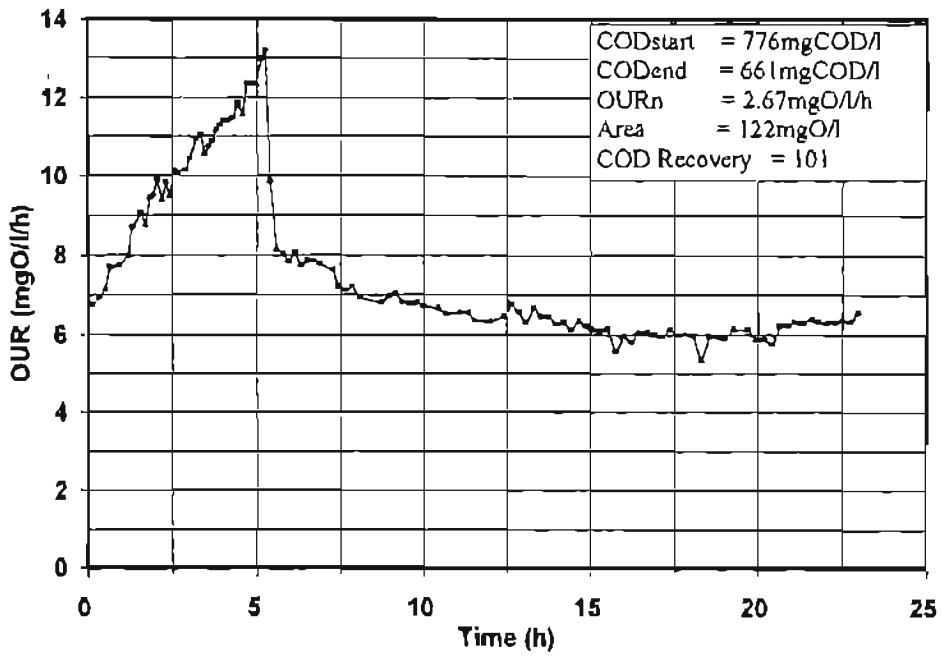


Fig B64a OUR graph for wastewater plus mixed liquor batch test, 17-01, batch no.21

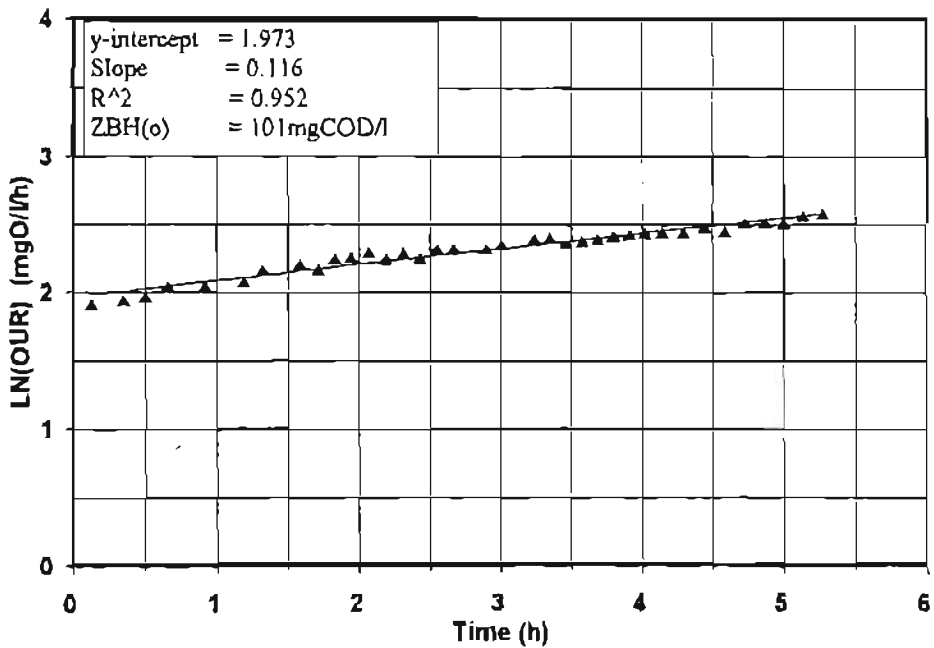


Fig B64b ln(OUR) graph for wastewater plus mixed liquor batch test, 17-03, batch no.21

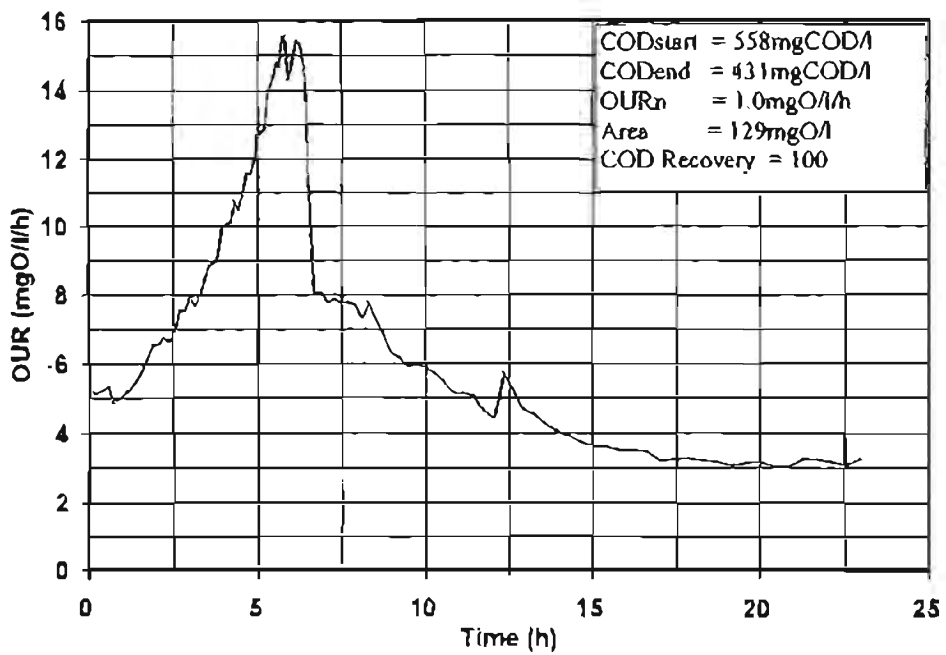


Fig B65a OUR graph for wastewater plus mixed liquor batch test, 18-03, batch no. 21

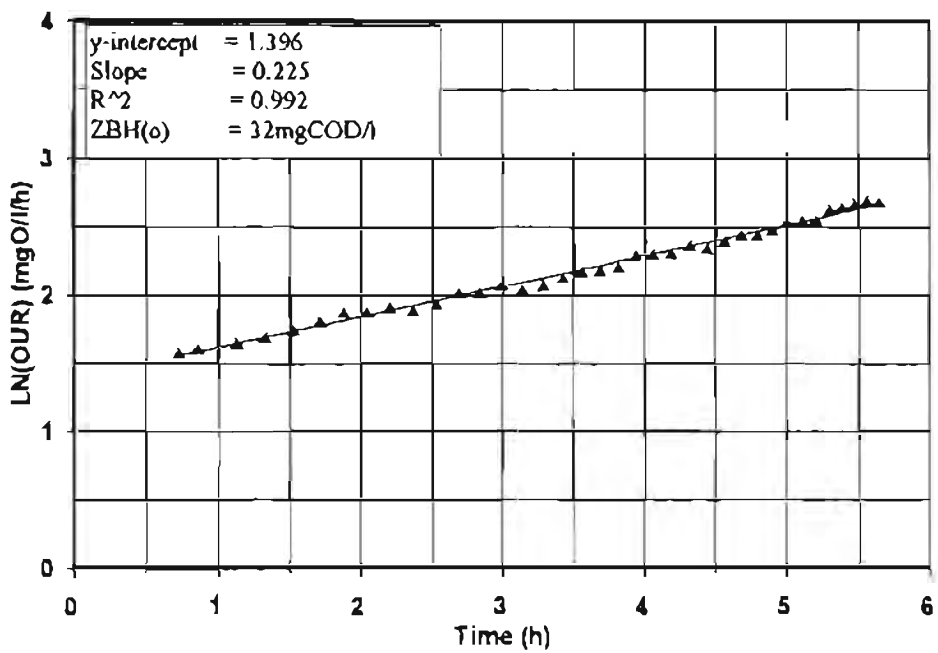


Fig B65b Ln(OUR) graph for wastewater plus mixed liquor batch test, 18-03, batch no. 21

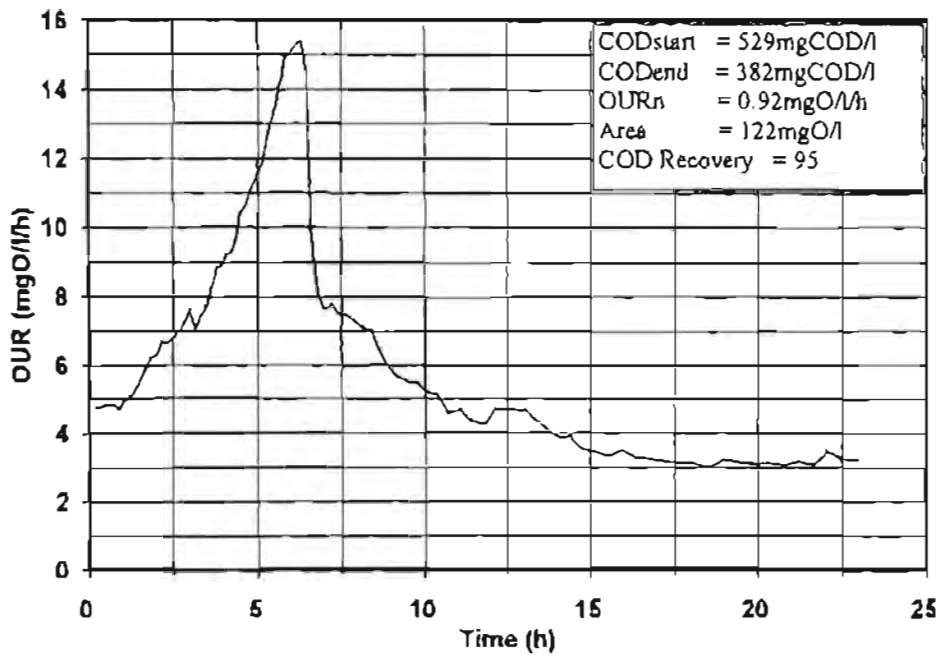


Fig a66a OUR graph for wastewater plus mixed liquor batch test, 19-03, batch no. 21

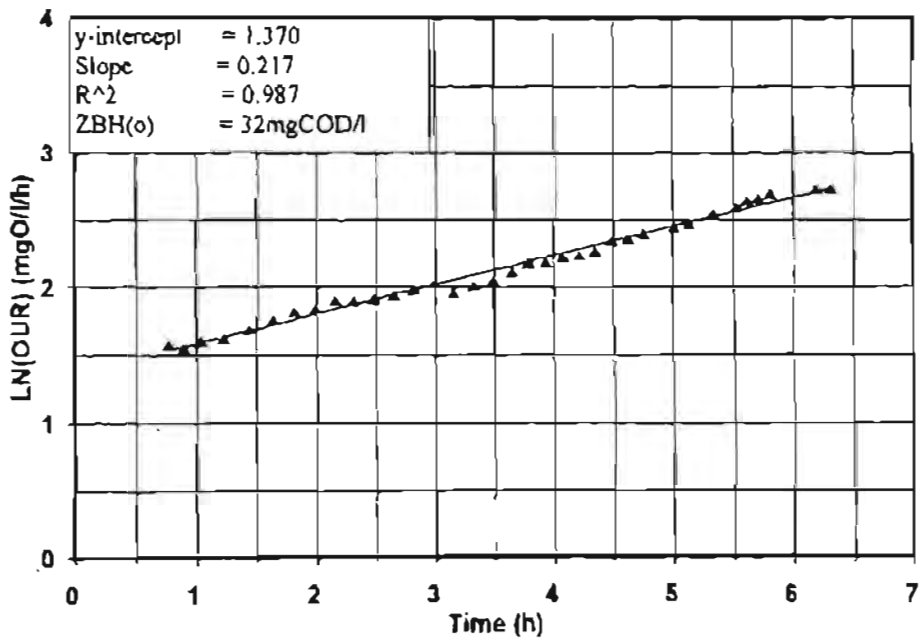


Fig B66b Ln(OUR) graph for wastewater plus mixed liquor batch test, 19-03, batch no. 21

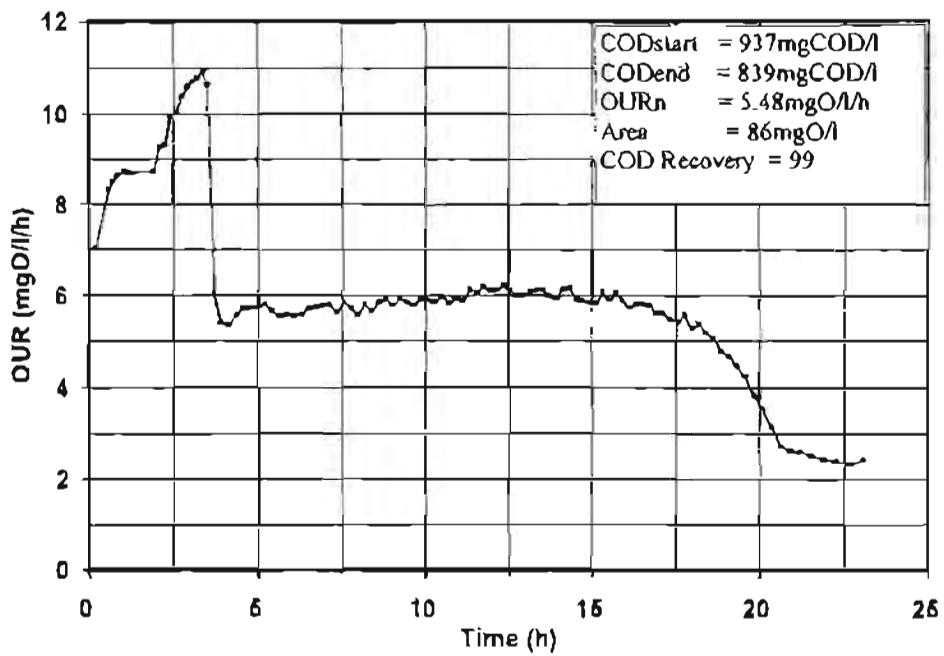


Fig B67a OUR graph for wastewater plus mixed liquor batch test, 06-04, batch no. 22

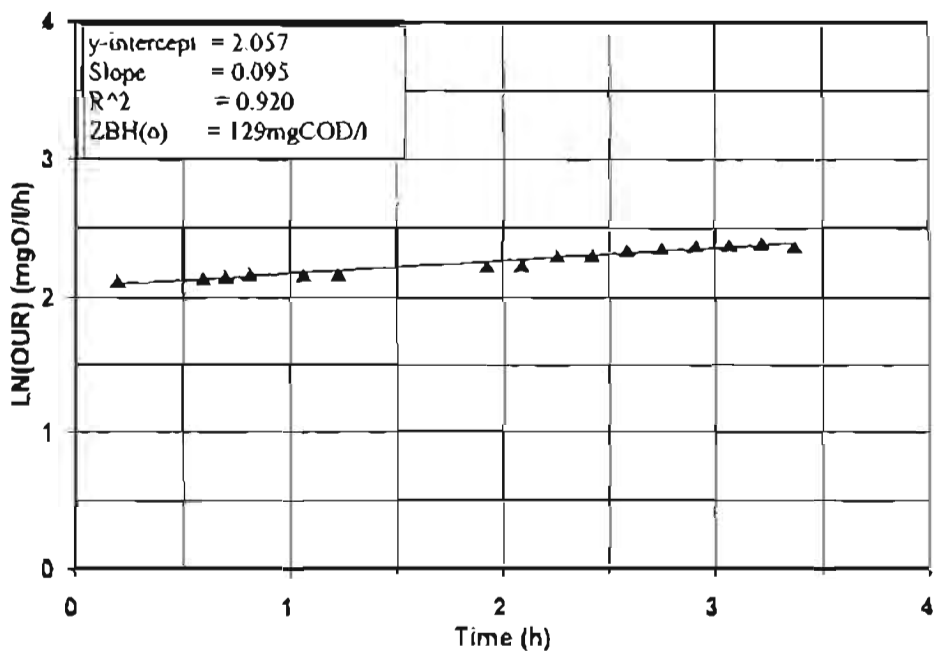


Fig B67b ln(OUR) graph for wastewater plus mixed liquor batch test, 06-04, batch no. 22

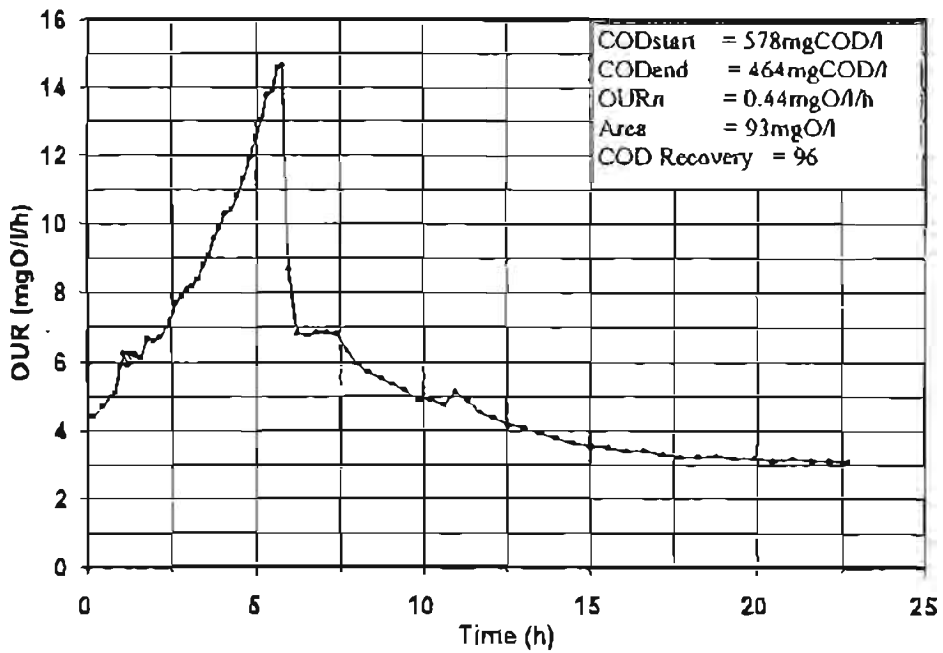


Fig B68a OUR graph for wastewater plus mixed liquor batch test, 07-04, batch no. 22

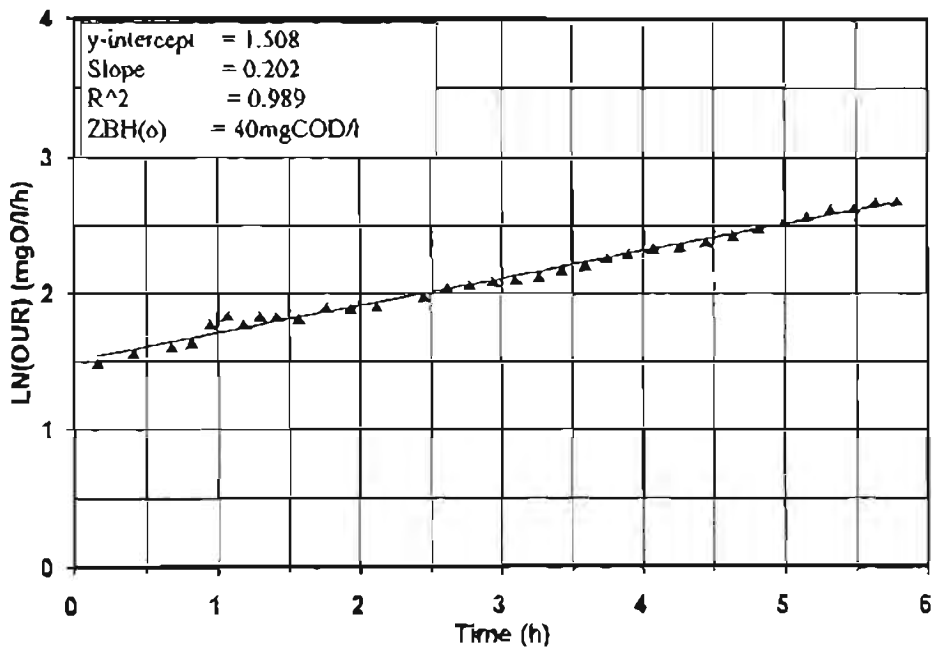


Fig B68b ln(OUR) graph for wastewater plus mixed liquor batch test, 07-04, batch no. 22

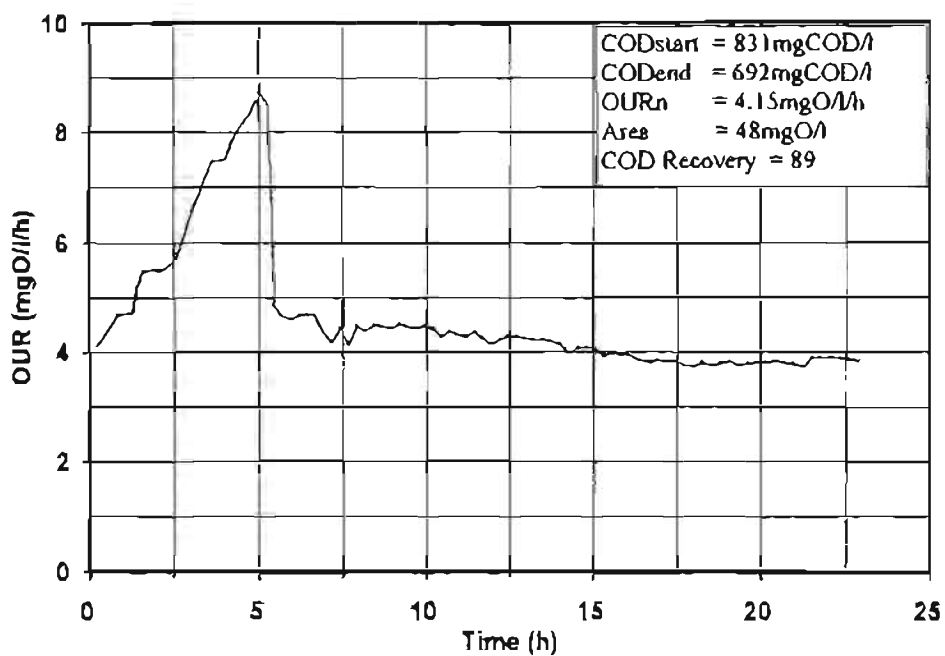


Fig B69a OUR graph for wastewater plus mixed liquor batch test, 08-04, batch no. 22

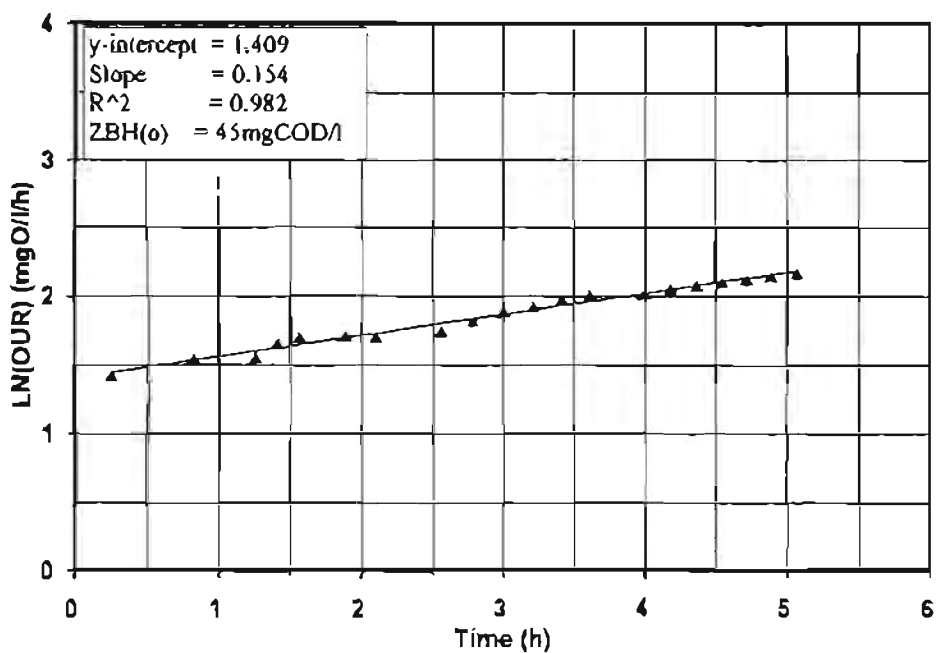


Fig B69b ln(OUR) graph for wastewater plus mixed liquor batch test, 08-04, batch no. 22

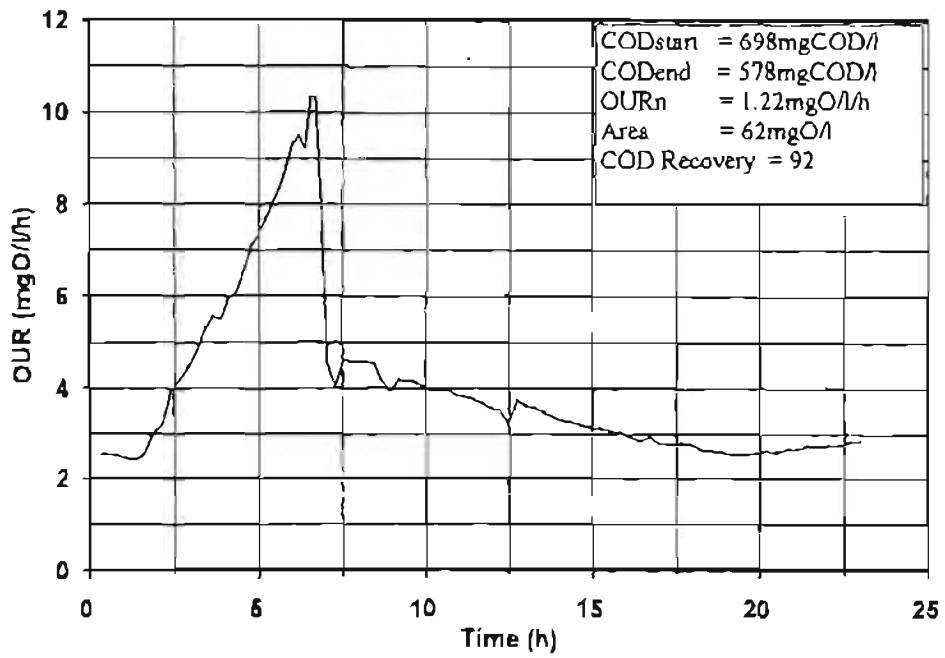


Fig B70a OUR graph for wastewater plus mixed liquor batch test, 09-04, batch no. 22

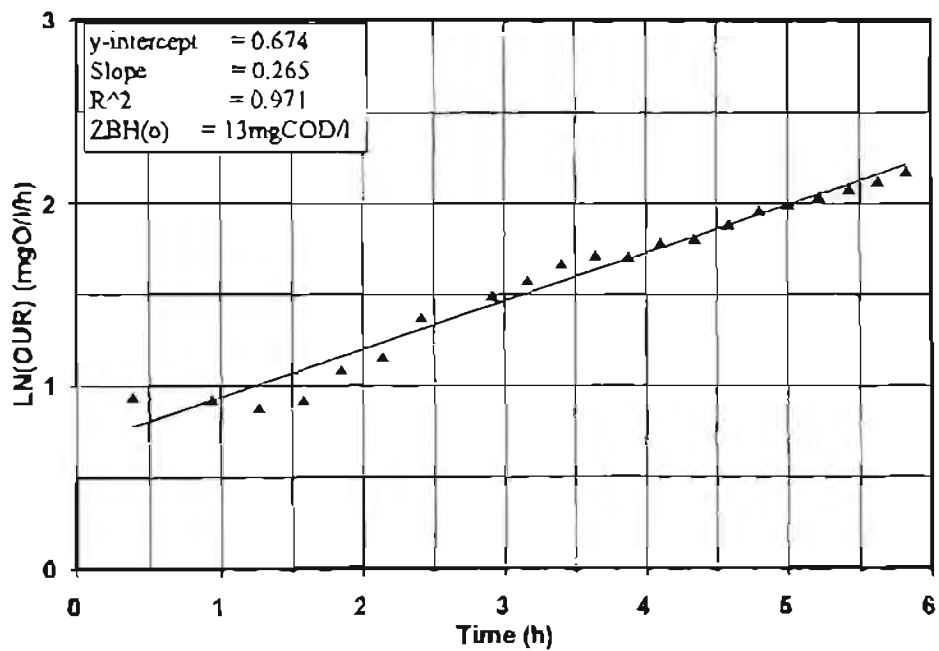


Fig B70 ln(OUR) graph for wastewater plus mixed liquor batch test, 09-04, batch no. 22

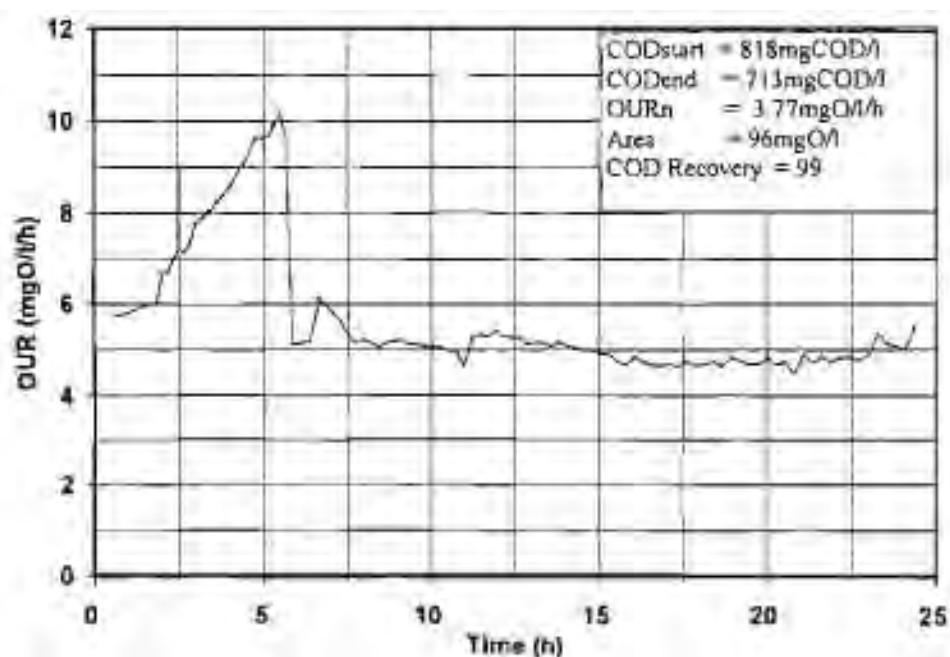


Fig B71a OUR graph for wastewater plus mixed liquor batch test, 10-04, batch no 22

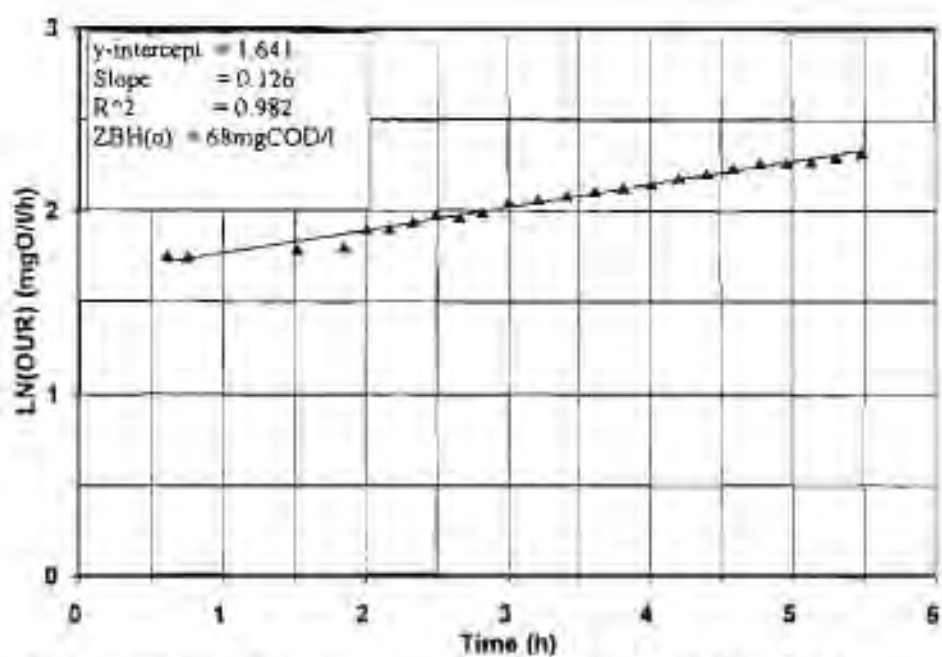


Fig B71b ln(OUR) graph for wastewater plus mixed liquor batch test, 10-04, batch no 22

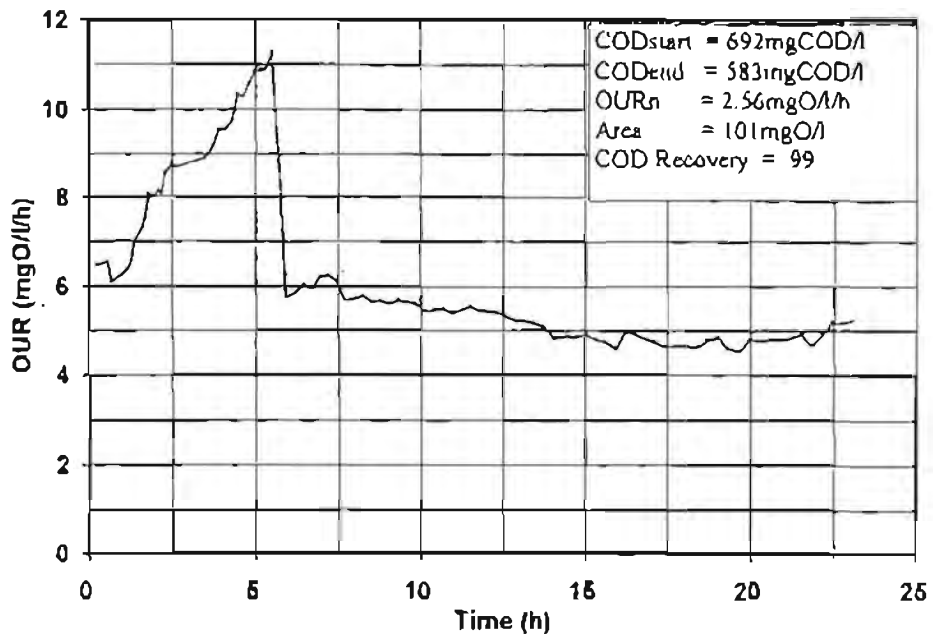


Fig B72a OUR graph for wastewater plus mixed liquor batch test, 11-04, batch no. 22

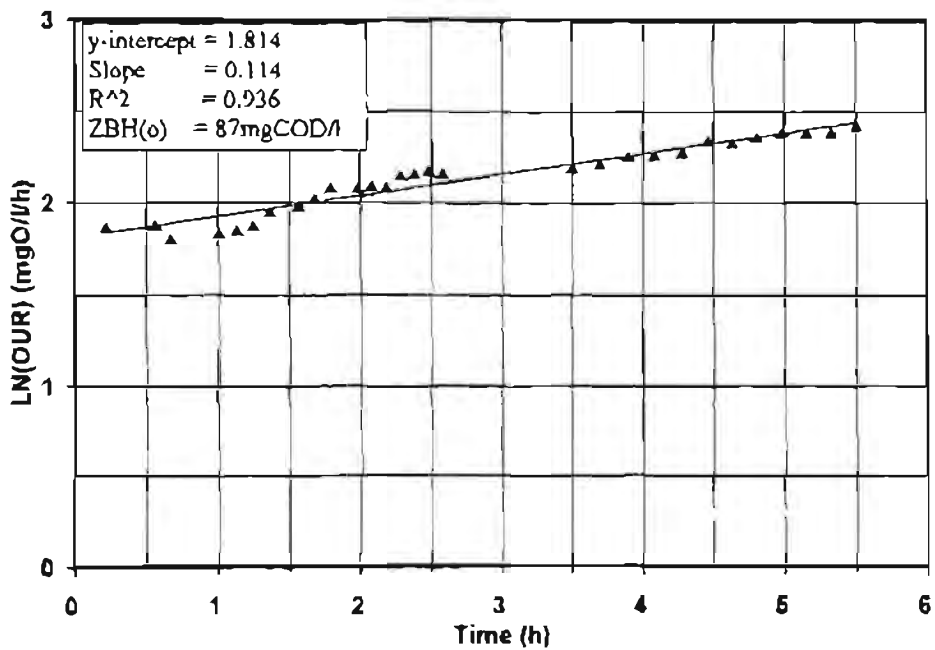


Fig B72b ln(OUR) graph for wastewater plus mixed liquor batch test, 11-04, batch no. 22

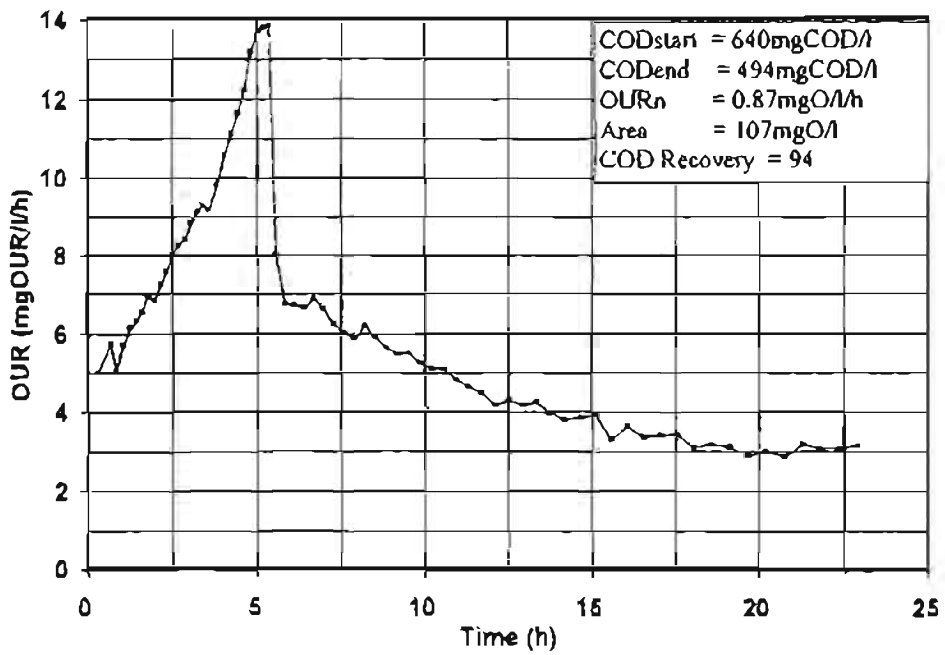


Fig B73a OUR graph for wastewater plus mixed liquor batch test, 15-04, batch no.23

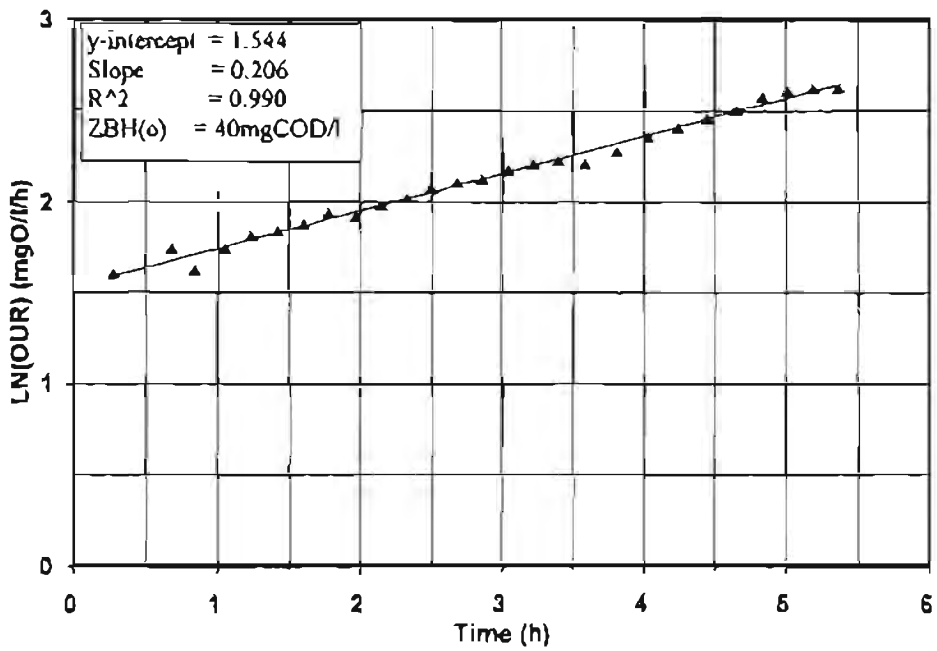


Fig B73b Ln(OUR) graph for wastewater plus mixed liquor batch test, 15-04, batch no. 23

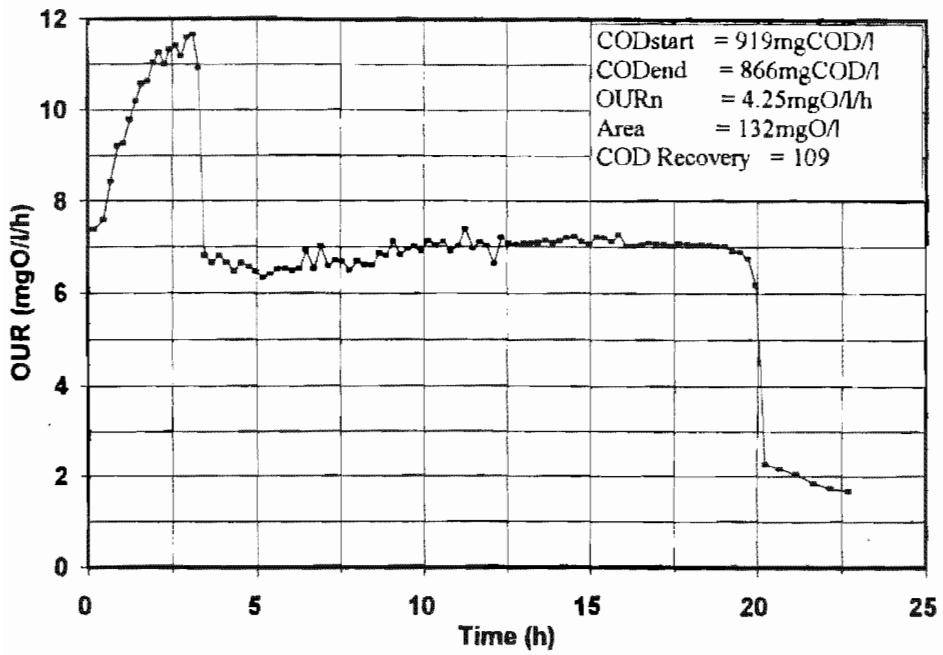


Fig B74a OUR graph for wastewater plus mixed liquor batch test, 16-04, batch no.23

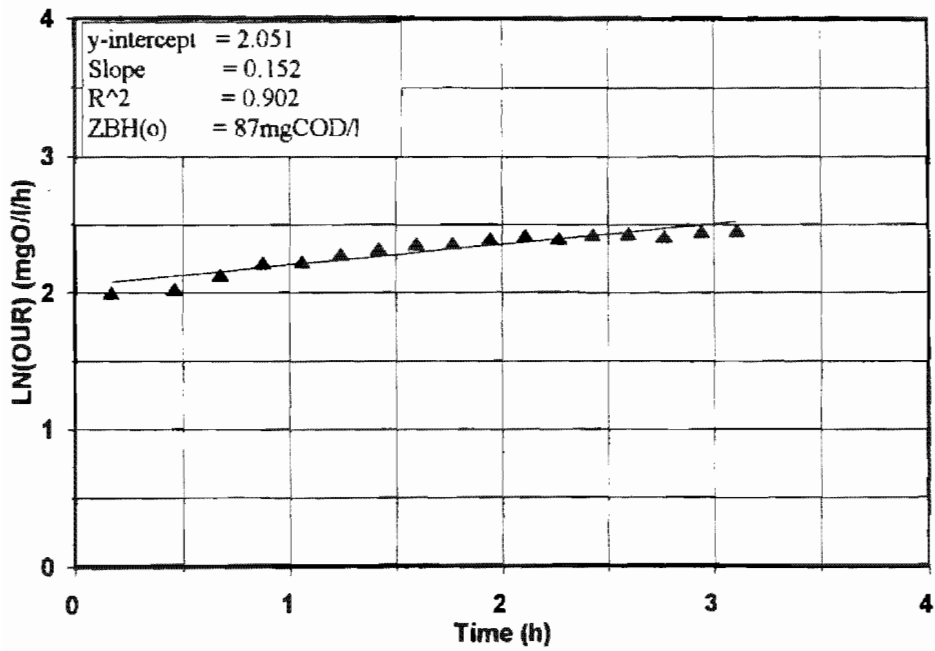


Fig B74b ln(OUR) graph for wastewater plus mixed liquor batch test, 16-04, batch no. 23

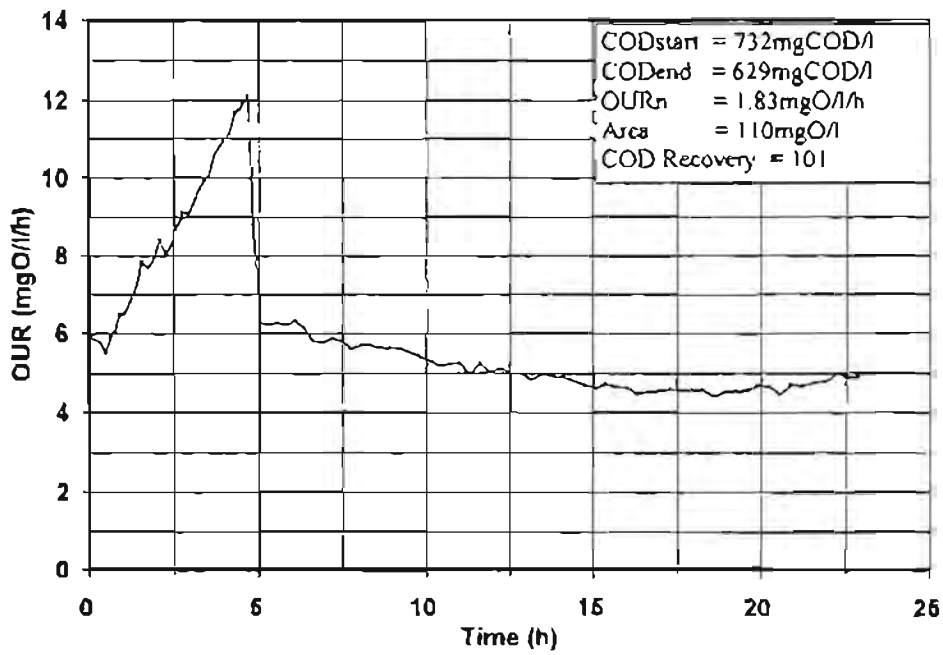


Fig B75a OUR graph for wastewater plus mixed liquor batch test, 17-04, batch no. 23

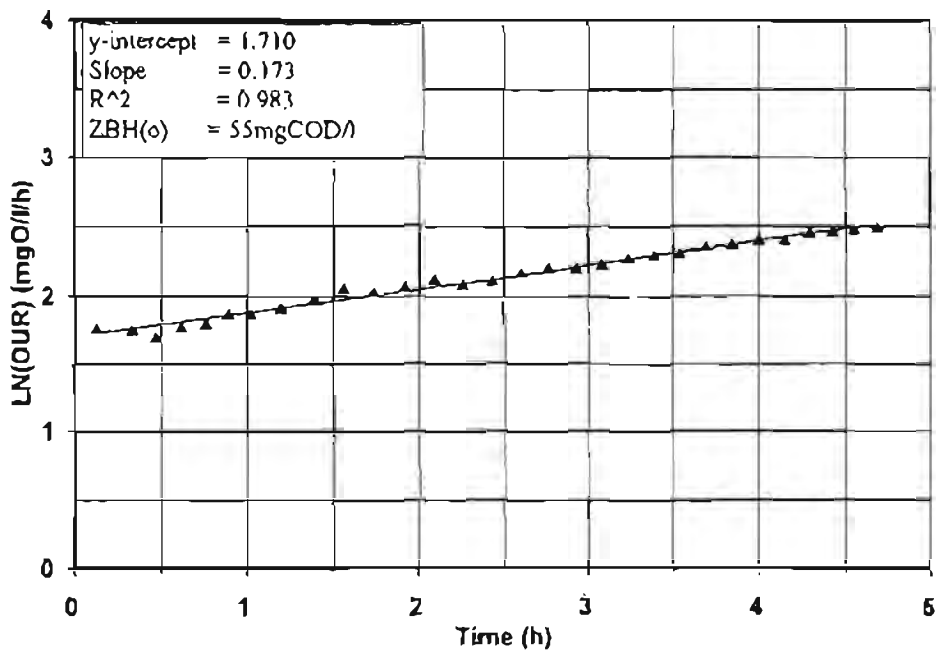


Fig B75b ln(OUR) graph for wastewater plus mixed liquor batch test, 17-04, batch no. 23

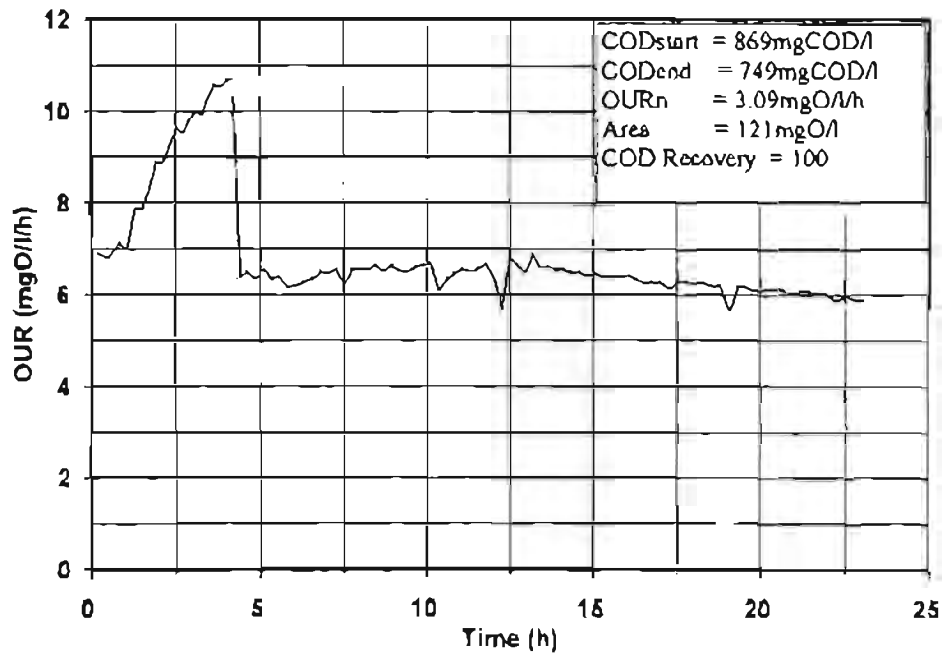


Fig B76a OUR graph for wastewater plus mixed liquor batch test, 18-04, batch no. 23

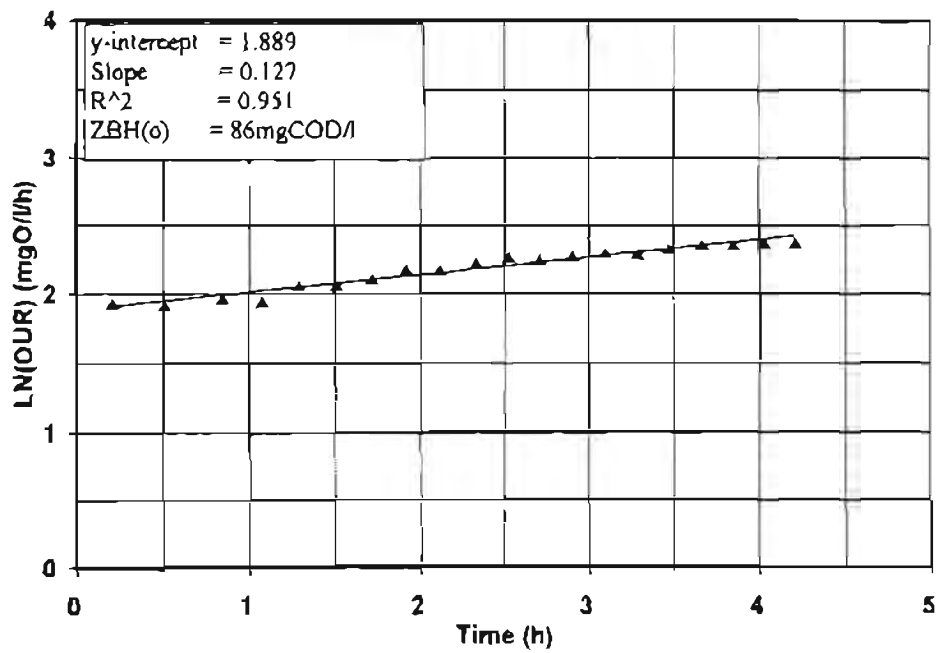


Fig B76b Ln(OUR) graph for wastewater plus mixed liquor batch test, 18-04, batch no. 23

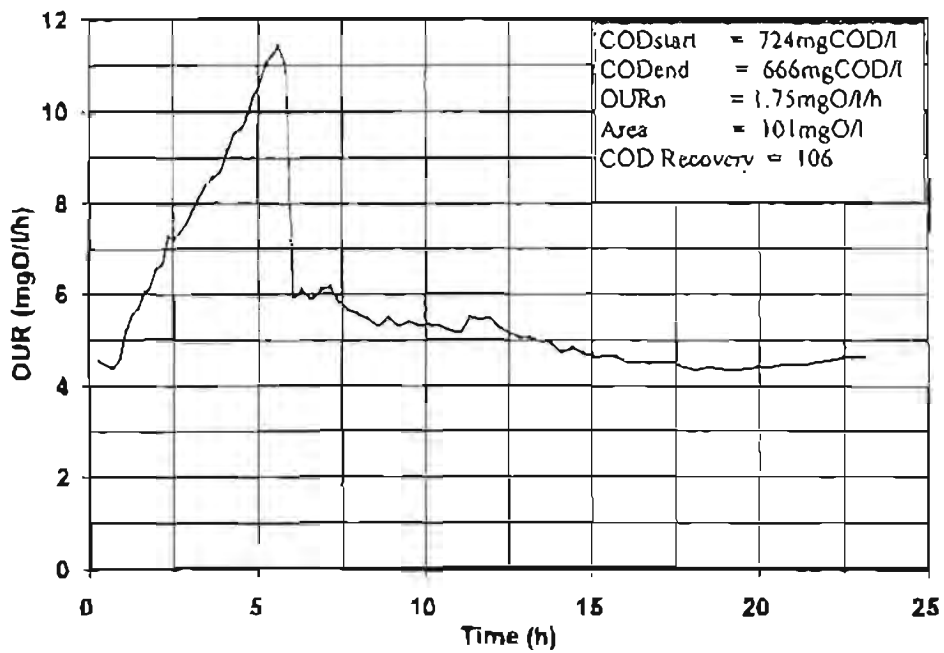


Fig B77a OUR graph for wastewater plus mixed liquor batch test, 19-04, batch no. 23

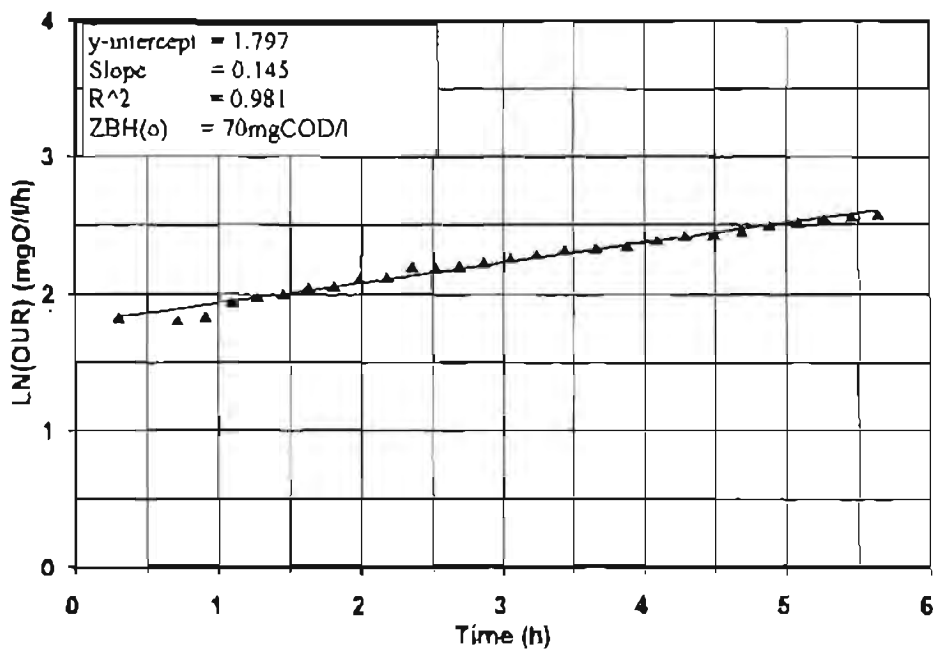


Fig B77b Ln(OUR) graph for wastewater plus mixed liquor batch test, 19-04, batch no. 23

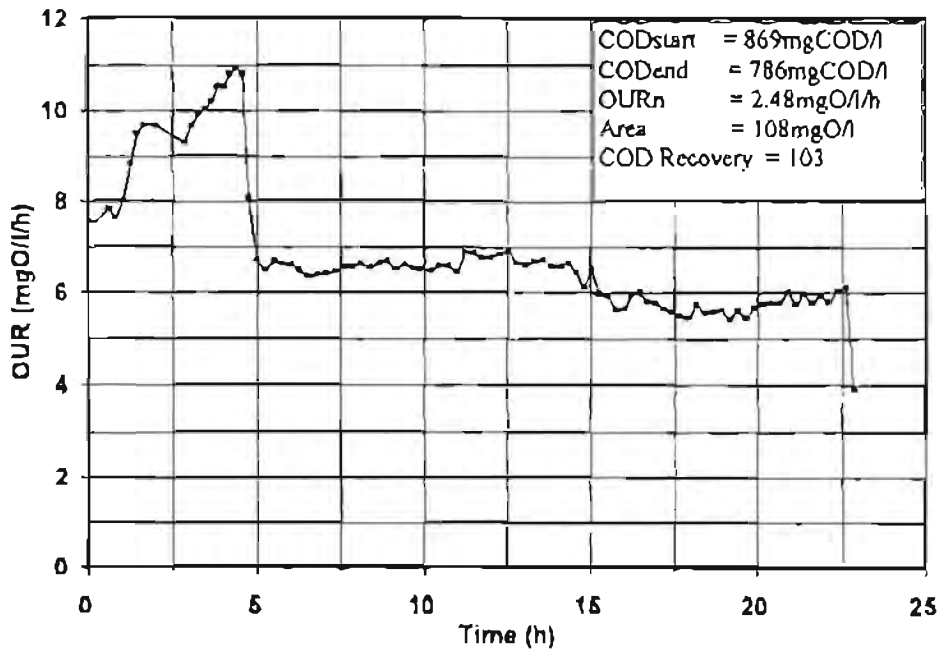


Fig B78a OUR graph for wastewater plus mixed liquor batch test, 20-04, batch no. 23

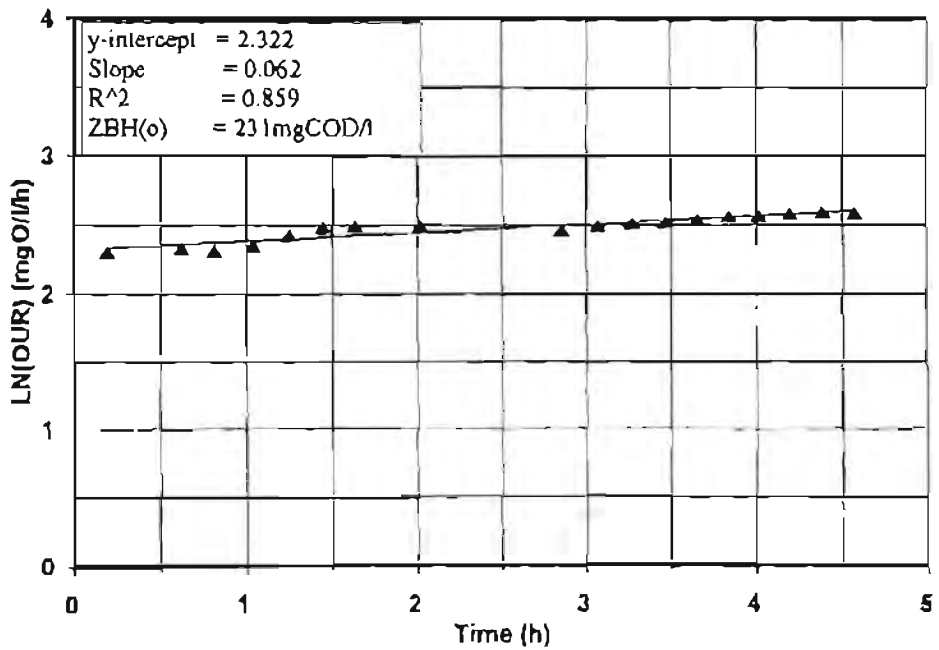


Fig B78b LN(OUR) graph for wastewater plus mixed liquor batch test, 20-04, batch no. 23

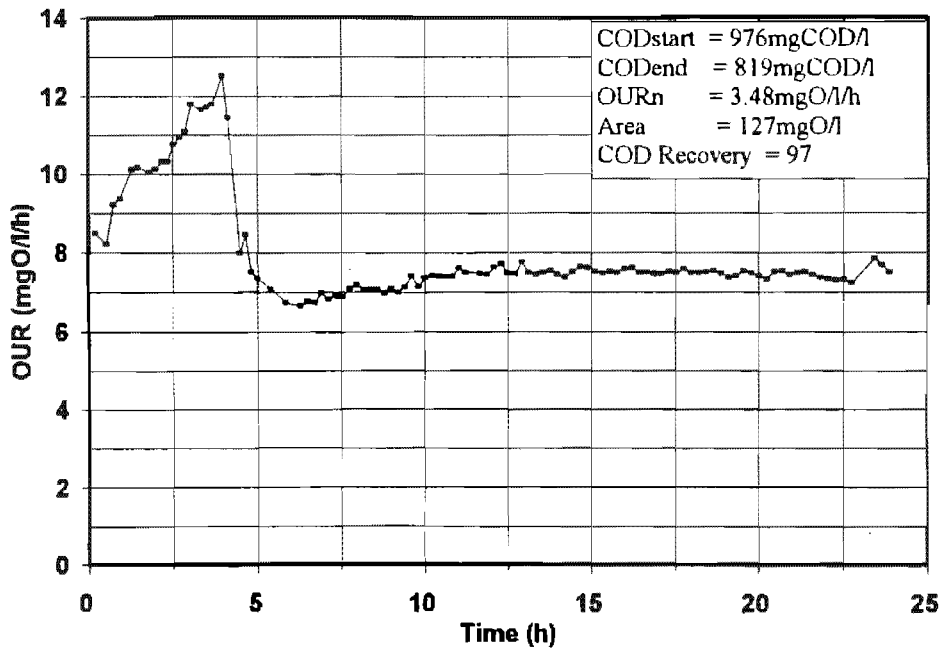


Fig B79a OUR graph for wastewater plus mixed liquor batch test, 21-04, batch no. 23

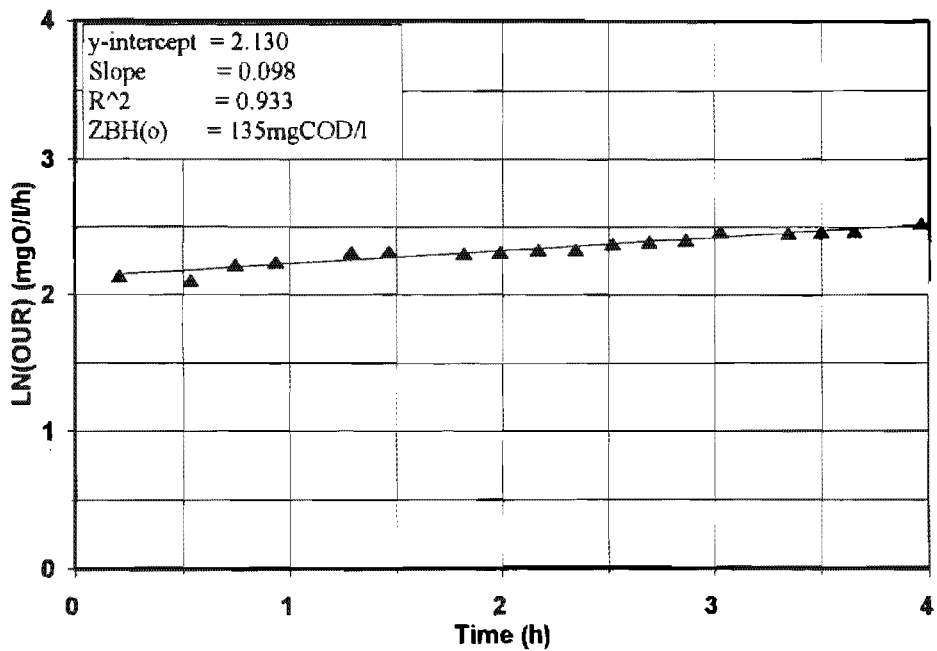


Fig B79b ln(OUR) graph for wastewater plus mixed liquor batch test, 21-04, batch no. 23

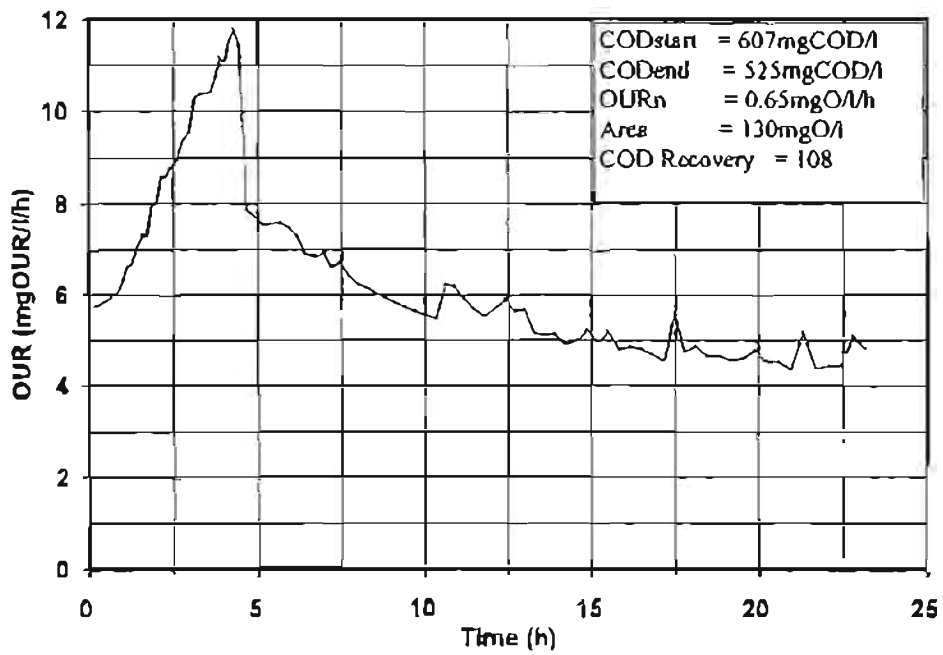


Fig B80a OUR graph for wastewater plus mixed liquor batch test, 22-04, batch no. 23

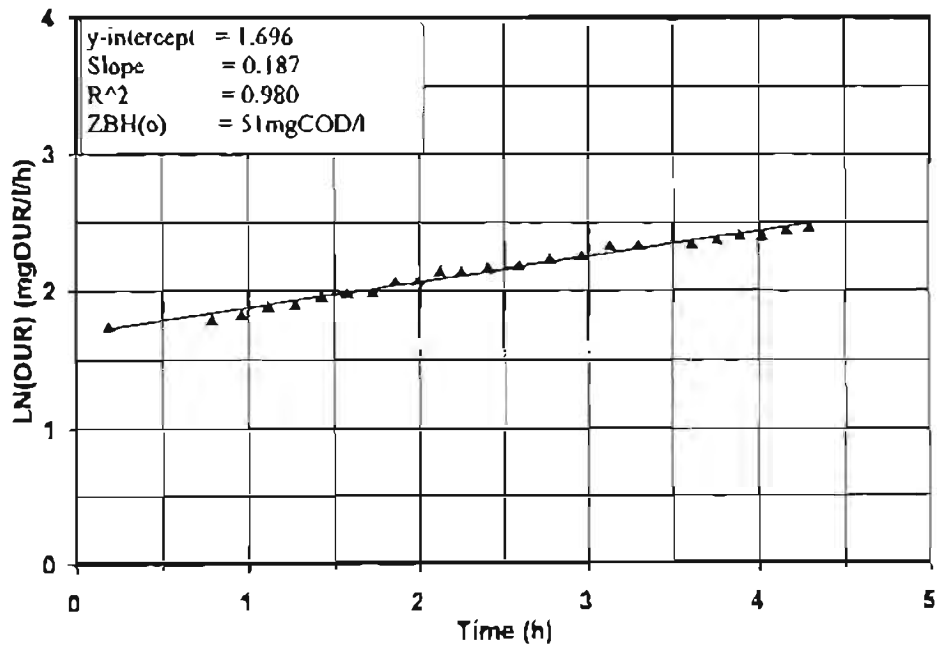


Fig B80b ln(OUR) graph for wastewater plus mixed liquor batch test, 22-04, batch no. 23

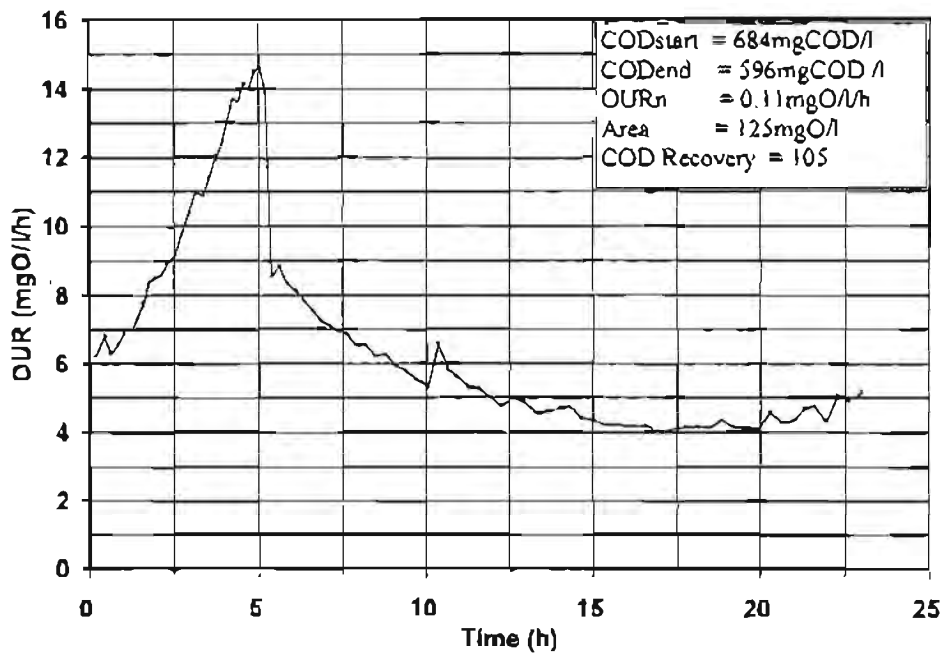


Fig B81a OUR graph for wastewater plus mixed liquor batch test, 29-04, batch no. 24

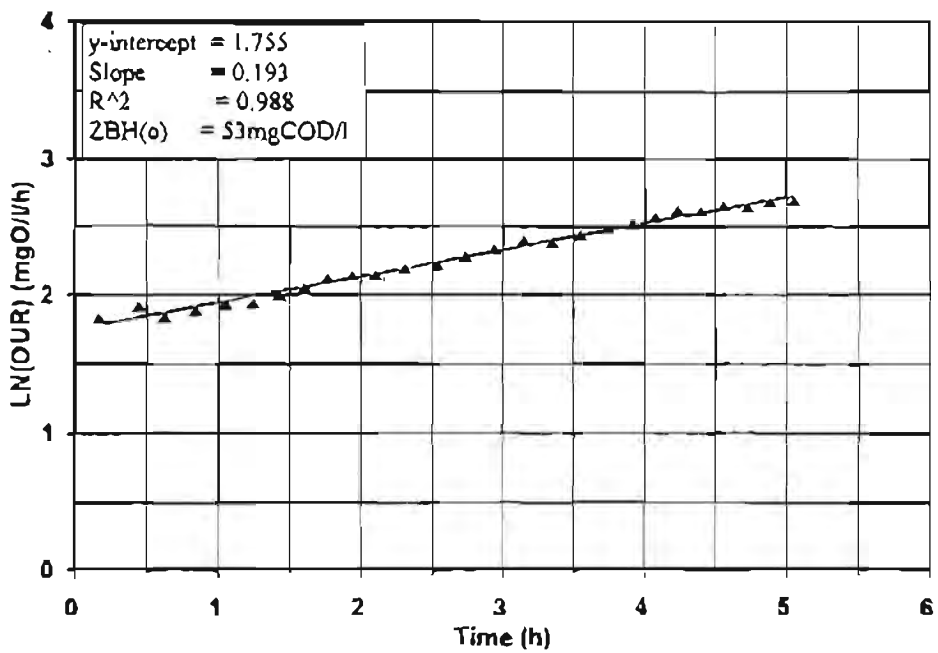


Fig B81b Ln(OUR) graph for wastewater plus mixed liquor batch test, 29-04, batch no. 24

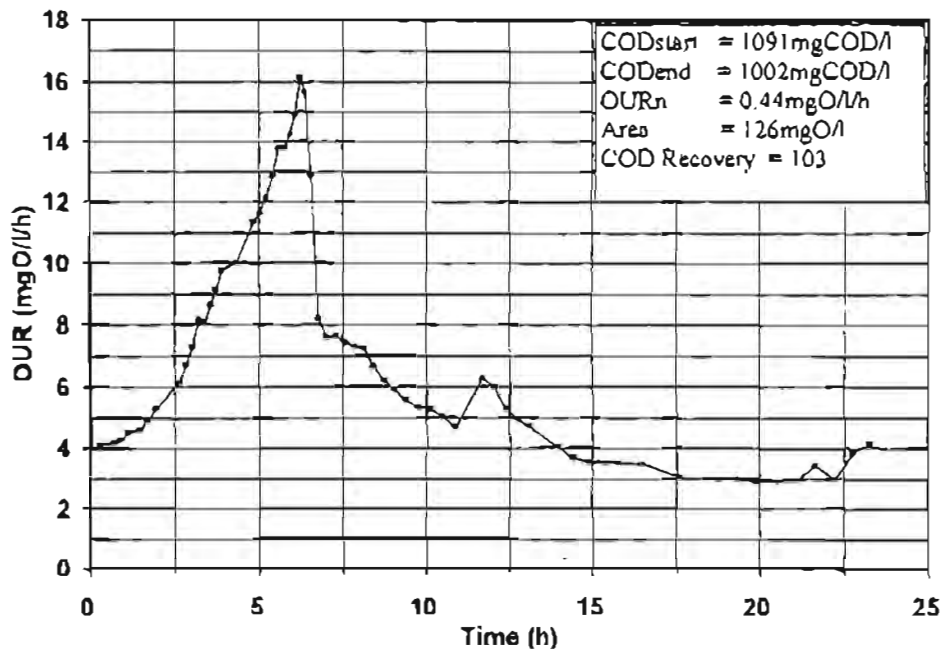


Fig B82a OUR graph for wastewater plus mixed liquor batch test, 30-04, batch no. 24

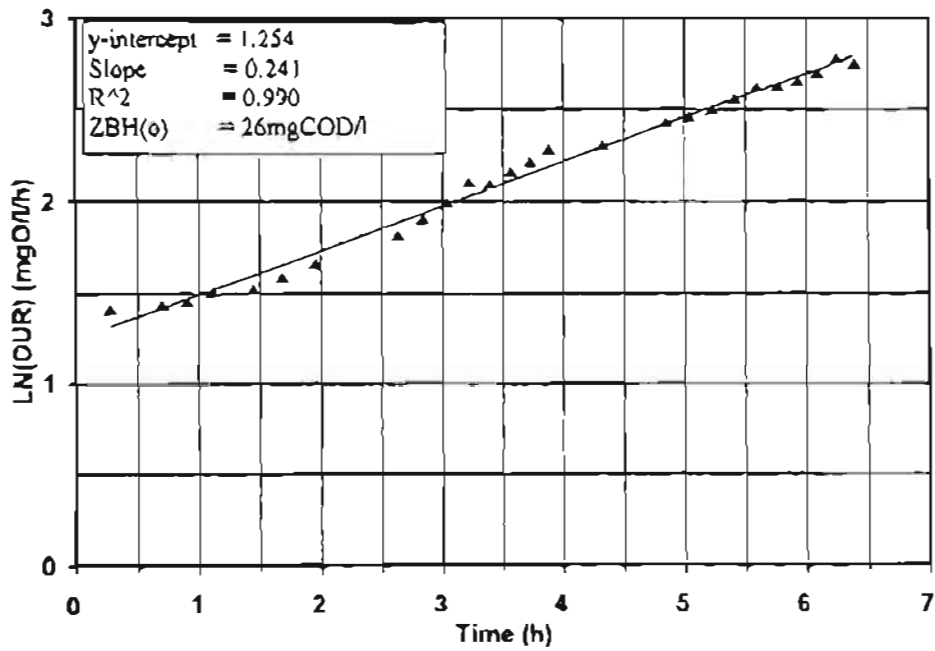


Fig B82b ln(OUR) graph for wastewater plus mixed liquor batch test, 30-04, batch no. 24

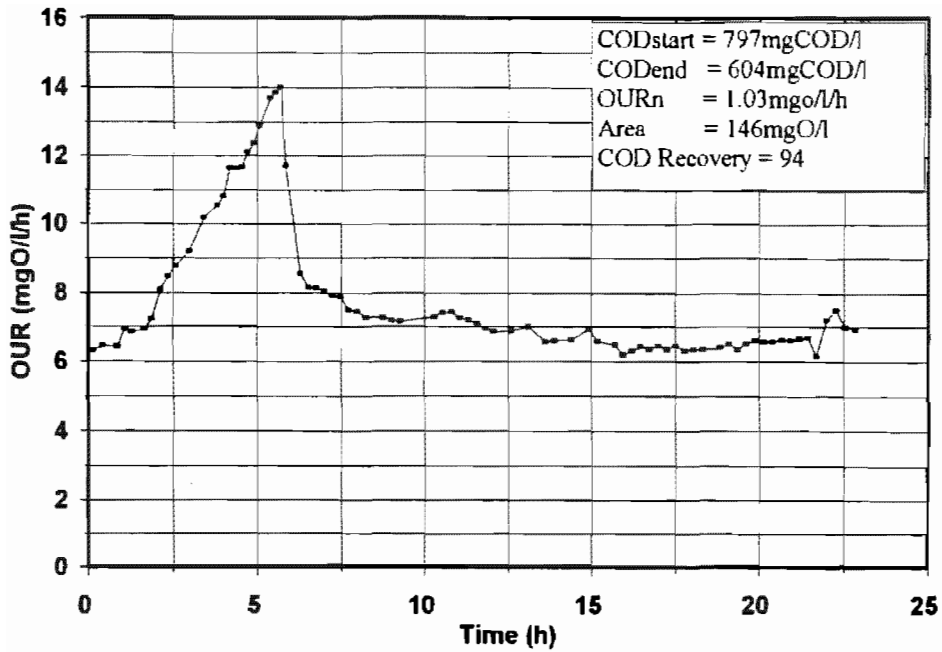


Fig B83a OUR graph for wastewater plus mixed liquor batch test,01-05, batch no.24

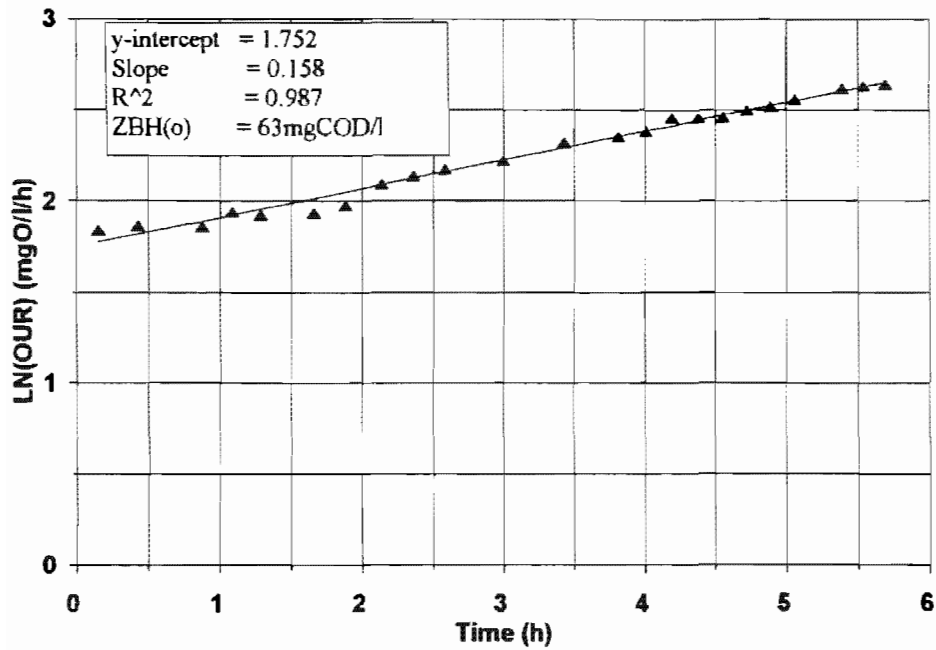


Fig B83b ln(OUR) graph for wastewater plus mixed liquor batch test, 01-05, batch no.24

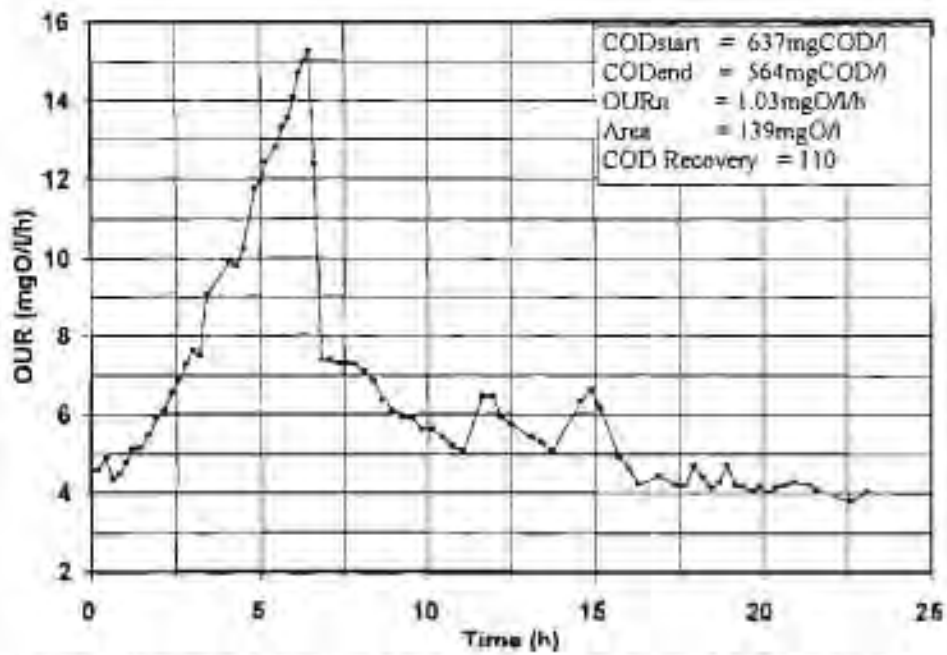


Fig B84a OUR graph for wastewater plus mixed liquor batch test, 02-05, batch no. 24

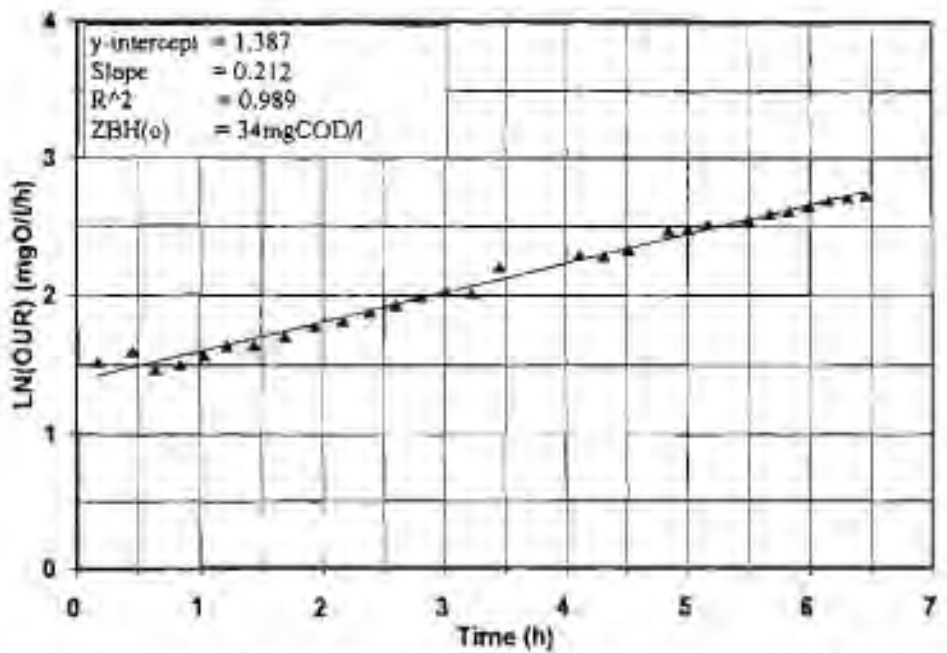


Fig B84b ln(OUR) graph for wastewater plus mixed liquor batch test, 02-05, batch no. 24

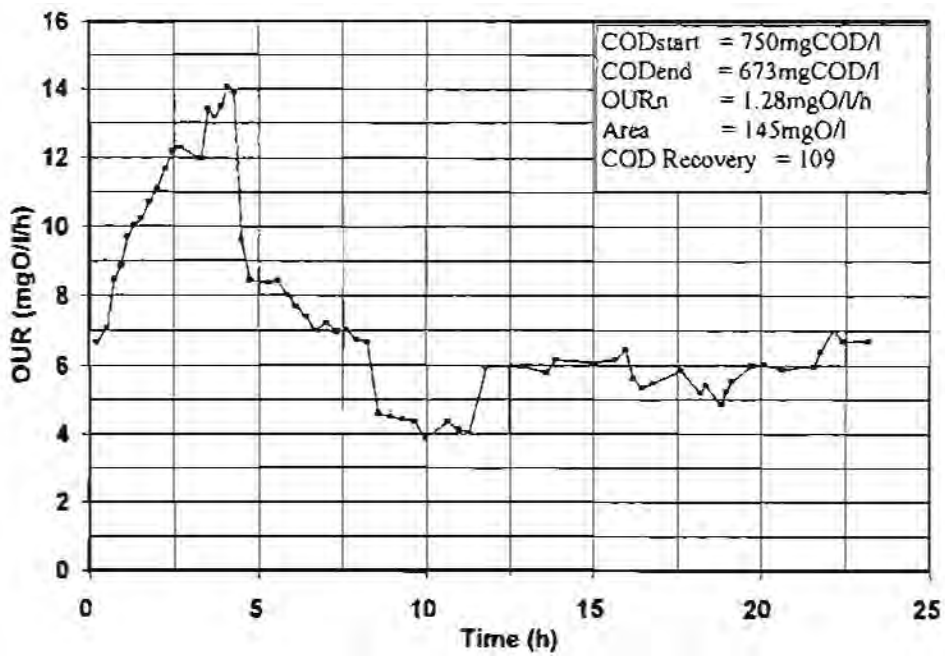


Fig B85a OUR graph for wastewater plus mixed liquor batch test, 03-05, batch no, 24

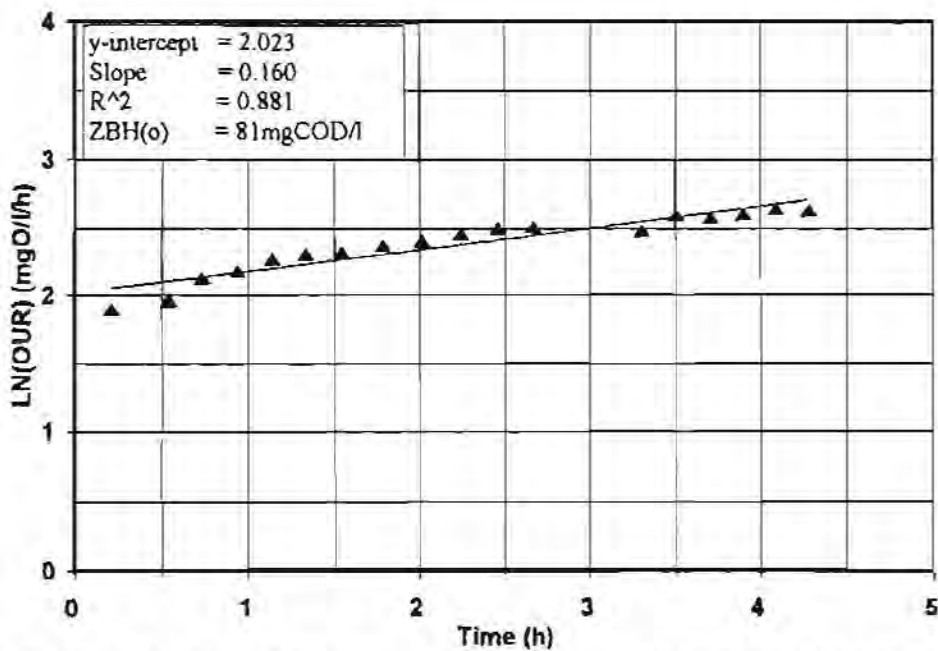


Fig B85b Ln(OUR) graph for wastewater plus mixed liquor batch test, 03-05, batch no, 24

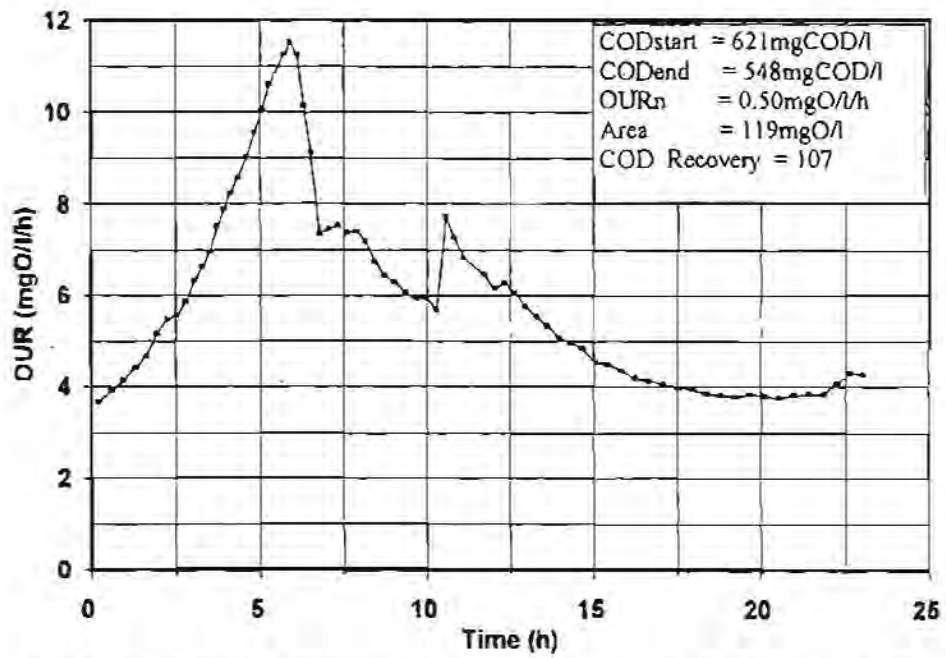


Fig B86a OUR graph for wastewater plus mixed liquor batch test, 04-05, batch no. 24

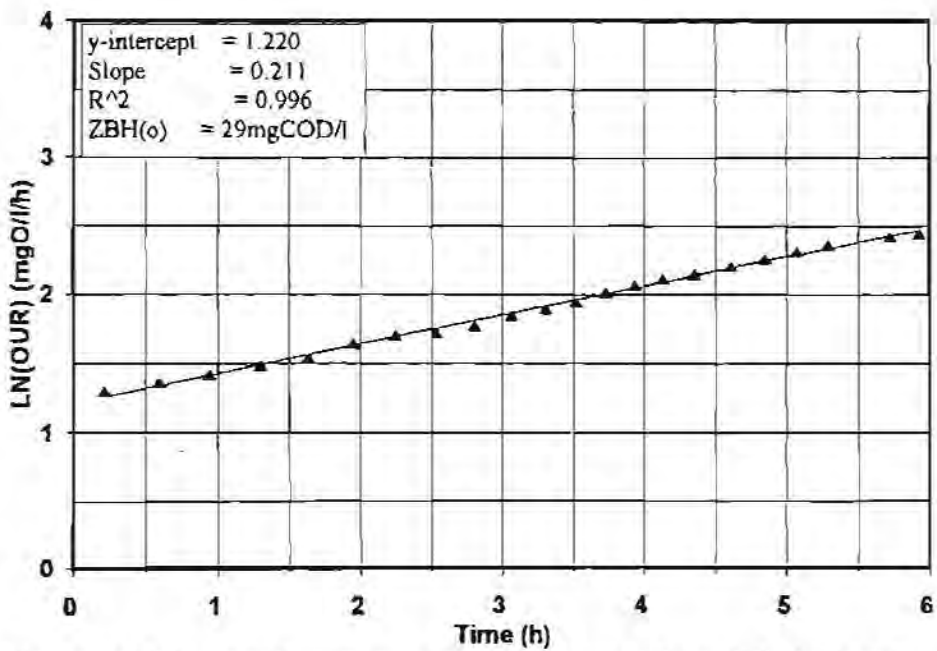


Fig B86b ln(OUR) graph for wastewater plus mixed liquor batch test, 04-05, batch no. 24

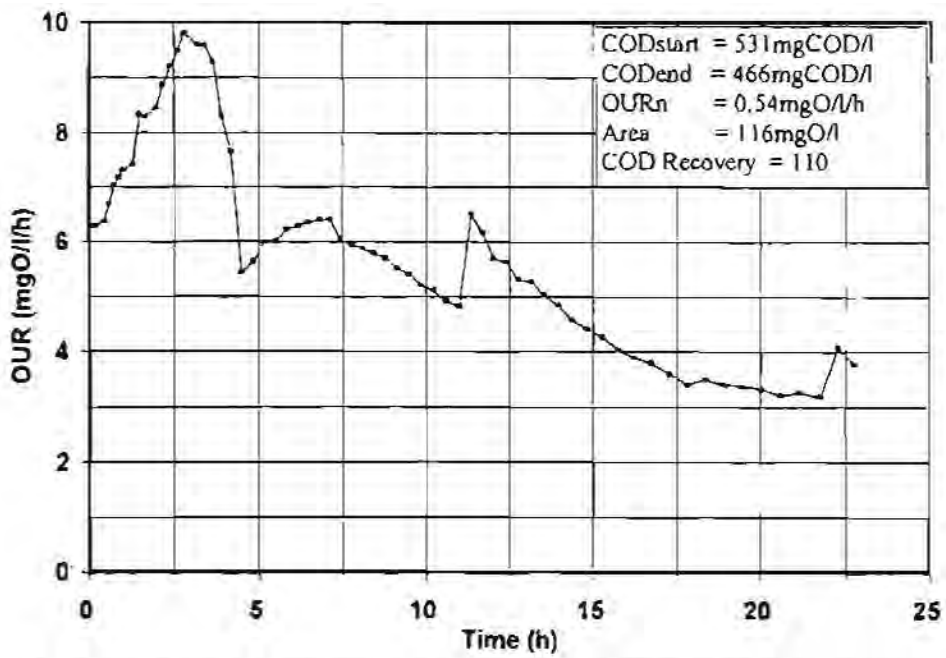


Fig B87a OUR graph for wastewater plus mixed liquor batch test, 05-05, batch no. 24

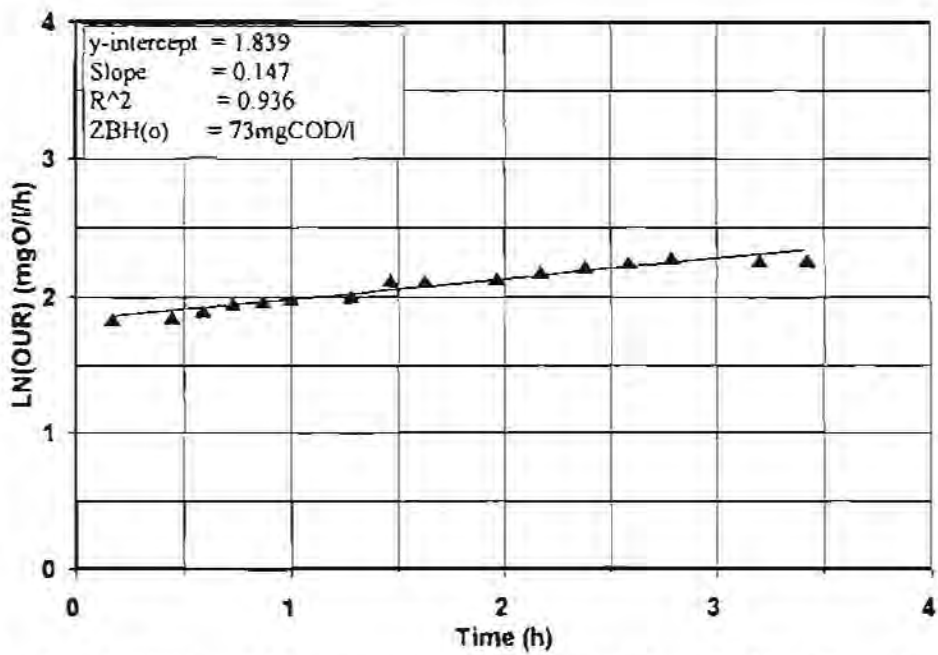


Fig B87b Ln(OUR) graph for wastewater plus mixed liquor batch test, 05-05, batch no. 24

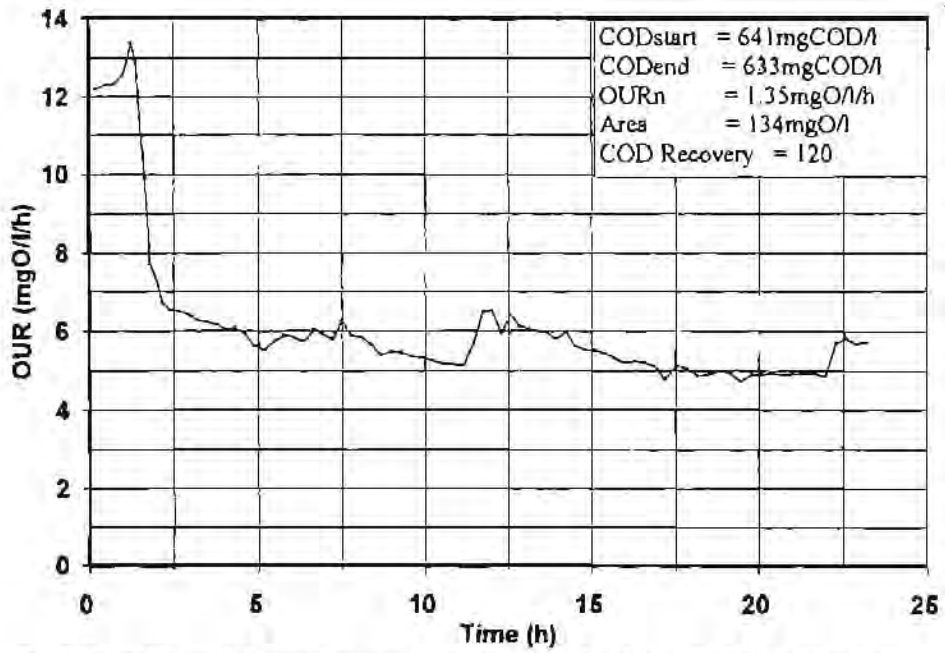


Fig B88a OUR graph for wastewater plus mixed liquor batch test, 06-05, batch no. 24

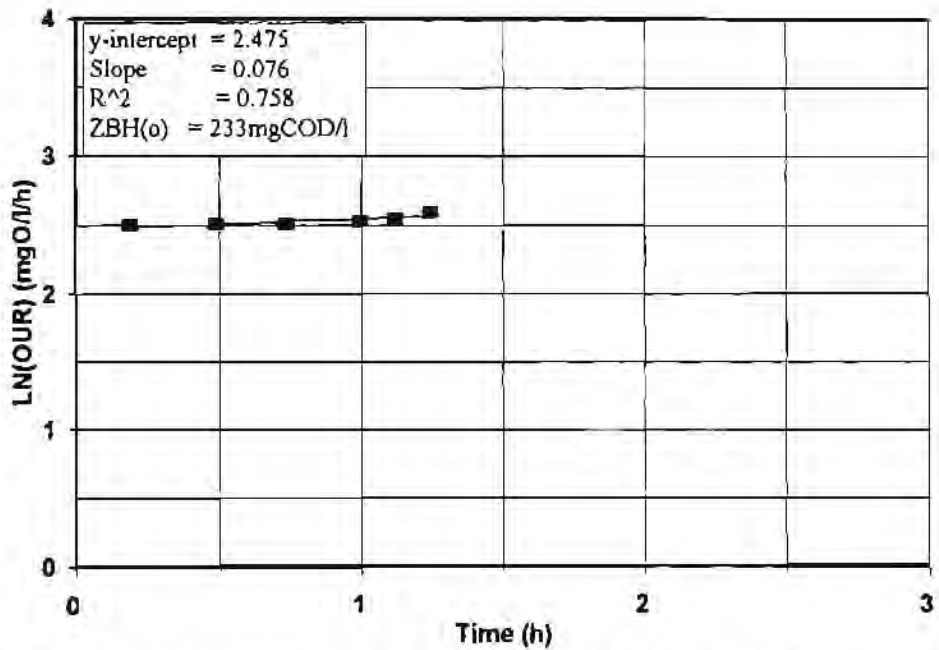


Fig B88b ln(OUR) graph for wastewater plus mixed liquor batch test, 06-05, batch no. 24

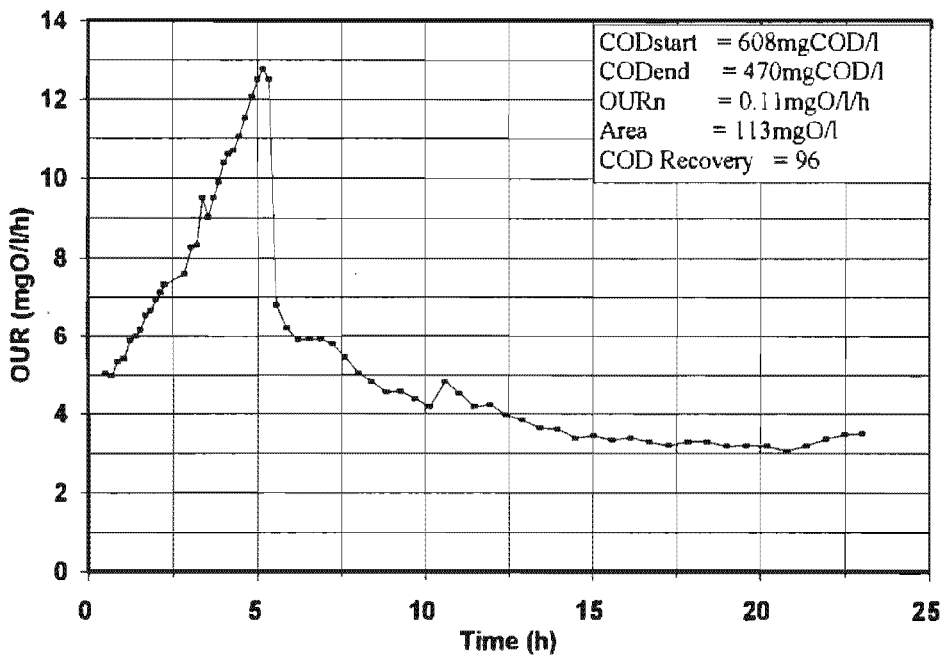


Fig B97a OUR graph for wastewater plus mixed liquor batch test, 28-05, batch no.26

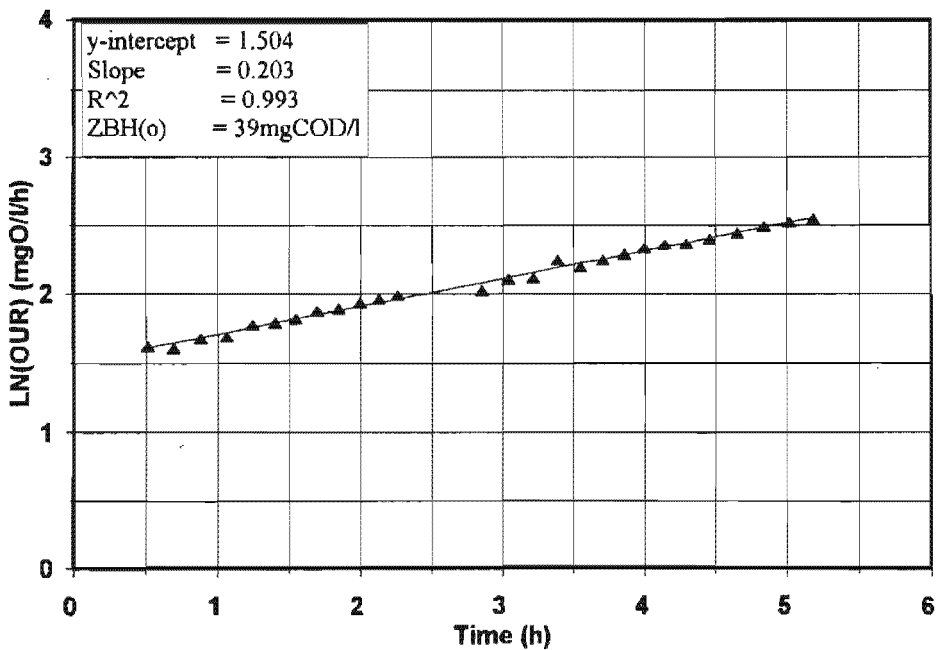


Fig B97b ln(OUR) graph for wastewater plus mixed liquor batch test, 28-05, batch no.26

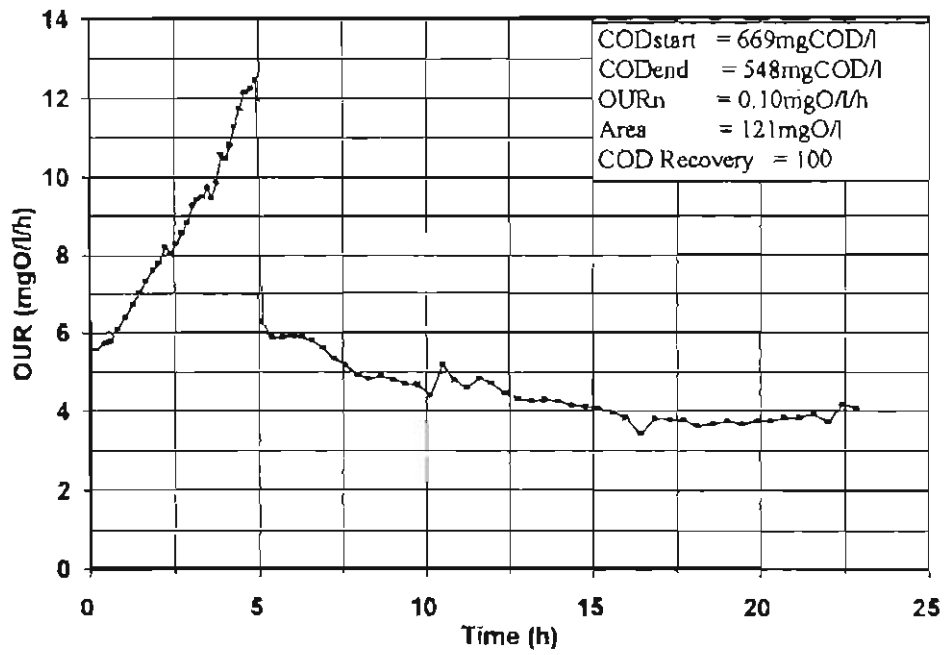


Fig B98a OUR graph for wastewater plus mixed liquor batch test, 29-05, batch no. 26

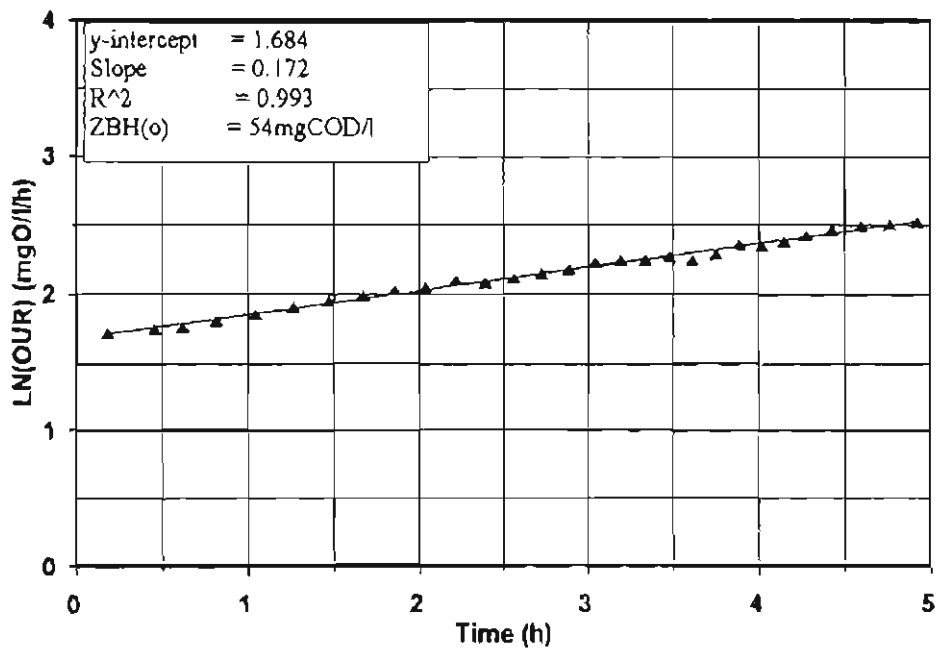


Fig B98b ln(OUR) graph for wastewater plus mixed liquor batch test, 29-05, batch no.26

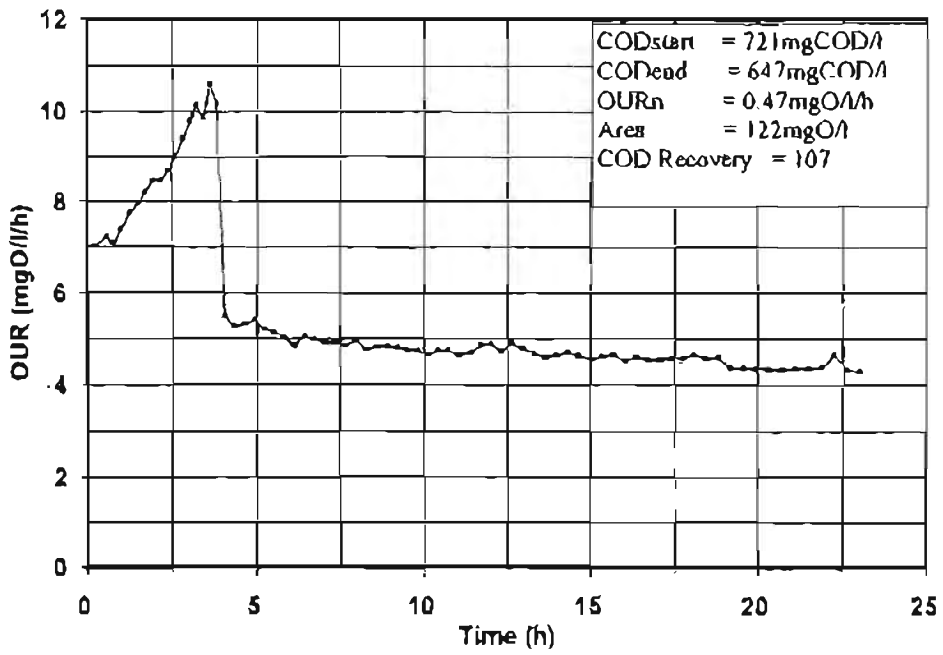


Fig B95a OUR graph for wastewater plus mixed liquor batch test, 26-05, batch no. 26

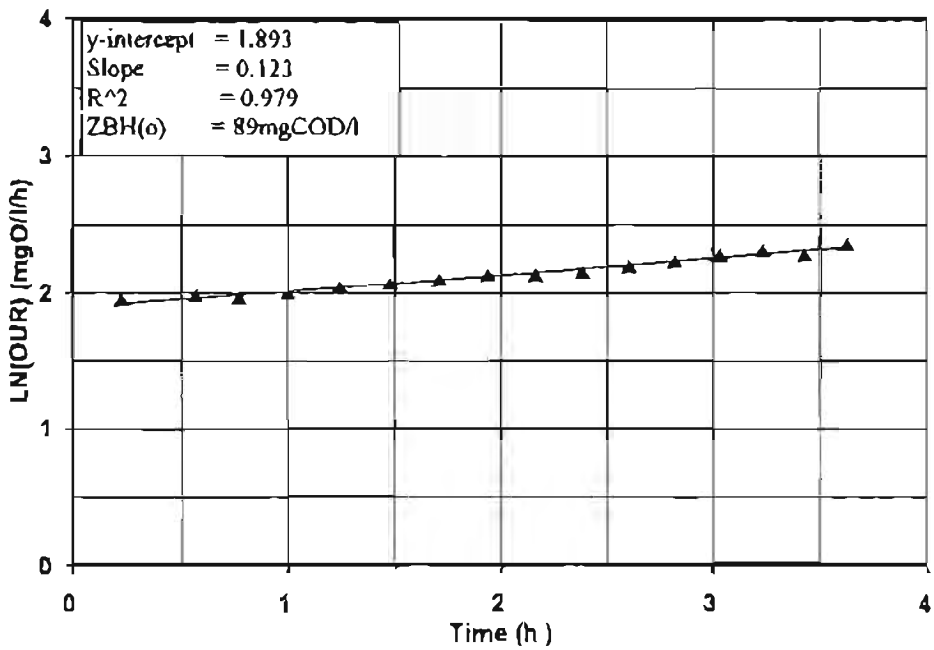


Fig B95b Ln(OUR) graph for wastewater plus mixed liquor batch test, 26-05, batch no. 26

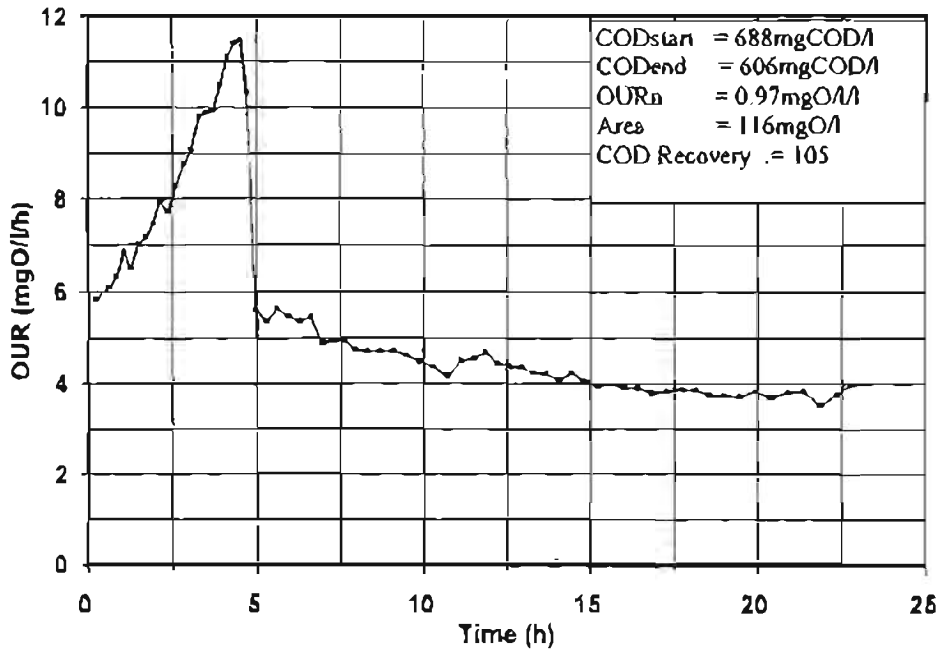


Fig B96a OUR graph for wastewater plus mixed liquor batch test, 27-05, batch no. 26

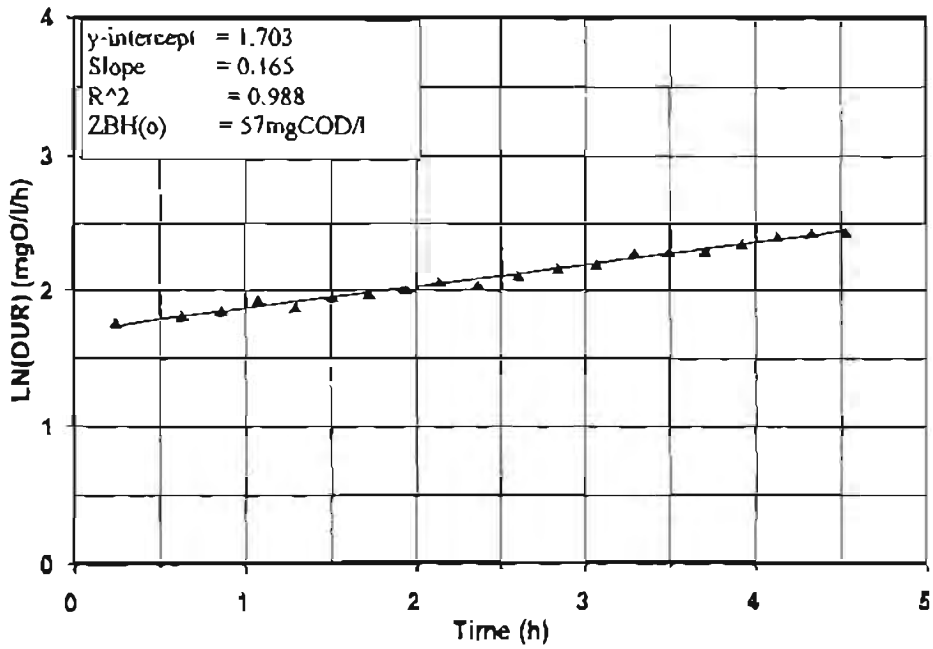


Fig B96b ln(OUR) graph for wastewater plus mixed liquor batch test, 27-05, batch no. 26

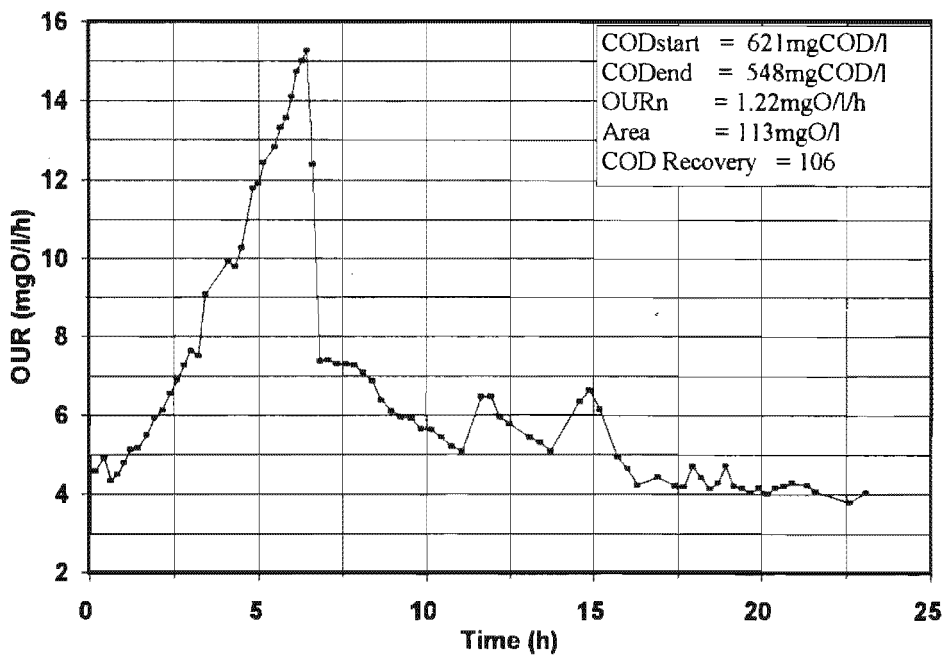


Fig B89a OUR graph for wastewater plus mixed liquor batch test, 07-05, batch no. 24

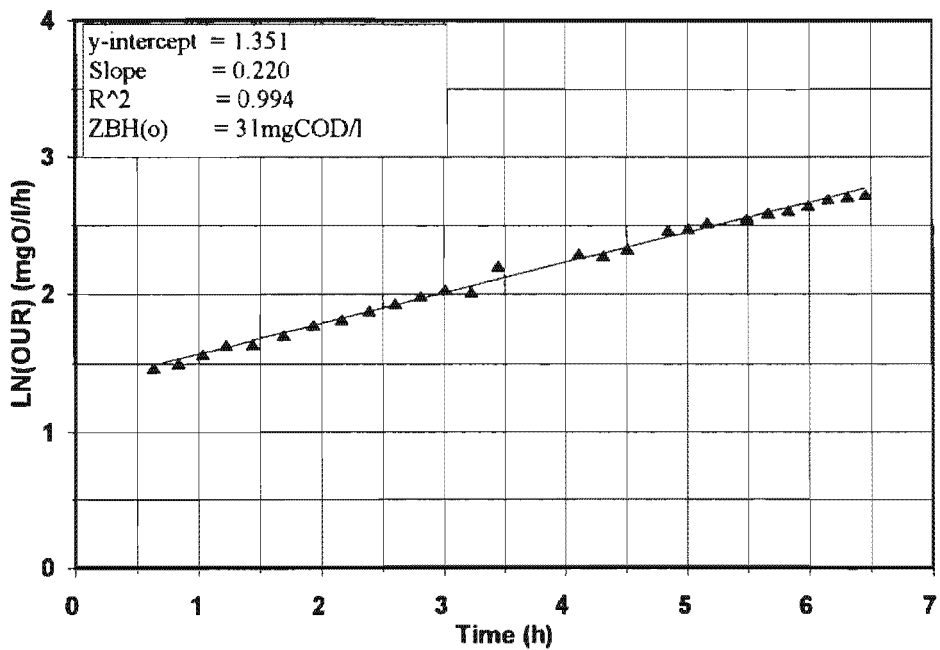


Fig B89b ln(OUR) graph for wastewater plus mixed liquor batch test, 07-05, batch no. 24

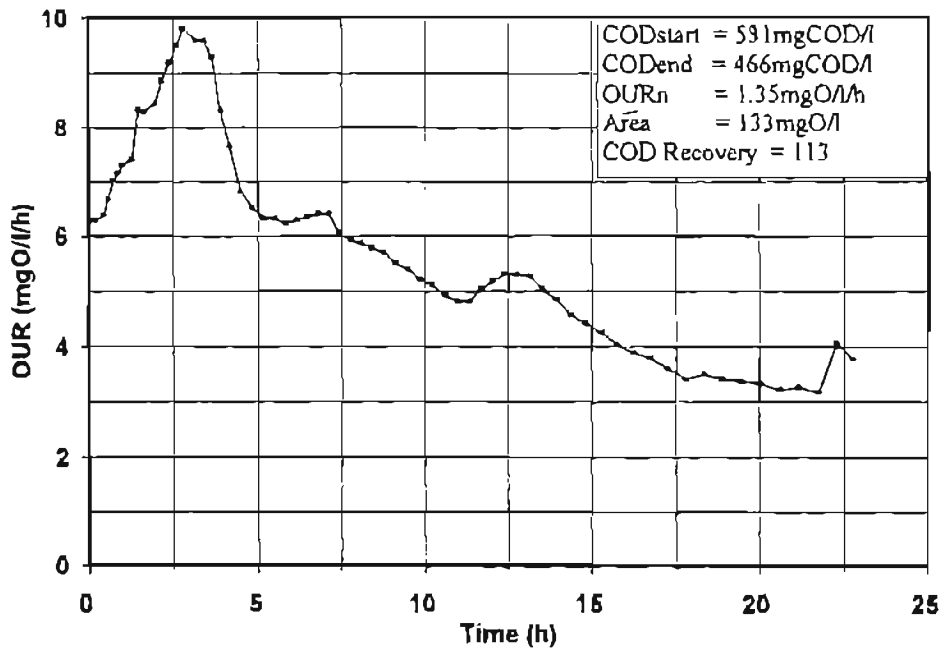


Fig B90a OUR graph for wastewater plus mixed liquor batch test, 08-05, batch no. 24

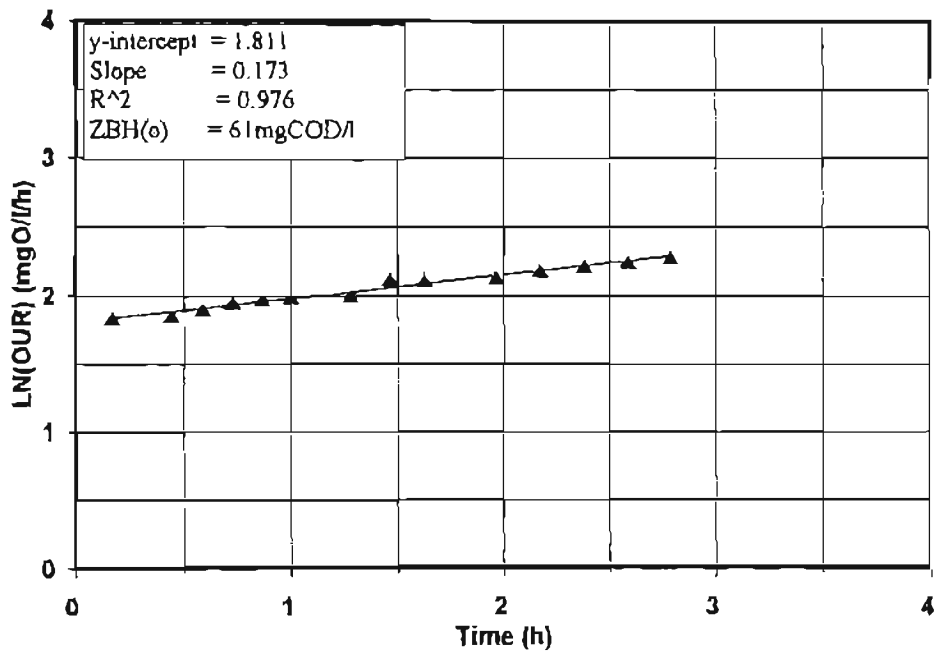


Fig B90b ln(OUR) graph for wastewater plus mixed liquor batch test, 08-05, batch no. 24

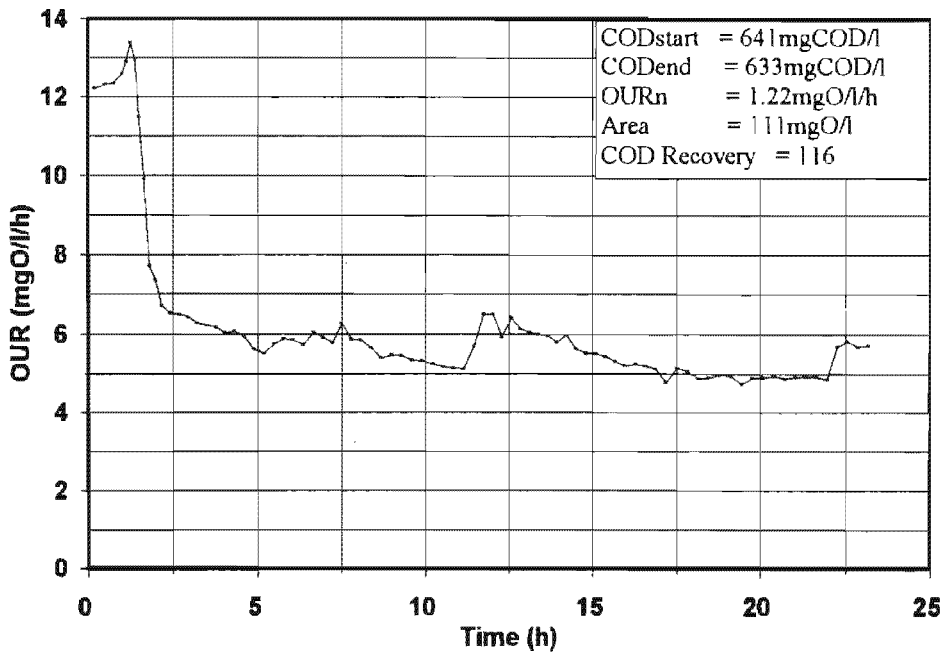


Fig B91a OUR graph for wastewater plus mixed liquor batch test, 09-05, batch no. 24

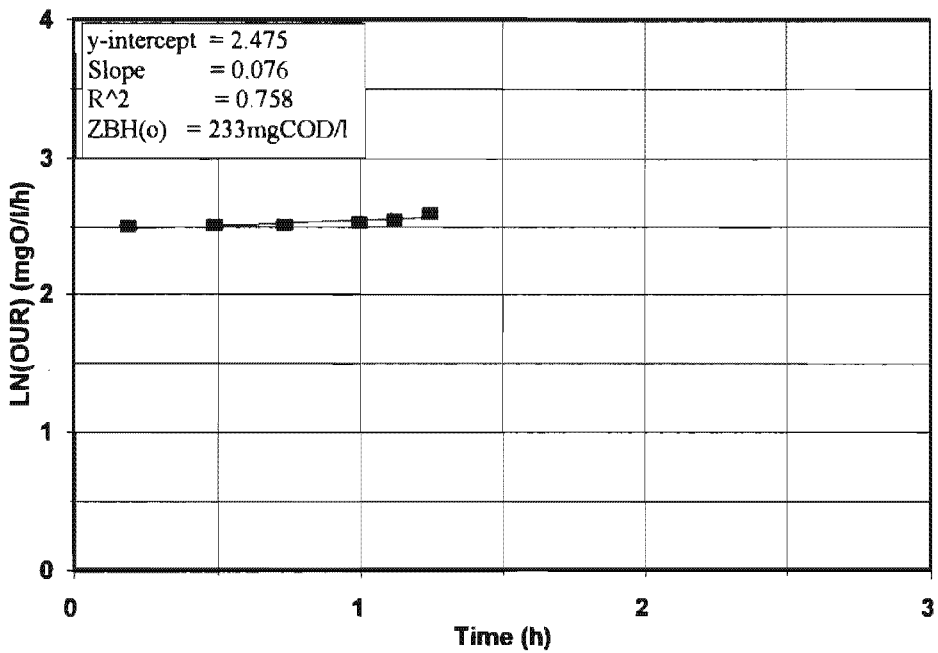


Fig B91b ln(OUR) graph for wastewater plus mixed liquor batch test, 09-05, batch no. 24

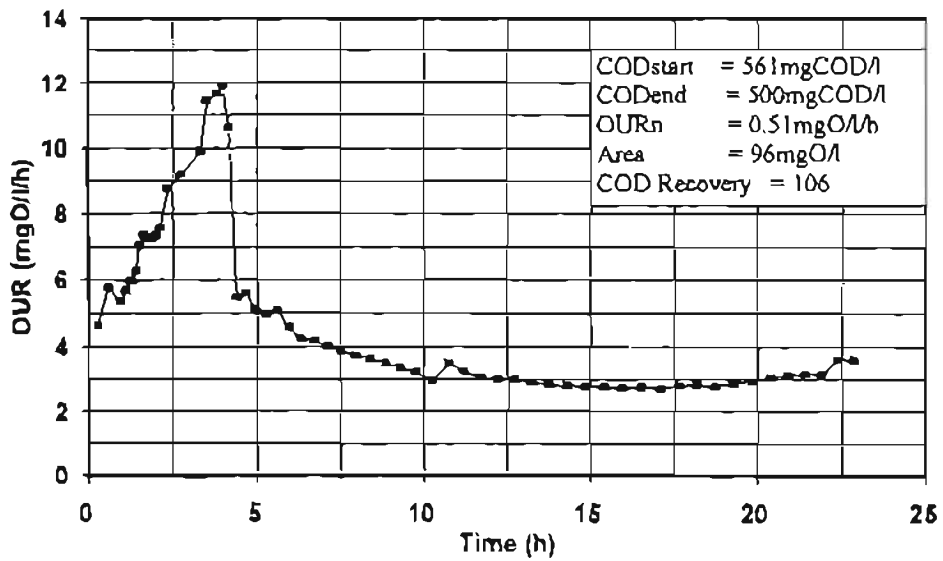


Fig B92a OUR graph for wastewater plus mixed liquor batch test, 23-05, batch no. 26

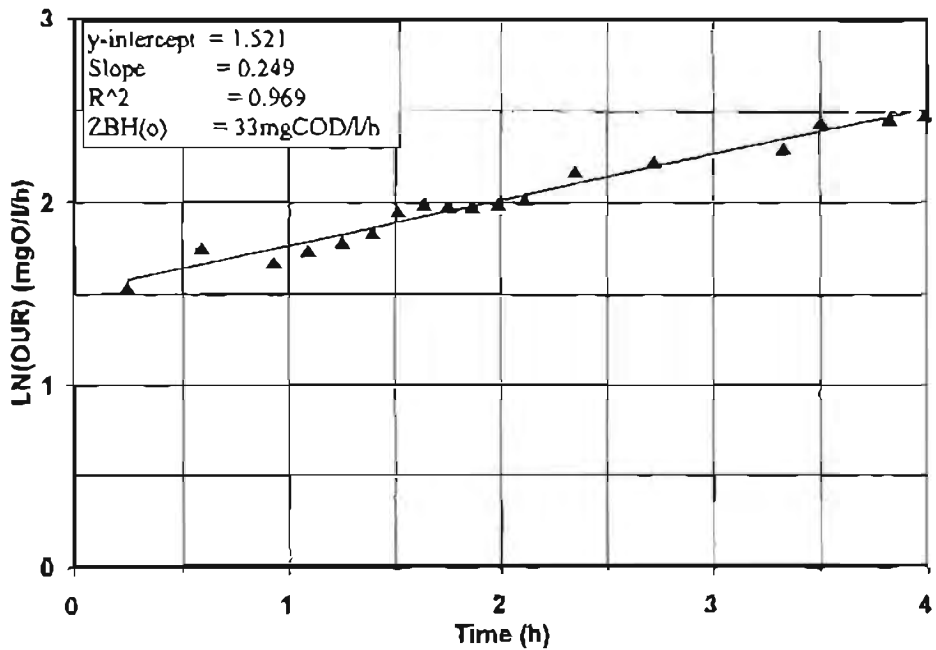


Fig B92b ln(OUR) graph for wastewater plus mixed liquor batch test, 23-05, batch no.26

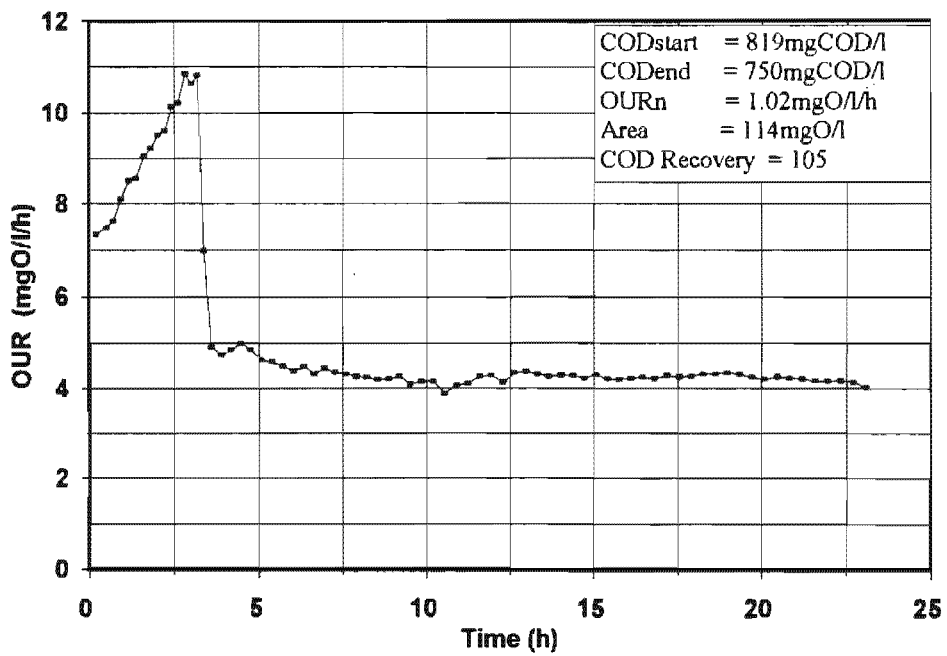


Fig B93a OUR graph for wastewater plus mixed liquor batch test, 24-05, batch no.26

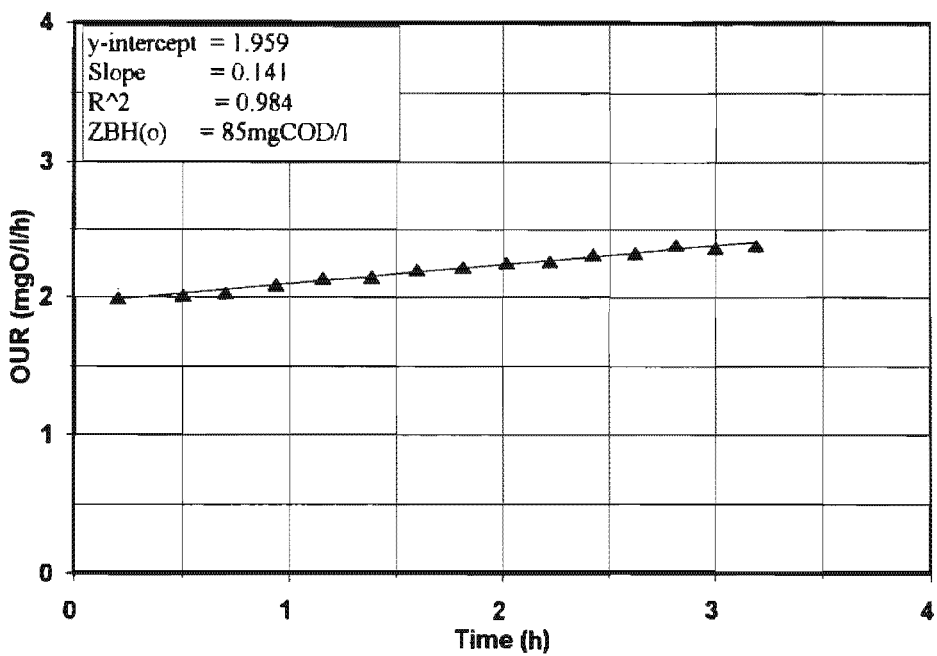


Fig B93b ln(OUR)graph for wastewater plus mixed liquor batch test, 24-05, batch no. 26

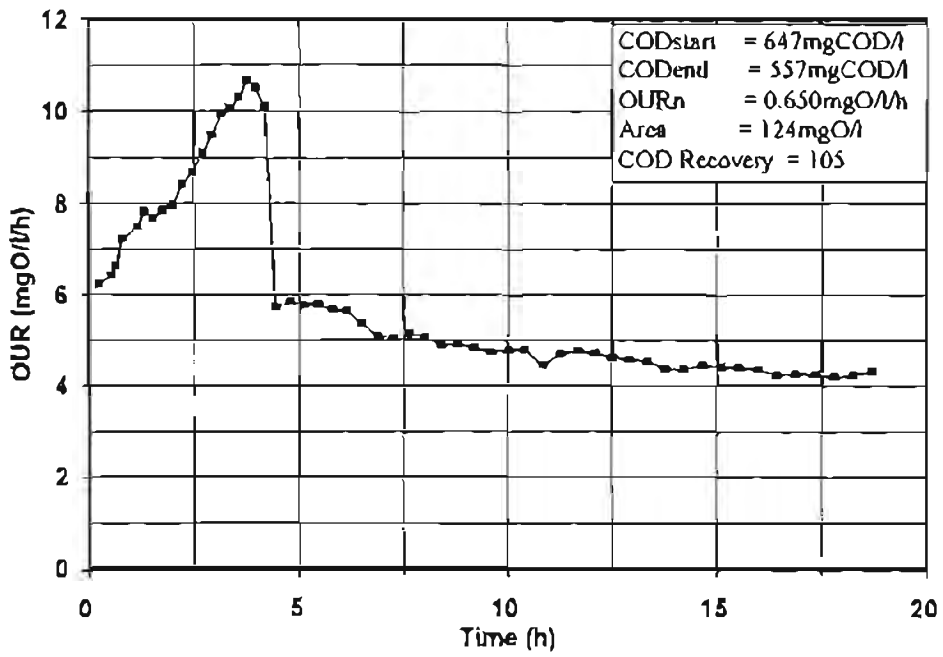


Fig B94a OUR graph for wastewater plus mixed liquor batch test, 25-05, batch no. 26

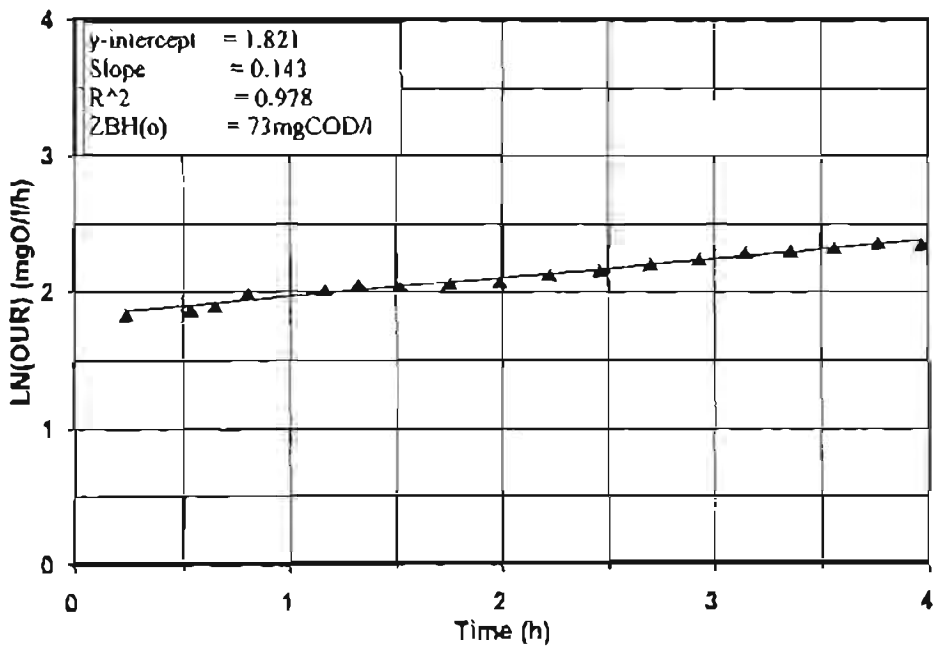


Fig B94b ln(OUR) graph for wastewater plus mixed liquor batch test, 25-05, batch no. 26

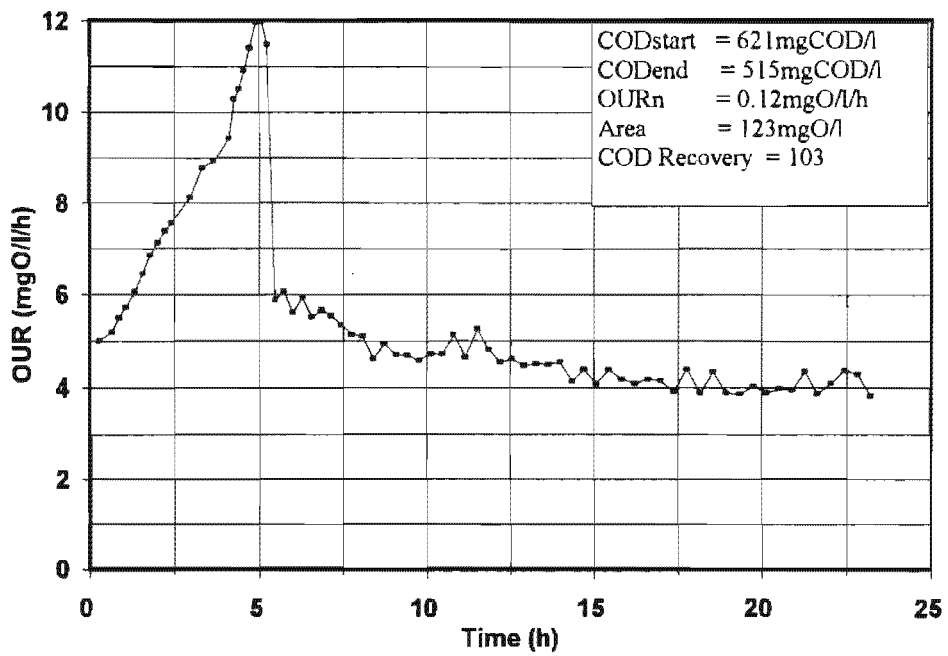


Fig B99a OUR graph for wastewater plus mixed liquor batch test, 29-05, batch no.26

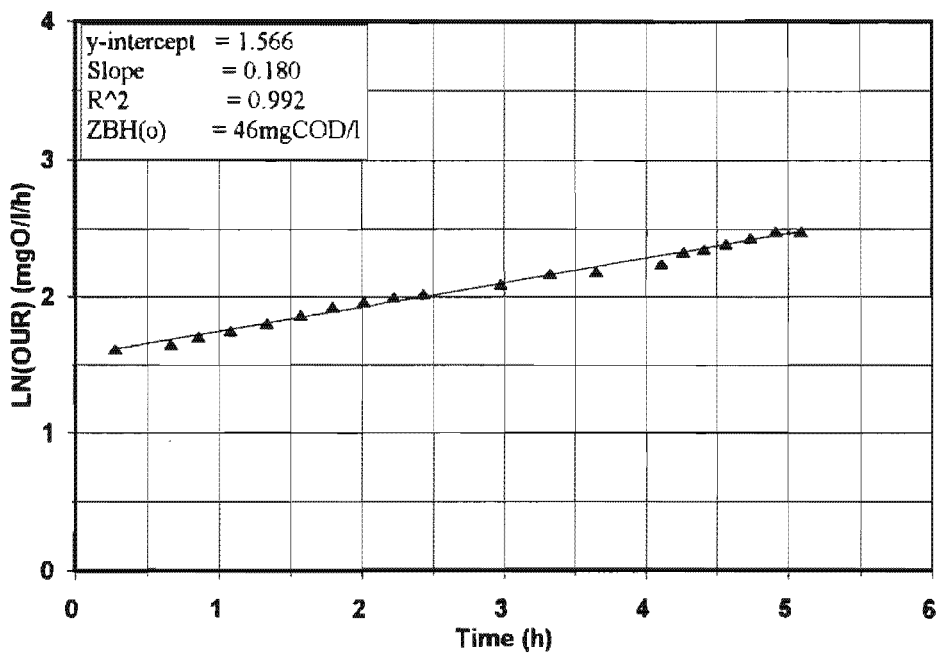


Fig B99b ln(OUR) graph for wastewater plus mixed liquor batch test, 29-05, batch no. 26

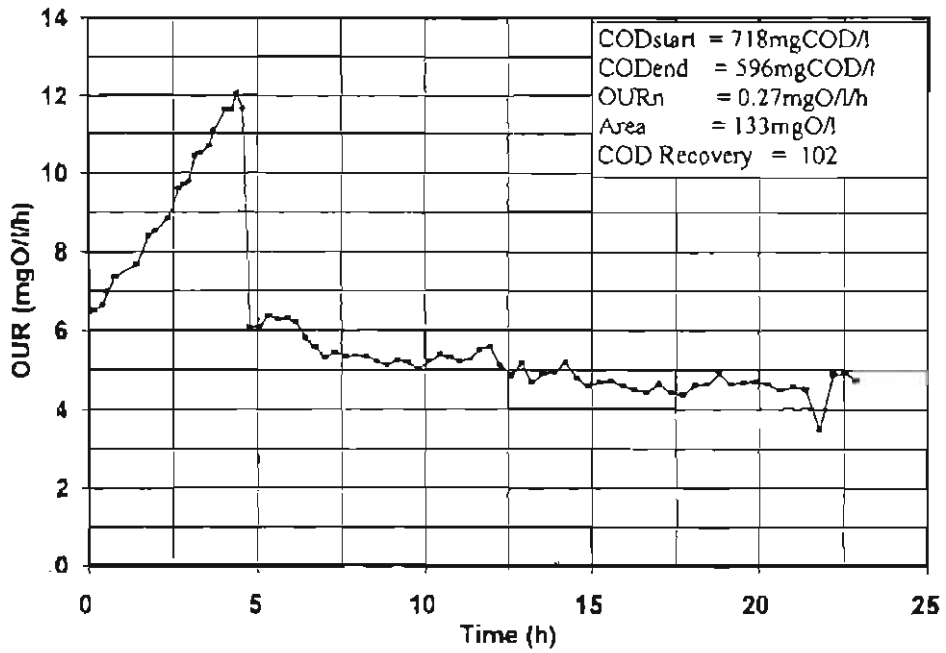


Fig B100a OUR graph for wastewater plus mixed liquor batch test, 30-05, batch no. 26

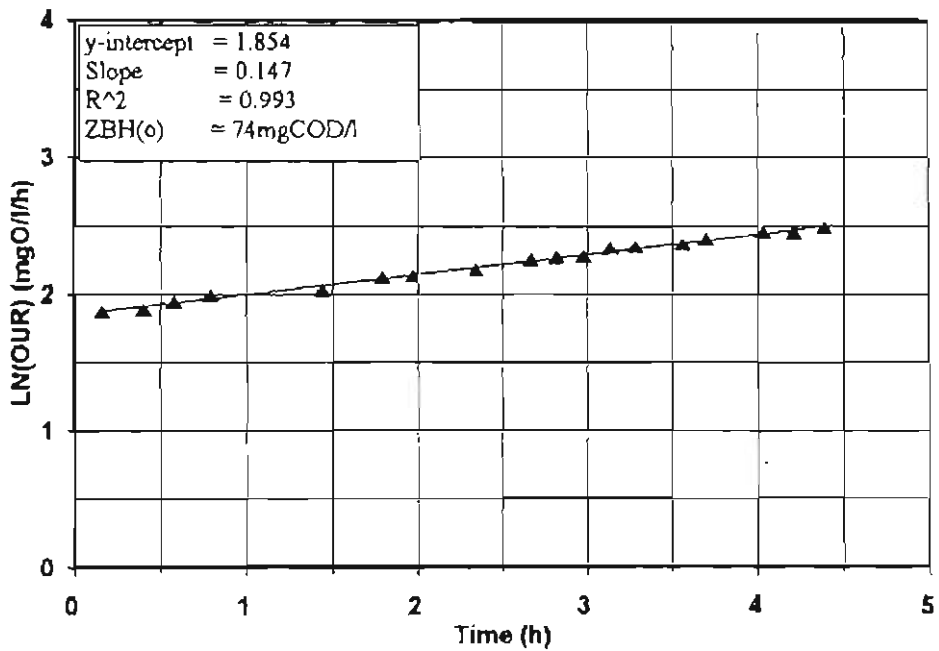


Fig B100b ln(OUR) graph for wastewater plus mixed liquor batch test, 30-05, batch no.26

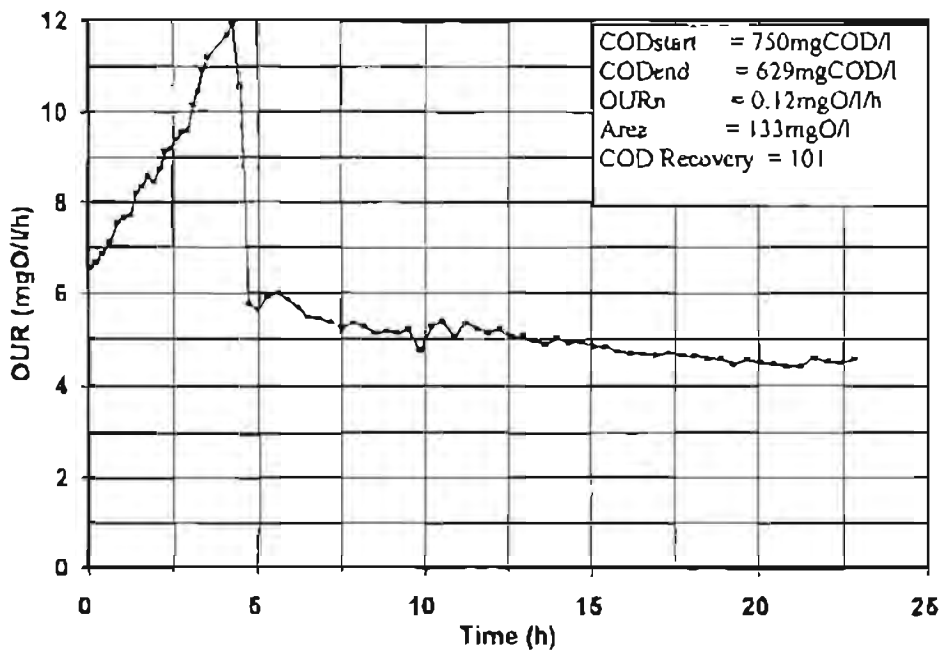


Fig B101a OUR graph for wastewater plus mixed liquor batch test, 30-05, batch no. 26

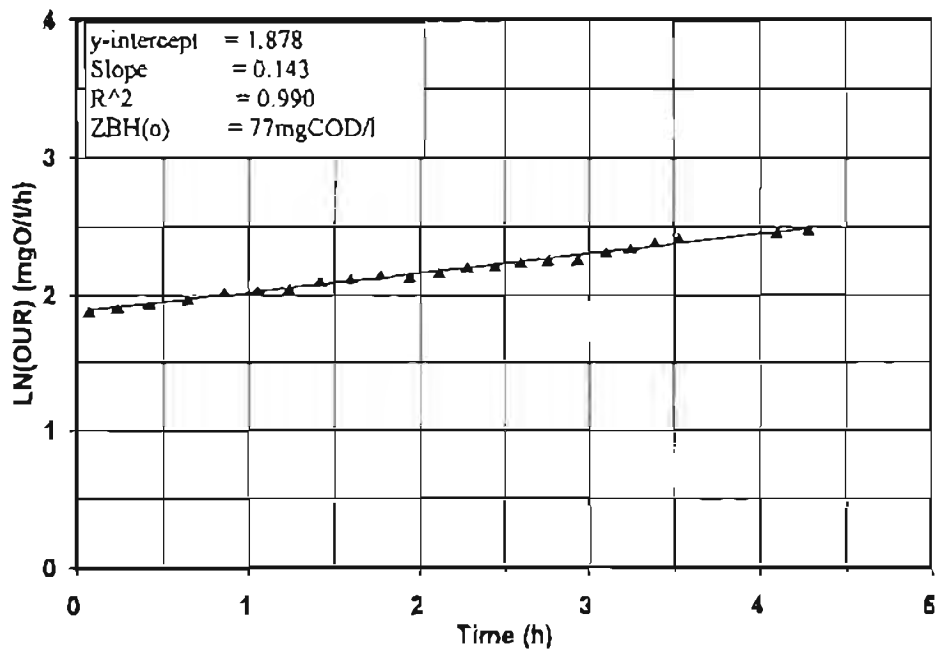


Fig B101b ln(OUR) graph for wastewater plus mixed liquor batch test, 30-05, batch no. 26

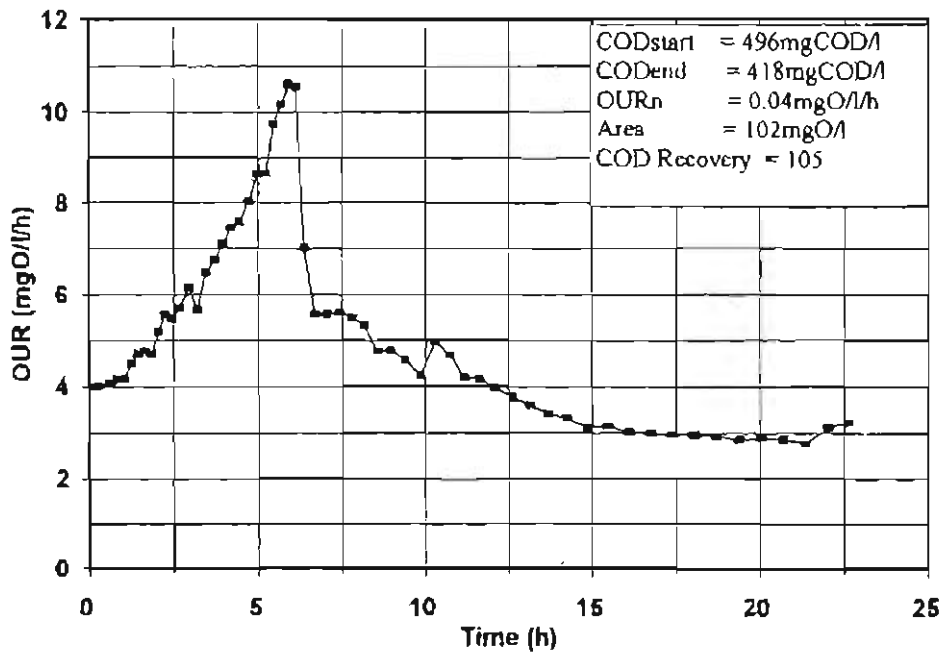


Fig B102a OUR graph for wastewater plus mixed liquor batch test, 03-06, batch no. 27

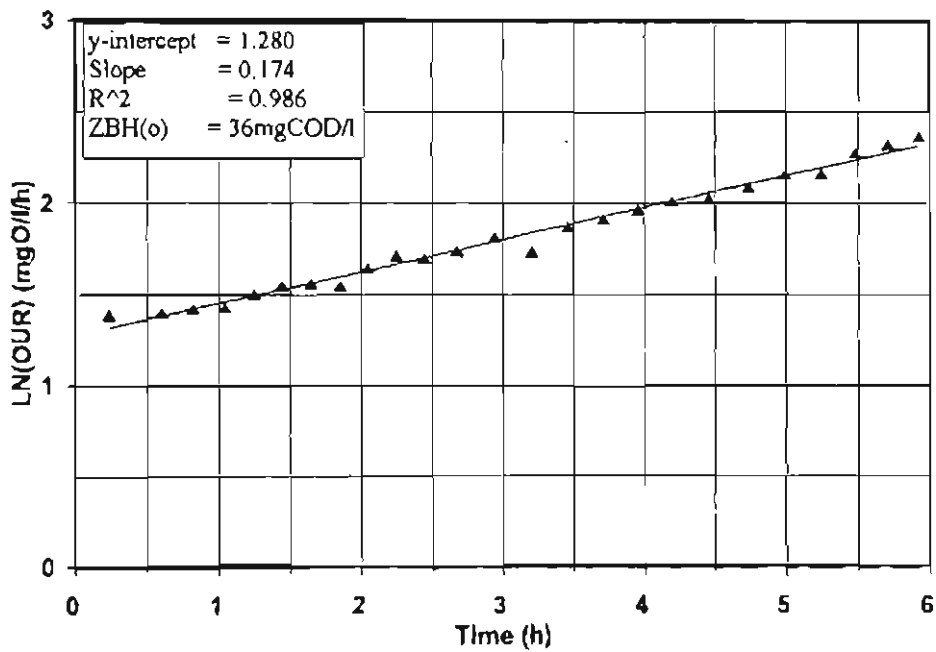


Fig B102b ln(OUR) graph for wastewater plus mixed liquor batch test, 03-06, batch no. 27

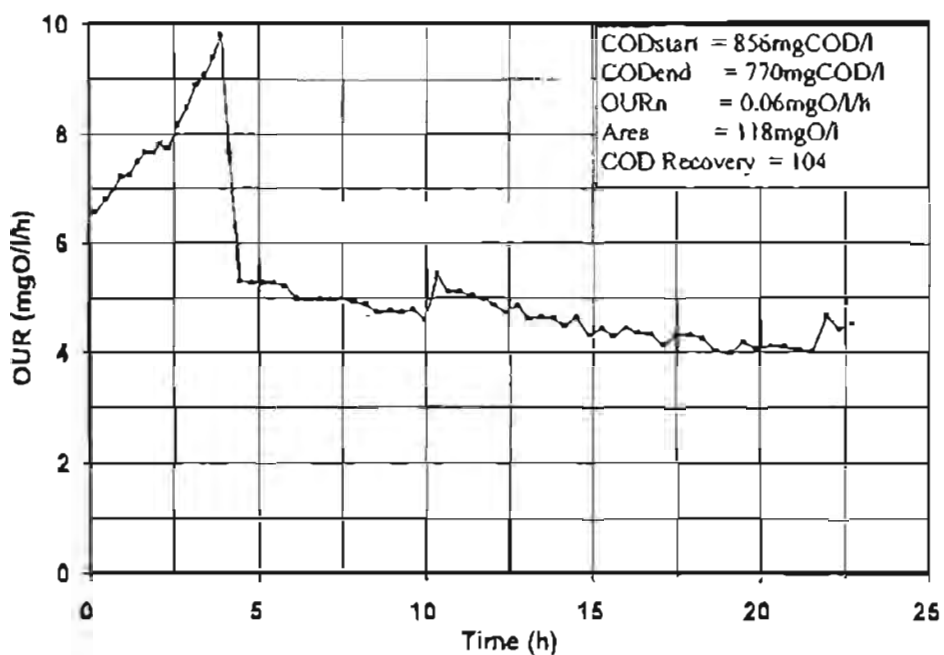


Fig B103a OUR graph for wastewater plus mixed liquor batch test, 04-06, batch no. 27

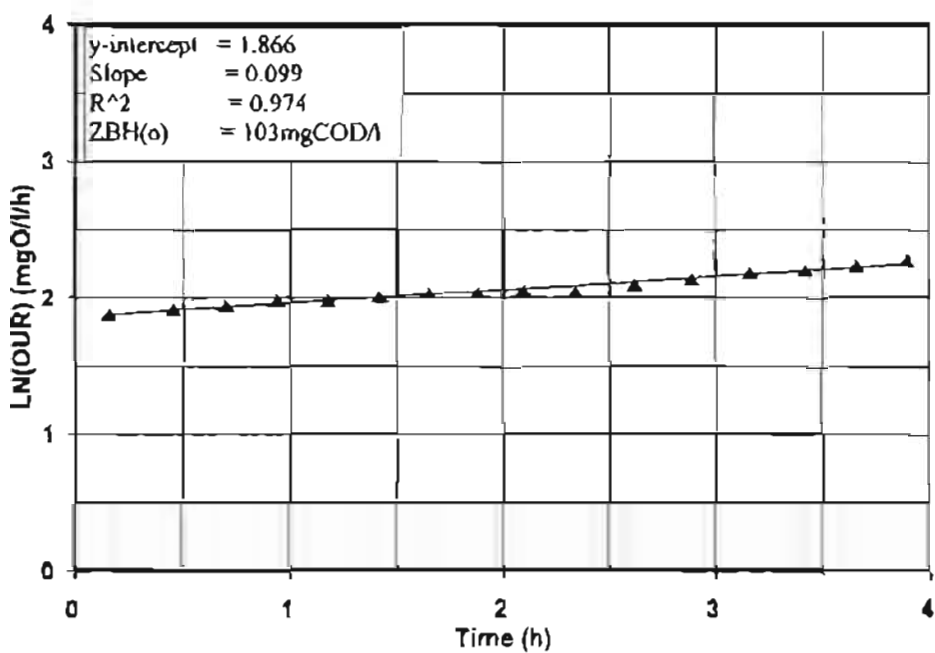


Fig B103b ln(OUR) graph for wastewater plus mixed liquor batch test, 04-06, batch no. 27

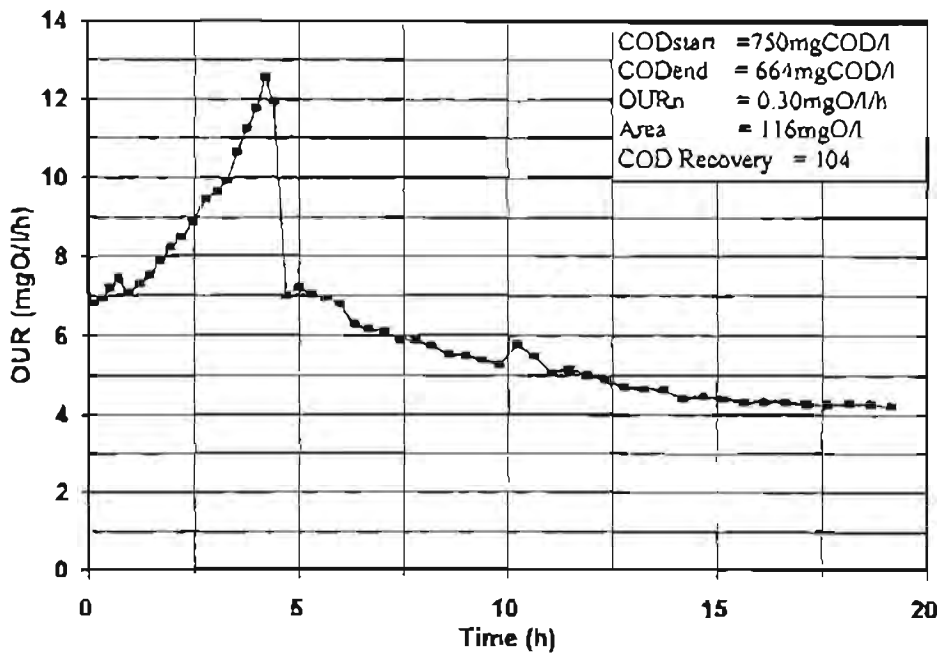


Fig B104a OUR graph for wastewater plus mixed liquor batch test, 05-06, batch no. 27

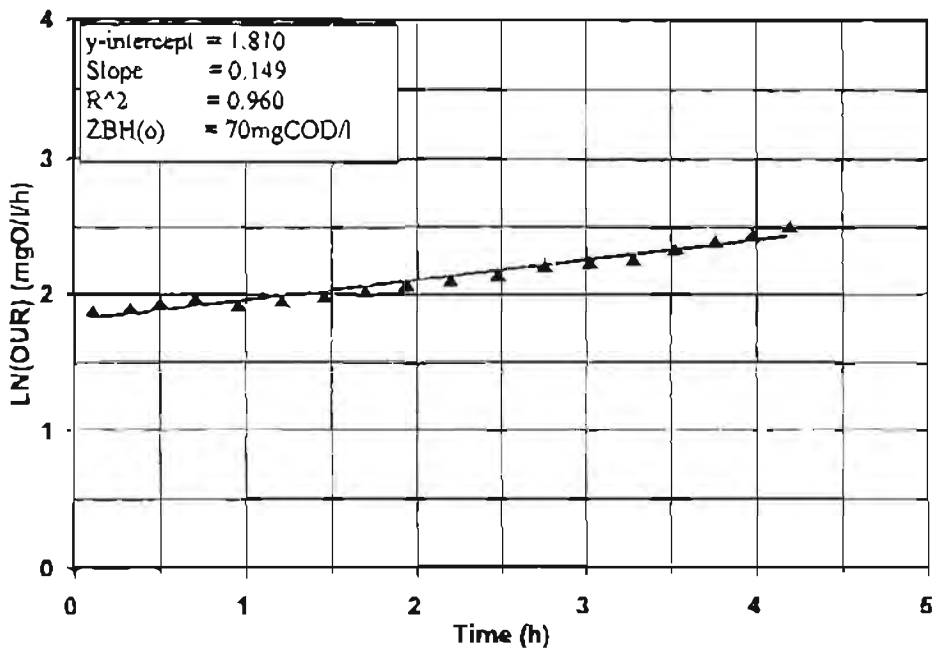


Fig B104b Ln(OUR) graph for wastewater plus mixed liquor batch test, 05-06, batch no.27

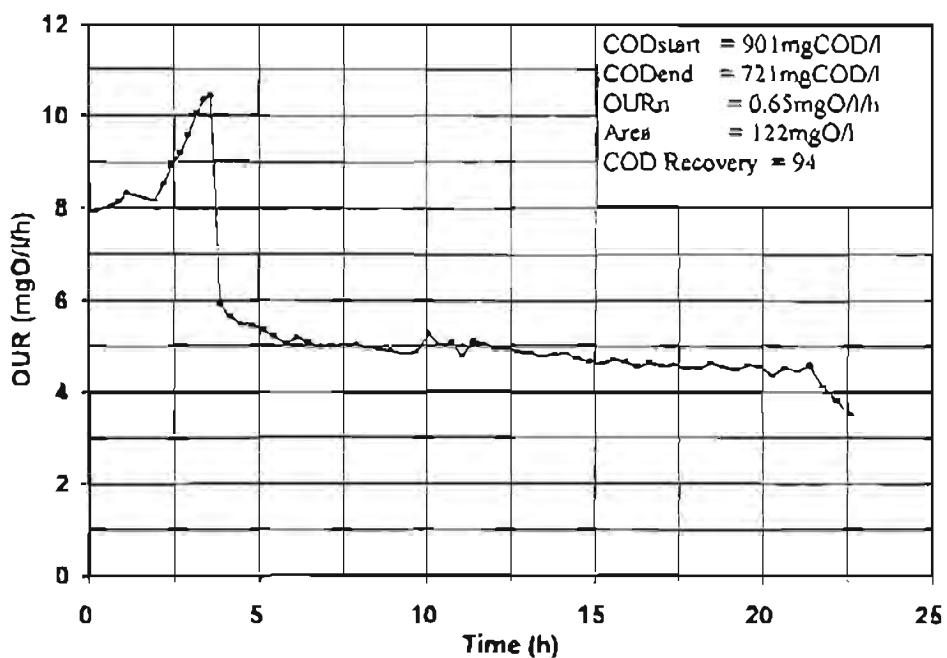


Fig B105a OUR graph for wastewater plus mixed liquor batch test, 06-06, batch no. 27

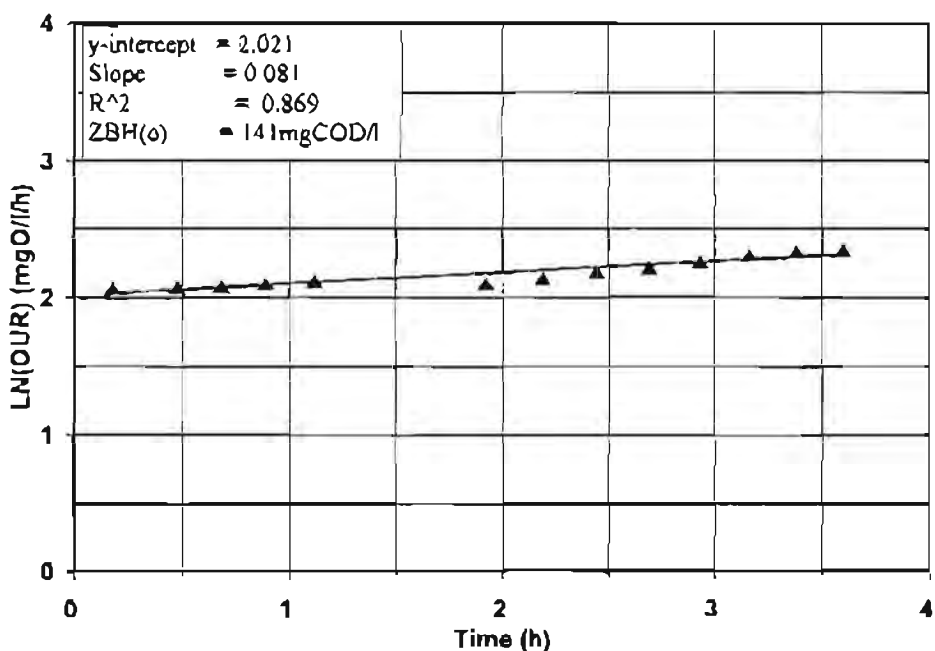


Fig B105b ln(OUR) graph for wastewater plus mixed liquor batch test, 06-06, batch no.27

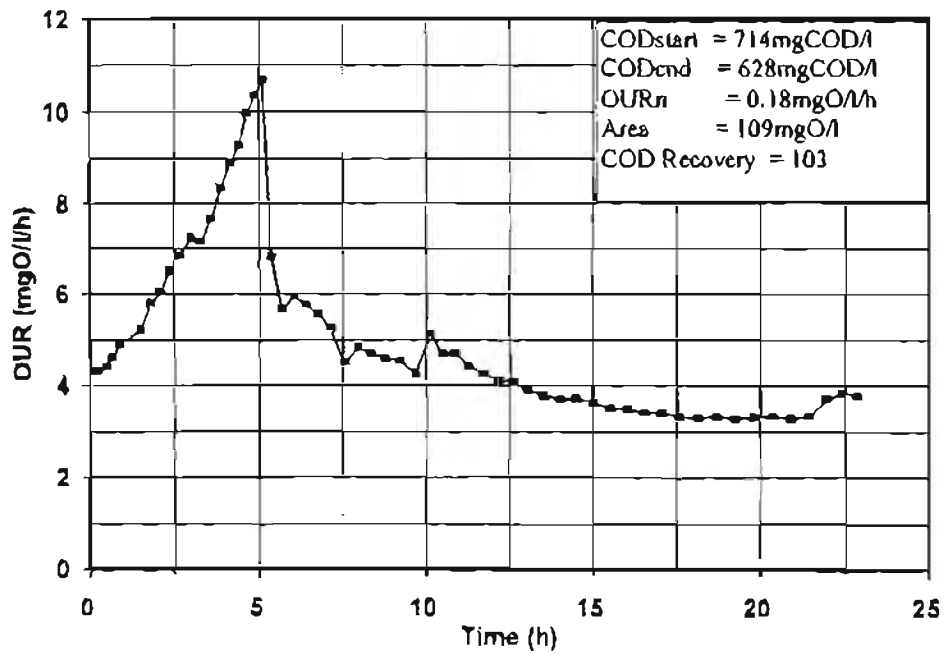


Fig B106a OUR graph for wastewater plus mixed liquor batch test, 07-06, batch no.27

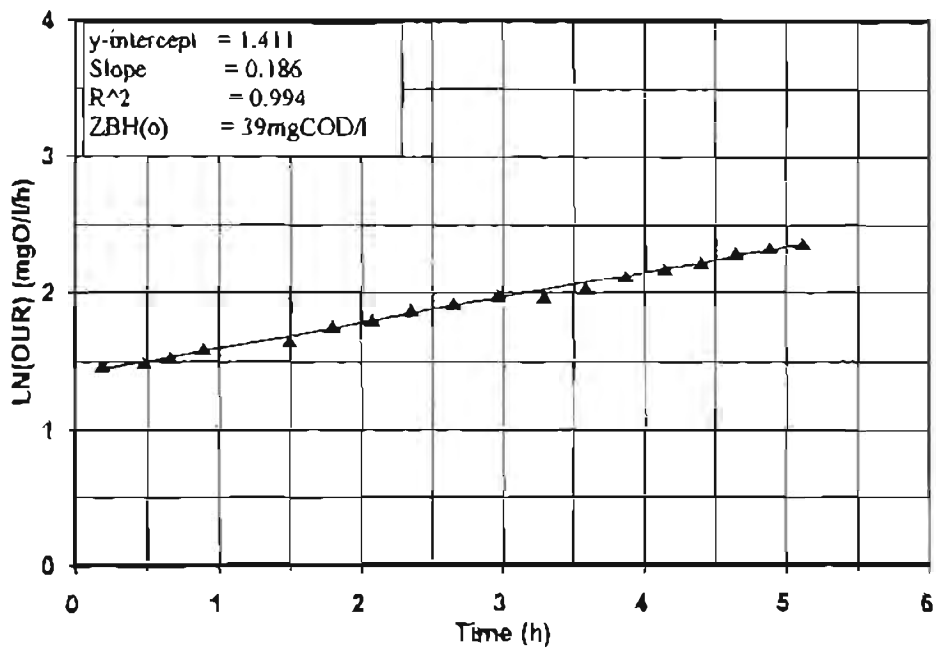


Fig B106b ln(OUR) graph for wastewater plus mixed liquor batch test, 07-06, batch no. 27

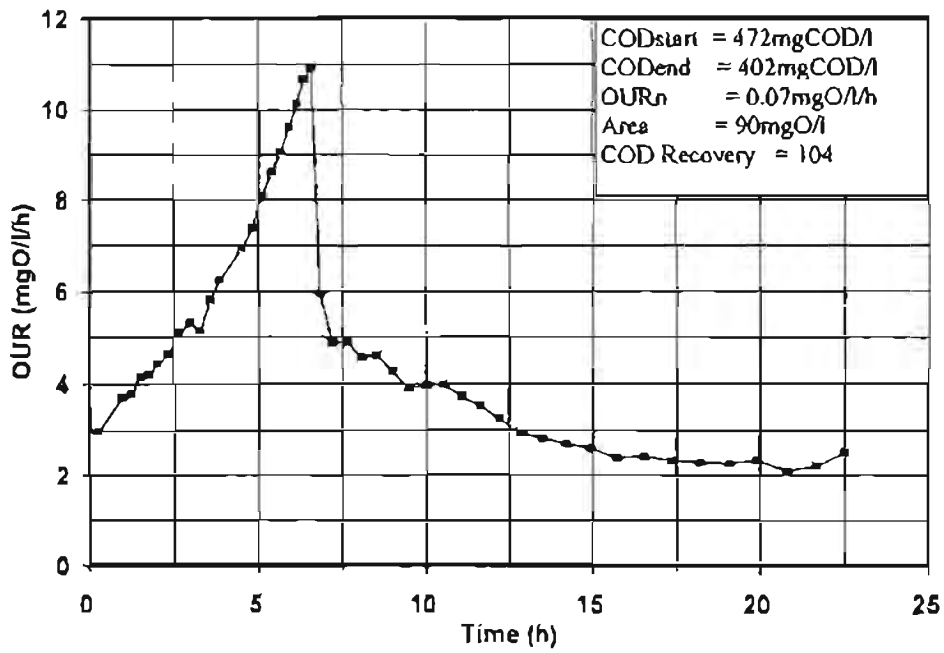


Fig B107a OUR graph for wastewater plus mixed liquor batch test, 08-06, batch no. 27

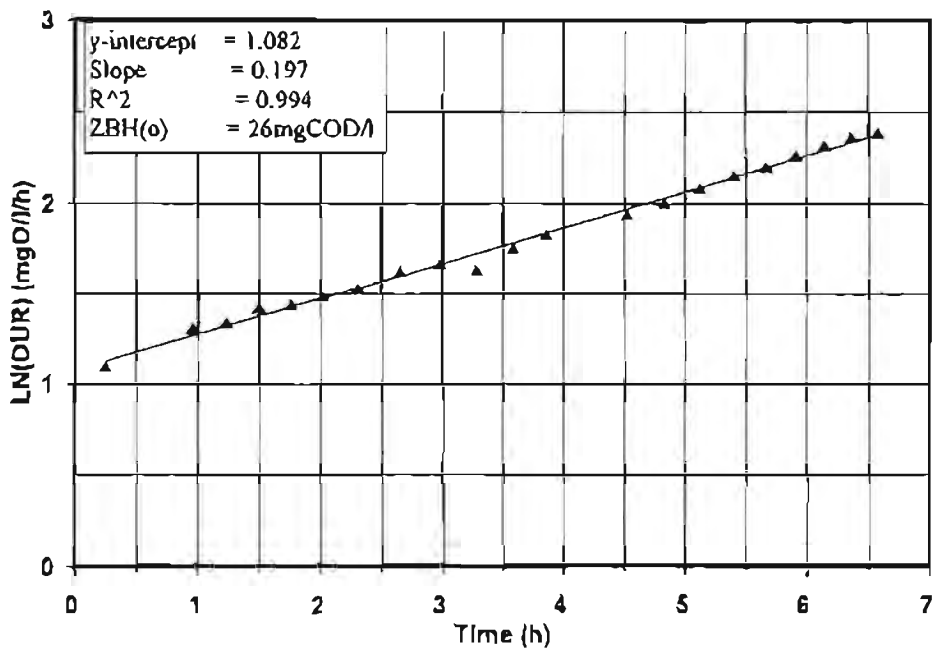


Fig B107b ln(OUR) graph for wastewater plus mixed liquor batch test, 08-06, batch no. 27

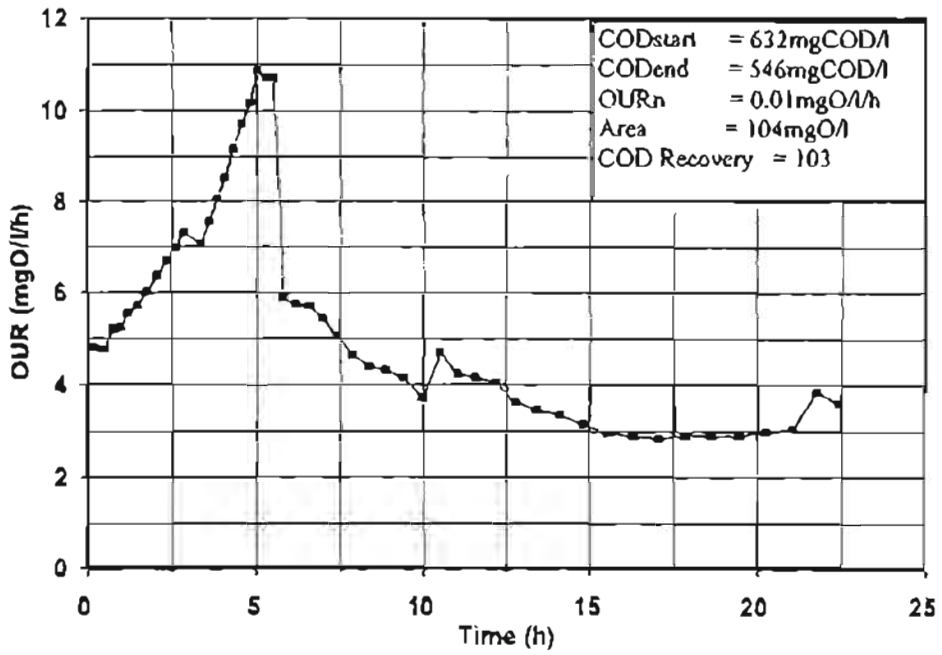


Fig B108a OUR graph for wastewater plus mixed liquor batch test, 09-06, batch no. 27

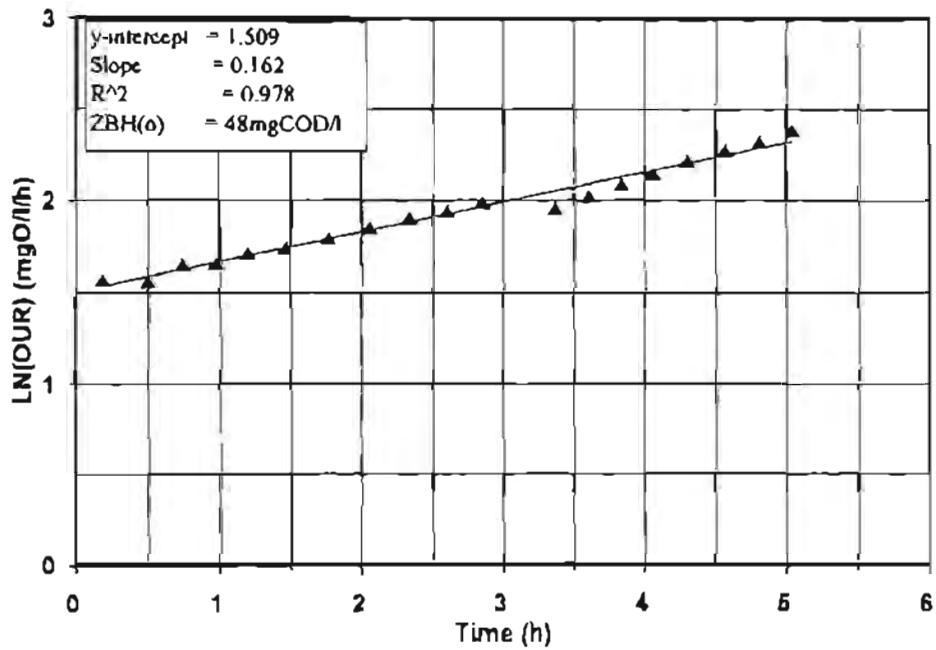


Fig B108b ln(OUR) graph for wastewater plus mixed liquor batch test, 09-06, batch no. 27

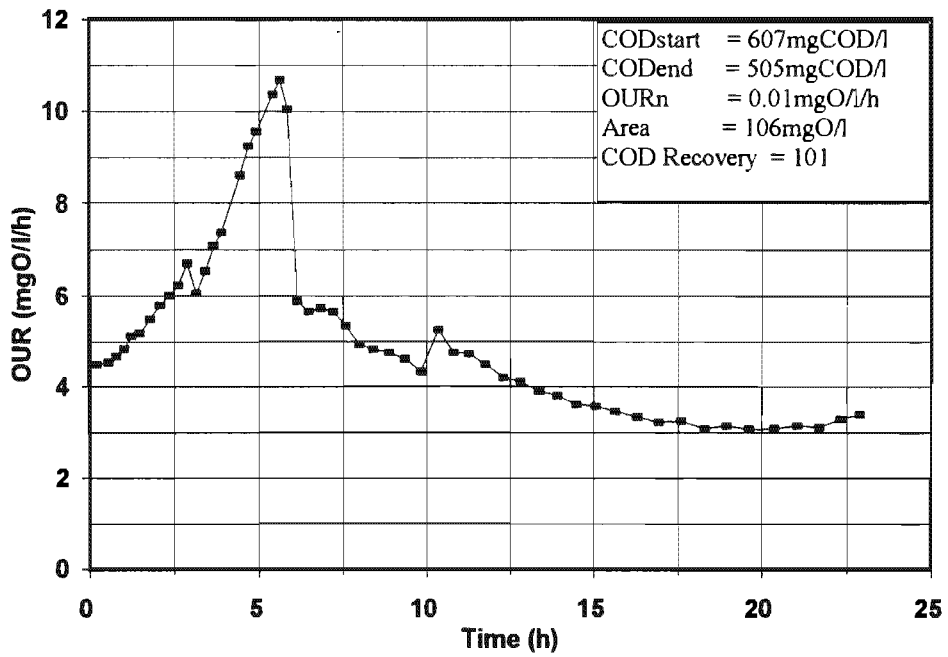


Fig B109a OUR graph for wastewater plus mixed liquor batch test, 09-06, batch no. 27

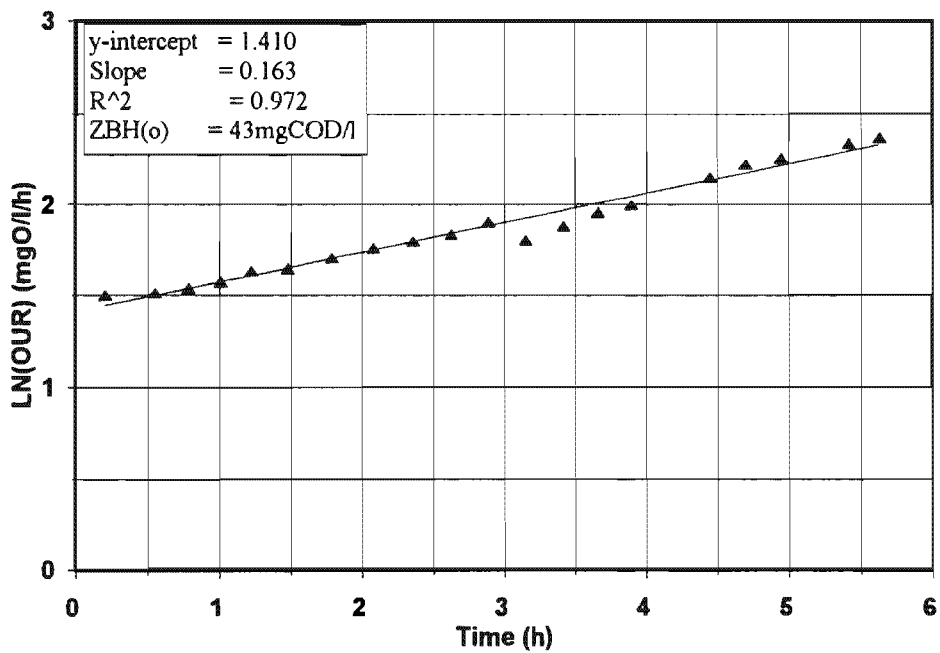


Fig B109b ln(OUR) graph for wastewater plus mixed liquor batch test, 09-06, batch no. 27

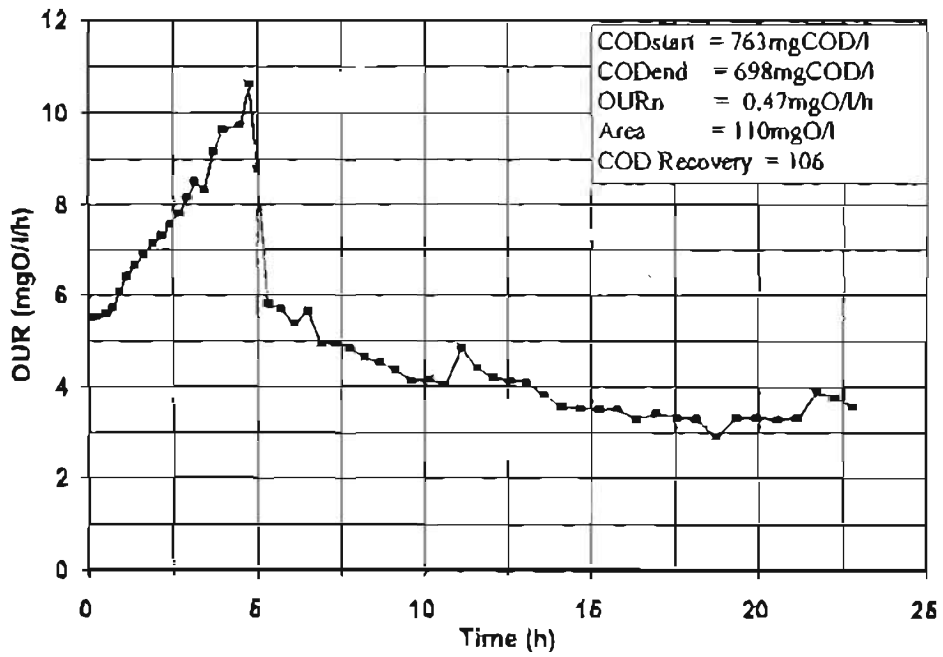


Fig B110a OUR graph for wastewater plus mixed liquor batch test, 10-6, batch no. 27

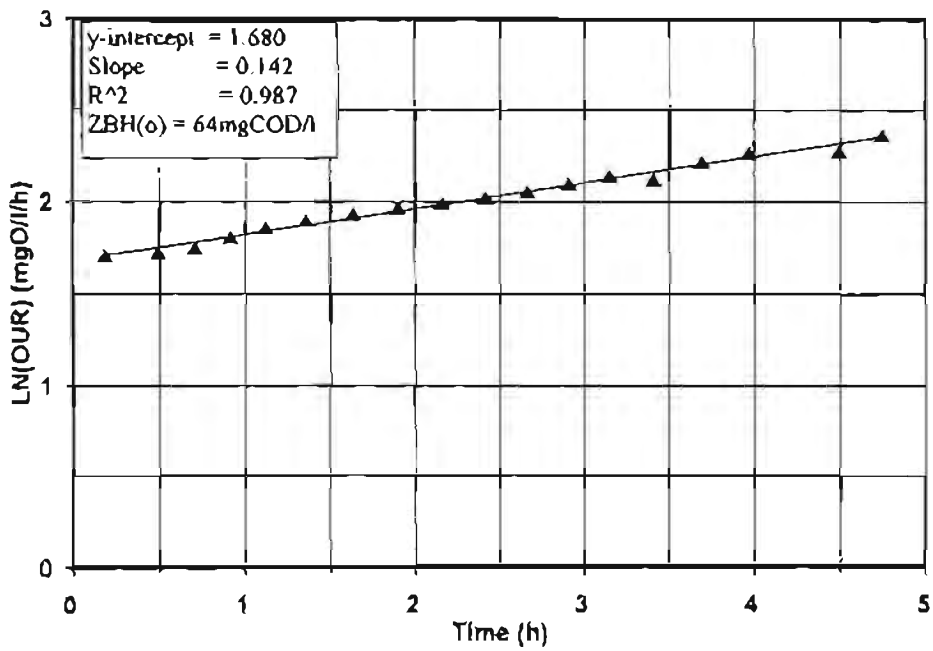


Fig B110b ln(OUR) graph for wastewater plus mixed liquor, 10-06, batch no. 27

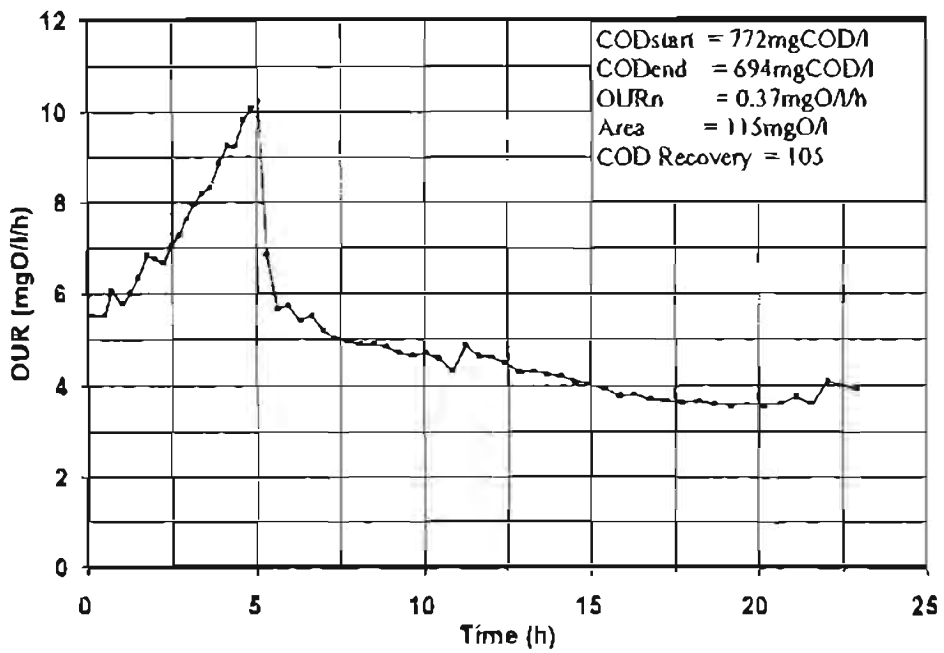


Fig B111a OUR graph for wastewater plus mixed liquor batch test, 10-06, batch no. 27

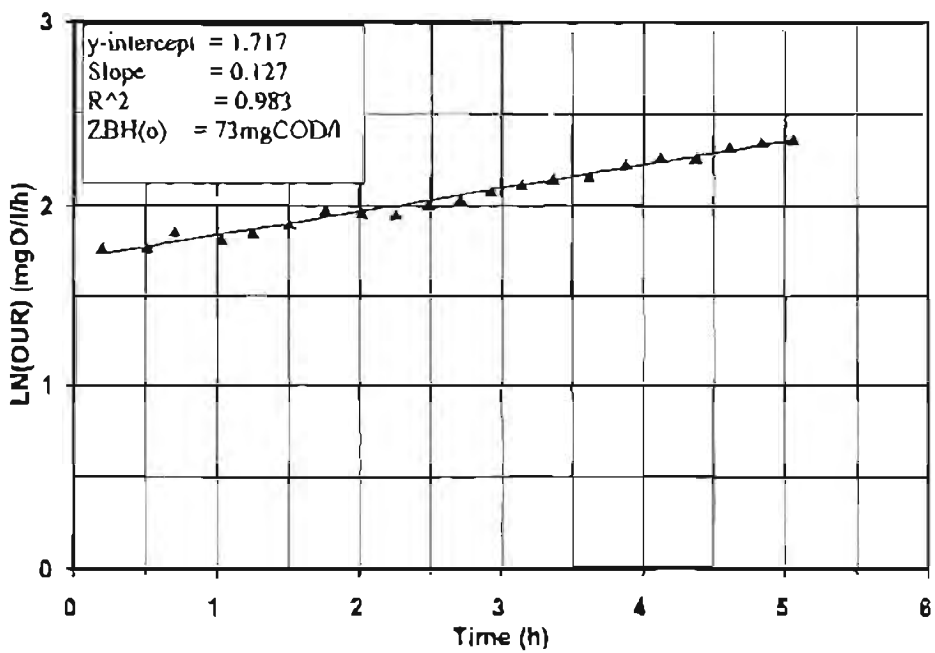


Fig B111b Ln(OUR) graph for wastewater plus mixed liquor batch test, 10-06, batch no. 27

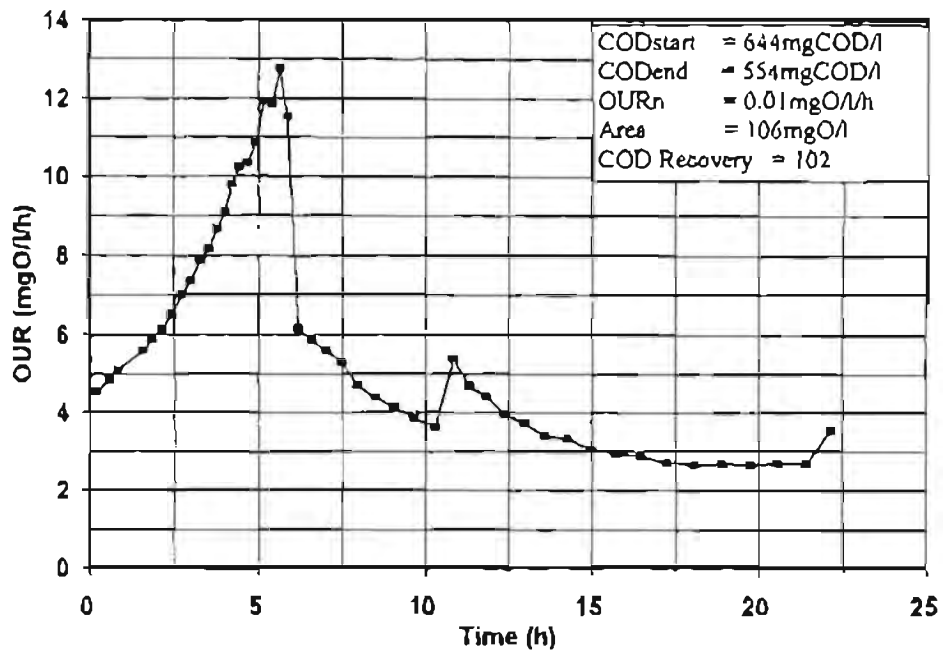


Fig B112a OUR graph for wastewater plus mixed liquor batch test, 11-06, batch no. 27

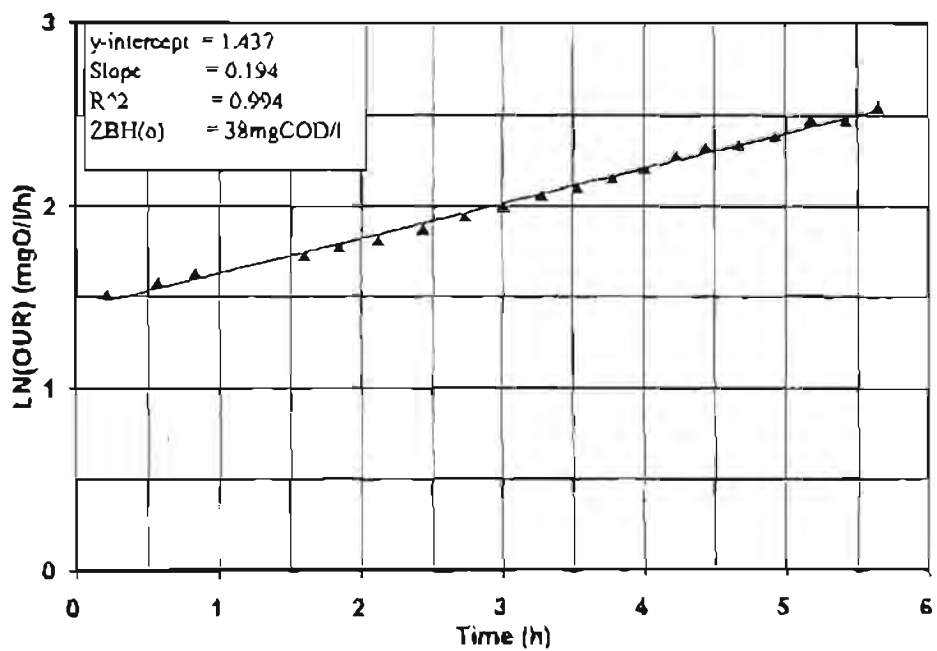


Fig B112b ln(OUR) graph for wastewater plus mixed liquor batch test, 11-06, batch no. 27

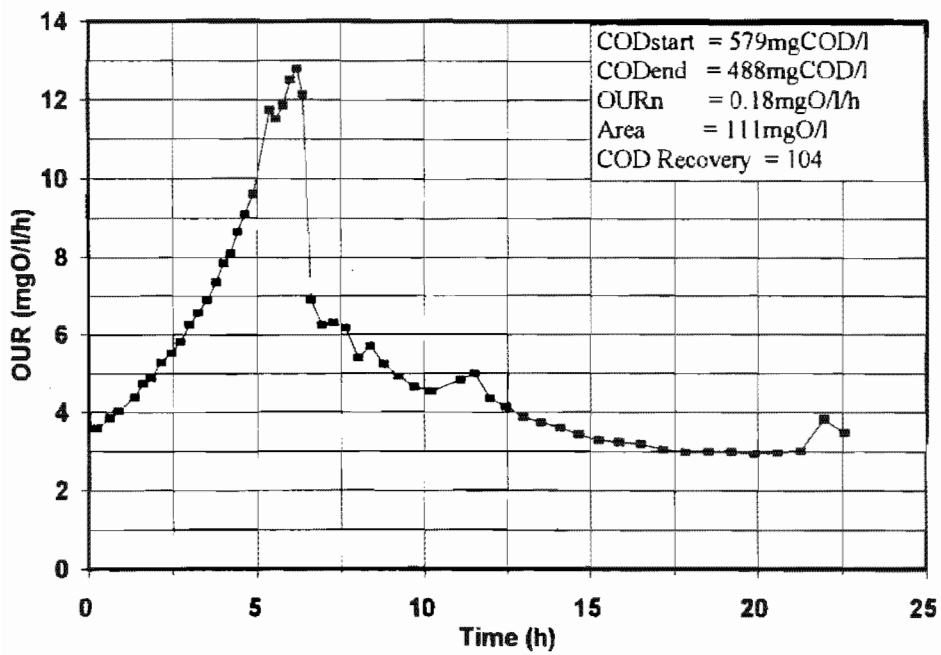


Fig B113a OUR graph for wastewater plus mixed liquor batch test, 11-06, batch no.27

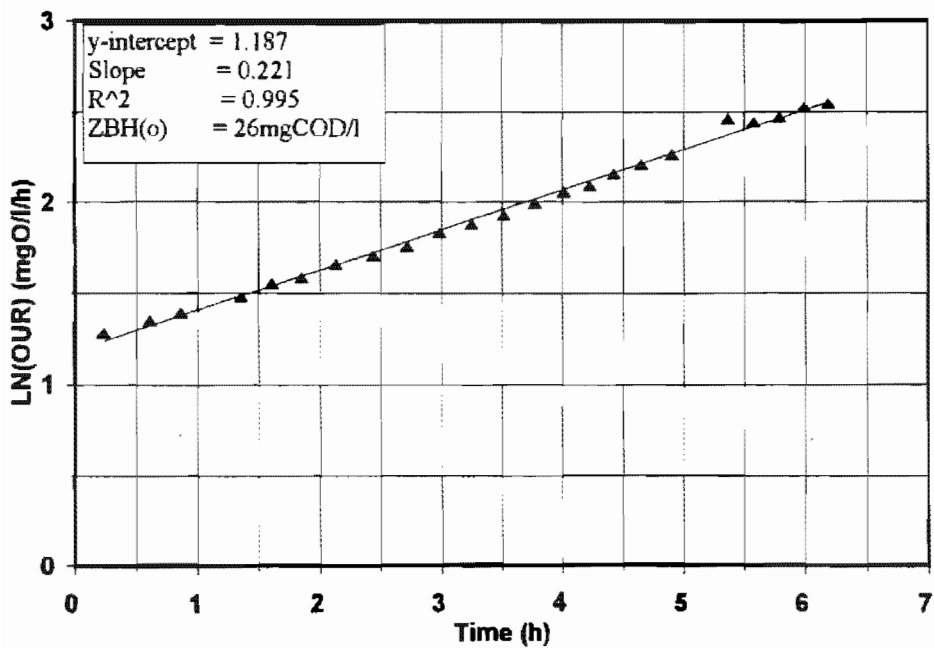


Fig B113b ln(OUR) graph for wastewater plus mixed liquor batch test, 11-06, batch no.27

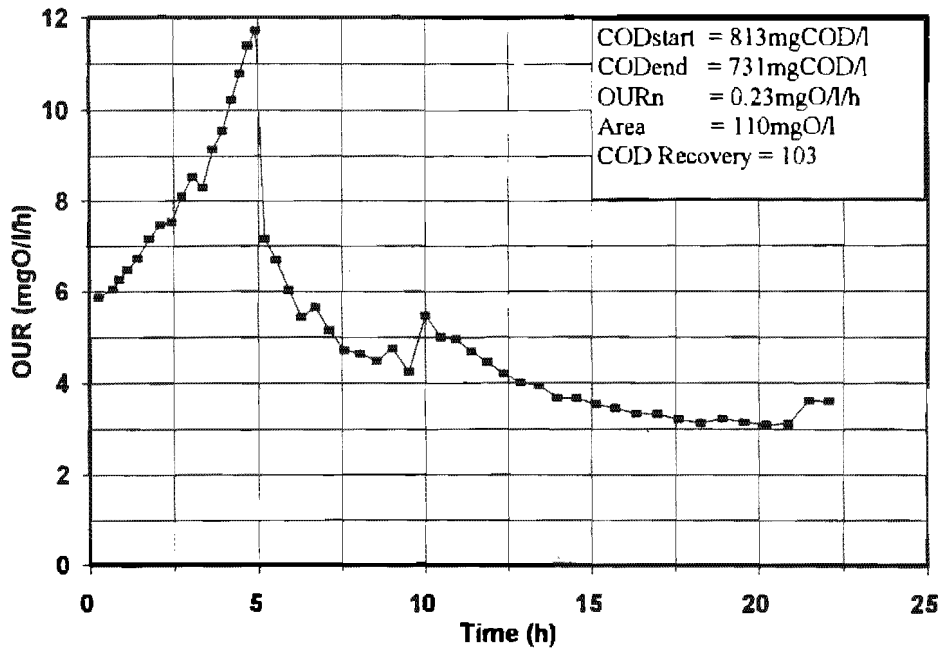


Fig B114a OUR graph for wastewater plus mixed liquor batch test, 12-06, batch no.27

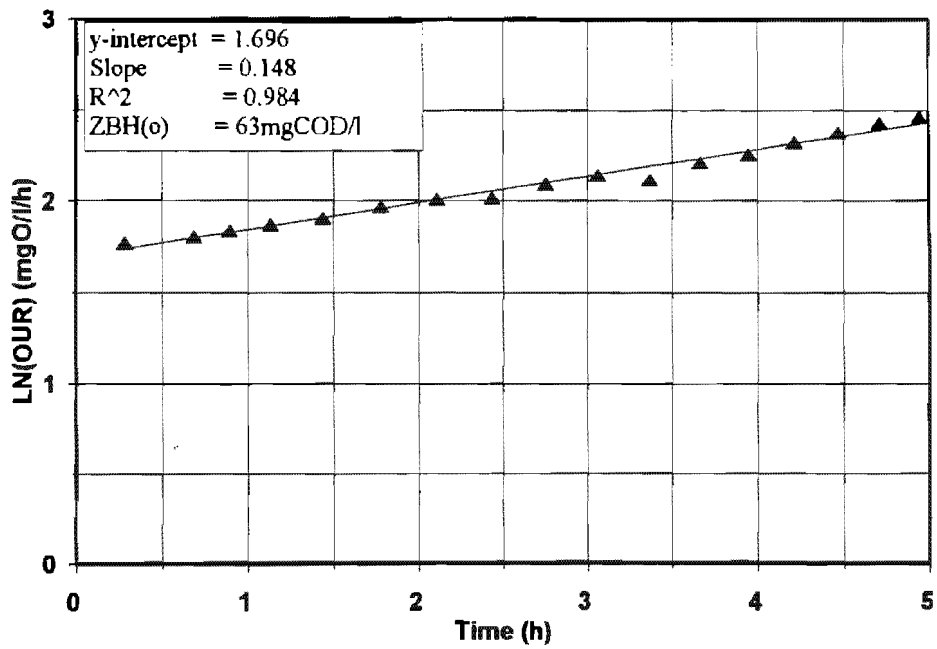


Fig B114b LN(OUR) graph for wastewater plus mixed liquor batch test, 12-06, batch no. 27

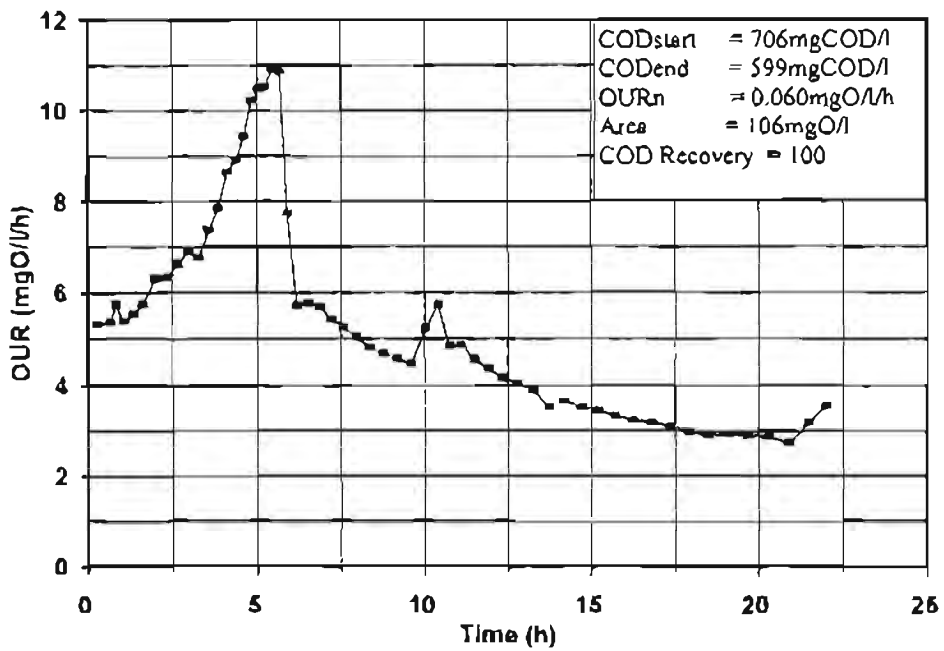


Fig B115a OUR graph for wastewater plus mixed liquor batch test, 12-06, batch no. 27

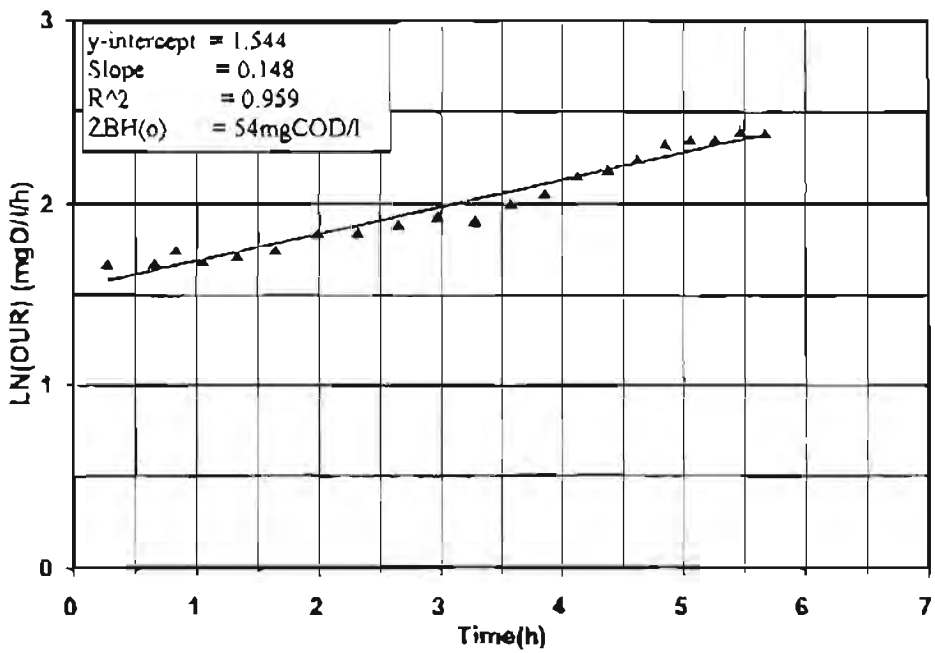


Fig B115b Ln(OUR) graph for wastewater plus mixed liquor batch test, 12-06, batch no. 27

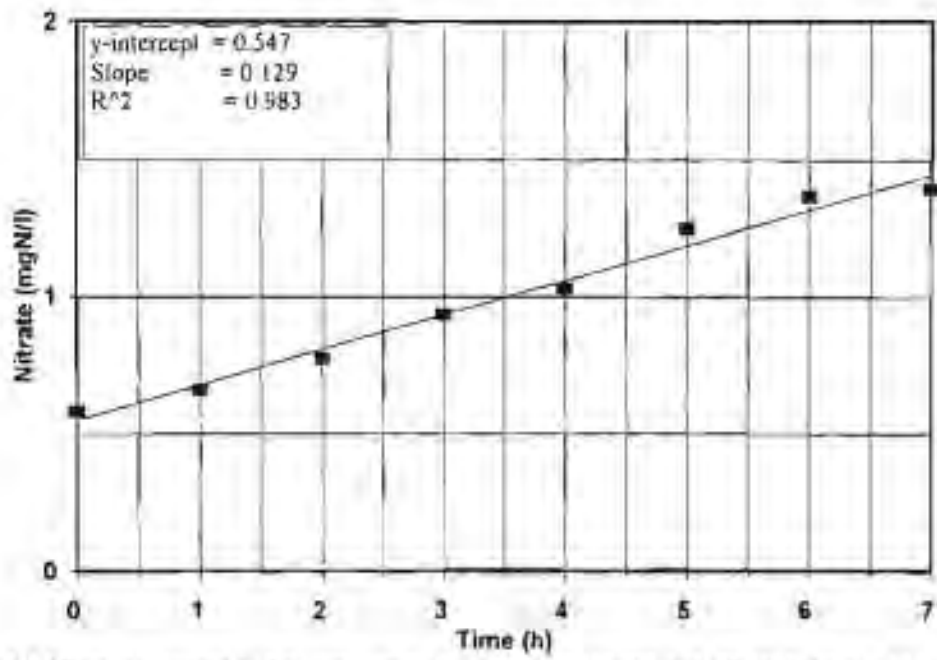


Fig N1 Nitrate concentration for wastewater plus mixed liquor batch test, 20-10, batch no. 12

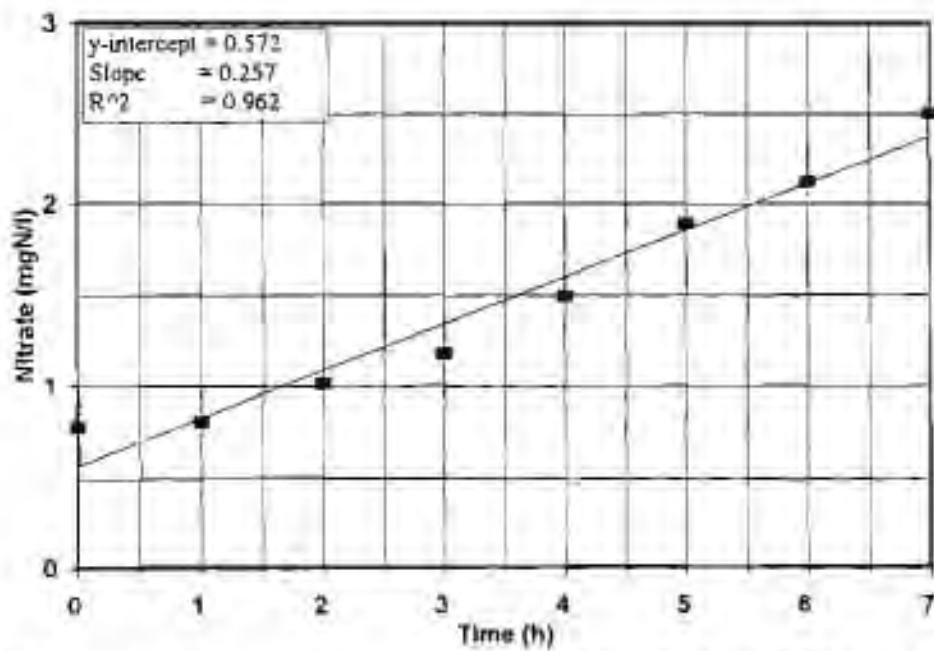


Fig N2 Nitrate concentration graph for wastewater plus mixed liquor batch test, 22-10, batch no. 12

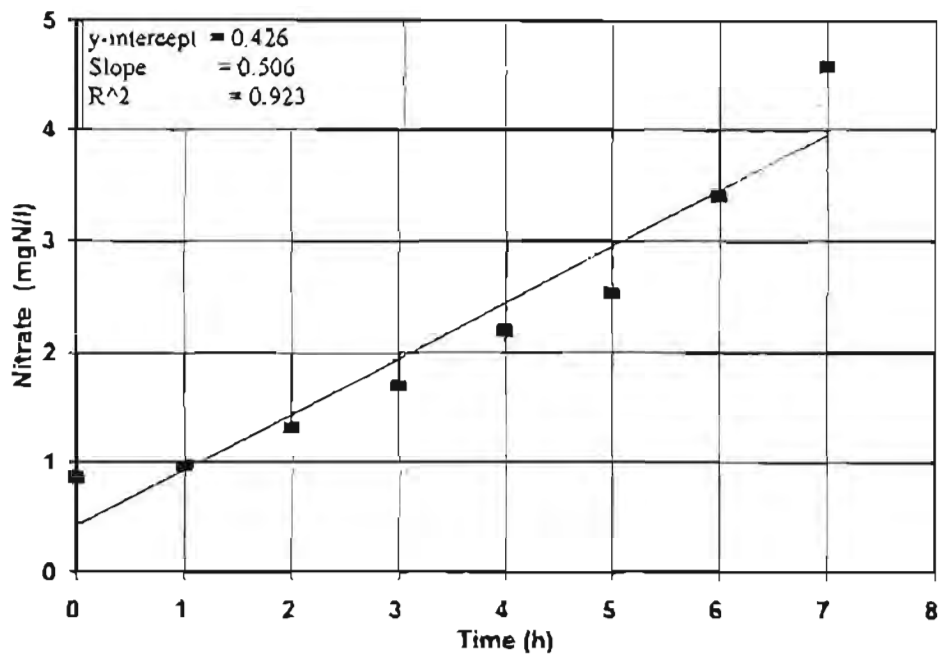


Fig N3 Nitrate concentration graph for wastewater plus mixed liquor batch test ,23-10, batch no. 12

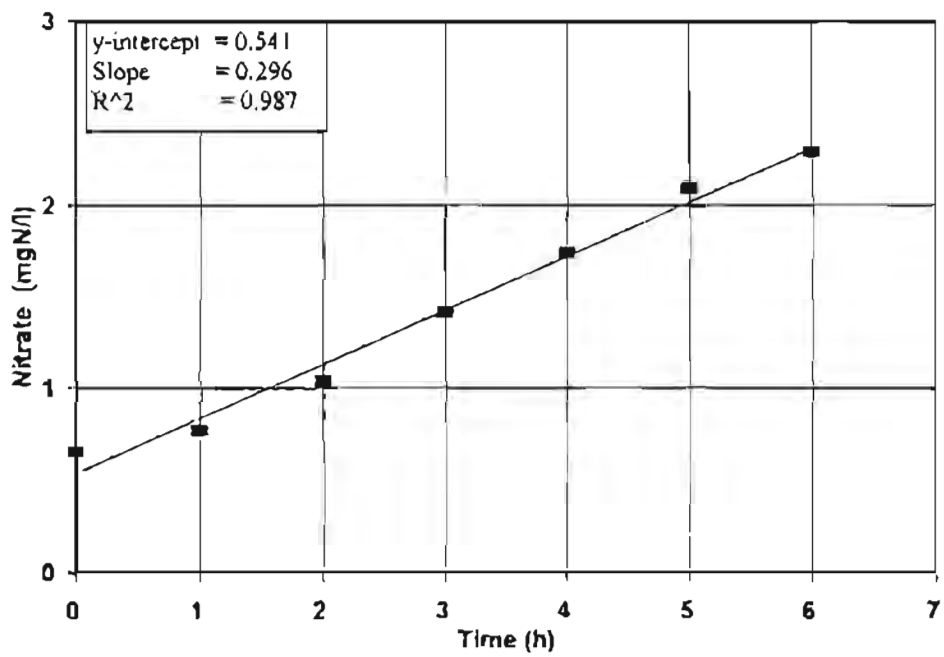


Fig N4 Nitrate concentration graph for wastewater plus mixed liquor batch test, 24-01, batch no. 12

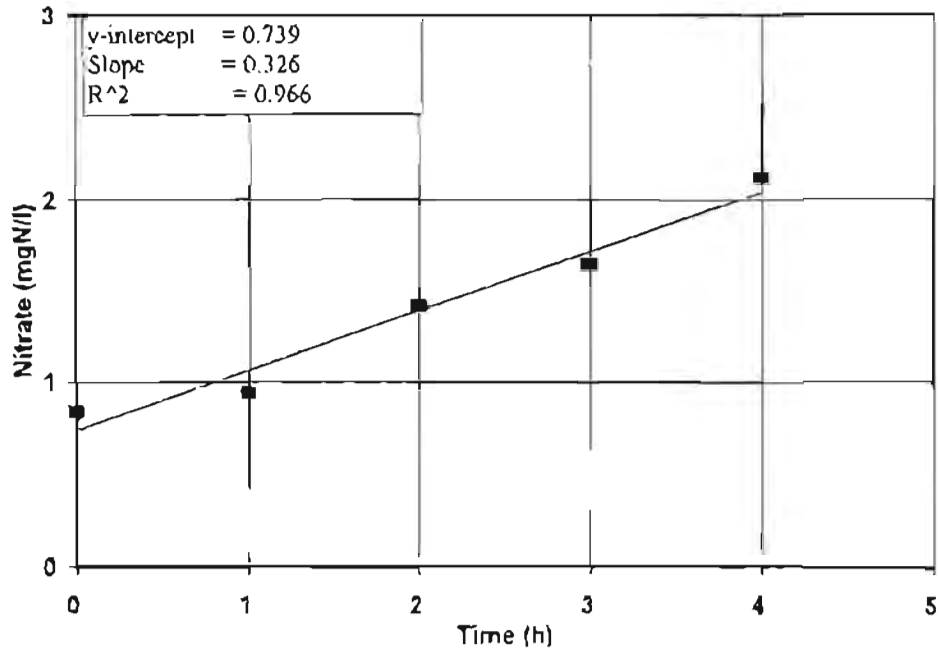


Fig N5 Nitrate concentration graph for wastewater plus mixed liquor batch test, 26-10, batch no.12

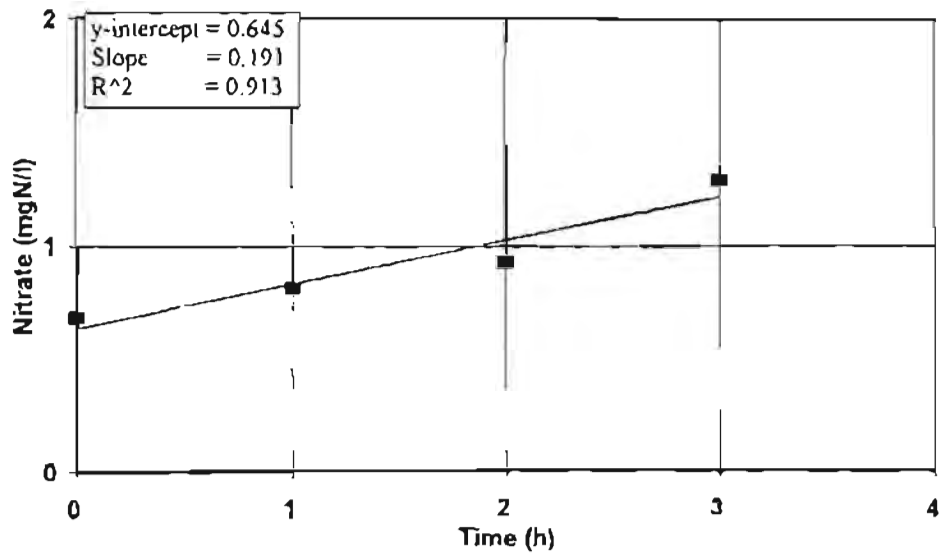


Fig N6 Nitrate concentration graph for wastewater plus mixed liquor batch test, 27-10, batch no.12

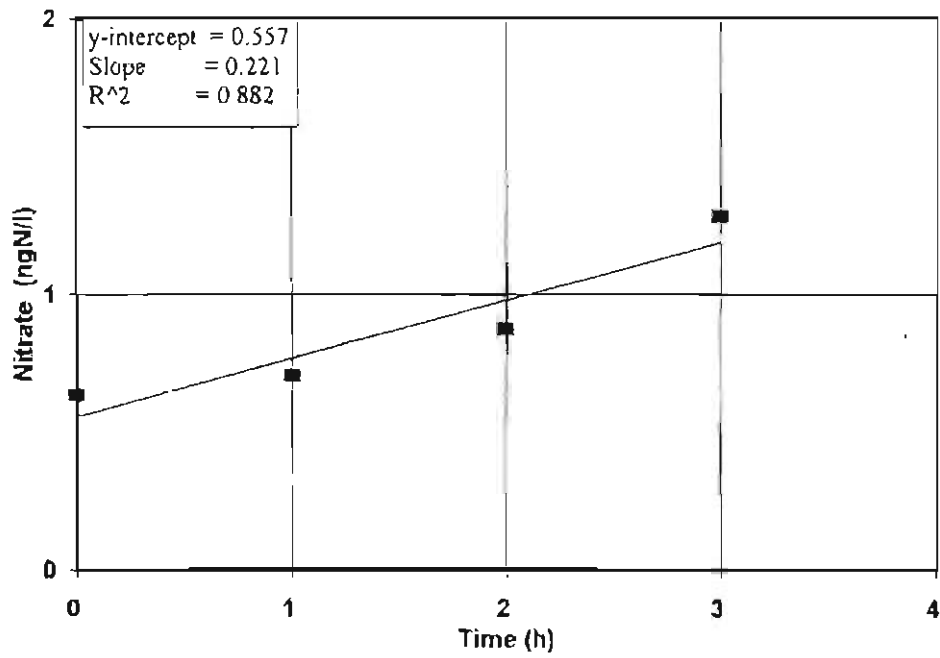


Fig N7 Nitrate concentration for wastewater plus mixed liquor batch test, 28-10, batch no. 12

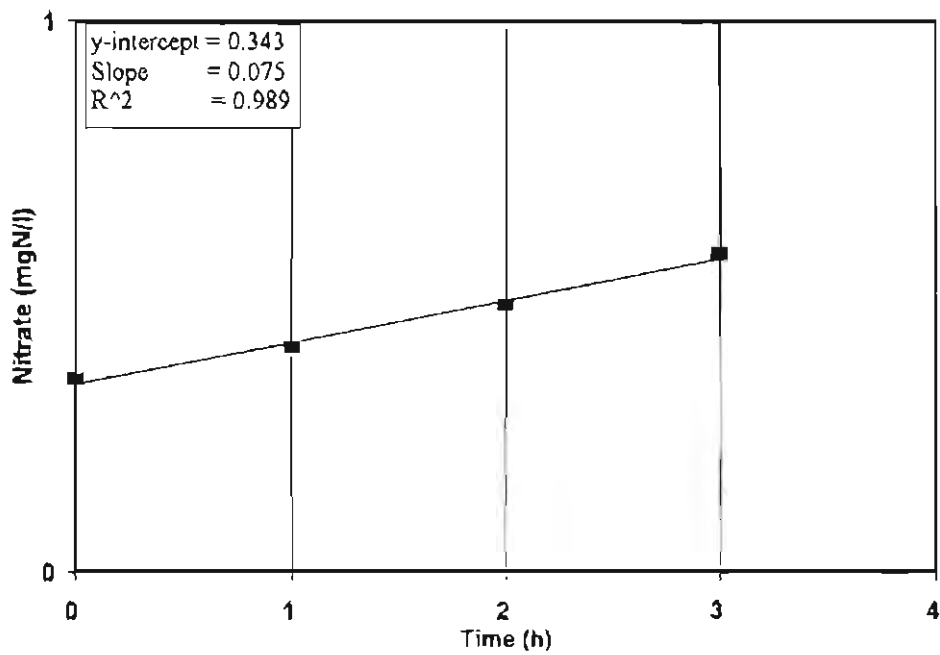


Fig N8 Nitrate concentration for wastewater plus mixed liquor batch test, 29-10, batch no. 12

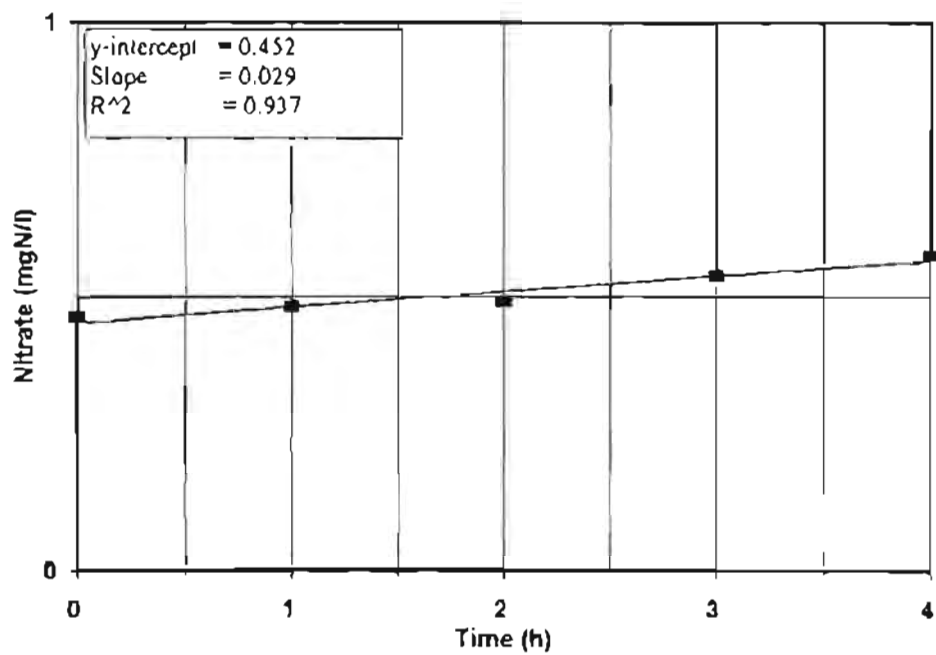


Fig N9 Graph for wastewater plus mixed liquor batch test, 01-11, batch no. 13

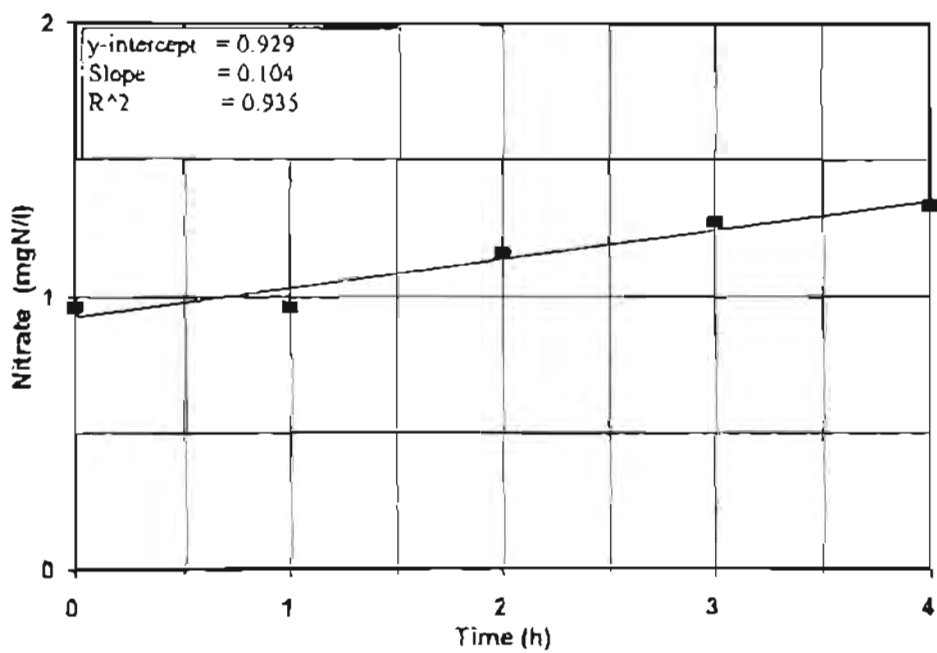


Fig N10 Nitrate concentration graph for wastewater plus mixed liquor batch test, 04-11, batch no. 13

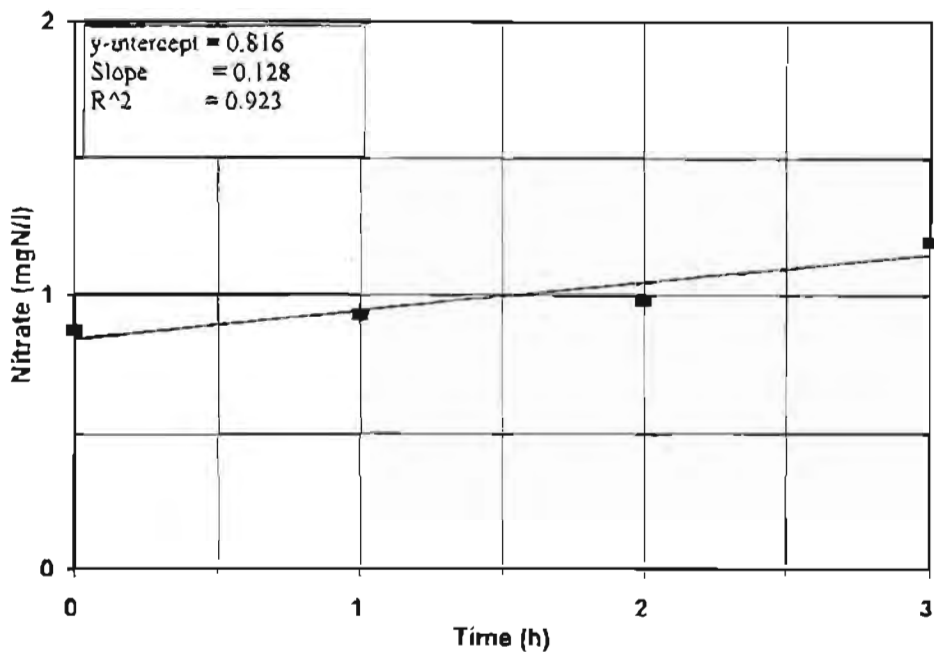


Fig N11 Nitrate concentration graph for wastewater plus mixed liquor batch test,06-11, batch no. 13

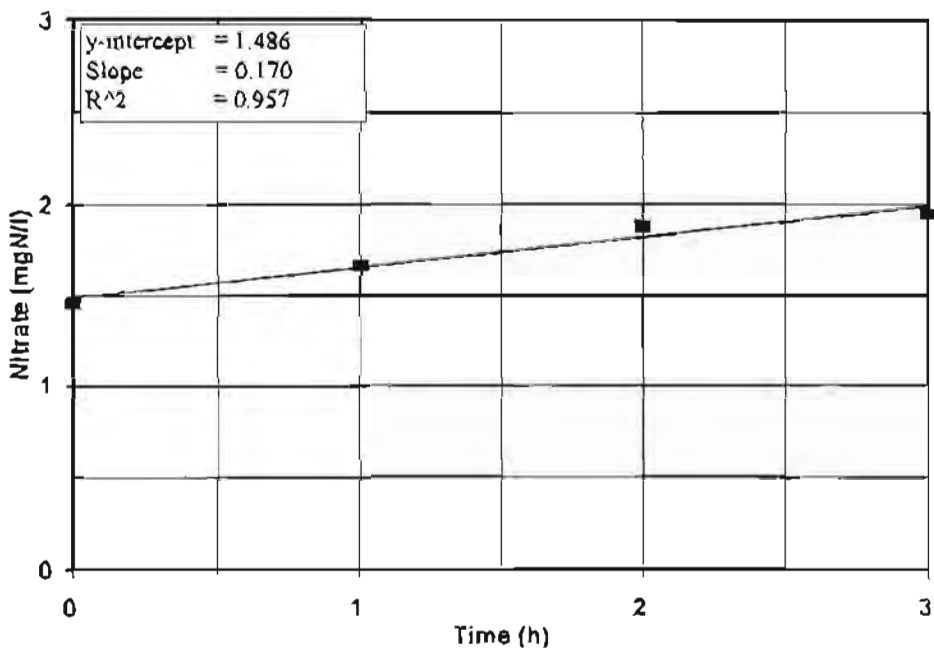


Fig N12 Nitrate concentration graph for wastewater plus mixed liquor batch test,07-11, batch no. 13

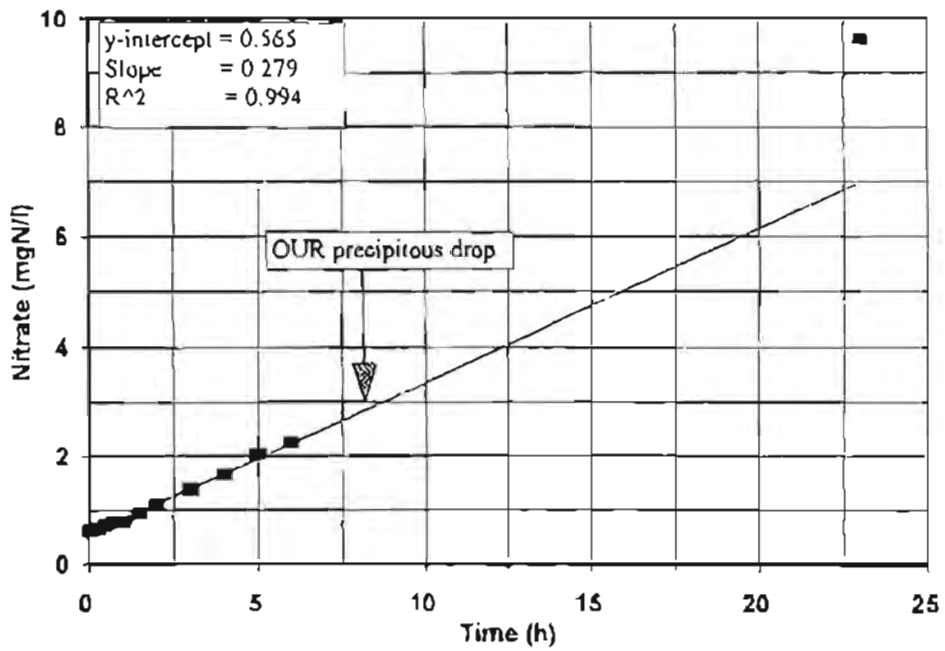


Fig N13 Nitrate concentration graph for wastewater plus mixed liquor batch test, 11-01, batch no.17

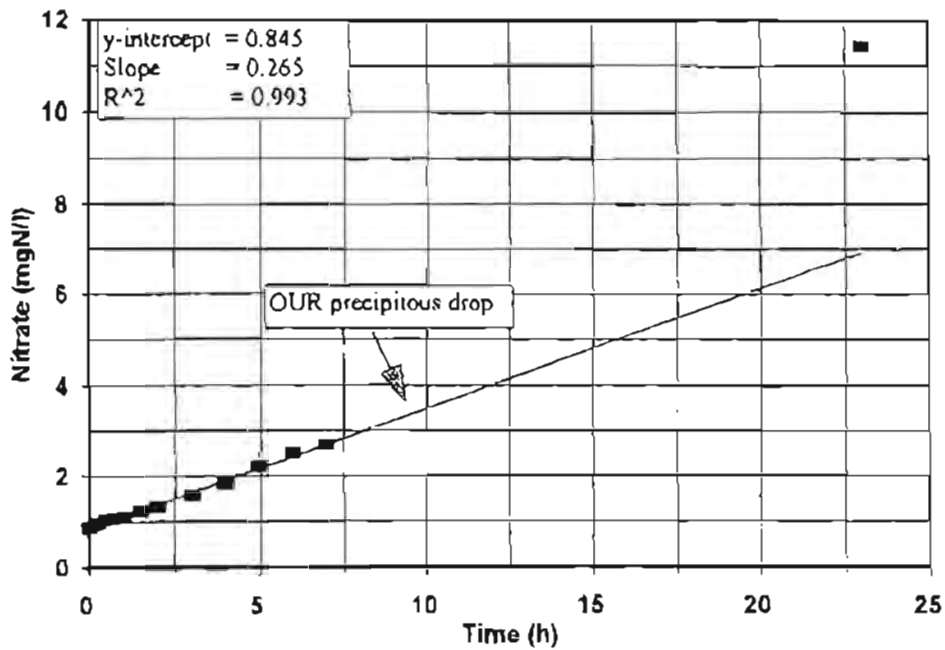


Fig N14 Nitrate concentration graph for wastewater plus mixed liquor batch test, 12-01, batch no.17



Fig N15 Nitrate concentration graph for wastewater plus mixed liquor: batch test.15-01, batch no 17

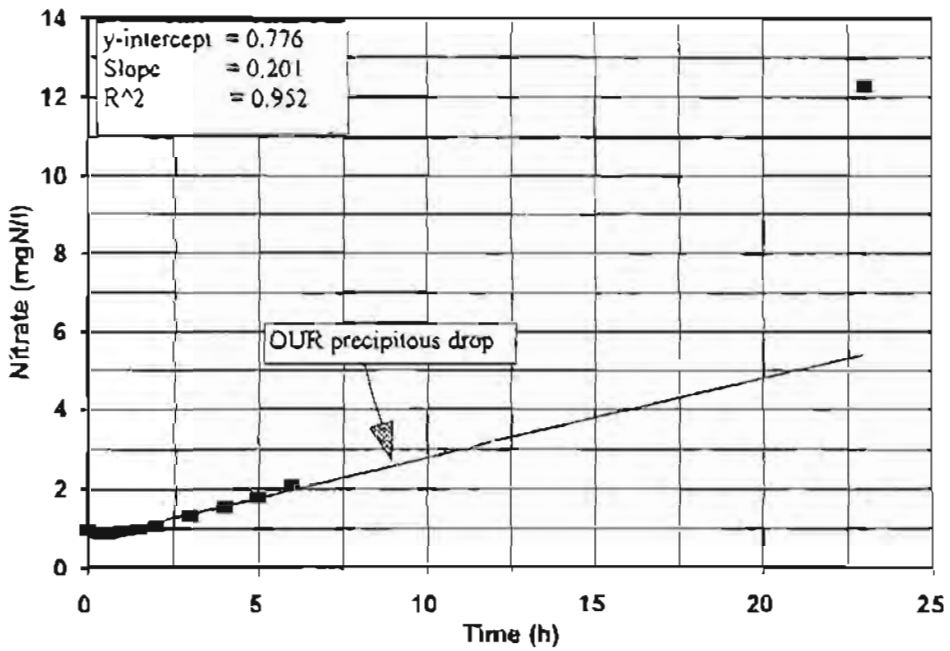


Fig N16 Nitrate concentration graph for wastewater plus mixed liquor batch test.16-01, batch no. 17

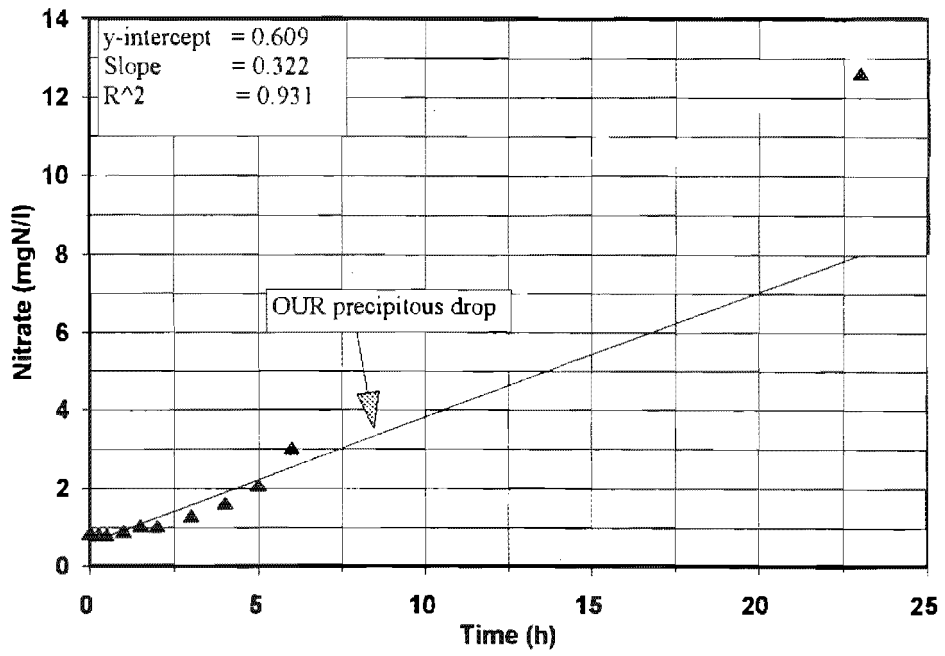


Fig N17 Nitrate concentration graph for wastewater plus mixed liquor batch test, 17-01, batch no.17

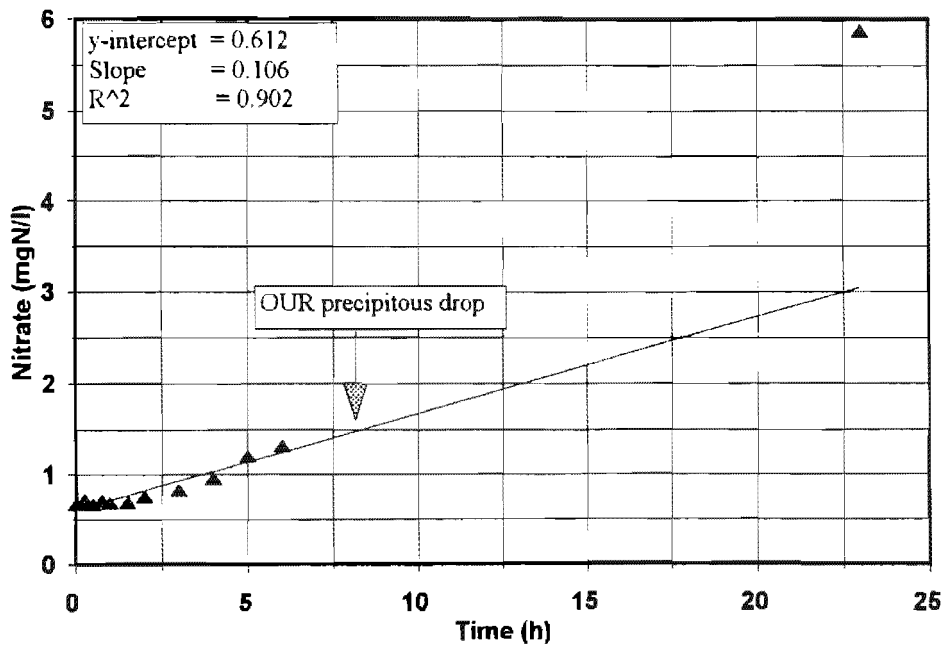


Fig N18 Nitrate concentration graph for wastewater plus mixed liquor batch test, 18-01, batch no 17

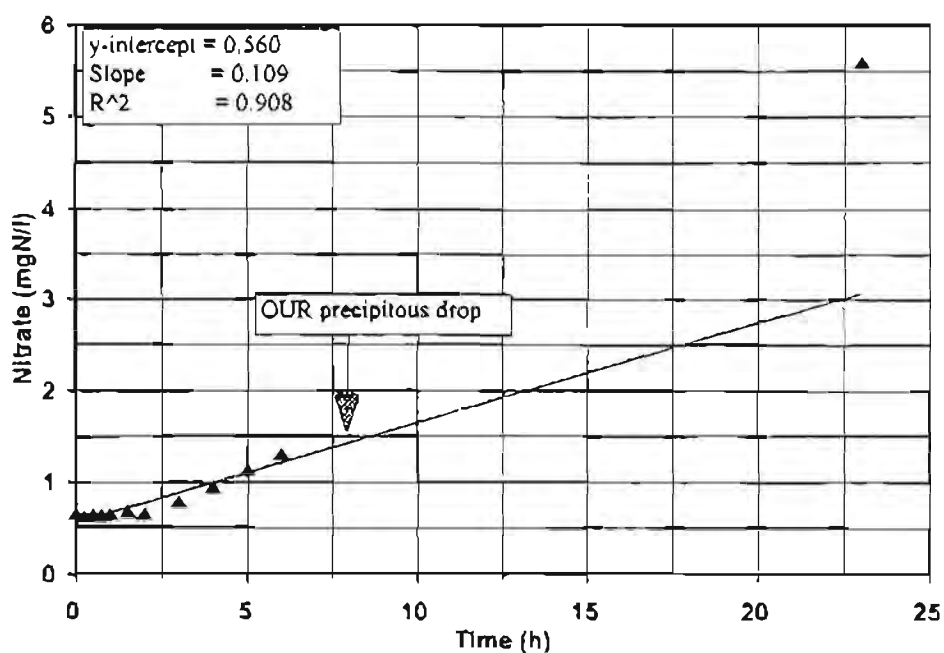


Fig N19 Nitrate concentration graph for wastewater plus mixed liquor batch test, 19-01, batch no.17

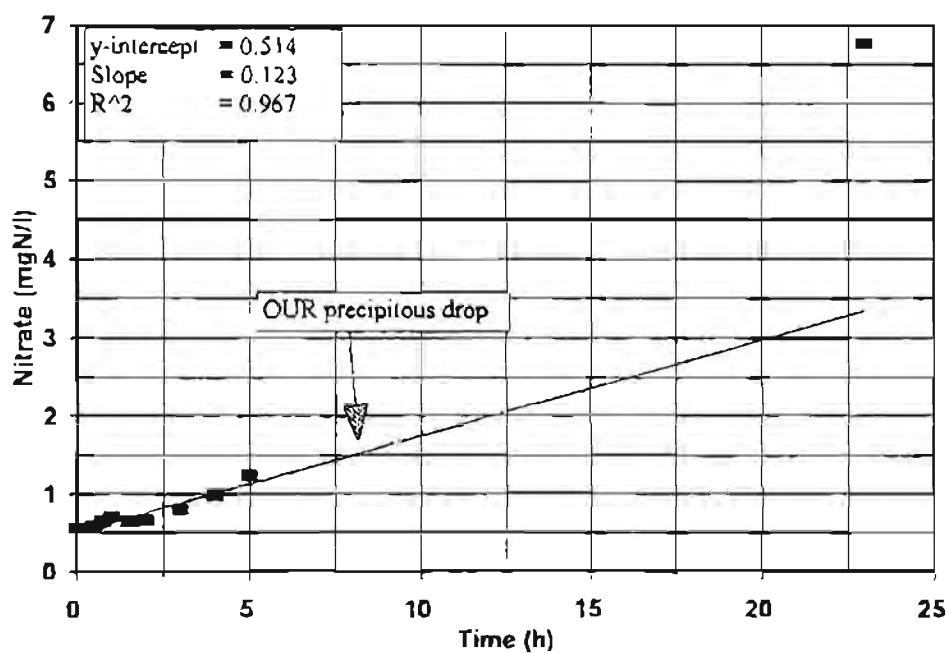


Fig N20 Nitrate concentration graph for wastewater plus mixed liquor batch test, 21-01, batch no.17

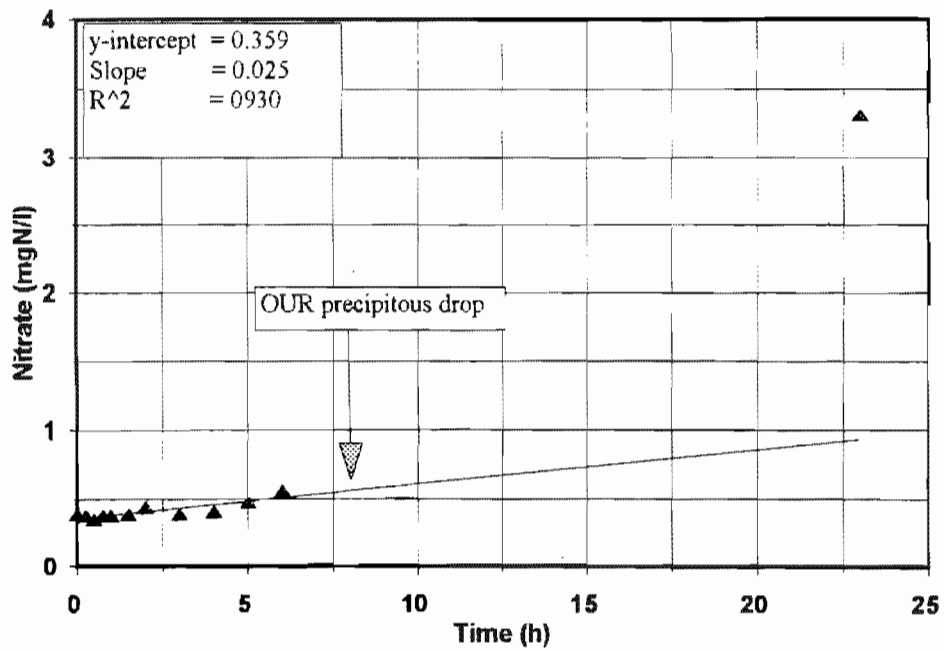


Fig N21 Nitrate concentration graph for wastewater plus mixed liquor batch test,22-01, batch no. 17

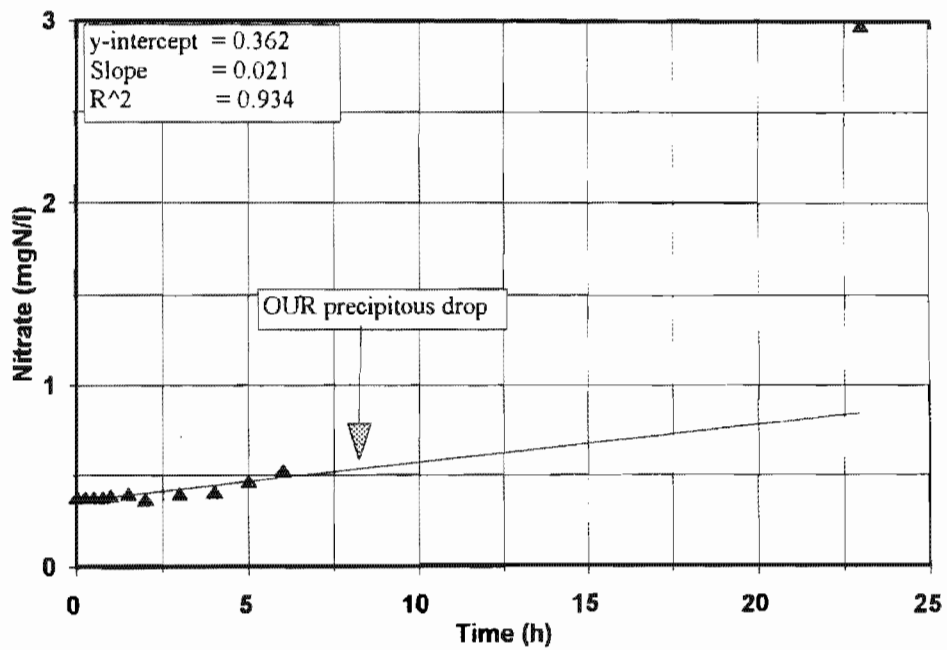


Fig N22 Nitrate concentration graph for wastewater plus mixed liquor batch test,23-01, batch no. 17

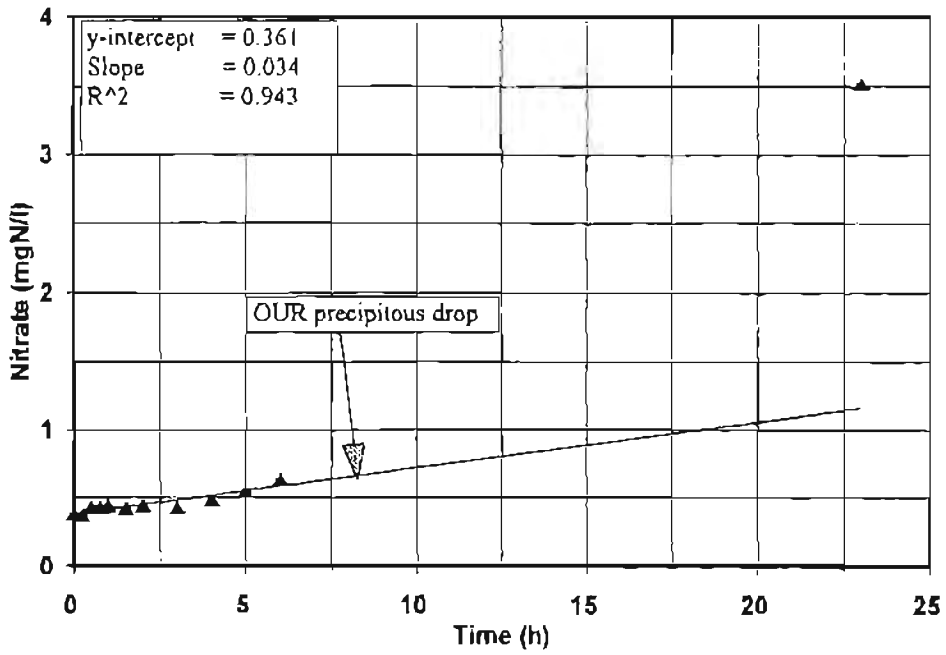


Fig N23 Nitrate concentration graph for wastewater plus mixed liquor batch test, 24-01, batch no. 17

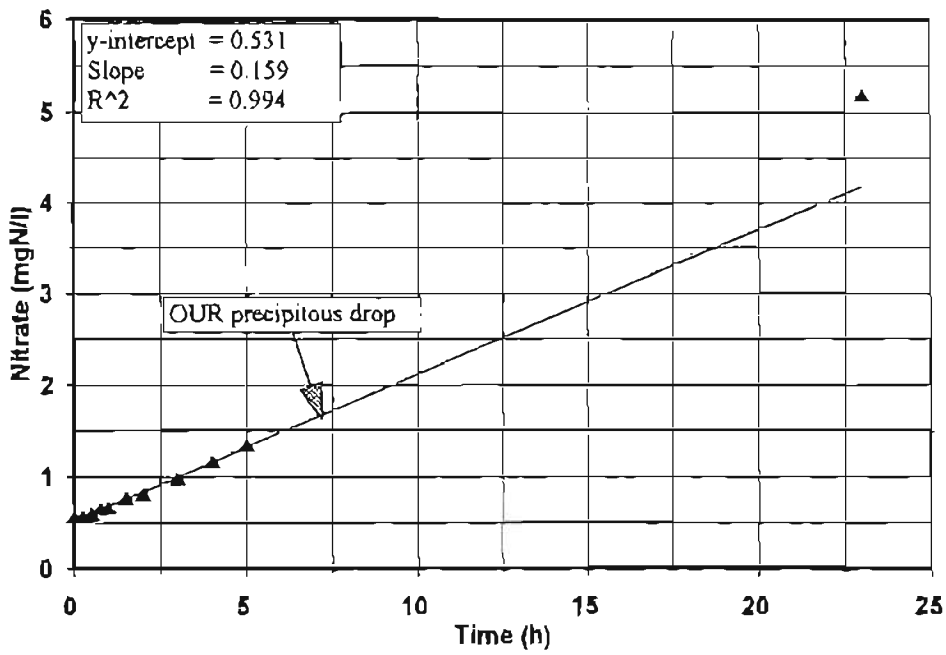


Fig N24 Nitrate concentration graph for wastewater plus mixed liquor batch test, 25-01, batch no. 18

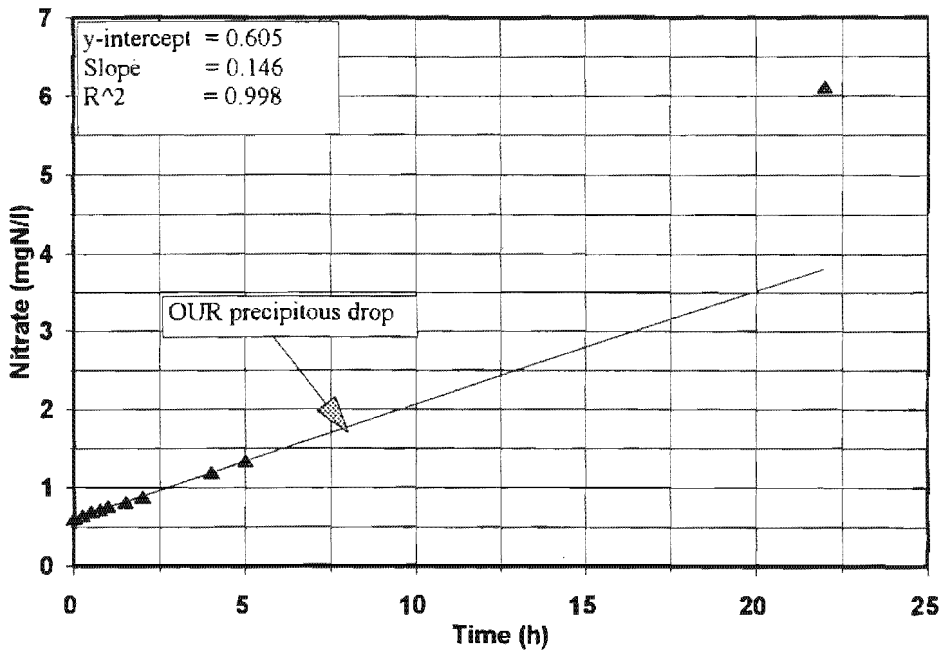


Fig N25 Nitrate concentration graph for wastewater plus mixed liquor batch test, 26-01, batch no. 18

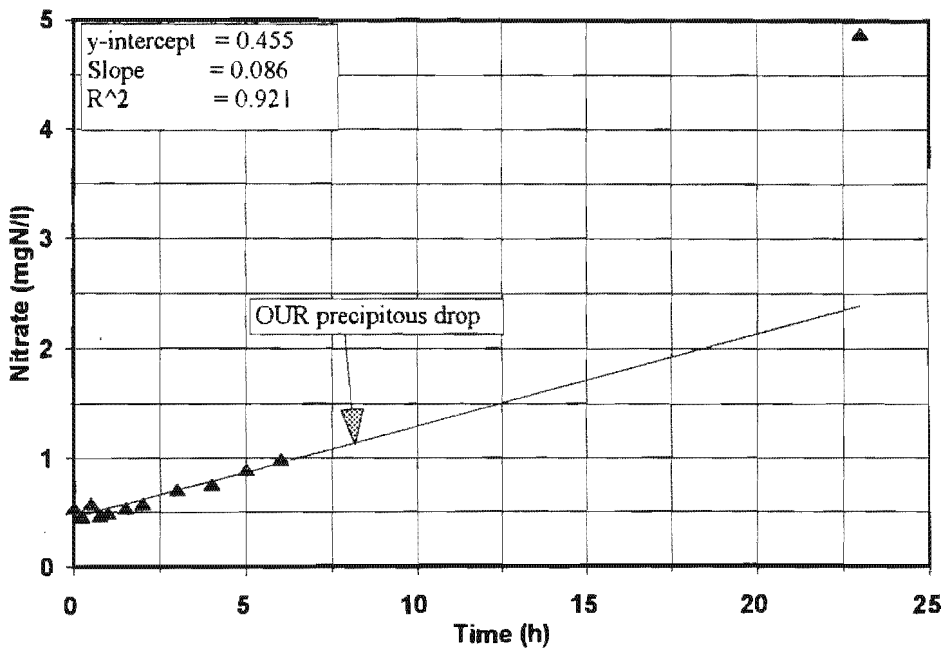


Fig N26 Nitrate concentration graph for wastewater plus mixed liquor batch test, 29-01, batch no. 18

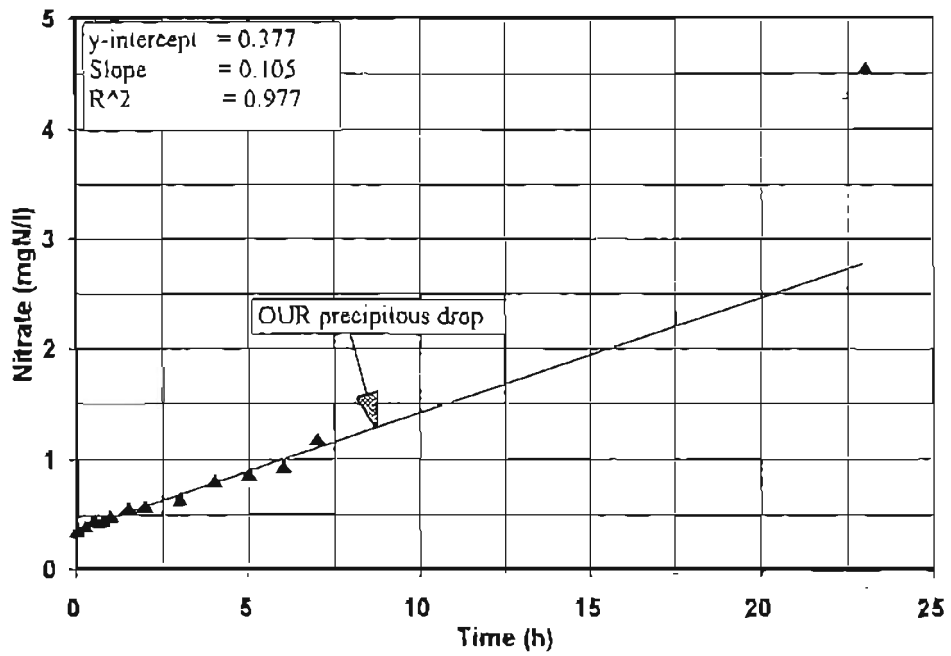


Fig N27 Nitrate concentration graph for wastewater plus mixed liquor batch test,30-01, batch no.18

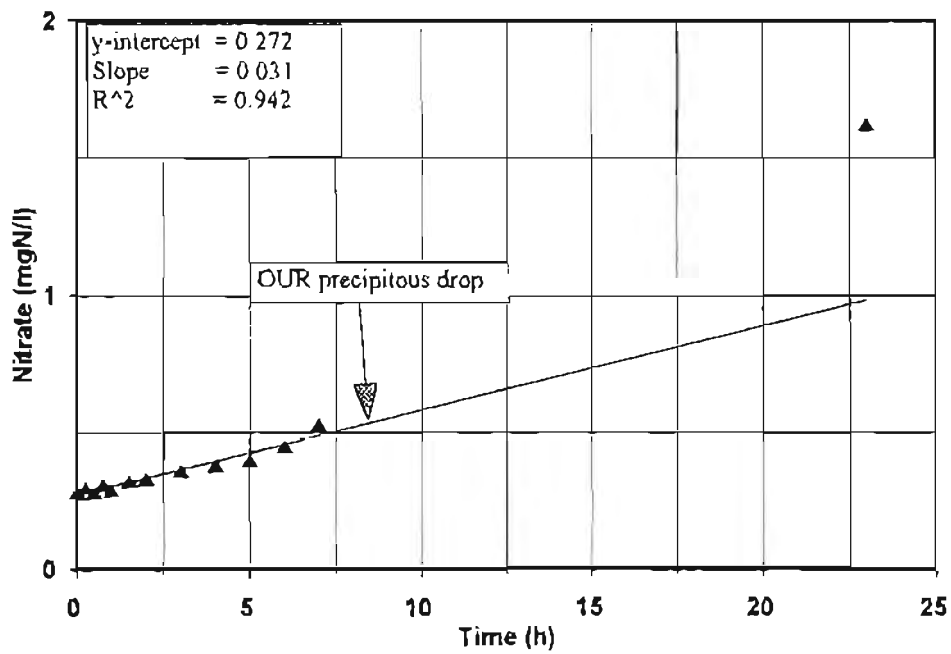


Fig N28 Nitrate concentration graph for wastewater plus mixed liquor batch test,31-01, batch no.18

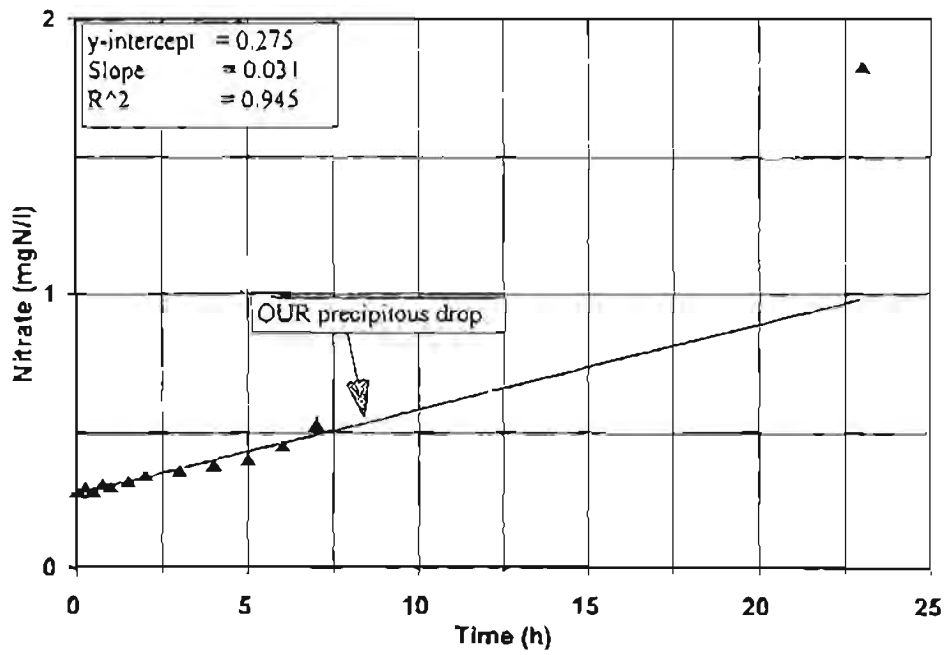


Fig N29 Nitrate concentration graph for wastewater plus mixed liquor batch test,01-02,batch no.18

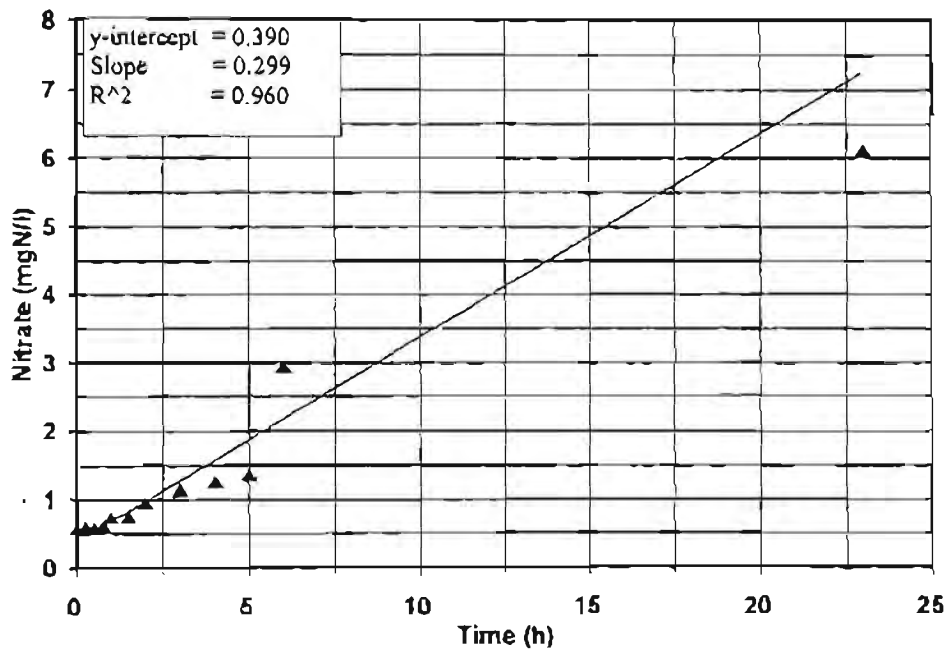


Fig N30 Nitrate concentration graph for wastewater plus mixed liquor batch test,02-02,batch no.18

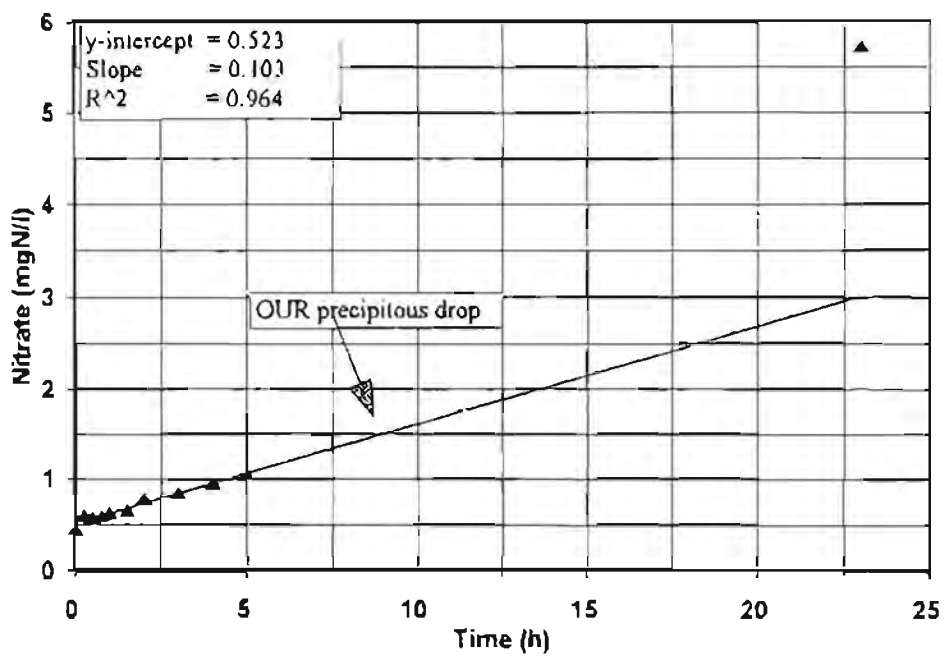


Fig N31 Nitrate concentration graph for wastewater plus mixed liquor batch test.03-02, batch no. 18

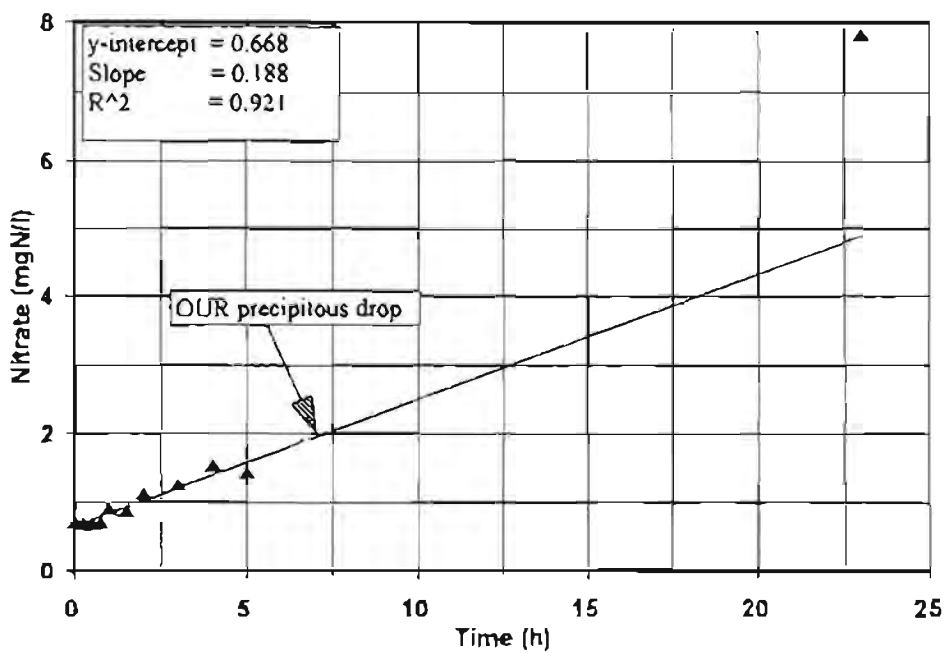


Fig N32 Nitrate concentration graph for wastewater plus mixed liquor batch test.04-02, batch no. 18

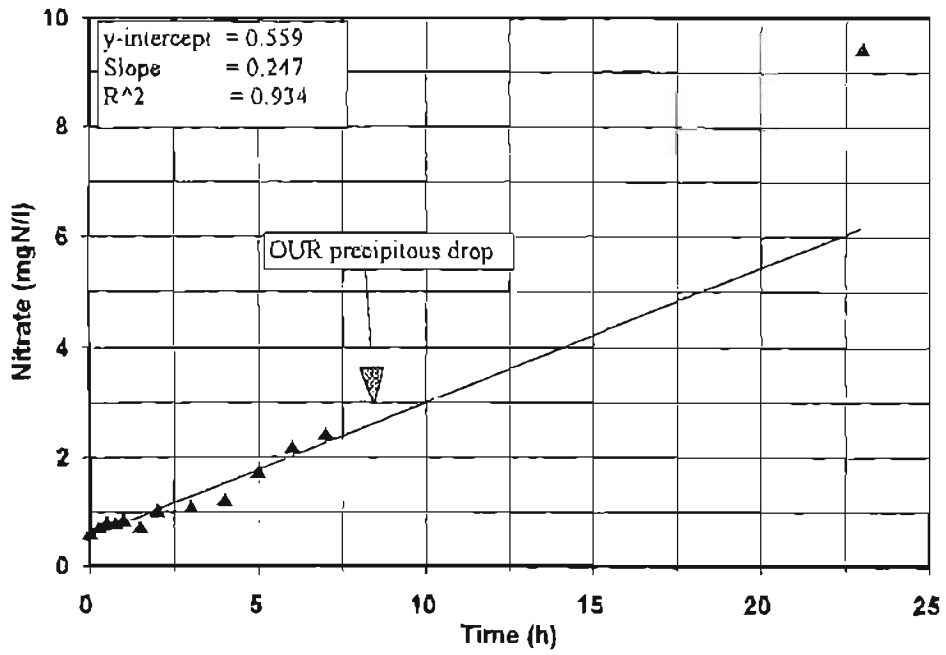


Fig N33 Nitrate concentration graph for wastewater plus mixed liquor batch test,05-02,batch no. 18

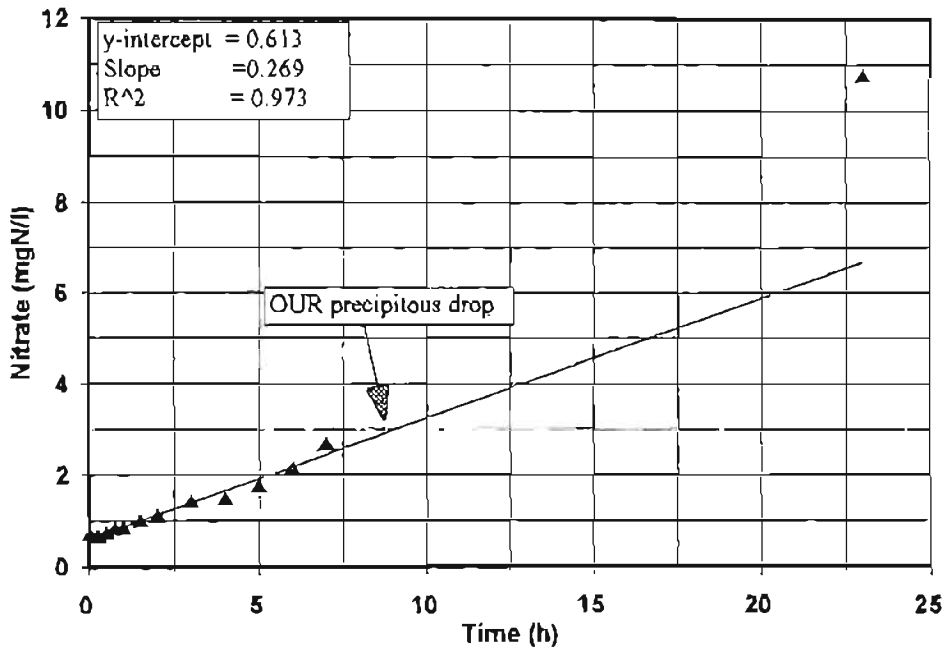


Fig N34 Nitrate concentration graph for wastewater plus mixed liquor batch test, batch no. 18

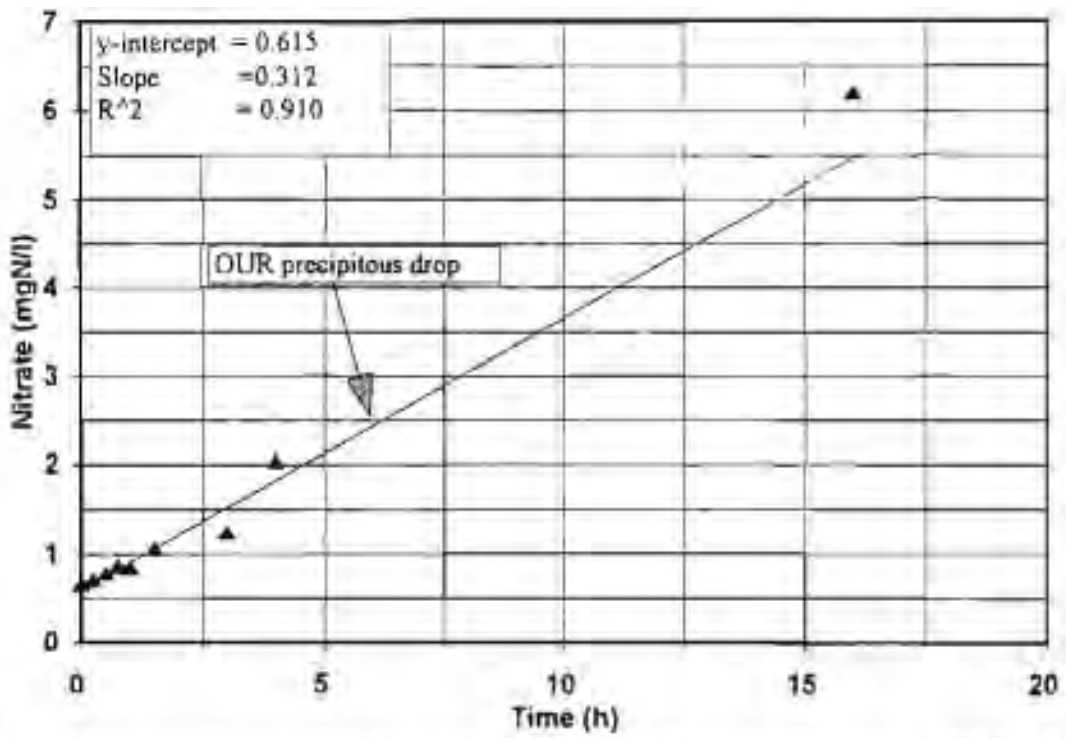


Fig N35 Nitrate concentration graph for wastewater plus mixed liquor batch test,07-02,batch no. 19

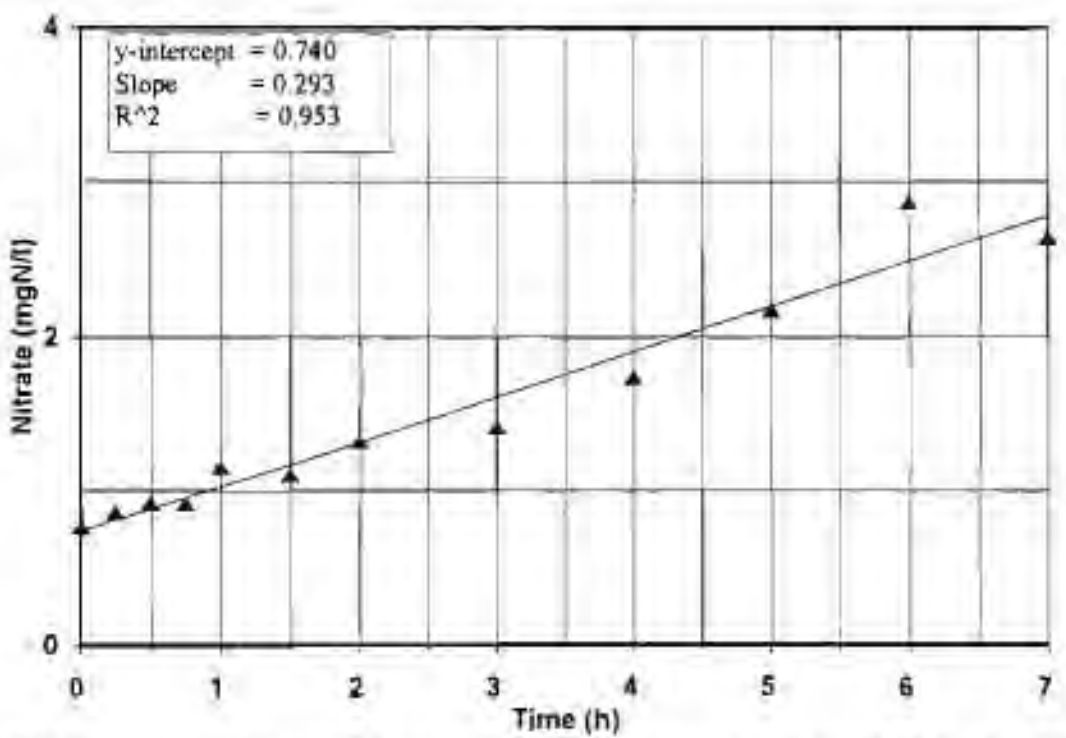


Fig N36 Nitrate concentration graph for wastewater plus mixed liquor batch test,08-02, batch no. 19

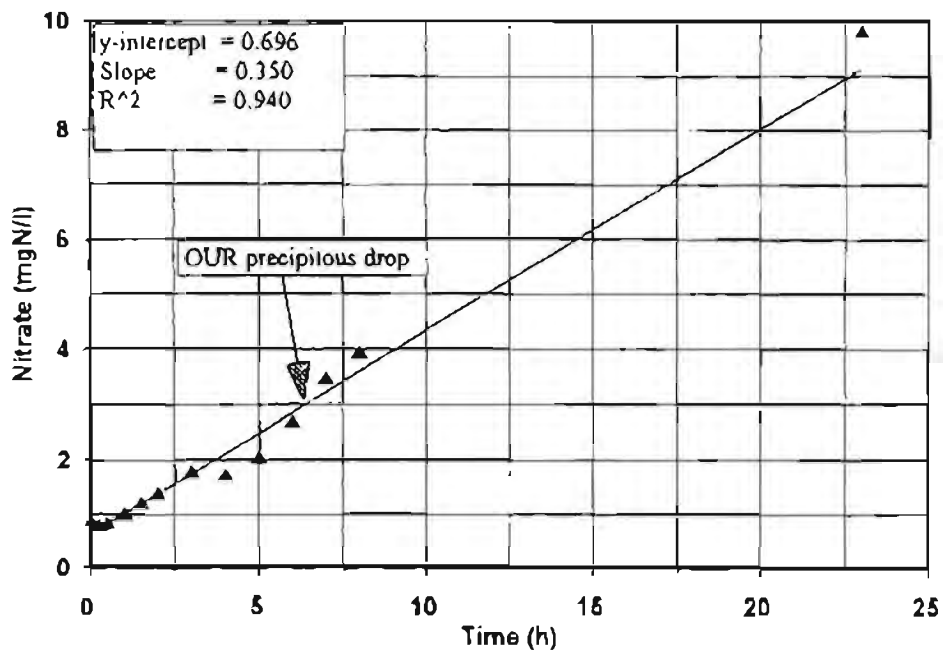


Fig N37 Nitrate concentration graph for wastewater plus mixed liquor batch test, 09-02, batch no. 19

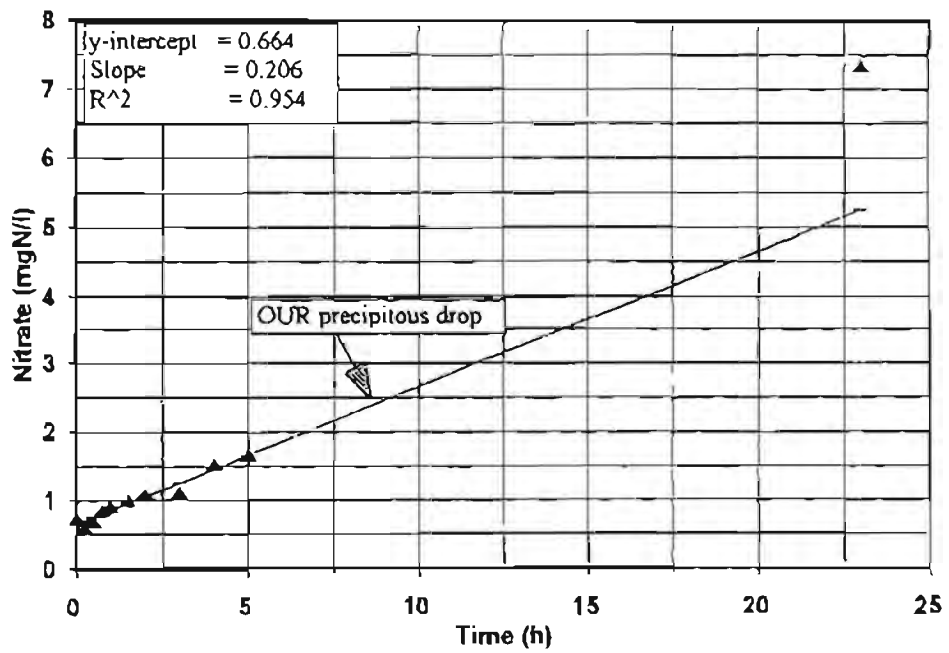


Fig N38 Nitrate concentration graph for wastewater plus mixed liquor batch test, 11-02, batch no 19

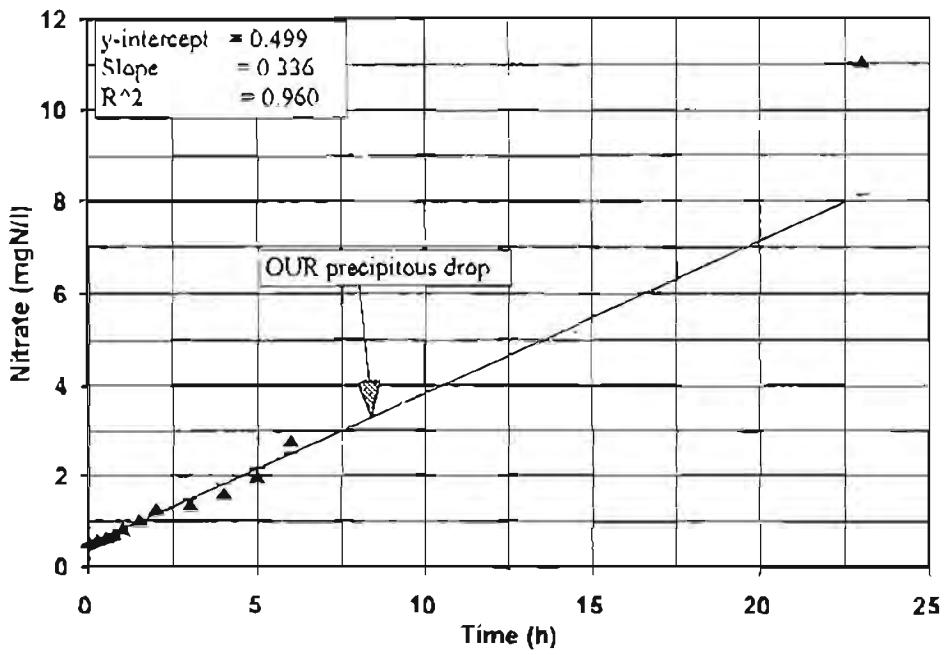


Fig N39 Nitrate concentration graph for wastewater plus mixed liquor batch test, 12-02, batch no. 19

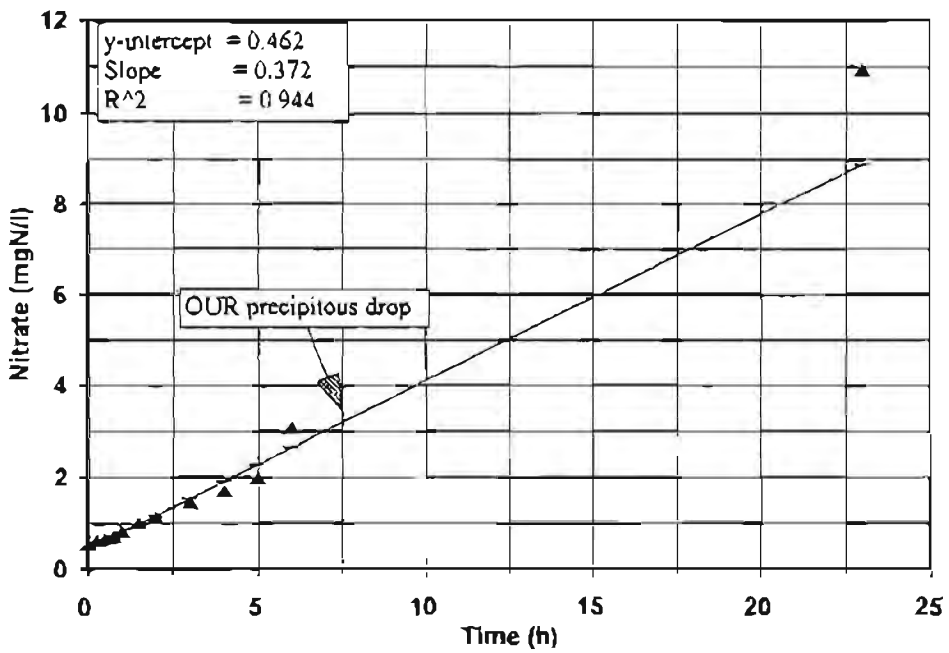


Fig N40 Nitrate concentration graph for wastewater plus mixed liquor batch test, 13-02, batch no. 19

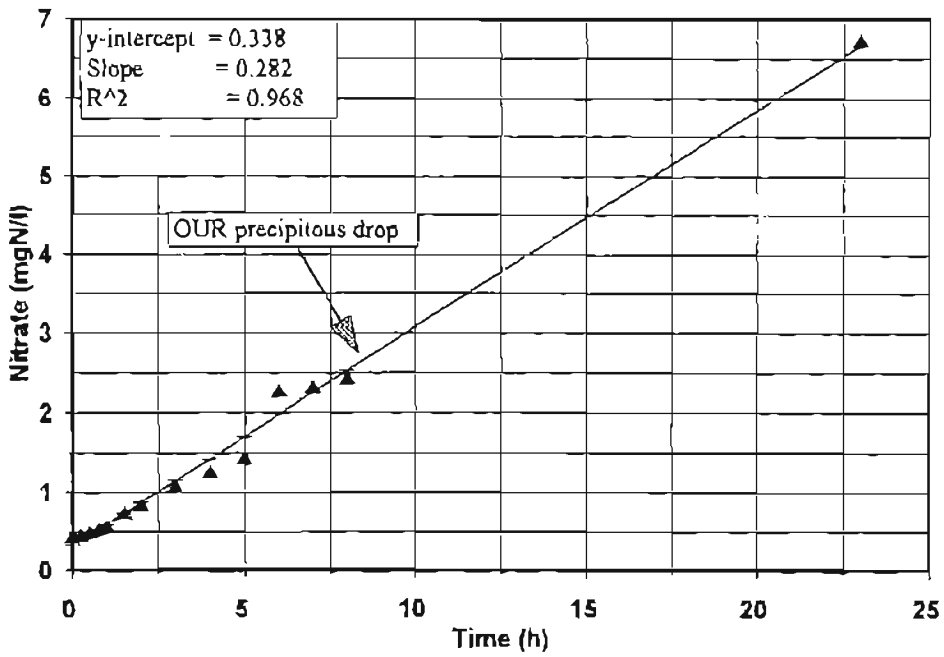


Fig N41 Nitrate concentration graph for wastewater plus mixed liquor batch test, 14-02, batch no. 19

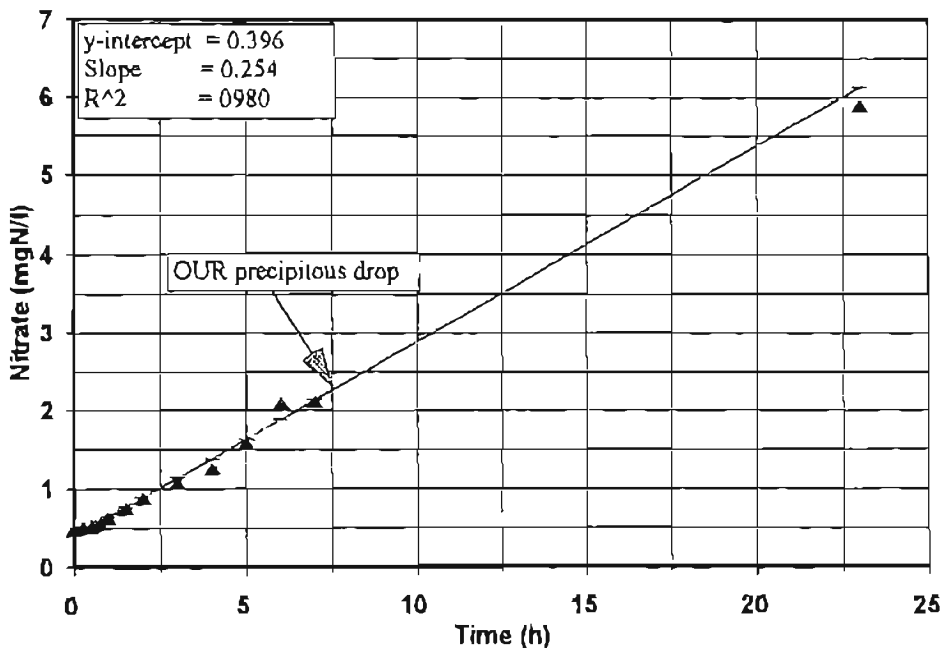


Fig N42 Nitrate concentration graph for wastewater plus mixed liquor batch test, 15-02, batch no. 19

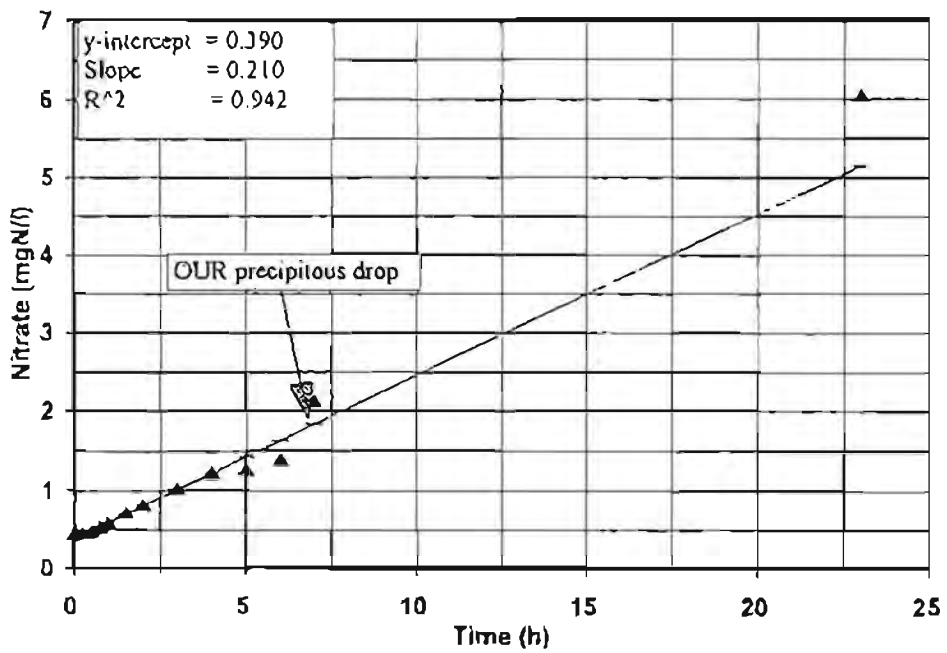


Fig N43 Nitrate concentration graph for wastewater plus mixed liquor batch test, 16-02, batch no. 19

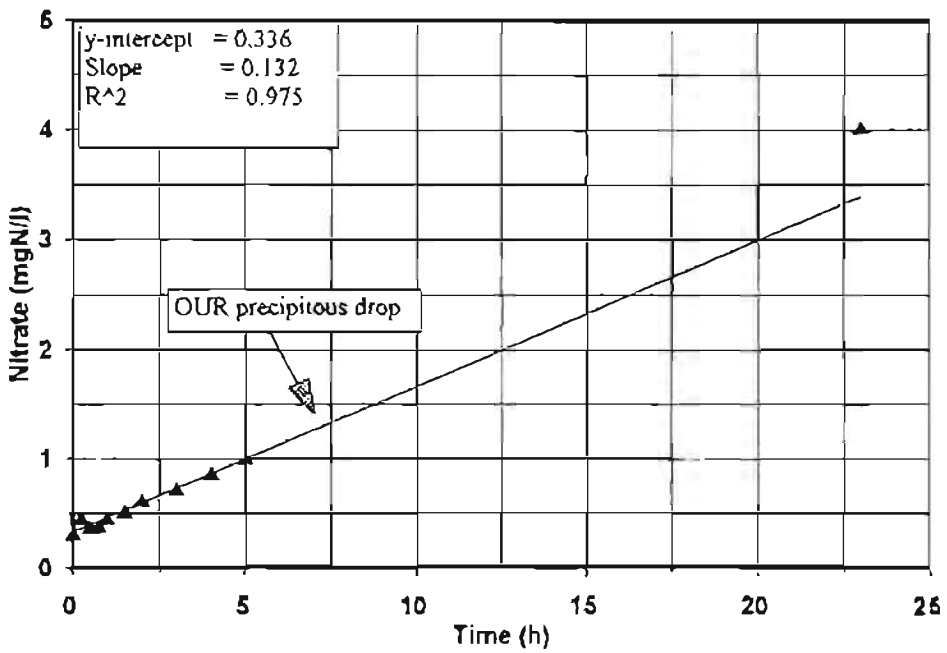


Fig N44 Nitrate concentration graph for wastewater plus mixed liquor batch test, 17-02, batch no. 19

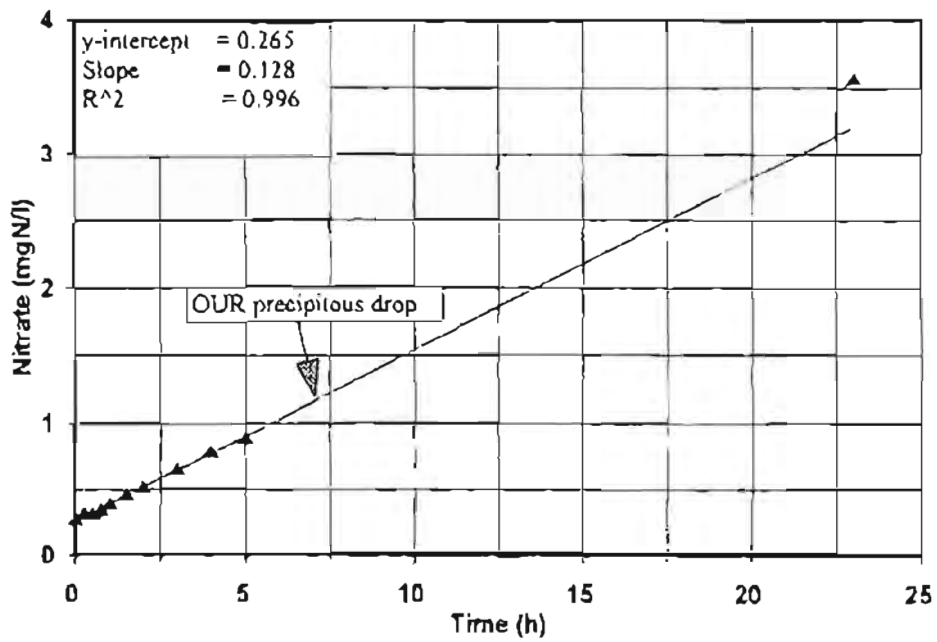


Fig N45 Nitrate concentration graph for wastewater plus mixed liquor batch test, 18-02, batch no. 19

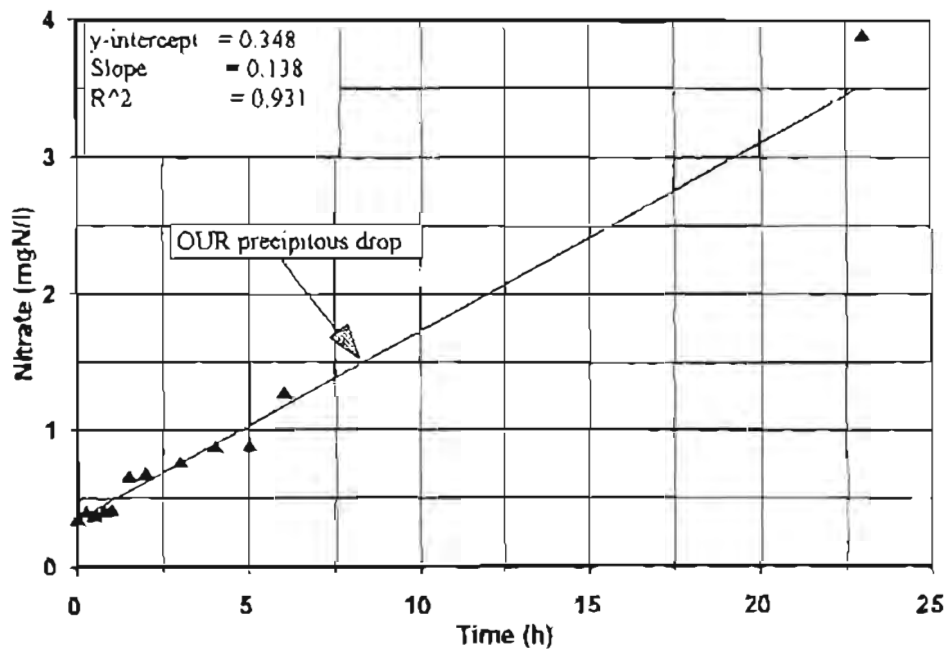


Fig N46 Nitrate concentration graph for wastewater plus mixed liquor batch test, 19-02, batch no. 19

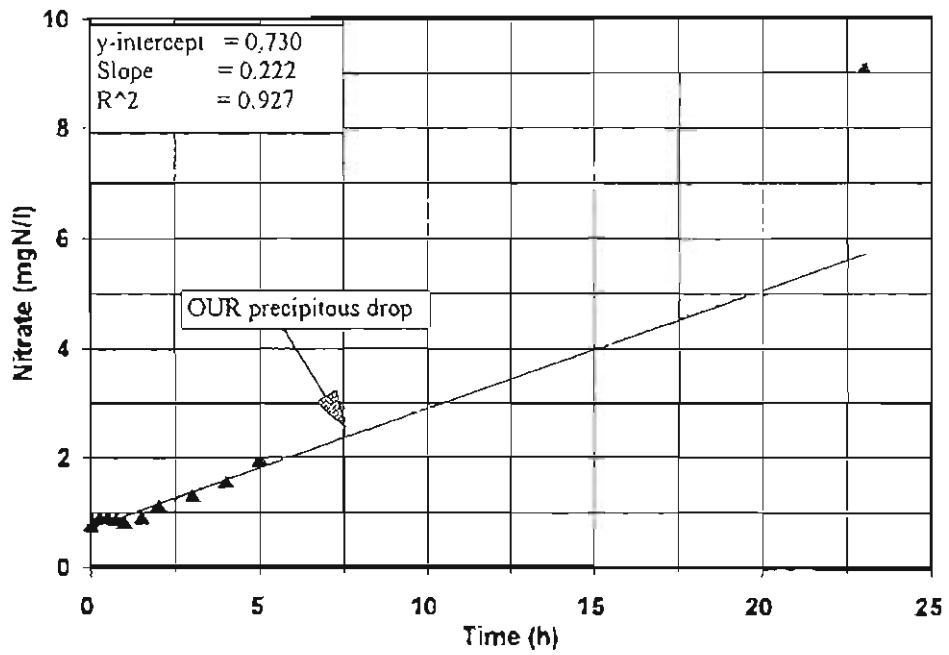


Fig N47 Nitrate concentration graph for wastewater plus mixed liquor batch test,20-02,batch no.20

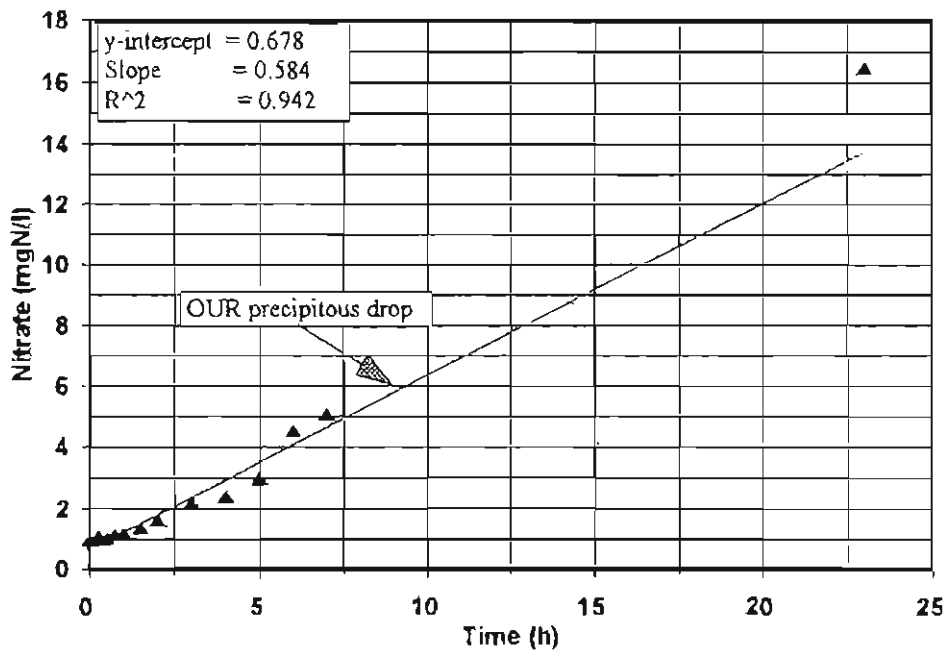


Fig N48 Nitrate concentration graph for wastewater plus mixed liquor batch test,21-02,batch no.20

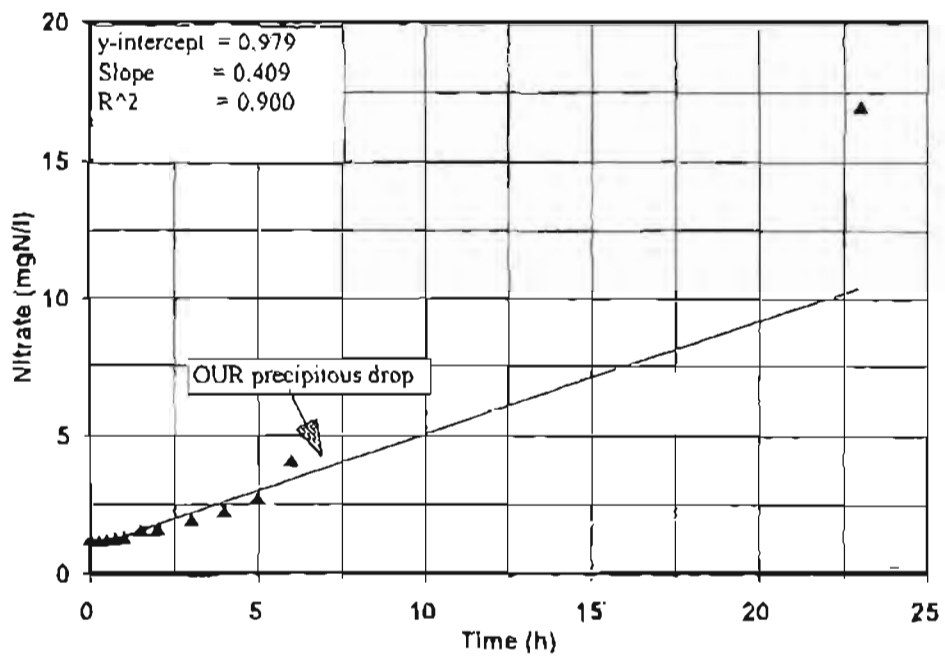


Fig N49 Nitrate concentration graph for wastewater plus mixed liquor batch test, 23-02, batch no. 20

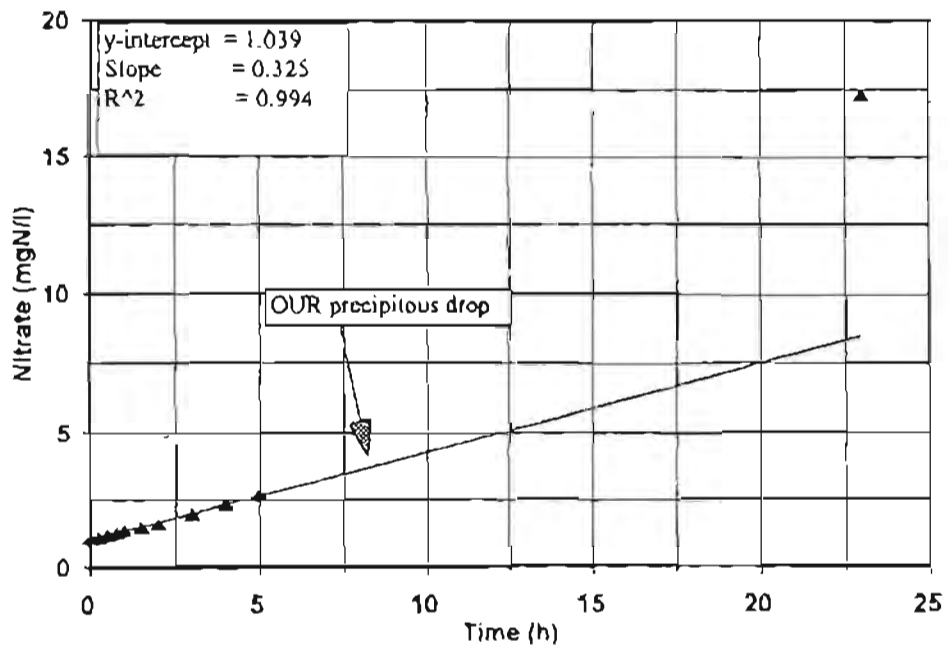


Fig N50 Nitrate concentration graph for wastewater plus mixed liquor batch test, 24-02, batch no. 20

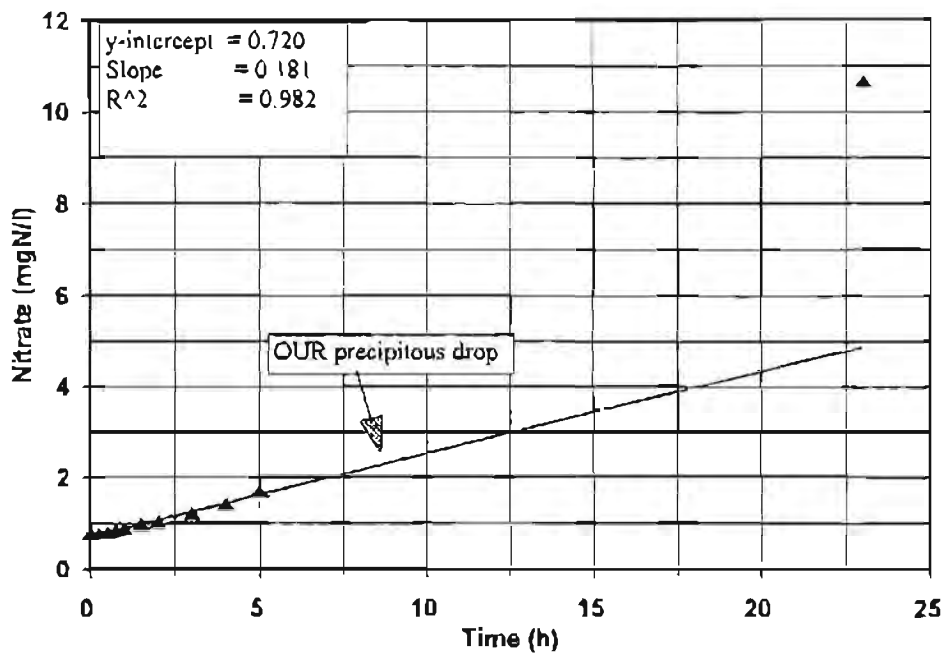


Fig NS1 Nitrate concentration graph for wastewater plus mixed liquor batch test.25-02. batch no.20

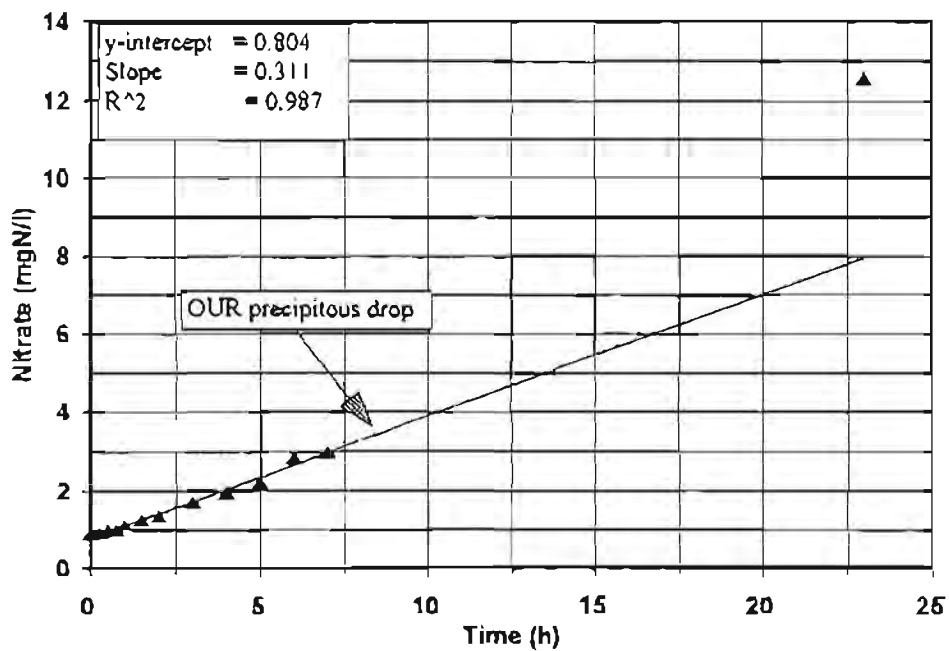


Fig NS2 Nitrate concentration graph for wastewater plus mixed liquor batch test.26-02. batch no.20

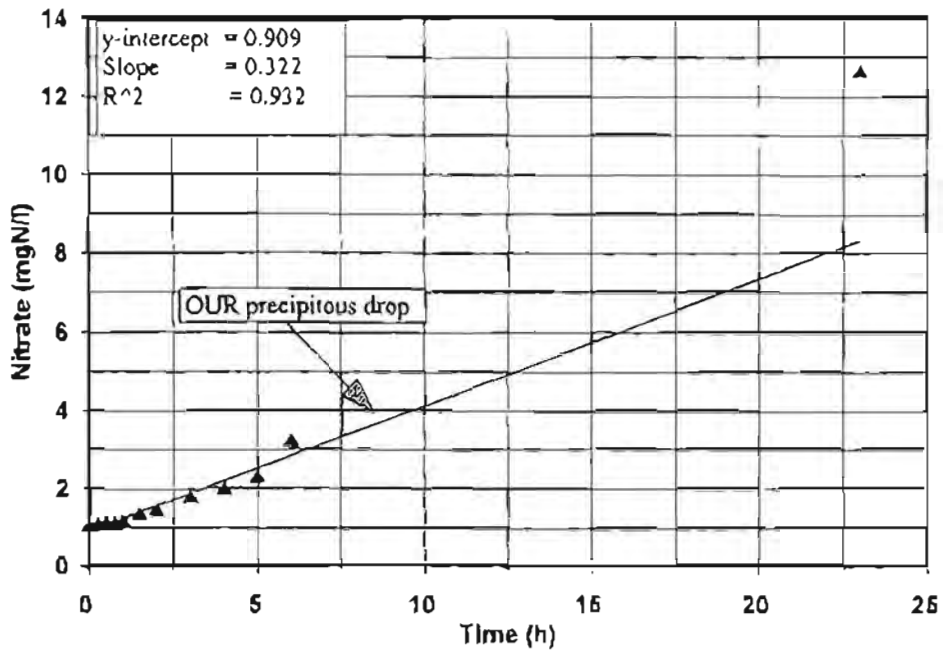


Fig N53 Nitrate concentration graph for wastewater plus mixed liquor batch test, 27-02, batch no. 20

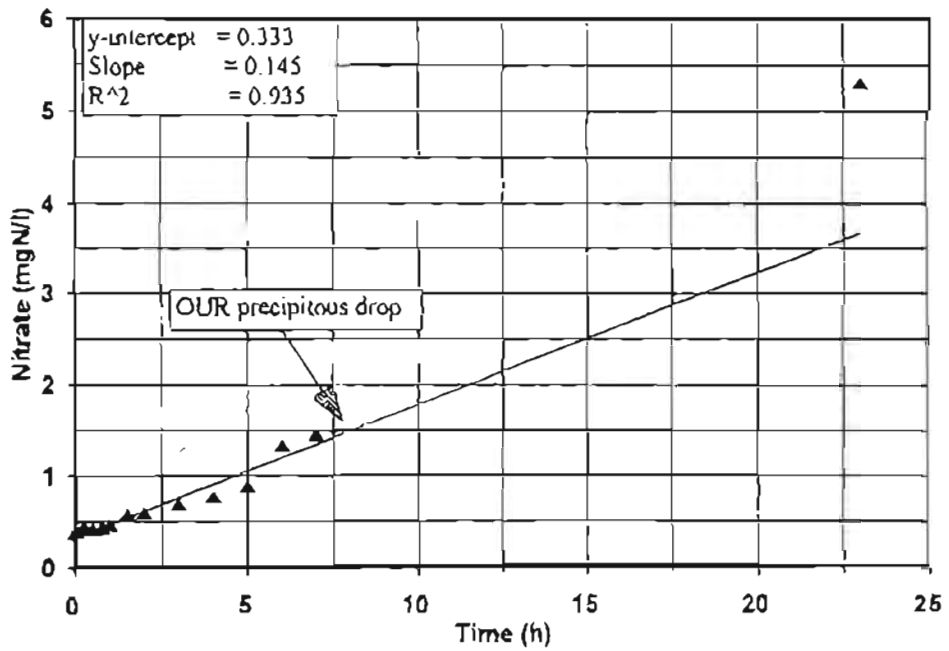


Fig N54 Nitrate concentration graph for wastewater plus mixed liquor batch test, 28-02, batch no. 20

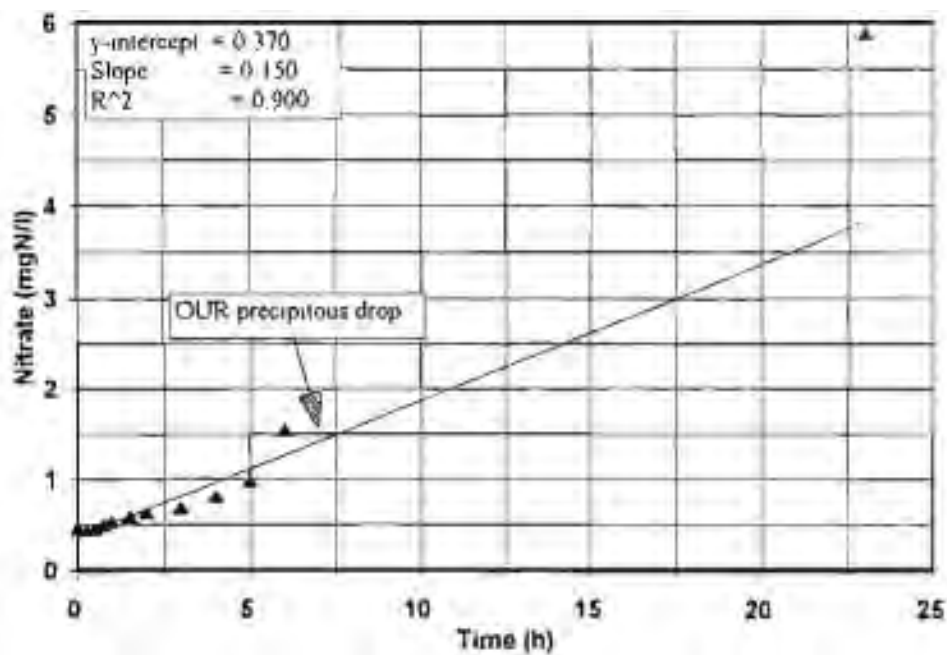


Fig N55 Nitrate concentration graph for wastewater plus mixed liquor batch test,29-02,batch no.20

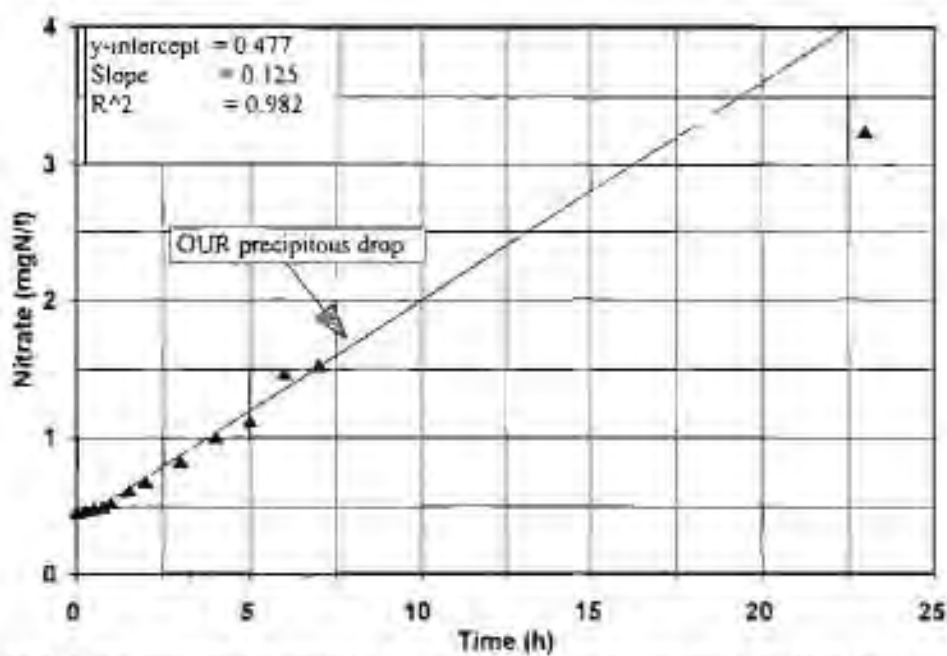


Fig N56 Nitrate concentration graph for wastewater plus mixed liquor batch test,01-03,batch no.20

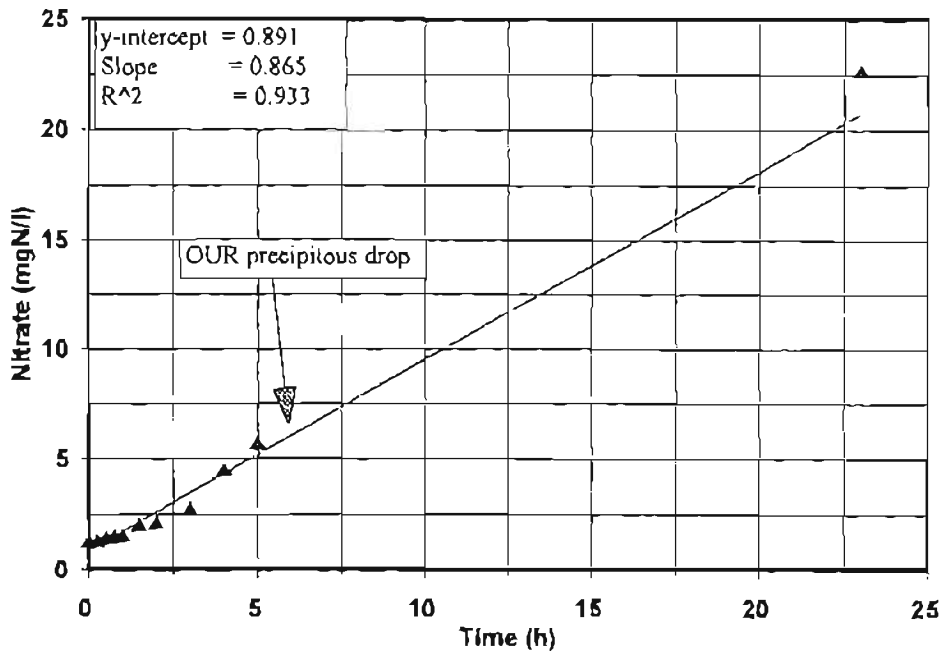


Fig N57 Nitrate concentration graph for wastewater plus mixed liquor batch test,02-03, batch no.20

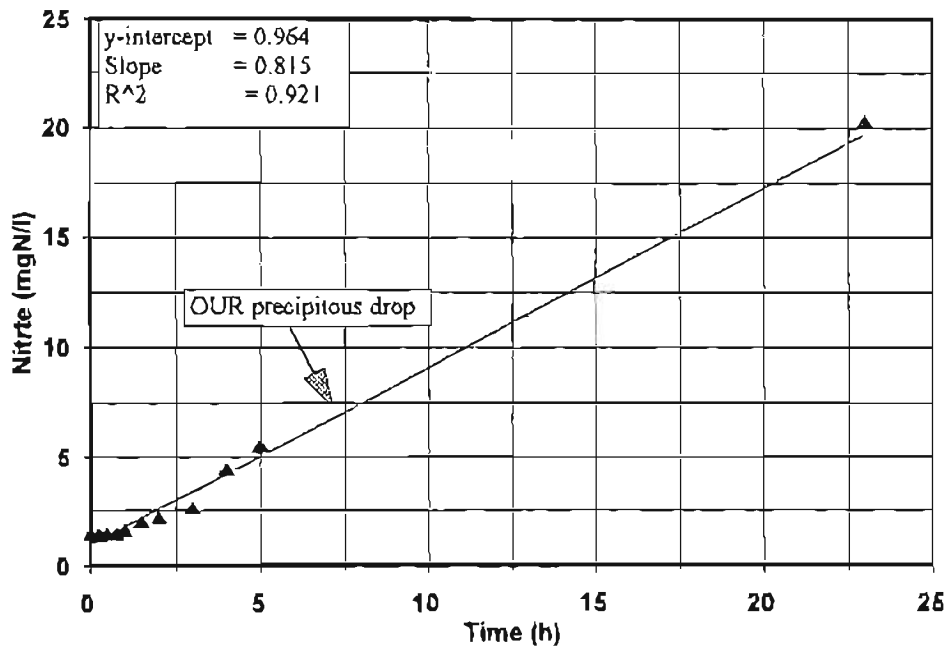


Fig N58 Nitrate concentration graph for wastewater plus mixed liquor batch test,03-03, batch no.20

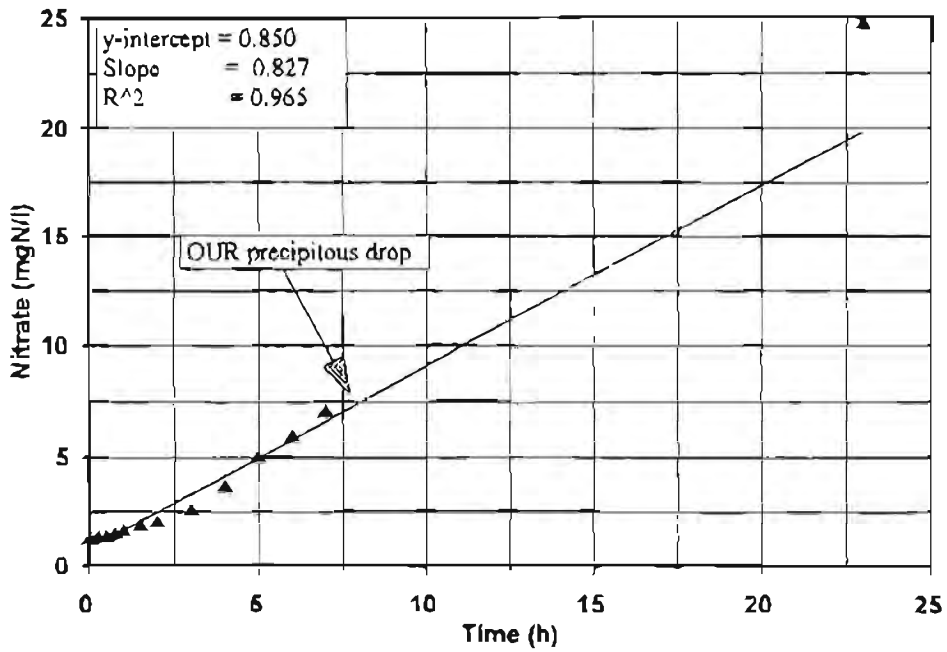


Fig N59 Nitrate concentration graph for wastewater plus mixed liquor batch test, 04-03, batch no.20

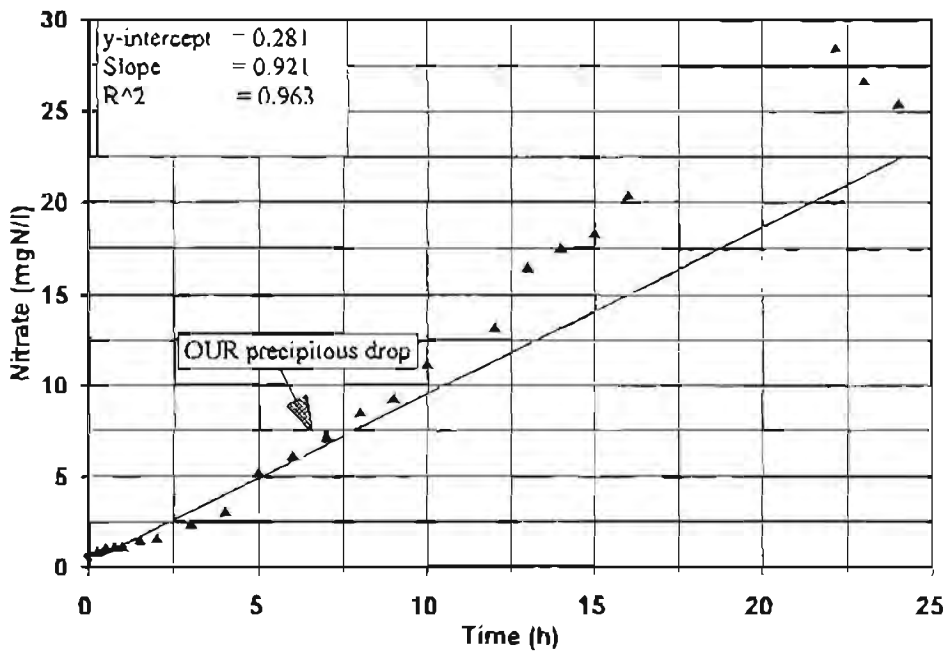


Fig N60 Nitrate concentration graph for wastewater plus mixed liquor batch test, 11-03, batch no.21

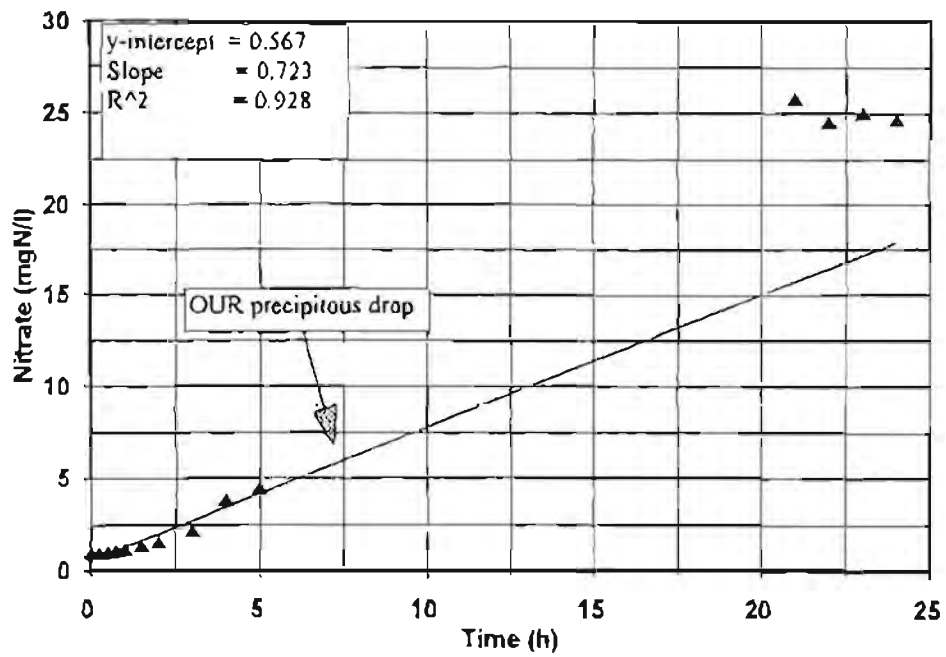


Fig N61 Nitrate concentration graph for wastewater plus mixed liquor batch test, 12-03, batch no. 21

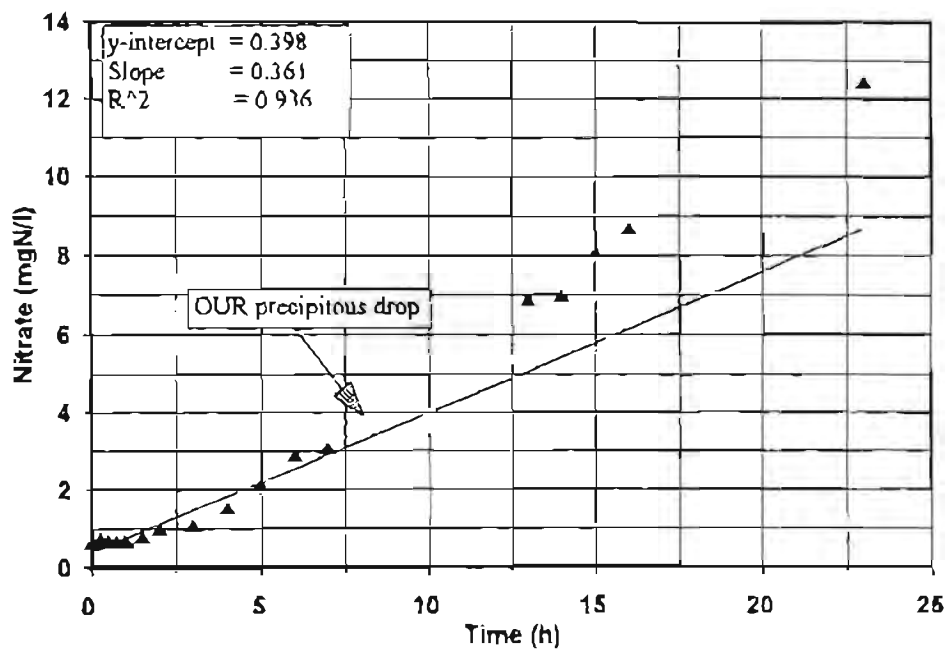


Fig N62 Nitrate concentration graph for wastewater plus mixed liquor batch test, 14-03, batch no. 21

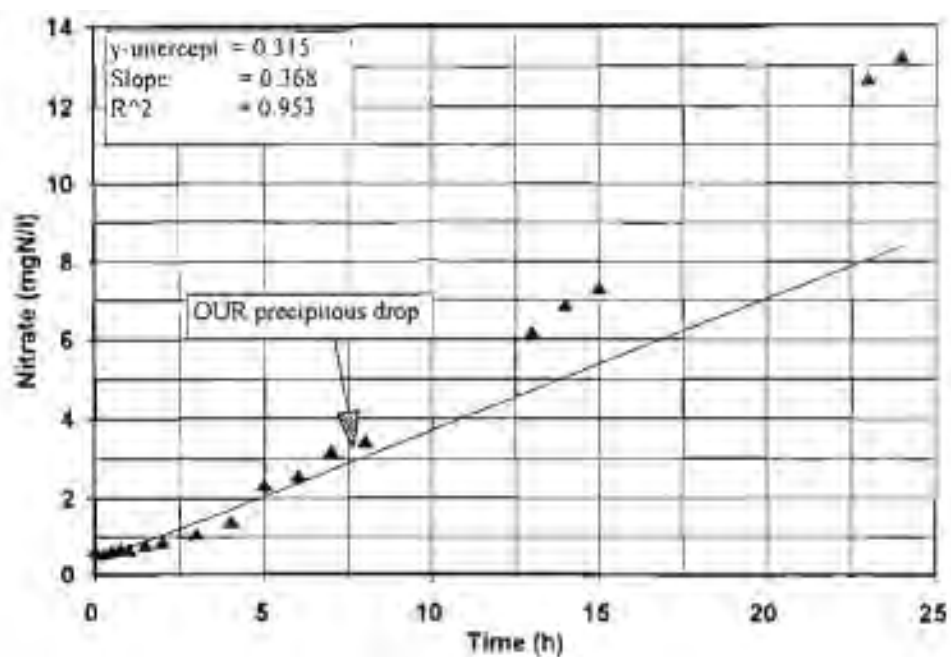


Fig N63 Nitrate concentration graph for wastewater plus mixed liquor batch test, 15-03, batch no.21

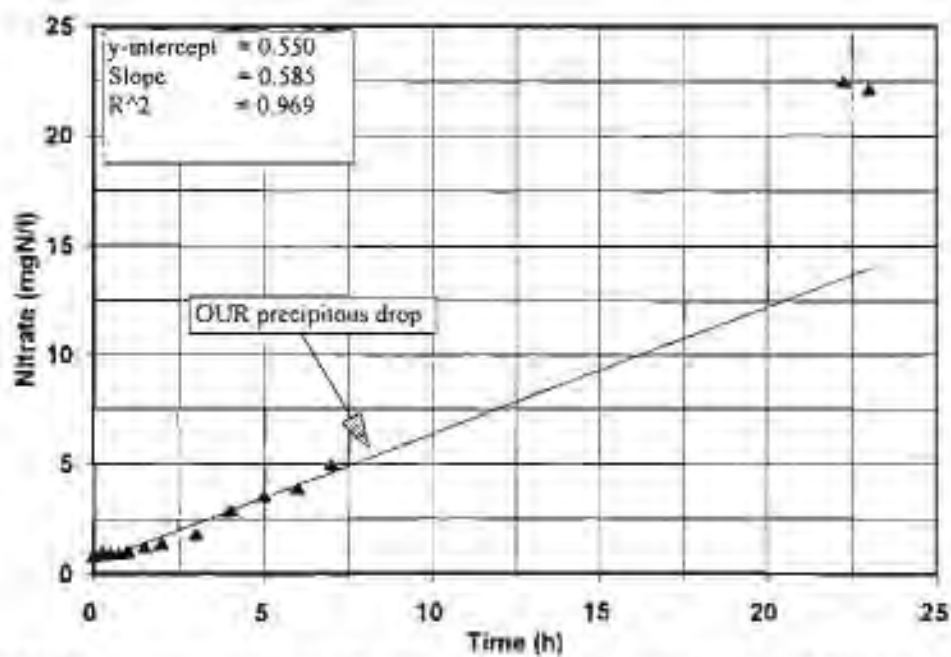


Fig N64 Nitrate concentration graph for wastewater plus mixed liquor batch test, 17-03, batch no.21

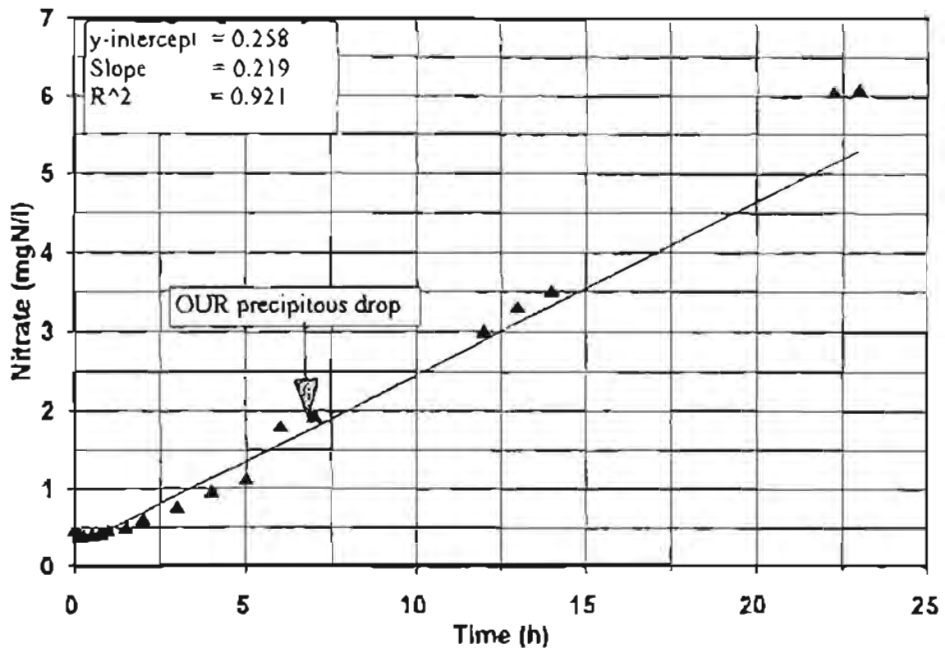


Fig N65 Nitrate concentration graph for wastewater plus mixed liquor batch test, 18-03, batch no.21

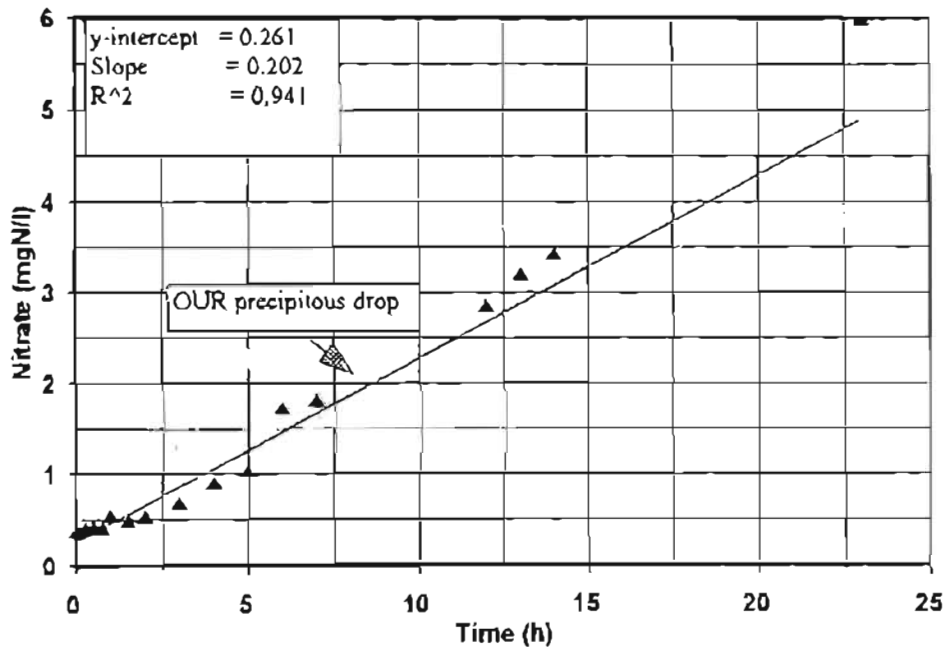


Fig N66 Nitrate concentration graph for wastewater plus mixed liquor batch test, 19-03, batch no.21

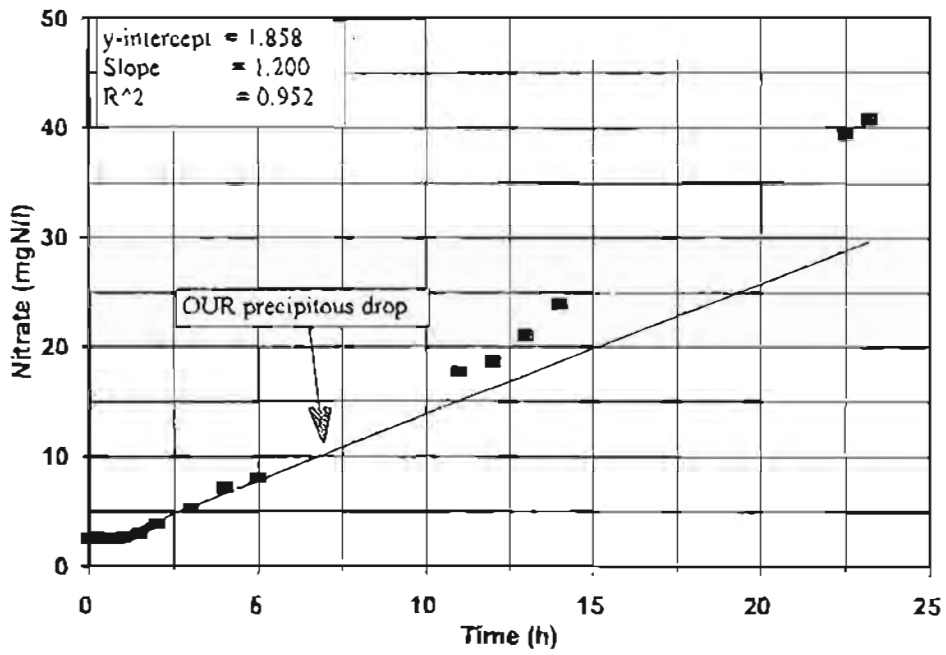


Fig N67 Nitrate concentration graph for wastewater plus mixed batch test.06-04, batch no.22

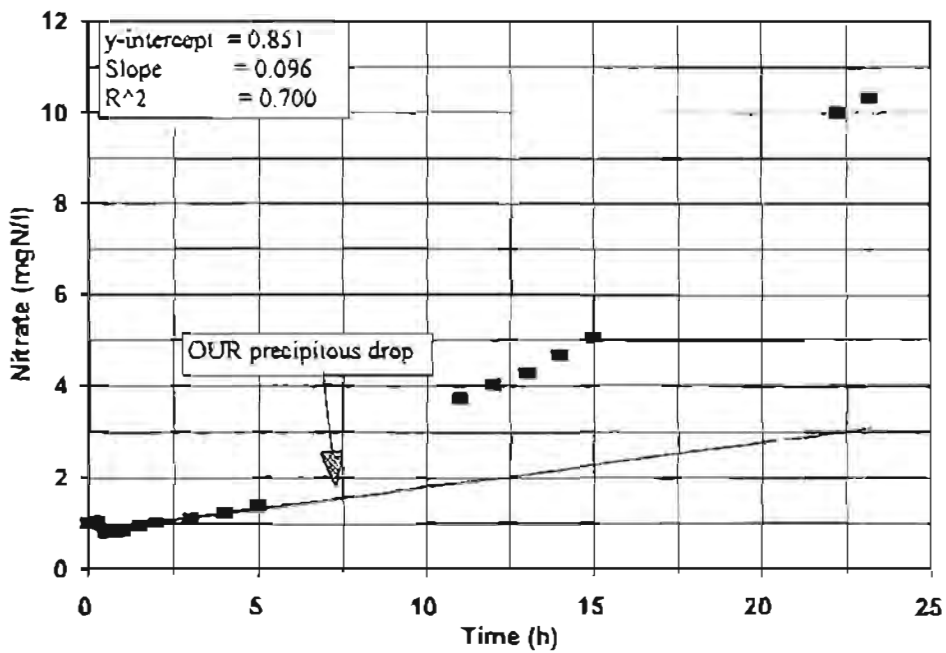


Fig N68 Nitrate concentration graph for wastewater plus mixed liquor batch test.07-04, batch no.22

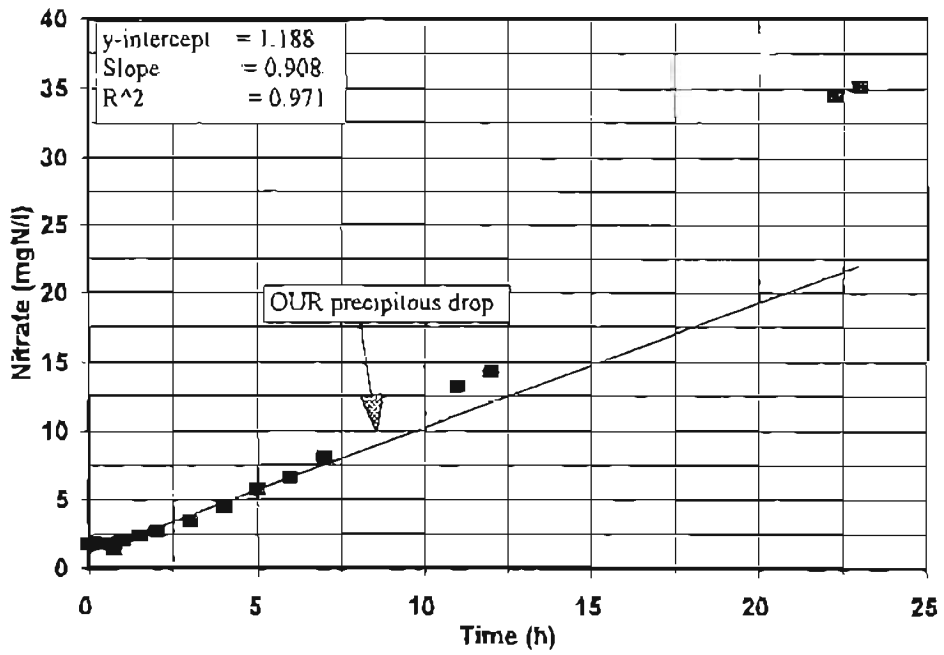


Fig N69 Nitrate concentration graph for wastewater plus mixed liquor batch test, 08-04, batch no. 22

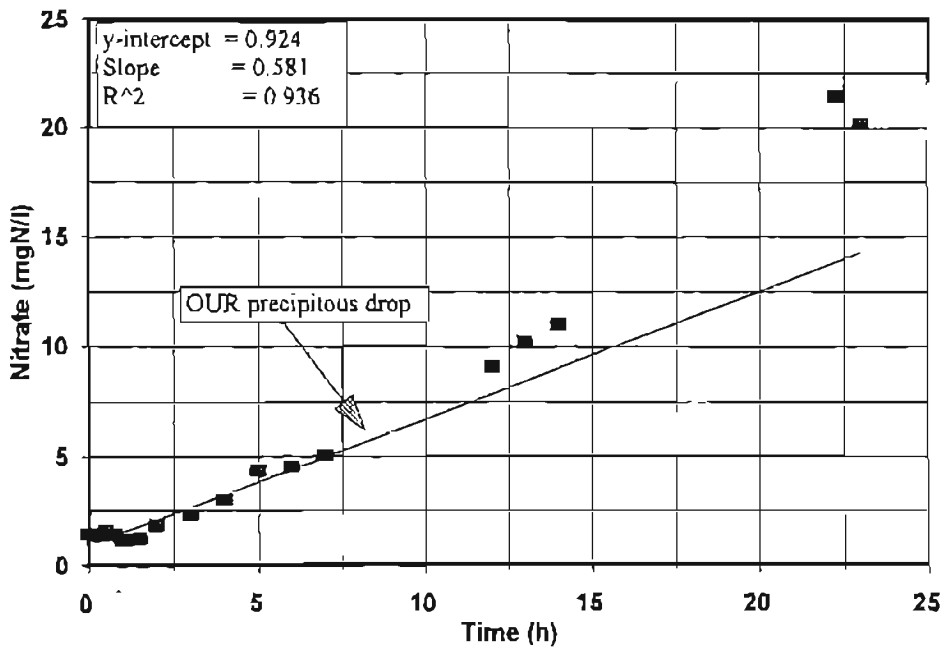


Fig N70 Nitrate concentration graph for wastewater plus mixed liquor batch test, 09-04, batch no. 22

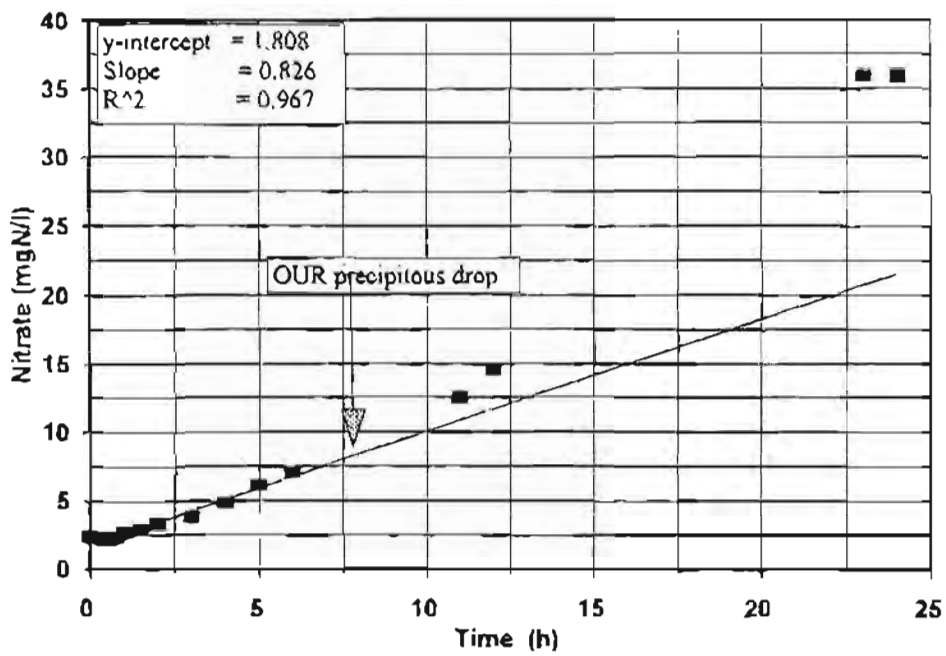


Fig N71 Nitrate concentration graph for wastewater plus mixed liquor batch test, 10-04, batch no.22

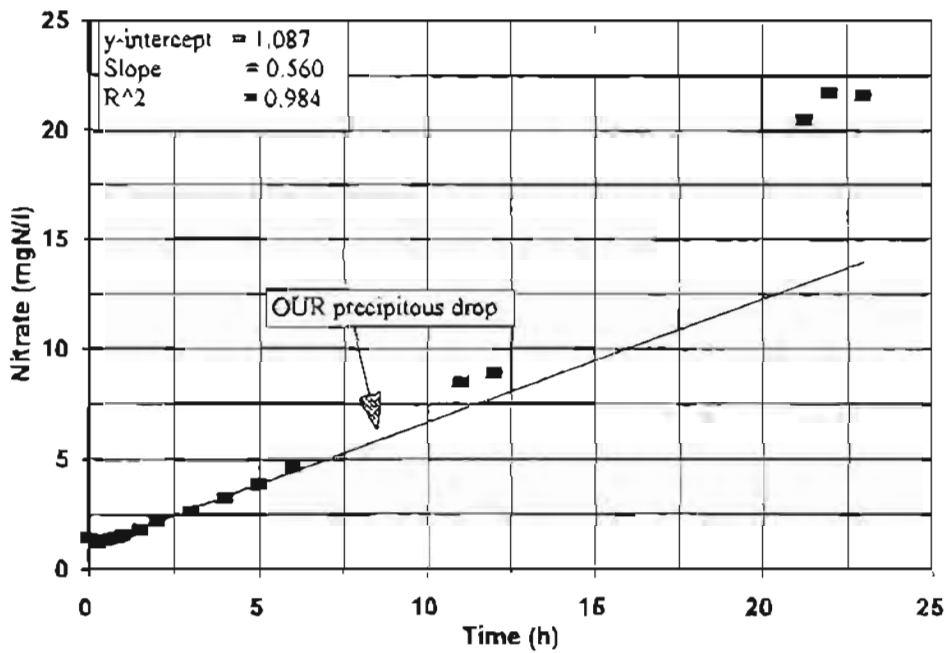


Fig N72 Nitrate concentration graph for wastewater plus mixed liquor batch test, 11-04, batch no.22

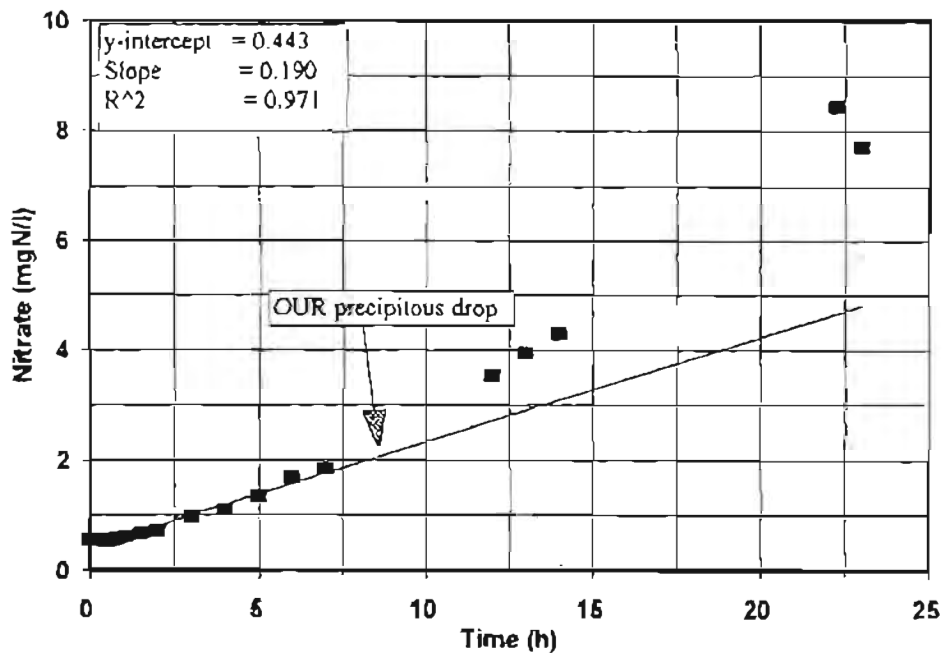


Fig N73 Nitrate concentration graph for wastewater plus mixed liquor batch test, 15-04, batch no.23

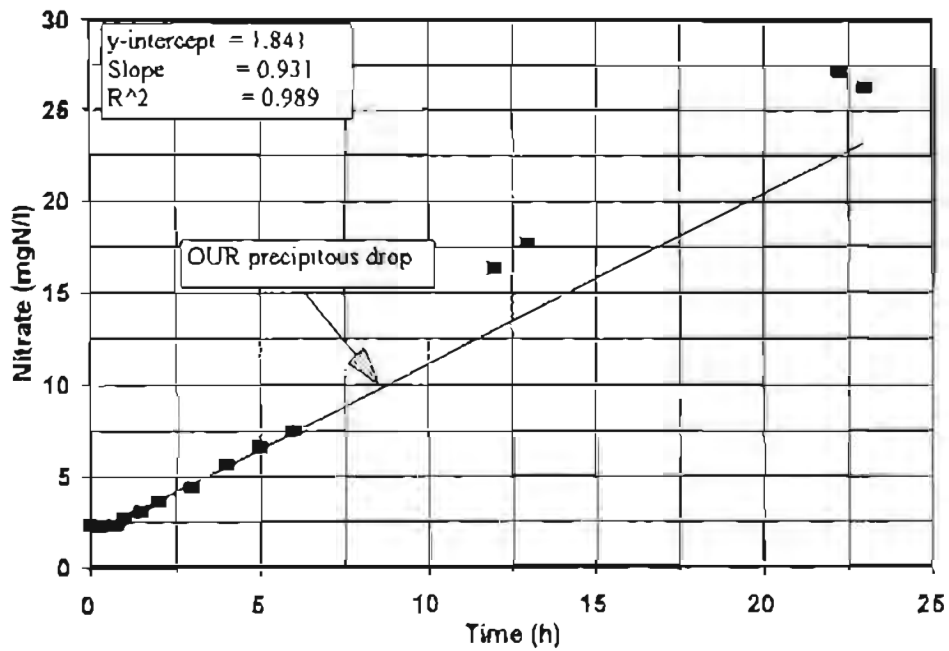


Fig N74 Nitrate concentration graph for wastewater plus mixed liquor batch test, 16-04, batch no.23

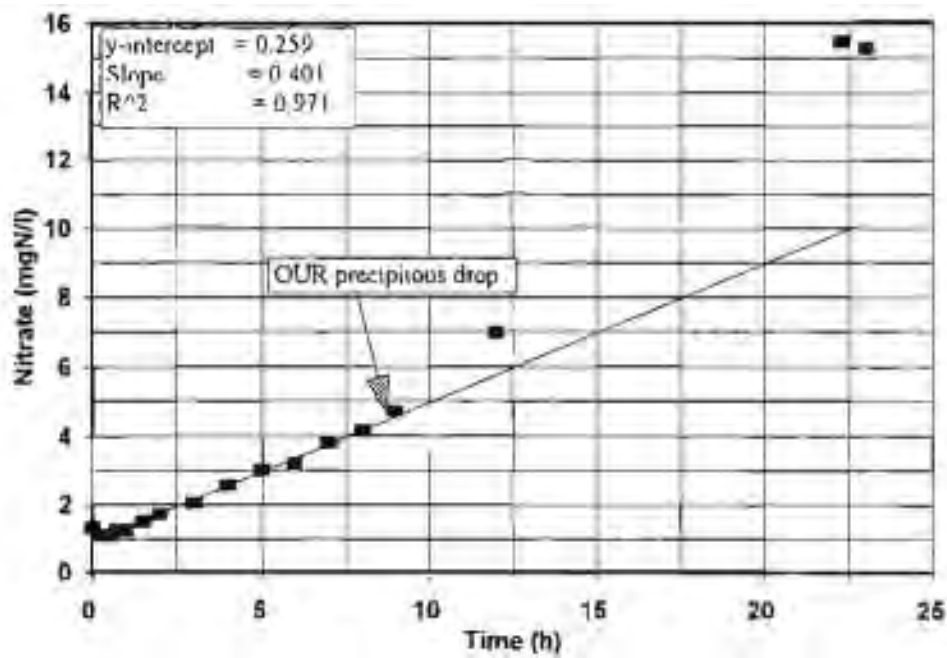


Fig N75 Nitrate concentration graph for wastewater plus mixed liquor batch test, 17-04, batch no. 23

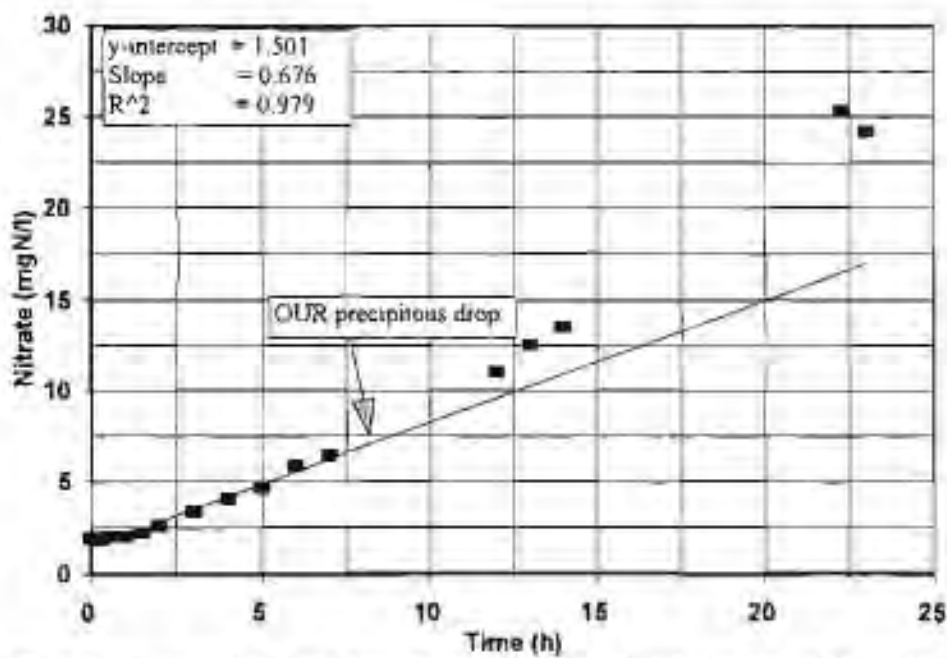


Fig N76 Nitrate concentration graph for wastewater plus mixed liquor batch test, 18-04, batch no. 23

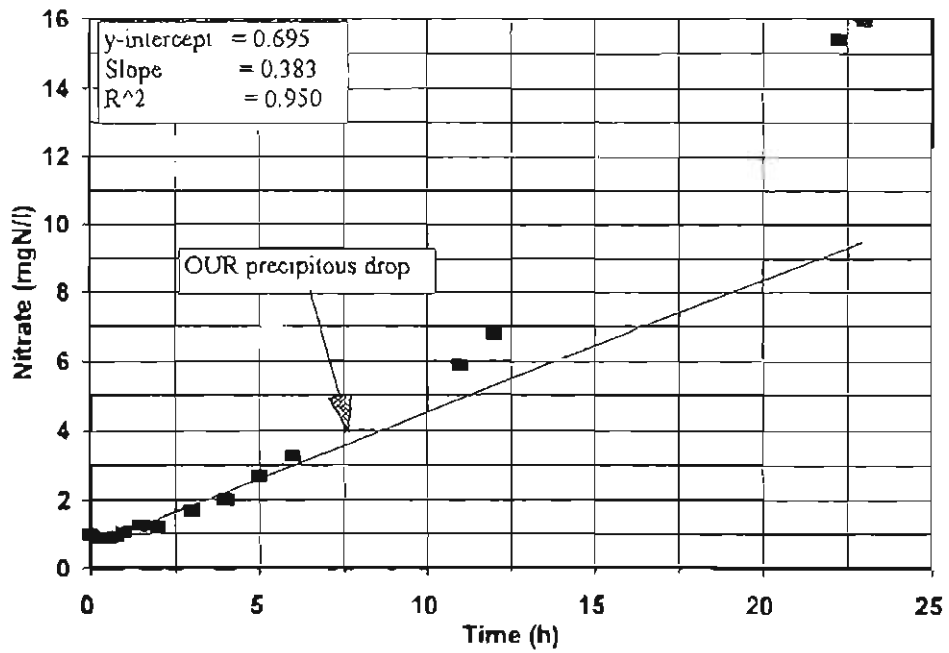


Fig N77 Nitrate concentration graph for wastewater plus mixed liquor batch test,19-04,batch no.23

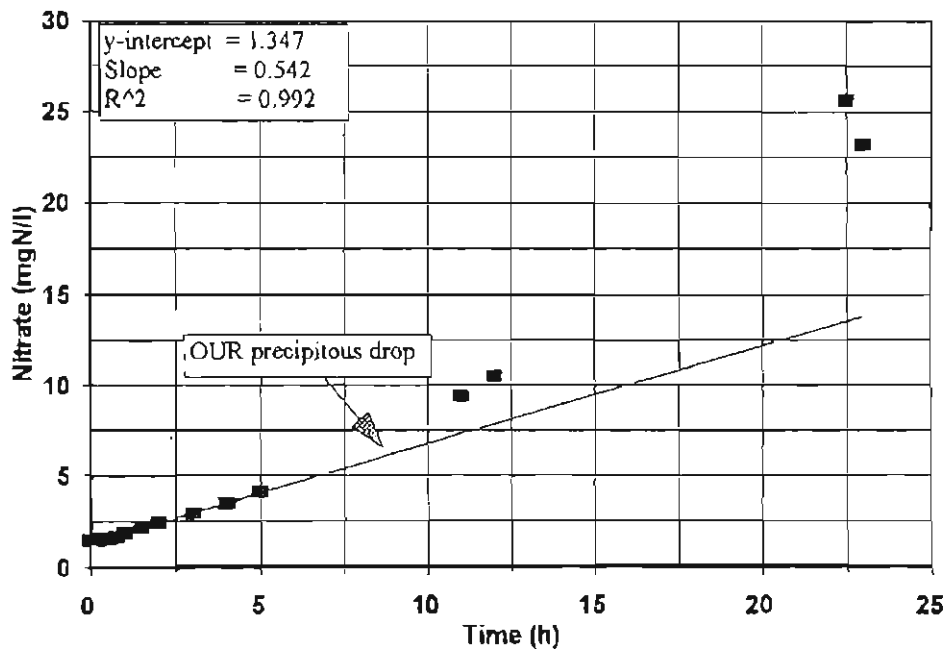


Fig N78 Nitrate concentration graph for wastewater plus mixed liquor batch test,20-04, batch no.23

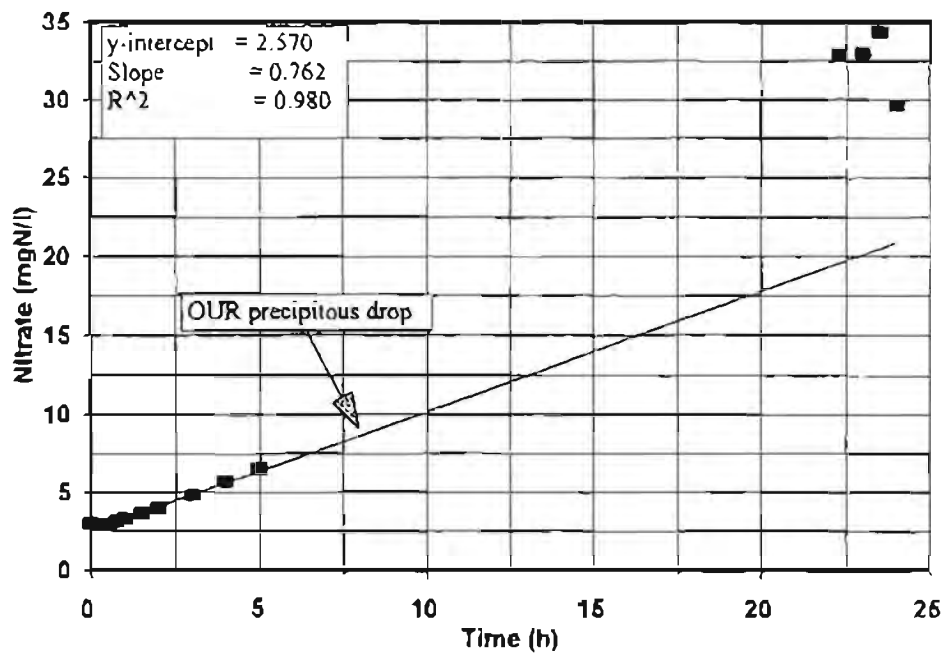


Fig N79 Nitrate graph for wastewater plus mixed liquor batch test, 21-04, batch no. 23

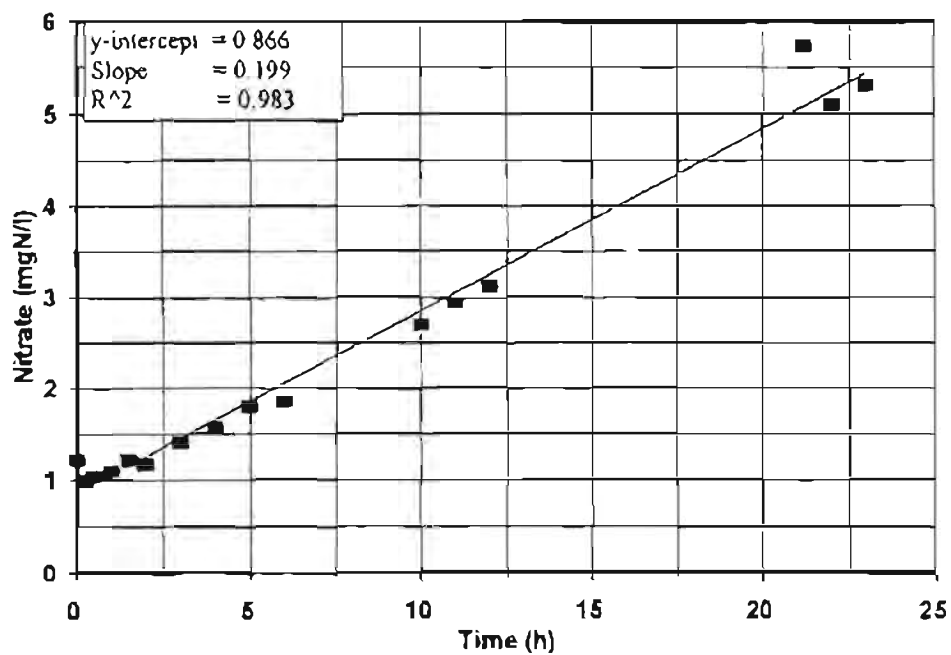


Fig N80 Nitrate concentration graph for wastewater plus mixed liquor batch test, 22-04, batch no. 23

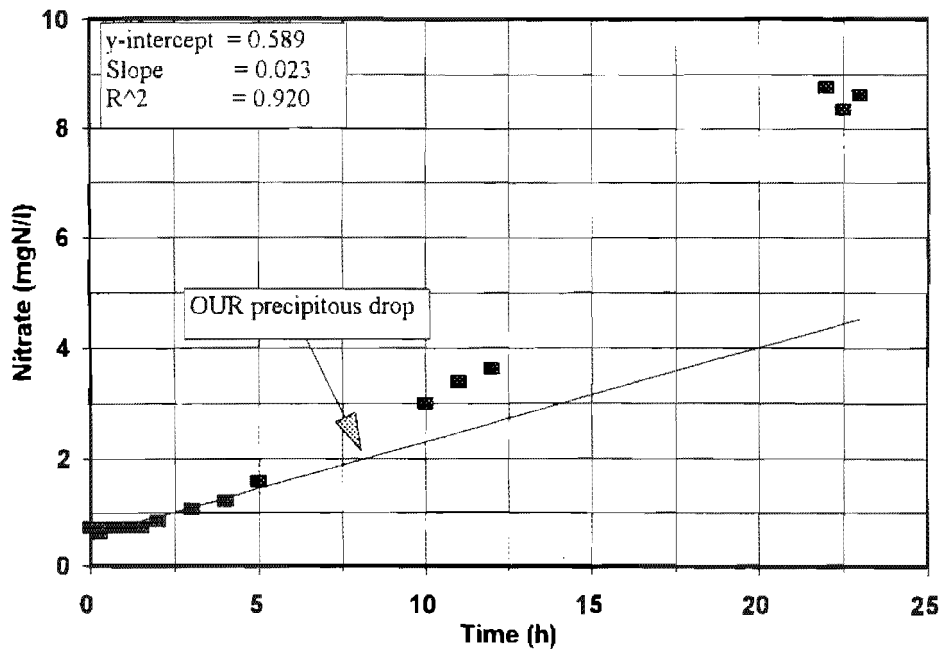


Fig N81 Nitrate concentration graph for wastewater plus mixed liquor batch test, 29-04, batch no. 24

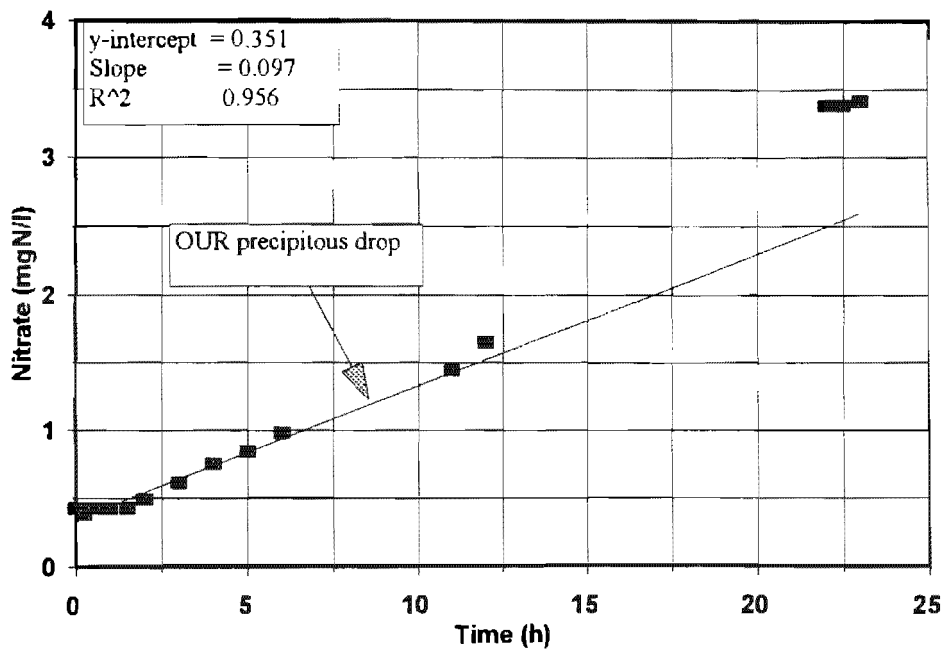


Fig N82 Nitrate concentration graph for wastewater plus mixed liquor batch test, 30-04, batch no. 24

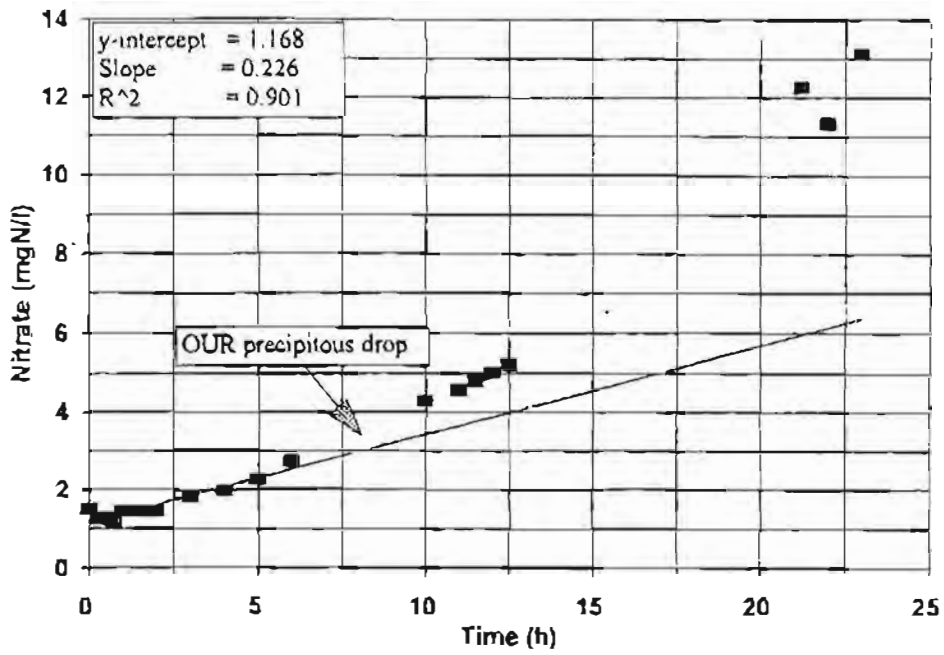


Fig N83 Nitrate concentration graph for wastewater plus mixed liquor batch test,01-05,batch no.24

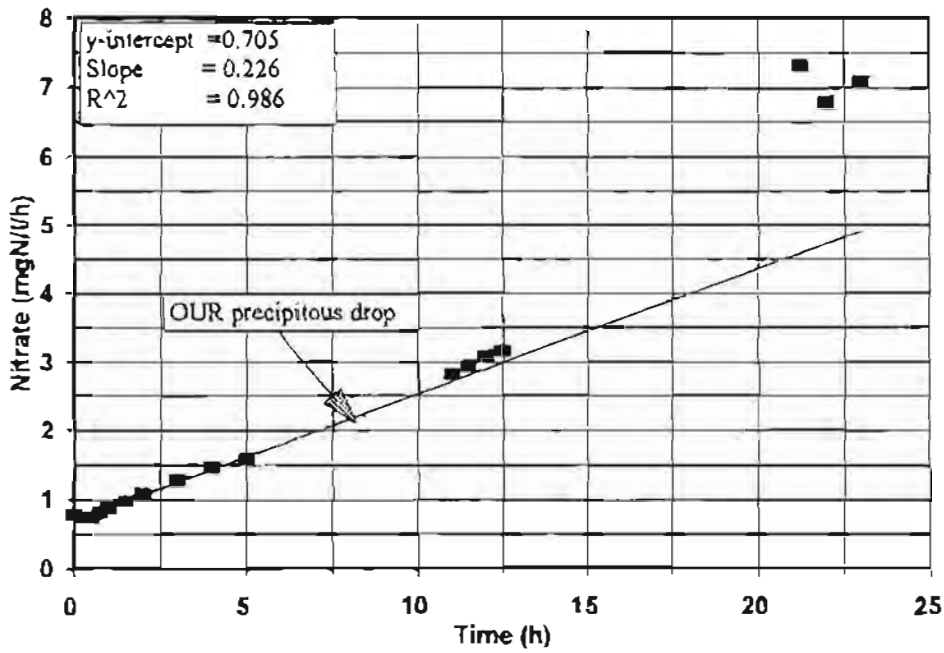


Fig N84 Nitrate concentration graph for wastewater plus mixed liquor batch test,02-05,batch no.24

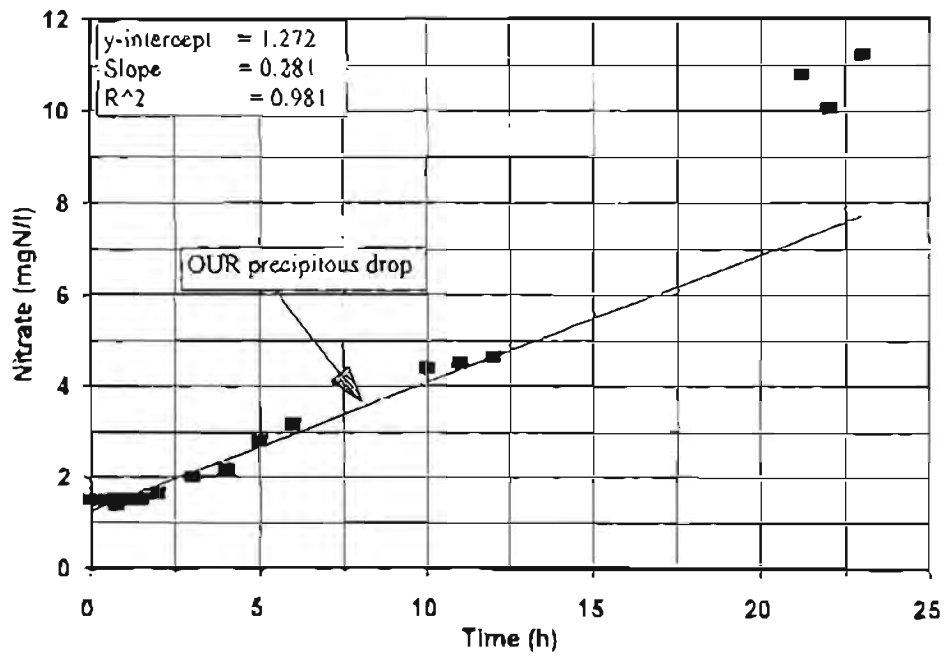


Fig.N85 Nitrate concentration graph for wastewater plus mixed liquor batch test,03-05,batch no.24

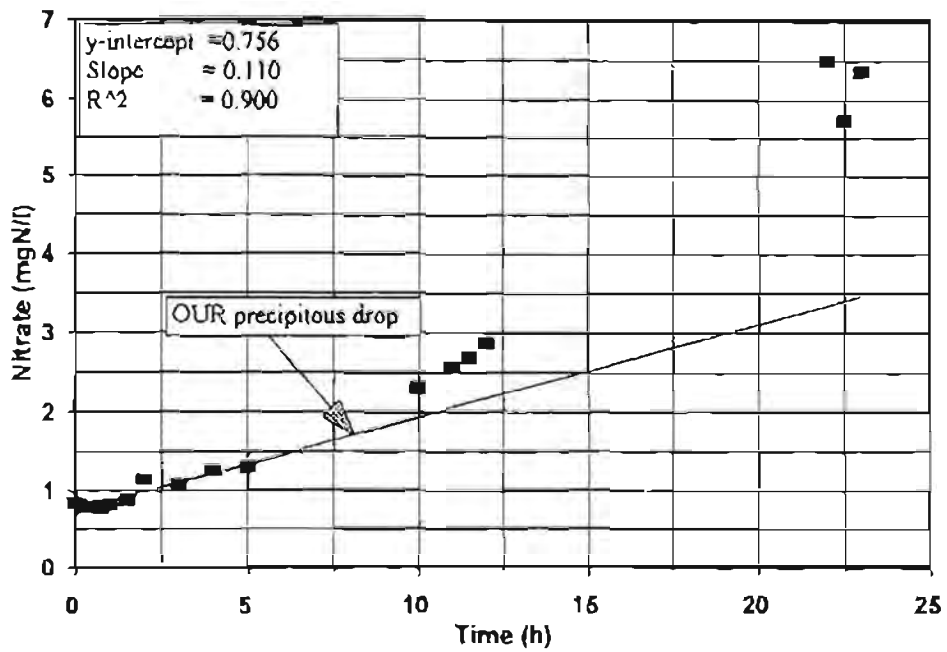


Fig N86 Nitrate concentration graph for wastewater plus mixed liquor batch test,04-05,batch no.24

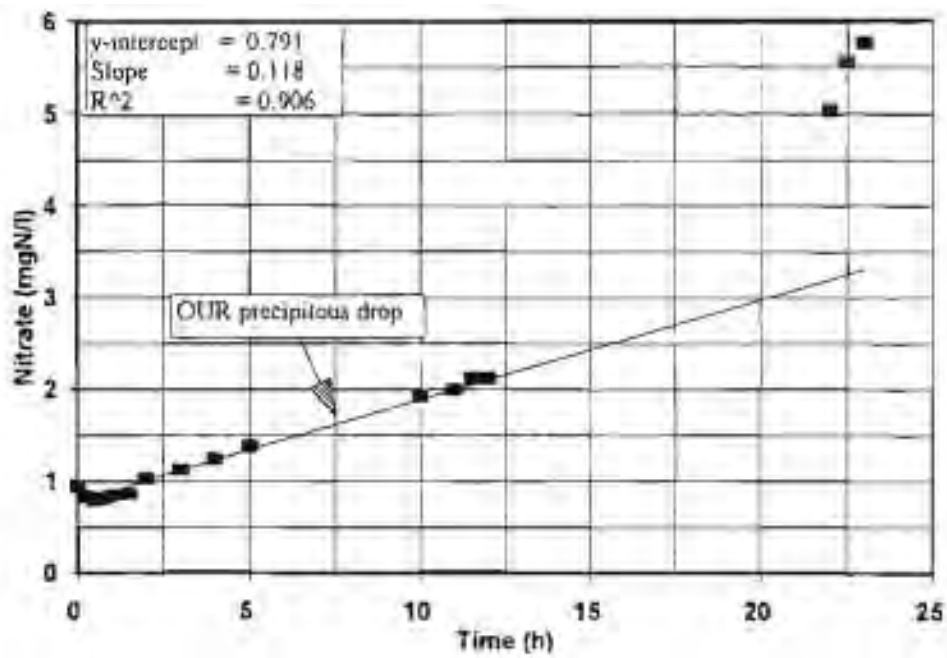


Fig N87 Nitrate concentration graph for wastewater plus mixed liquor batch test,05-05,batch no 24

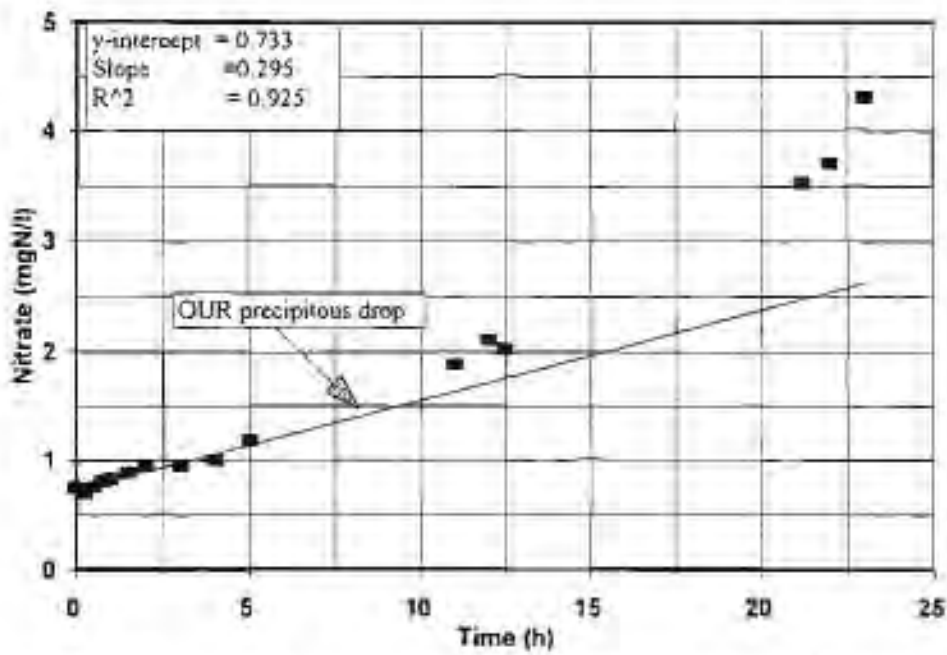


Fig N88 Nitrate concentration graph for wastewater plus mixed liquor batch test,06-05, batch no 24

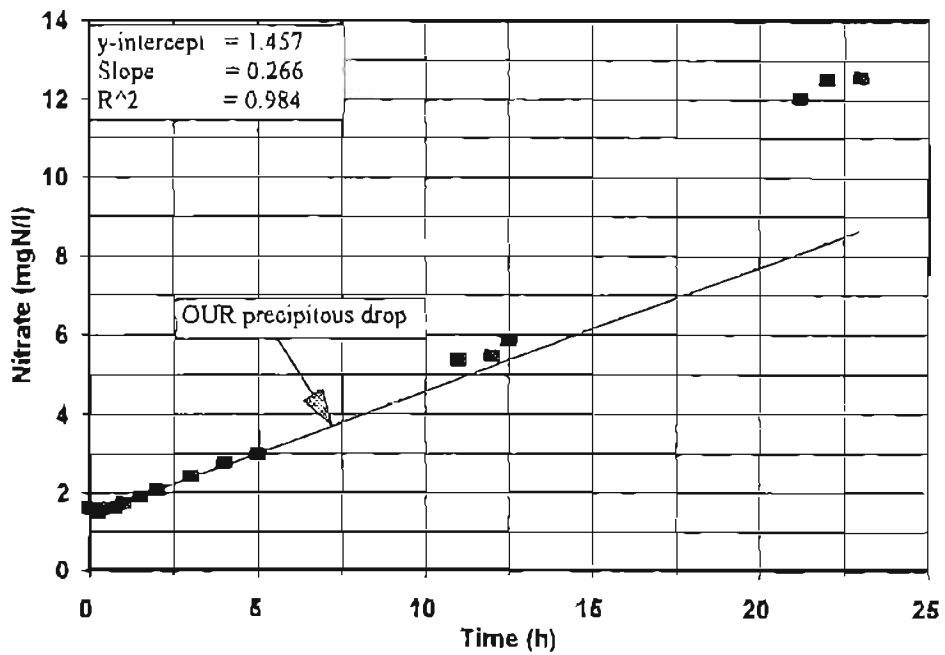


Fig N89 Nitrate concentration graph for wastewater plus mixed liquor batch test,07-05, batch no.24

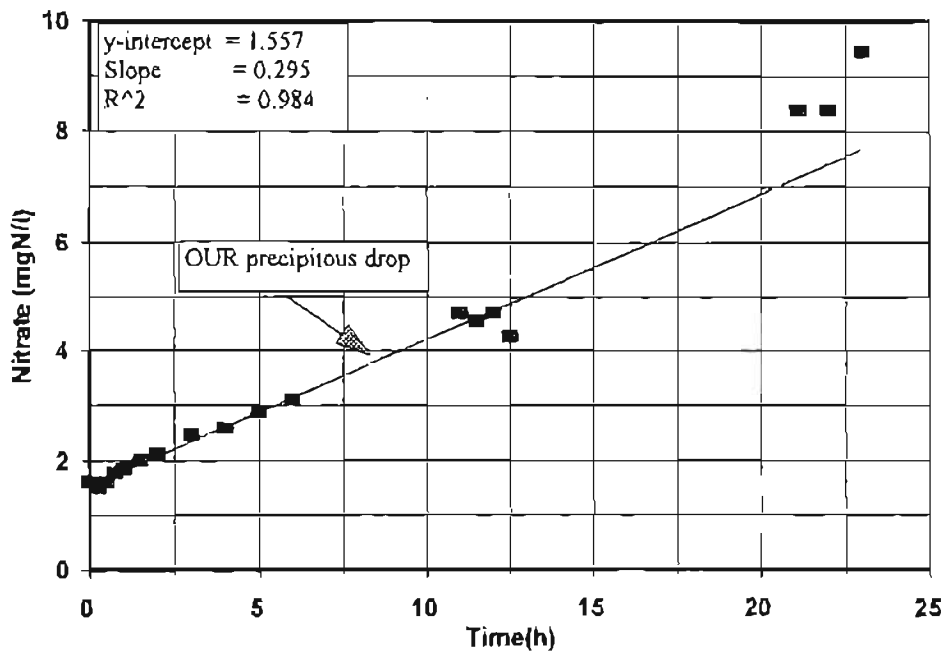


Fig N90 Nitrate concentration graph for wastewater plus mixed liquor batch test,08-05, batch no.24

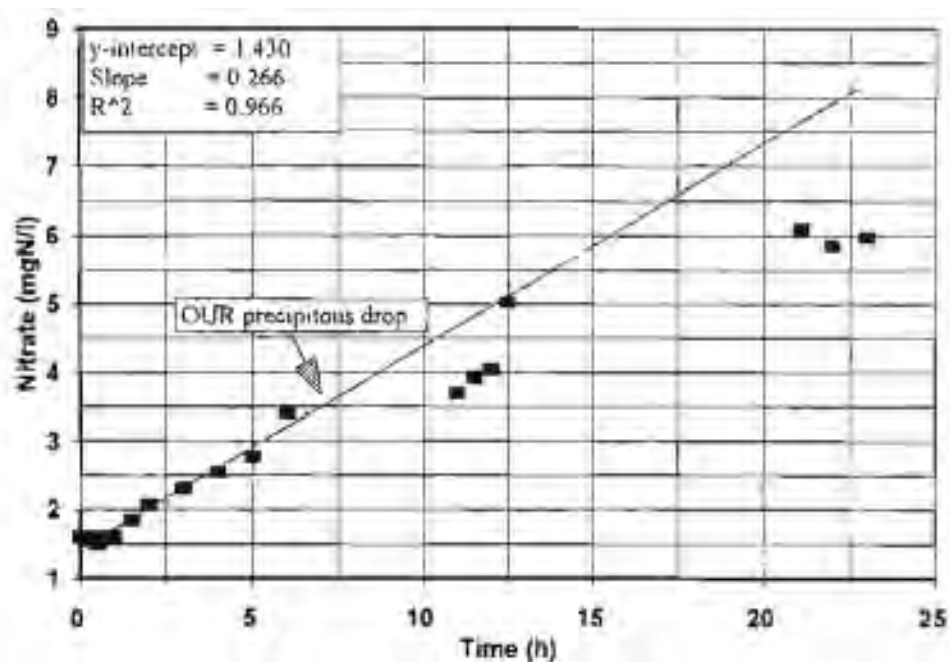


Fig N91 Nitrate concentration graph for wastewater plus mixed liquor batch test,09-05, batch no 24

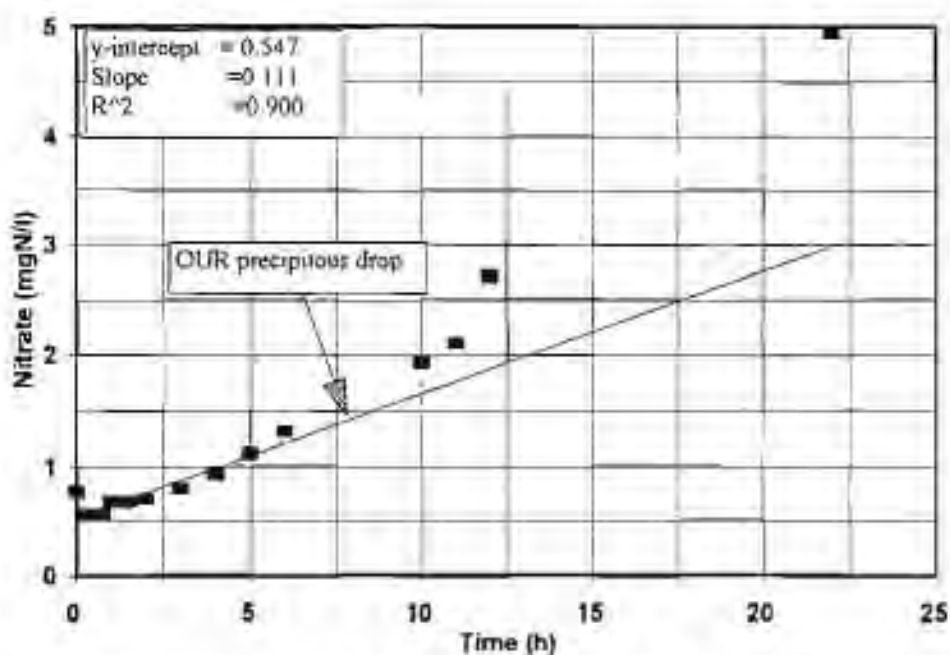


Fig N92 Nitrate concentration graph for wastewater plus mixed liquor batch test,23-05, batch no 26

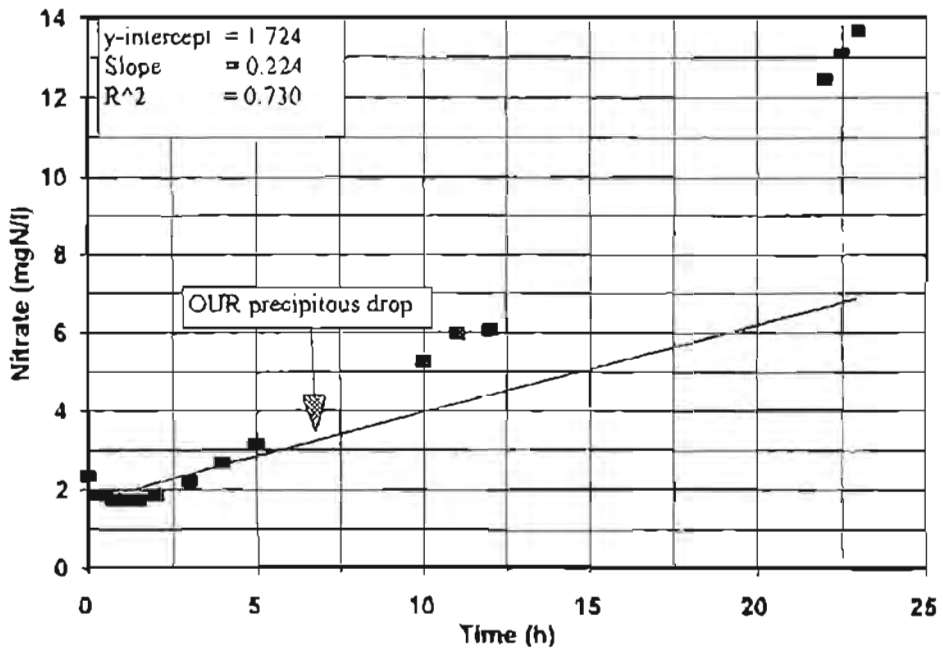


Fig N93 Nitrate concentration graph for wastewater plus mixed liquor batch test, 24-05, batch no. 26

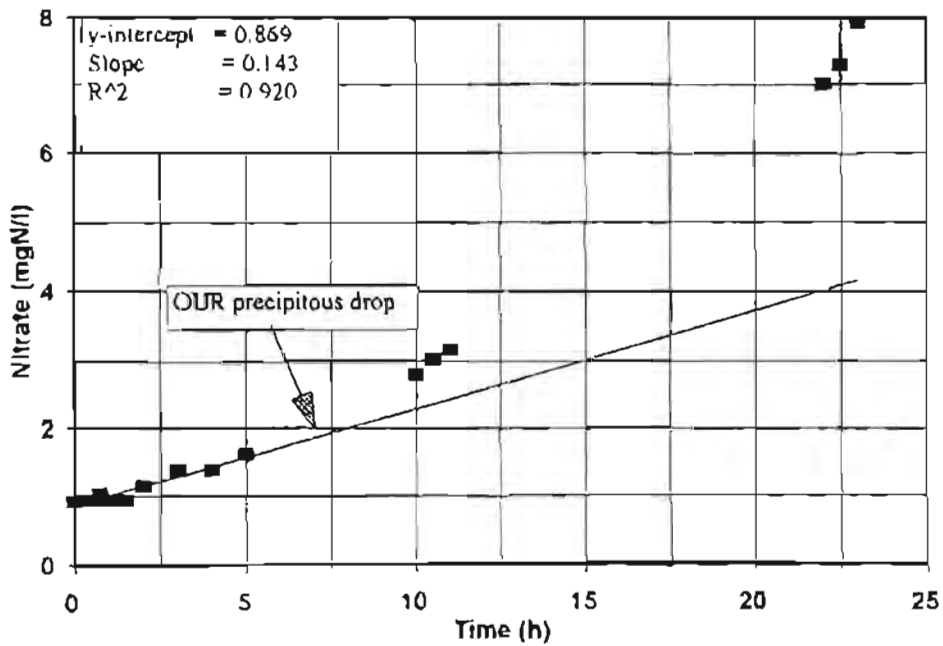


Fig N94 Nitrate concentration graph for wastewater plus mixed liquor batch test, 25-05, batch no. 26

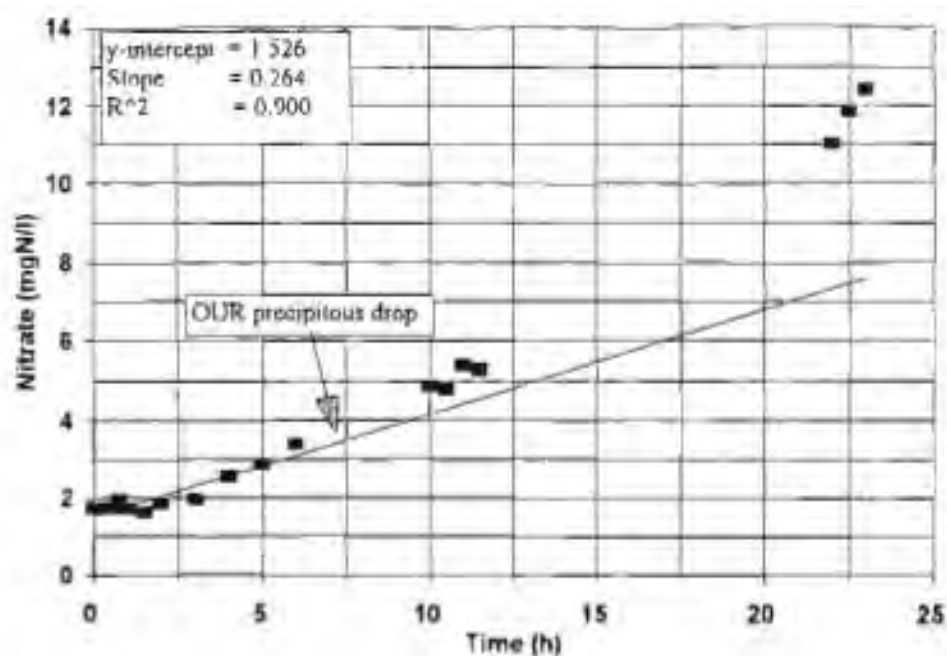


Fig N95 Nitrate concentration graph for wastewater plus mixed liquor batch test, 26-05, batch no. 26

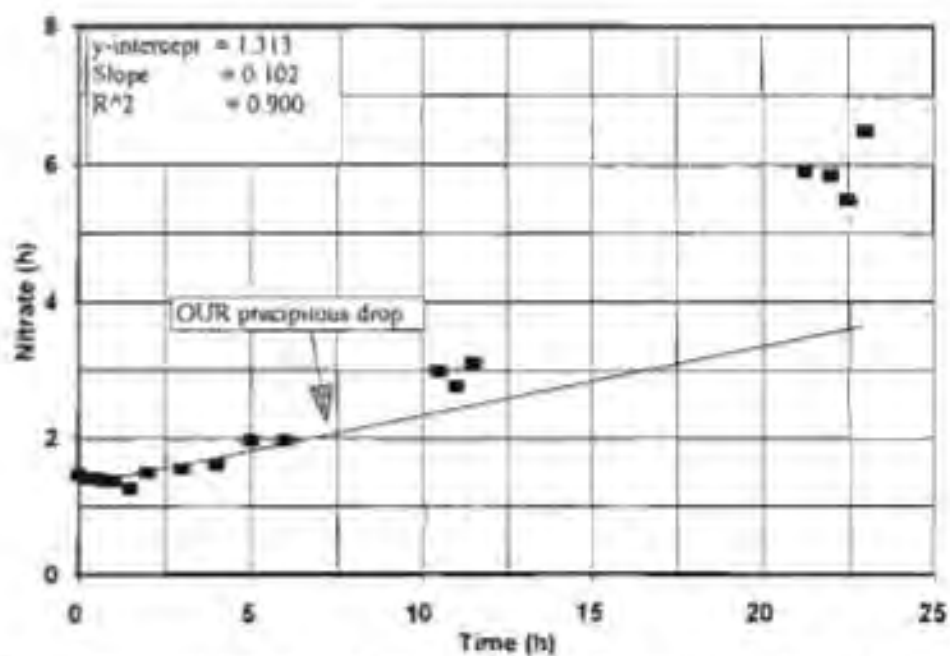


Fig N96 Nitrate concentration graph for wastewater plus mixed liquor batch test, 27-05, batch no. 26

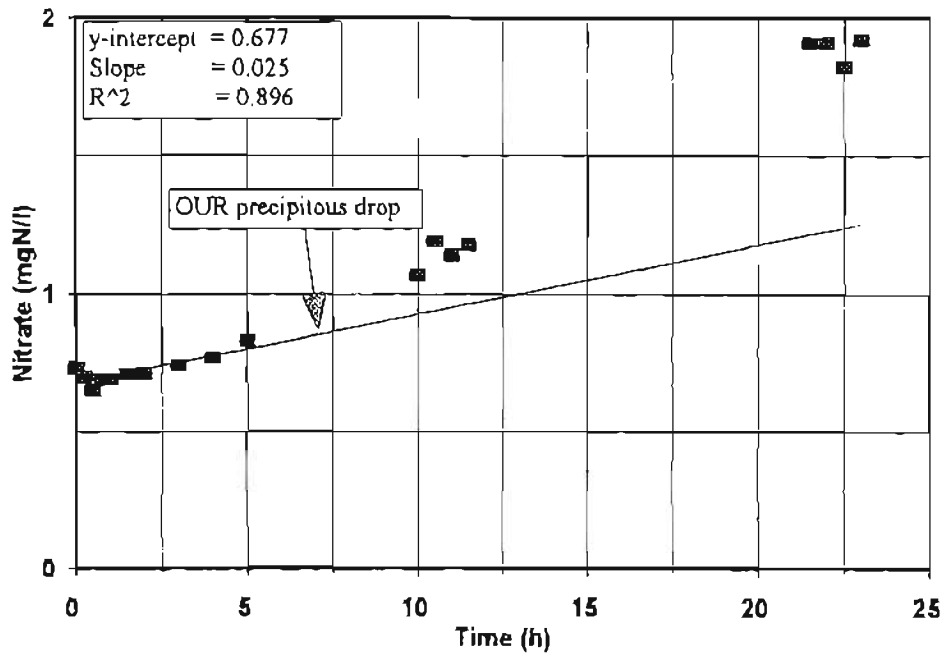


Fig N97 Nitrate concentration graph for wastewater plus mixed liquor batch test,28-05,batch no.26

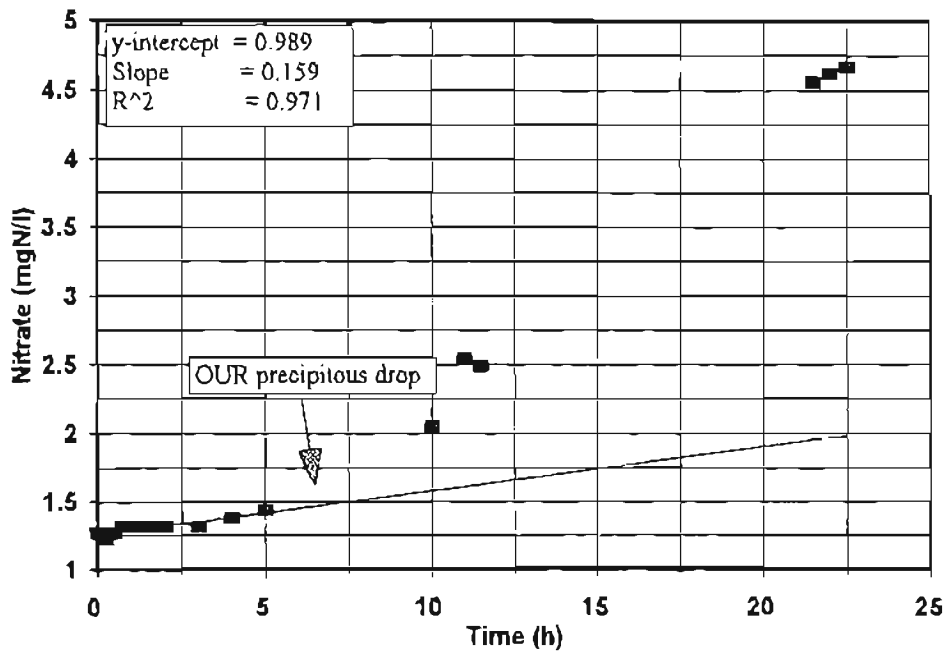


Fig N98 Nitrate concentration graph for wastewater plus mixed liquor batch test,29-05,batch no.26

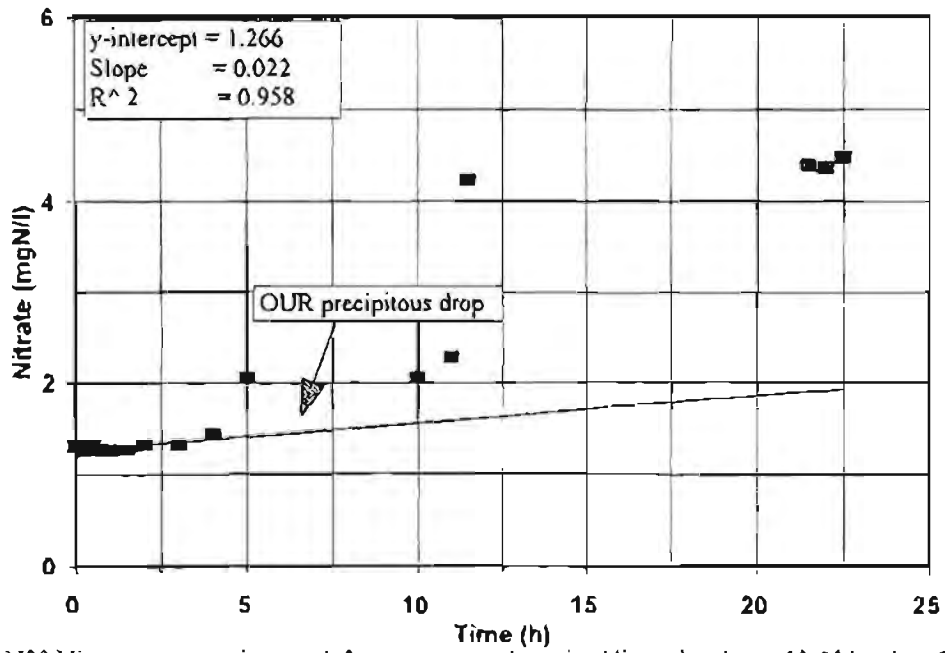


Fig N99 Nitrate concentration graph for wastewater plus mixed liquor batch test, 29-05, batch no.26

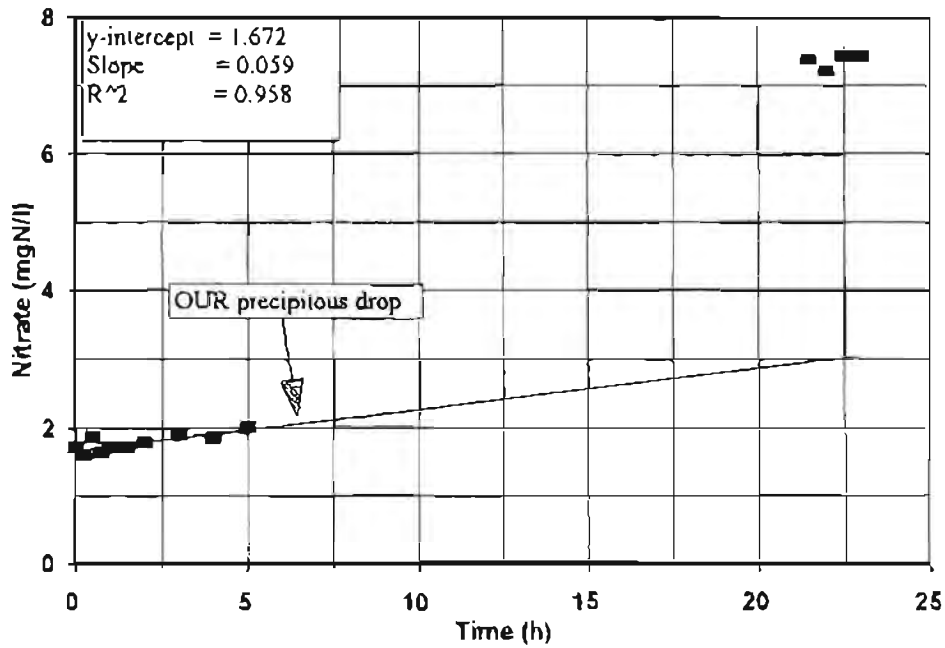
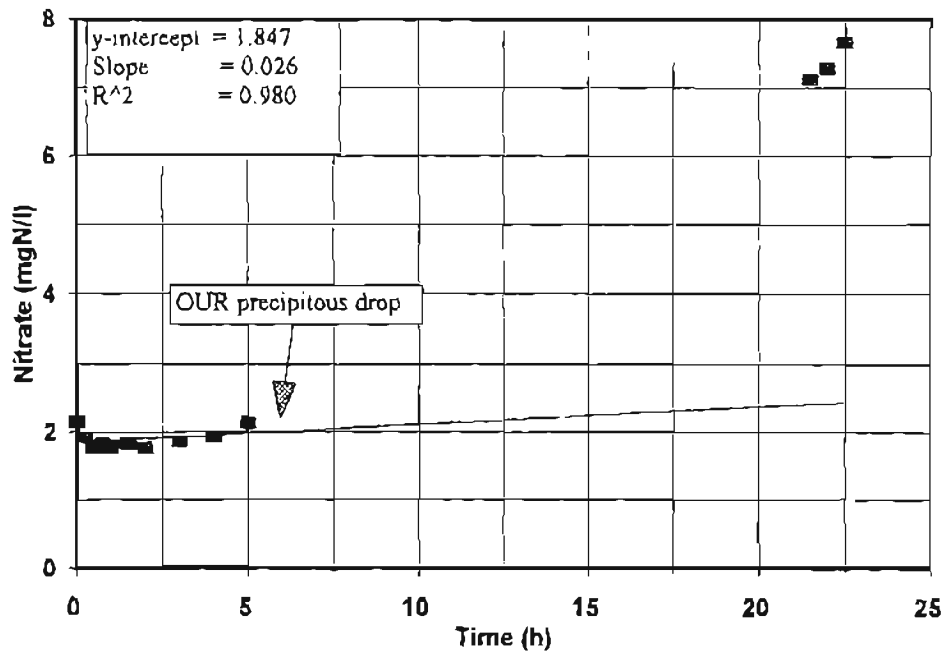
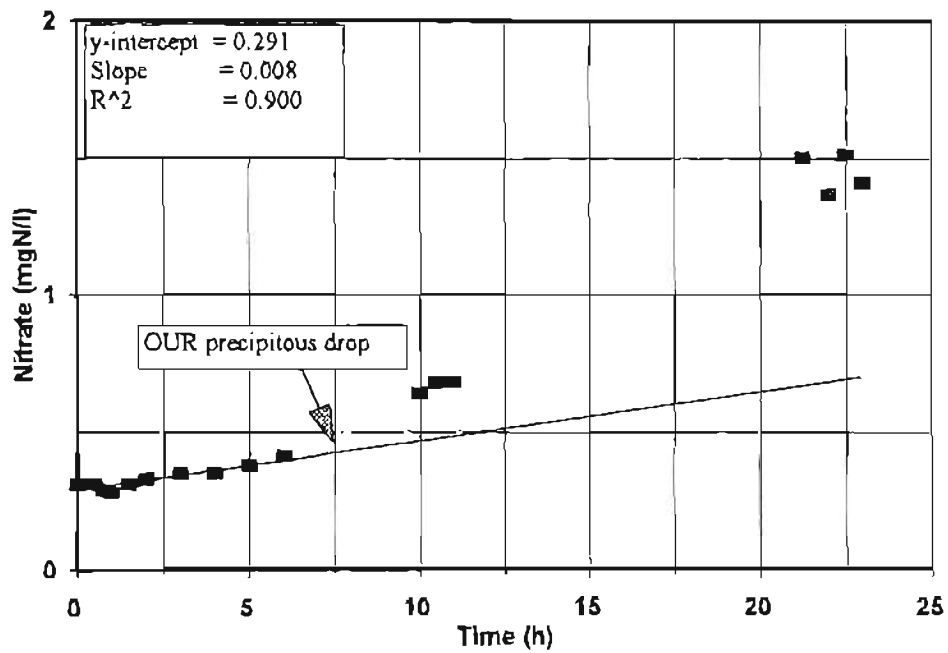


Fig N100 Nitrate concentration graph for wastewater plus mixed liquor batch test, 30-05, batch no.26



FigN101 Nitrate concentration graph for wastewater plus mixed liquor batch test,30-05,batch no.26



FigN102 Nitrate graph for wastewater plus mixed liquor batch test,03-06,batch no.27

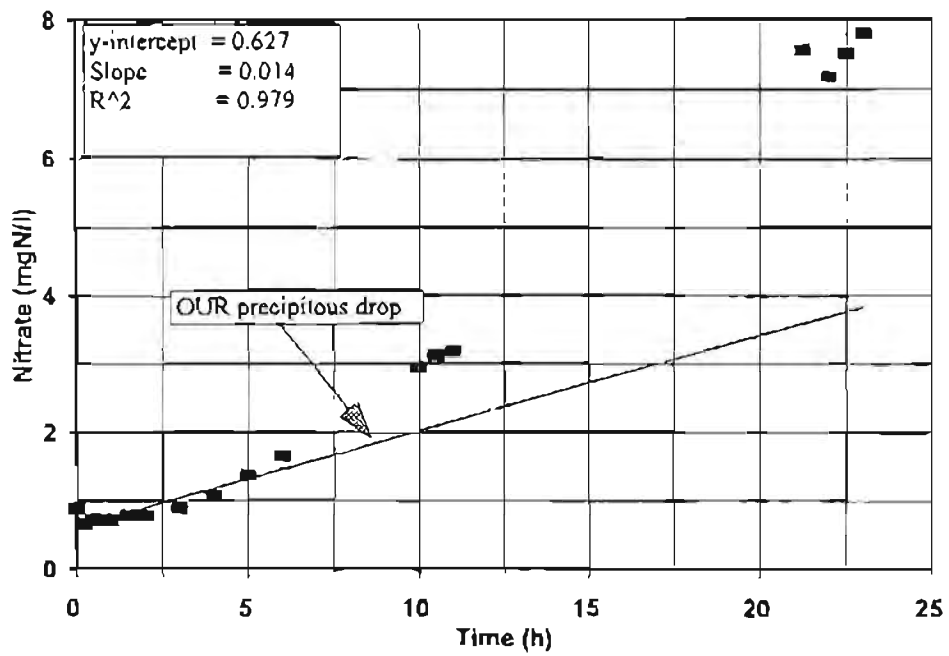


Fig N103 Nitrate concentration graph for wastewater plus mixed liquor batch test,04-06,batch no.27

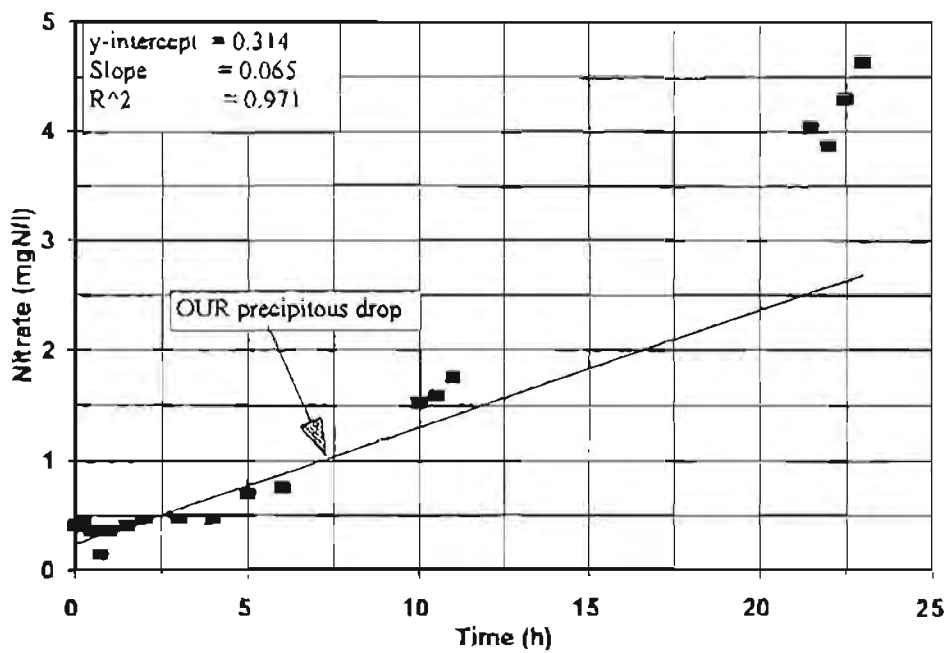
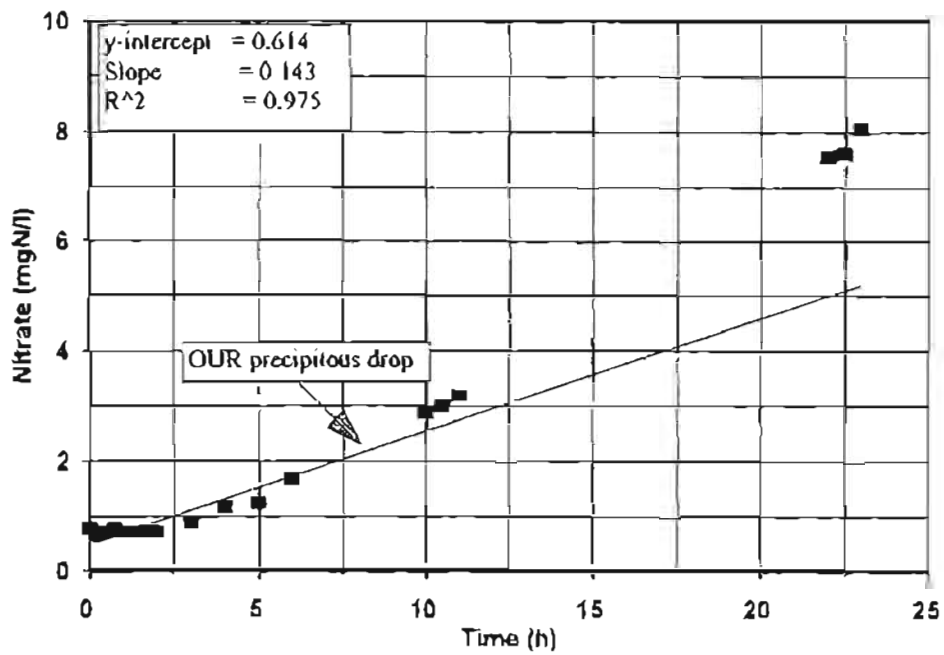
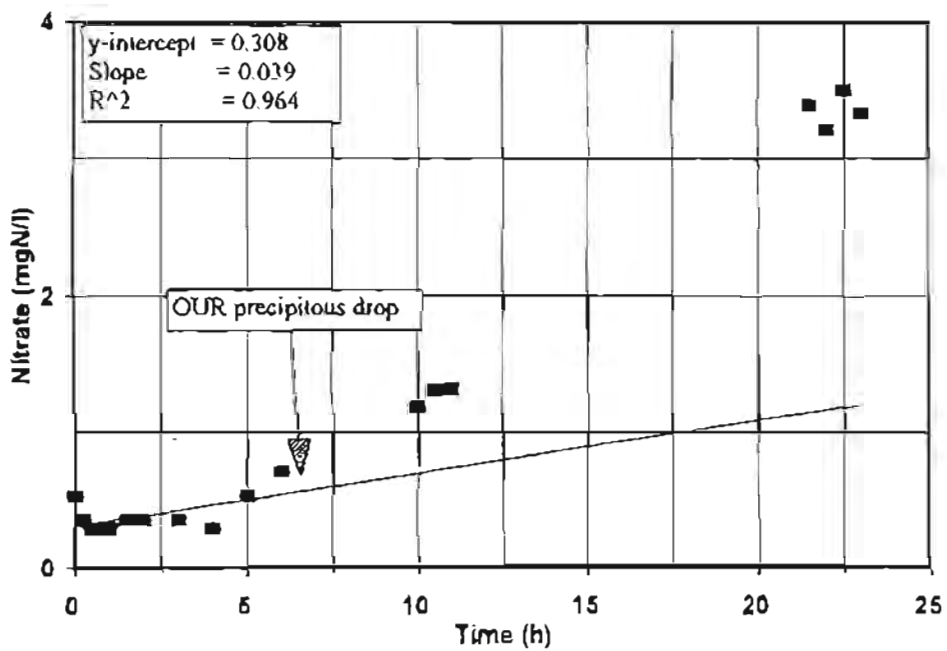


Fig N104 Nitrate concentration graph for wastewater plus mixed liquor batch test,05-06,batch no.27



FigN105 Nitrate concentration graph for wastewater plus mixed liquor batch test,06-06,batch no.27



FigN106 Nitrate concentration graph for wastewater plus mixed liquor batch test,07-06,batch no. 27

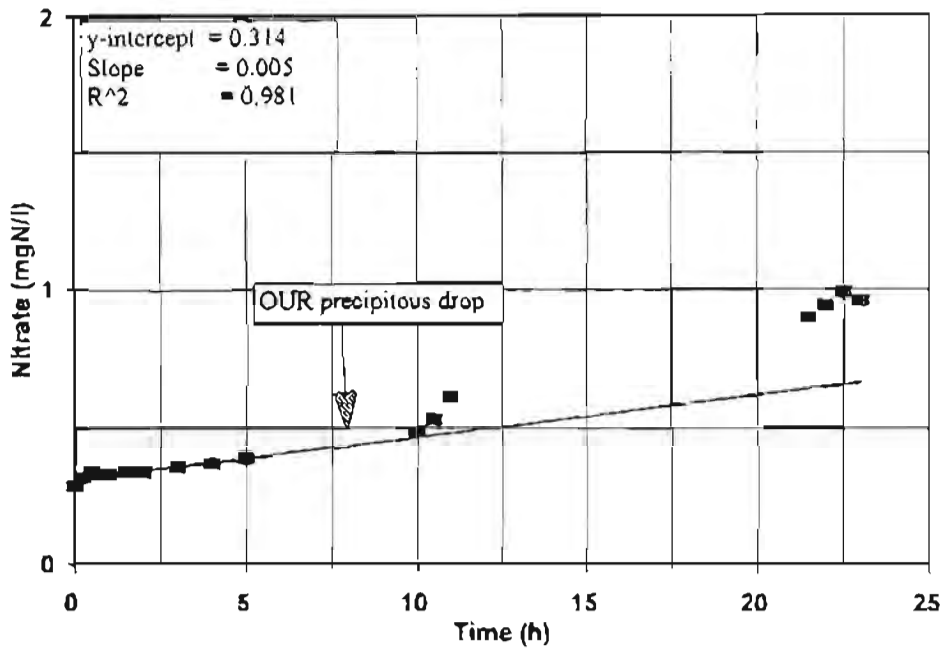


Fig N107 Nitrate concentration graph for wastewater plus mixed liquor batch test, 8-6, batch no. 27

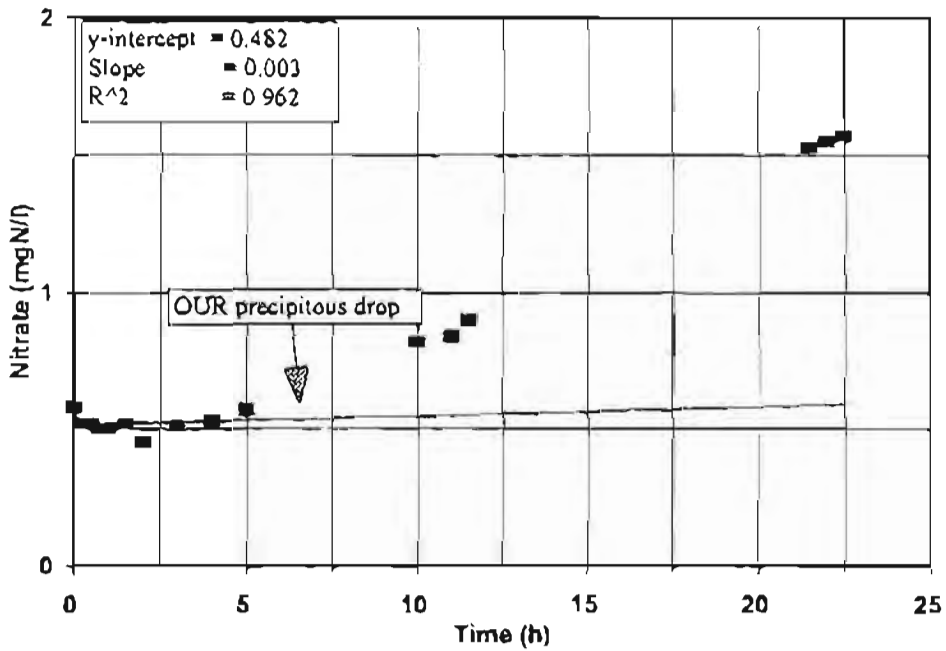
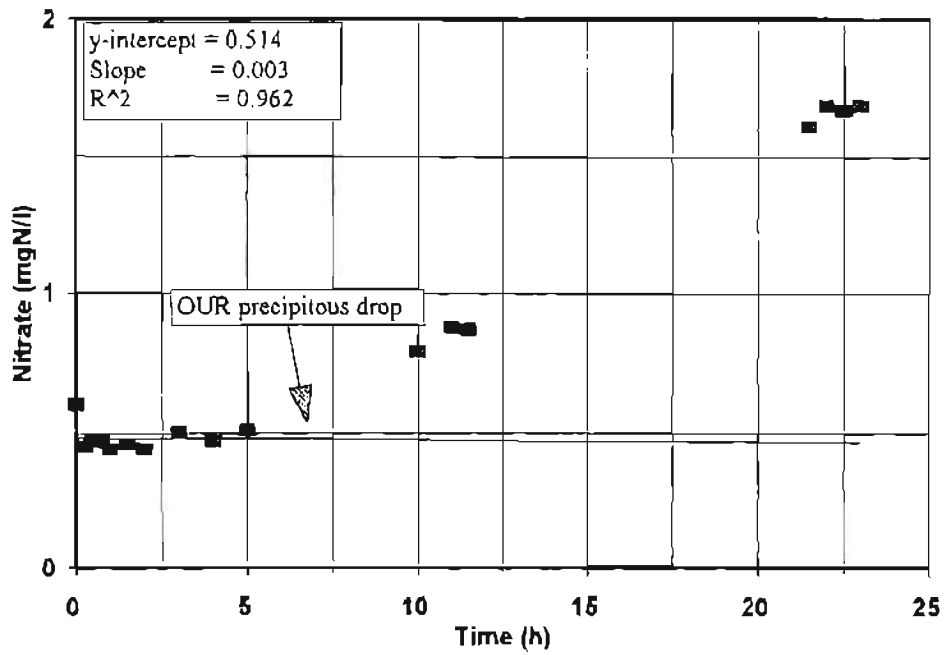
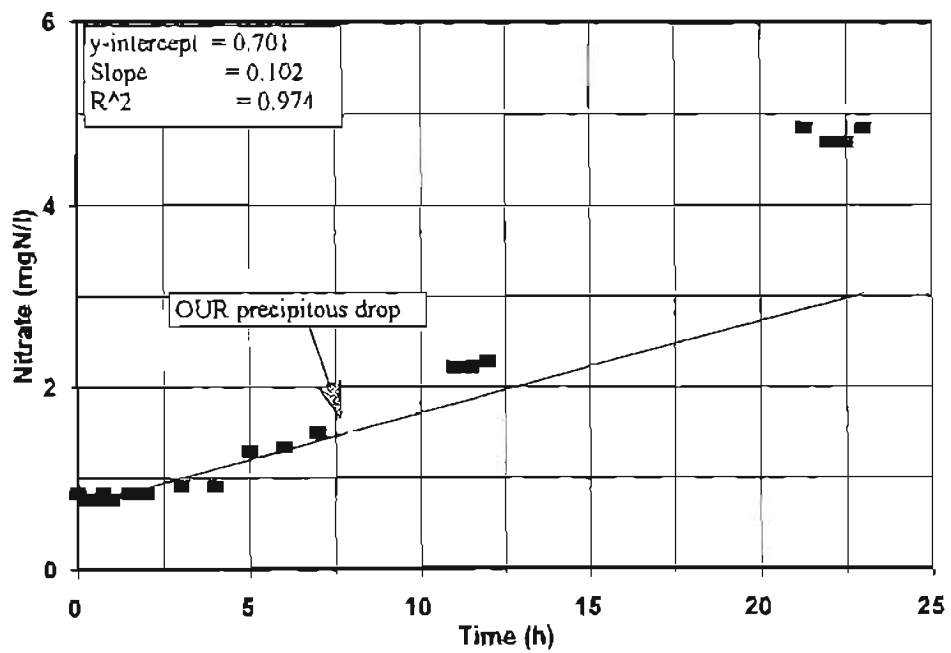


Fig N108 Nitrate concentration graph for wastewater plus mixed liquor batch test, 09-06, batch no. 27



FigN109 Nitrate concentration graph for wastewater plus mixed liquor batch test,09-06,batch no.27



FigN110 Nitrate concentration graph for wastewater plus mixed liquor batch test,10-06,batch no.27

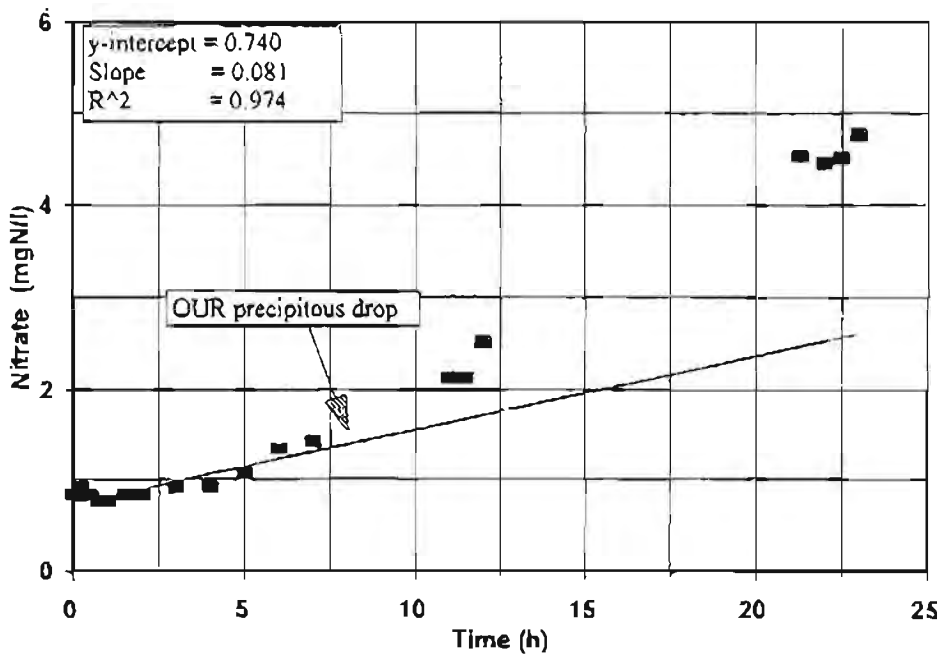


Fig N111 Nitrate concentration for wastewater plus mixed liquor batch test, 10-06, batch no.27

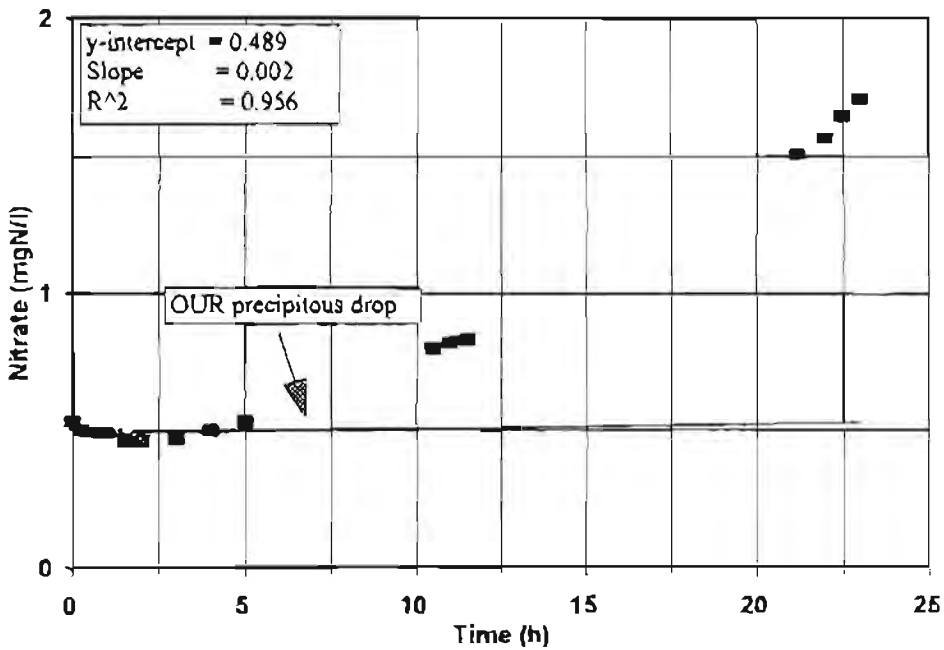


Fig N112 Nitrate concentration graph for wastewater plus mixed liquor batch test, 11-06, batch no.27

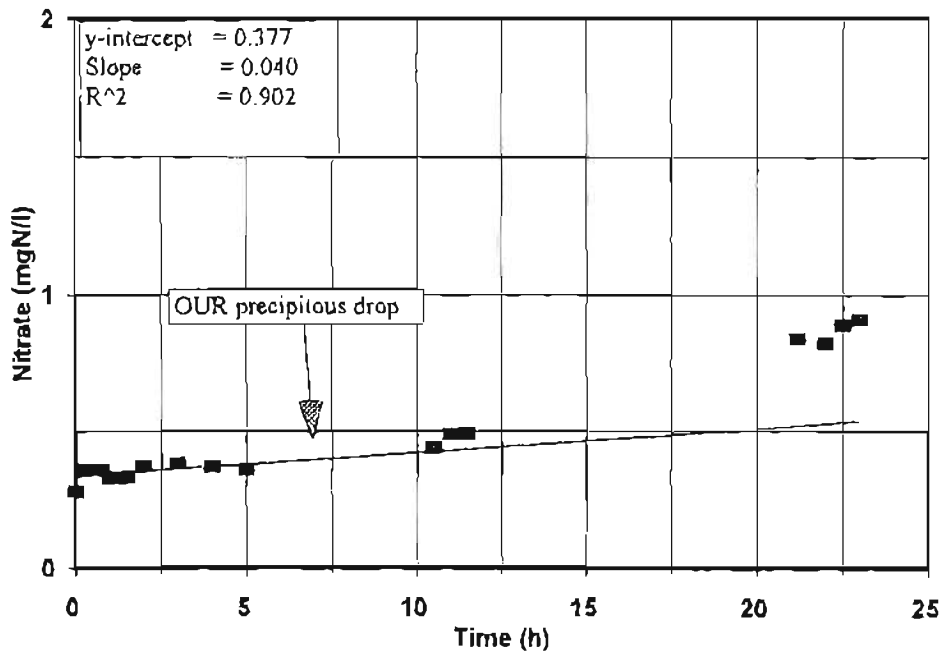


Fig N113 Nitrate concentration graph for wastewater plus mixed liquor batch test, I1-06, batch no.27

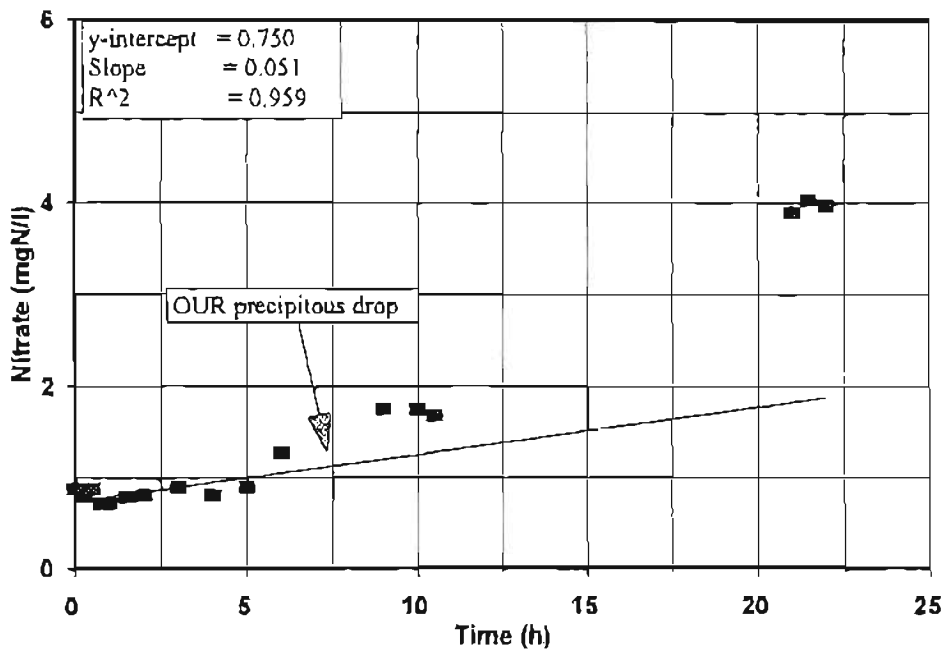


Fig N114 Nitrate concentration graph for wastewater plus mixed liquor batch test, I2-06, batch no.27

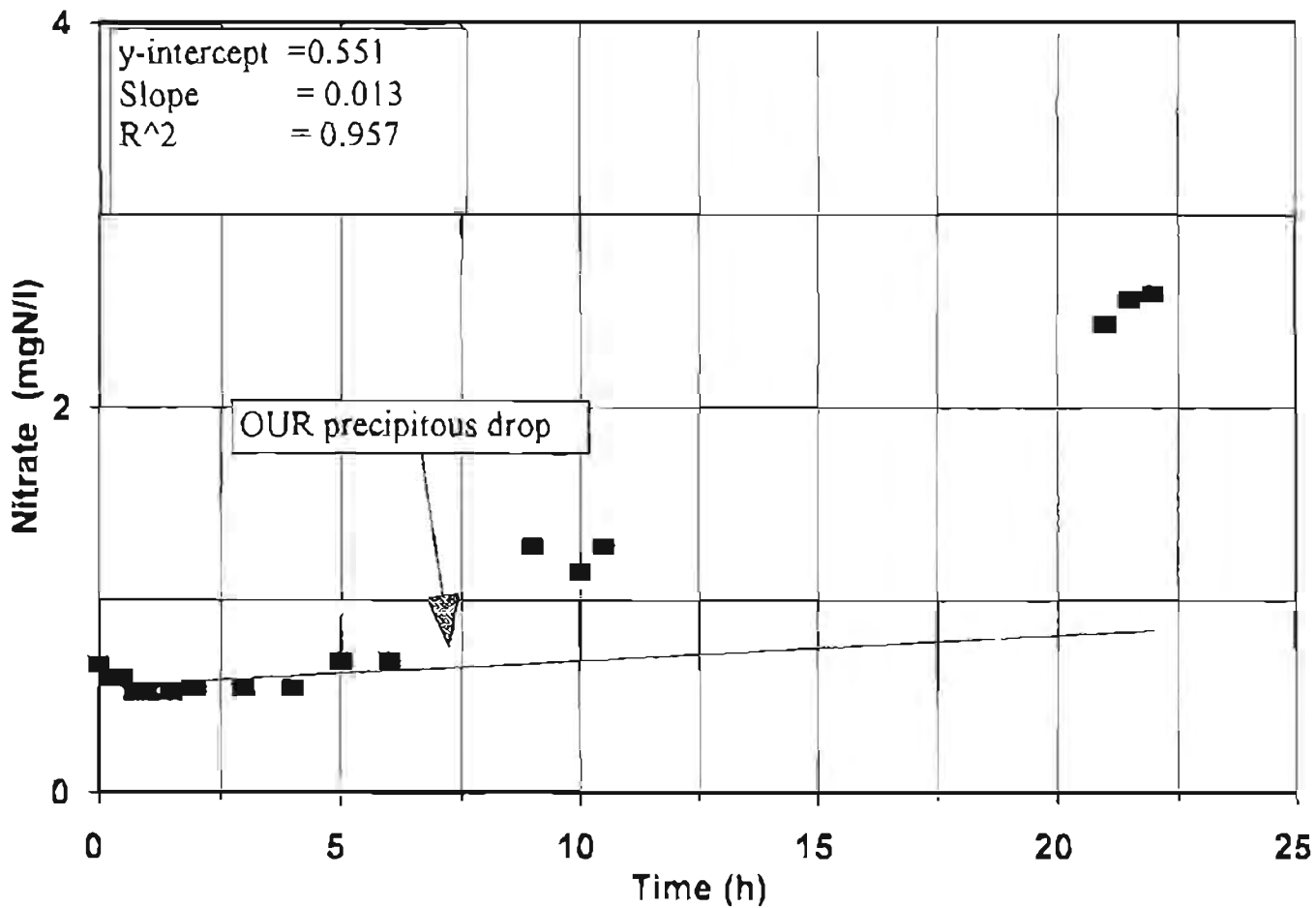


Fig N115 Nitrate concentration graph for wastewater plus mixed liquor batch test, 12-06, batch no.27

APPENDIX C

COMPREHENSIVE DATA FOR THE PARENT LABORATORY-SCALE ACTIVATED SLUDGE SYSTEM

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Table C1 Summary of the parent system COD, OUR and VSS statistical data for the various wastewater batches.

Sew. Batch No.	COD (mgCOD/l)												OUR (mgO ₂ /l/h)			VSS (mgVSS/l)		
	INFLUENT			UNFILTERED EFFLUENT			MIXED LIQUOR			Mean	std. dev. of sample	No. of tests	Mean	std. dev. of sample	No. of tests			
	Mean	std. dev. of sample	No. of tests	Mean	std. dev. of sample	No. of tests	Mean	std. dev. of sample	No. of tests									
1	498	9	13	39	5	12	3281	117	13	28.1	3.1	14	2394	89	14			
2	479	38	10	38	6	10	3294	110	6	25.5	2.9	6	2392	65	6			
3	512	20	18	44	6	19	2695	114	17	25.0	2.0	17	1949	93	18			
4	476	21	7	50	10	8	2718	111	8	25.2	2.7	8	1953	66	8			
5	512	15	19	49	13	19	3037	227	10	29.9	2.1	10	2306	149	10			
6	487	42	14	40	7	14	2876	280	13	30.6	2.2	14	1976	186	13			
7	521	17	18	39	9	18	2916	237	13	27.2	2.5	13	2094	187	13			
8	549	31	14	47	9	13	2925	190	13	27.1	1.9	11	1911	58	13			
9	481	35	13	66	8	12	2472	181	12	26.0	1.6	13	1661	78	13			
10	554	69	12	59	12	12	3372	330	12	27.6	2.1	12	2222	167	12			
11	526	27	13	46	13	13	3499	195	13	27.9	1.9	12	2339	169	13			
12	517	30	15	49	15	14	3433	341	13	24.6	1.7	15	2293	149	11			
13	492	19	15	46	10	16	2833	301	16	23.7	0.6	10	1684	118	16			
14	527	25	16	45	8	16	3125	202	17	25.3	2.0	16	1908	106	16			
15	531	23	10	49	9	9	2947	280	9	24.5	0.6	9	1932	56	9			
16	474	20	4	39	8	4	3160	275	4	25.7	1.4	4	2018	45	4			
17	481	30	14	44	10	13	2839	185	14	25.8	0.6	14	2033	78	13			
18	450	31	12	72	9	12	2513	144	12	22.7	1.6	13	1709	85	12			
19	492	27	13	59	8	12	2640	153	12	23.5	0.5	12	1775	28	12			
20	500	21	13	48	10	13	2958	286	13	24.3	0.9	13	2052	118	11			
21	503	34	14	49	10	14	3477	185	13	25.9	1.1	13	2116	112	13			
22	476	16	9	38	5	9	4284	151	8	27.4	0.3	9	2729	108	8			
23	493	39	11	33	8	9	4236	246	11	27.6	0.6	8	2668	51	11			
24	489	19	14	43	7	14	3659	236	15	29.3	0.3	15	2557	66	14			
25	498	41	11	46	6	10	4450	188	11	28.4	2.9	11	2747	71	10			
26	458	23	11	51	9	11	4297	227	11	27.9	0.5	11	2861	51	12			
27	479	39	13	46	8	13	4873	266	14	23.9	1.3	13	3185	101	13			
28	476	16	13	40	9	11	5103	204	13	25.9	1.3	12	3302	120	12			

Table C2 Summary for the parent system TKN and nitrate statistical data for the various wastewater batches.

Sew. Batch No.	TKN (mgN/l)						NITRATES (mgN/l)								
	INFLUENT		UNFILTERED EFFLUENT		MIXED LIQUOR		ANOXIC		AEROBIC		EFFLUENT				
	Mean	std. dev. of sample tests	No. of tests	Mean	std. dev. of sample tests	No. of tests	Mean	std. dev. of sample tests	No. of tests	Mean	std. dev. of sample tests	No. of tests			
1	53	2	13	4.3	1.2	13	227	13	14			31.0	3.9	12	
2	51	2	10	3.2	0.8	9	217	7	6			32.8	1.8	9	
3	42	2	19	3.4	0.6	18	181	14	18			25.2	1.8	17	
4	49	6	8	3.3	0.2	8	195	9	7	3.6	1.6	8	11.4	2.1	8
5	56	2	18	3.2	0.7	19	201	17	9	2.7	0.9	20	11.3	1.2	19
6	60	4	14	1.8	1.3	14	162	29	14	11.4	3.3	13	20.7	3.5	13
7	51	3	19	3.0	1.3	19	186	26	13	1.9	0.6	16	9.8	1.4	17
8	46	2	13	2.6	1.0	13	188	22	13	0.9	0.3	13	7.2	0.6	13
9	46	1	14	6.1	1.5	13	175	8	12	5.8	2.1	14	11.4	2.3	14
10	46	3	12	4.3	0.7	12	231	18	12	0.5	0.3	10	7.5	0.9	12
11	44	1	13	3.5	0.3	13	248	16	13	0.4	0.2	12	7.0	0.3	12
12	41	3	14	3.6	0.6	15	255	13	13	0.4	0.1	14	5.3	0.6	15
13	47	3	15	3.5	0.4	13	210	16	16	1.7	0.7	13	10.9	1.2	13
14	47	2	17	3.3	0.5	16	222	14	15	5.4	3.1	17	14.7	2.5	11
15	45	2	10	2.9	0.4	9	217	26	10	0.6	0.3	9	5.4	0.5	9
16	37	1	4	3.5	0.3	4	231	5	4	3.6	0.4	4	4.7	0.4	4
17	48	1	13	3.7	0.3	13	222	11	13	1.6	0.9	14	8.7	1.0	14
18	37	1	11	3.5	0.6	13	193	15	12	0.6	0.4	11	5.3	0.3	12
19	45	2	12	3.2	0.4	12	222	9	12	0.5	0.5	12	5.9	1.3	10
20	49	1	13	3.4	0.3	12	221	20	12	6.0	0.7	13	13.1	1.2	13
21	52	4	14	3.8	0.5	13	258	21	14	1.6	0.5	10	7.9	0.6	12
22	58	1	8	3.0	0.4	9	294	11	8	9.6	0.7	8	19.7	0.5	8
23	57	4	11	3.2	0.5	11	314	24	11	6.8	1.4	11	16.0	1.1	10
24	53	2	14	3.1	0.4	15	284	24	15	3.2	2.5	14	13.0	2.7	14
25	51	6	10	3.3	0.5	11	309	12	11	4.8	1.3	11	14.1	2.3	11
26	58	3	11	3.1	0.6	11	303	14	12	12.8	1.2	11	23.4	1.4	10
27	47	4	13	3.0	0.5	13	333	15	14	2.8	1.1	9	9.8	2.4	12
28	57	7	13	3.0	0.6	13	344	32	12	6.8	1.7	13	16.5	2.2	13

Table C3

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
1	March 30	54	3.8	504	38			34.6
	March 31	55	3.6	490	36			34.6
	April 01	53	3.7	492	42			33.8
	April 02	55	4.2					33
	April 03	54	3.9	500	32			32.8
	April 04	55	4.2	518	38			31.4
	April 05	50	3.9	492	34			32
	April 06	48*	2.7	506	36			33.2
	April 07	52	4.3	496	42			27.6
	April 08	54	7.3	496	40			20*
	April 09	52	3.9	489	22*			26.4
	April 10	51	11.3*	486	40			9.4*
	April 11	53	6.1	493	37			21.6
April 12	50	3.9	509	47			28.2	
		53	4.3	496	39			31
2	April 13	55	4.6	511	39			31.4
	April 14	52	2.5	538	39			32.4
	April 15	50	2.7	527	37			32
	April 16	48	3.2	470	41			34.8
	April 17	48	3.1	478	41			31.4
	April 18	47	3.2	466	29			30.8
	April 22	53	3.6	476	35			32
	April 23	50	2.0	470	31			34.8
	April 24	51	3.9	433	45			35.6
	April 25	51	6.1*	417	47			23*
		51	3.2	477	38			38
3	April 26	37	3.0	450*	43			24.2
	April 27	37	2.0	468	37			24
	April 28	38	1.5*	517	43			22.6
	April 29	42	3.6	528	37			20.8
	April 30	40	3.0	532	49			22
	May 01	43	3.6	534	37			24
	May 02	41	3.7	492	51			26.6
	May 03	42	3.0	528	43			25.6
	May 04	42	2.8	520	37			24.2
	May 05	42	2.9	520	39			25.6
	May 06	41	4.0	530	43			26.4
	May 07	43	2.9	526	39			24.6
	May 08	45	3.6	511	44			26.4
	May 09	43	3.7	487	38			28
	May 10	44	3.4	523	44			27
	May 11	43	3.6	497	52			25.2
May 12	43	4.0	483	52			27.6	
May 13	43	4.1	499	50			35.6*	
May 14	44	3.8	517	50			34.6*	
		42	3.4	512	44			25

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** test rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
4	June 20	39	3.2	495	57	6.6		14.4
	June 21	43	3.4	437	59	5.2		15
	June 22	49	3.0	493	53	3.8		10
	June 23	51	3.2	478	54	2.2		10.7
	June 24	50	3.4	489	61	2.2		9.9
	June 25	49	3.5	482	37	2.5		9.6
	June 26	51	3.6	460	33	2.5		10.6
	June 27	58	3.0	565*	49	3.4		11.3
		48	3.3	476	50	3.6		11
5	June 28	55	3.0	528	51	4.0		11.3
	June 29	48*	2.7	496	47	4.0		11.5
	July 03	53	7.4*	510	69	1.8		11
	July 04	53	2.1	506	49	2.4		8.8
	July 05	54	2.4	524	40	2.2		10
	July 06	55	3.4	491	37	2.7		10.5
	July 07	56	3.3	507	45	2.5		11.9
	July 08	57	3.0	521	45	4.1		11.3
	July 09	54	4.1	421*	75	4.4		12.4
	July 10	58	4.3	487	29	2.4		13.4*
	July 11	53	3.9	487	65	2.5		10.8
	July 12	59	3.2	509	75	2.2		10.8
	July 13	56	3.8	527	51	1.0		8.5
	July 14	57	3.7	517	35	1.5		8.4
	July 15	56	3.1	508	43	2.1		8.7
	July 16	57	3.0	545	41	2.2		10.4
July 17	55	3.6	514	45	2.1		10.6	
July 18	57	3.4	508	83*	3.2		9.9	
July 19	55	2.2	526	39	3.1	11.3	10.6	
July 20	46*	2.2	514	43	2.8	11.3	11.6	
		56	3.2	512	49	2.7	11.3	10
6	July 21	59	1.6	520	37	7.8	18.1	14.8
	July 22	61	1.4	522	37	10.9	20.2	19.2
	July 23	56	0.8	475	47	8.4	19.6	18.8
	July 24	55	0.6	459	33	11.8	15.6	18.5
	July 25	53	0.3	526	39	12.2	20.4	20.2
	July 26	59	0.4	487	33	10.8	18.8	20.8
	July 27	59	0.6	555	51	9.8	20.0	20.2
	July 28	57	0.6	489	33	10.0	21.0	21.2
	July 29	67	4.1	528	53	8.2	20.0	21.4
	July 30	63	2.9	412	45	10.8	18.8	22.6
	July 31	62	3.4	416	45	11.8	21.2	22.2
	August 1	61	3.3	450	37	17.2	26.4	25.6
	August 2	64	2.9	478	35	19.0	29.2	29
	August 3	63	2.7	495	35	20.4*	30.2*	30.2*
		60	1.8	487	40	11.4	20.7	21

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)			
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent	
7	August 4	53	4.0	517	49	11.6*	21.0*	25*	
	August 5	51	3.4	521	51	5.0*	12.8*	15.2*	
	August 6	52	4.1	505	26	2.4	9.6	10.4	
	August 7	53	4.0	511	33	1.8	8.6	8.6	
	August 8	55	4.2	511	31	1.8	9.6	7.2	
	August 9	53	3.2	502	61	1.6	8.6	9	
	August 10	52	4.5	494	83*	2.4	9.4	9	
	August 11	54	4.3	520	34	1.6	7.2	8.6	
	August 12	49	3.4	508	40	2.5	10.2	10.2	
	August 13	47	2.7	439*	40	1.0	9.6	9.2	
	August 14	51	3.4	536	32	0.9	9.6	9.6	
	August 15	52	4.0	514	26	1.7	9.4	8.6	
	August 16	53	3.5	512	34	1.3	10.2	9.6	
	August 17	53	2.0	551	43	1.5	10.8	10	
	August 18	48	1.3	524	35	1.9	10.6	10.2	
	August 19	49	1.3	534	47	2.7	11.6	9.7	
	August 20	47	0.8	557	39	2.2	11.0	11.3	
	August 21	48	1.3	530	37	2.7	10.4	12.4	
	August 22	48	1.0	534	47	7.8*	15.5*	12.9	
			51	3.0	521	39	1.9	9.3	10
	8	August 23	38*	0.6	518	43	5.1*	11.8*	14.6*
		August 24	44	2.0	526	39	0.8	7.5	13.6*
August 25		48	2.5	562	57	1.2	6.8	7	
August 26		49	2.2	605	33	0.8	7.3	7.2	
August 27		43	1.8	523	51	0.8	6.4	6.4	
August 28		47	1.5	568	53	1.0	7.0	6.7	
August 29		44	3.3	546	47	0.4	7.5	7	
August 30		45	2.7	531	35	0.6	7.2	7.3	
Sept. 01		46	5*	515	35	0.5	6.8	6.8	
Sept. 02		45	3.3	537	55	1.3	6.4	6.5	
Sept. 03		47	2.7	516	49	1.3	7.1	6.8	
Sept. 04		47	4.1	571	55	1.0	7.8	7.2	
Sept. 05		47	3.4	555	61	0.7	7.9	7.5	
Sept. 06		48	3.9	608	92*	1.3	8.3	7.5	
		46	2.8	549	47	0.9	7.2	7	
9	Sept. 07	46	0.3*	567	96*	2.6	8.4	8.3	
	Sept. 08	46	4.3	459	59	2.8	13.5	8.1	
	Sept. 09	45	5.1	481	71	8.2	12.0	14	
	Sept. 10	48	5.2	573*	75	9.5	15.9	15.5	
	Sept. 11	46	6.2	483	69	7.7	14.3	14.8	
	Sept. 12	46	7.3	521	92*	4.5	11.5	12.8	
	Sept. 13	46	8.1	497	69	3.6	8.4	10	
	Sept. 14	46	9.2	474	71	4.8	9.7	9.5	
	Sept. 15	45	6.1	452	59	5.3	7.7	12.2	
	Sept. 16	48	6.2	462	59	7.0	12.4	13.4	
	Sept. 17	42	5.9	438	55	7.0	12.4	11.2	
	Sept. 18	44	6.9	455	63	6.9	11.2	11.7	
	Sept. 19	47	4.3	481	57	6.6	11.4	12.5	
	Sept. 20	47	4.3	506	79	5.0	11.4	11.1	
		46	6.1	481	66	5.8	11.4	12	

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems.

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
10	Sept. 21	50	4.5	443	77	0.4	8.6	10.5*
	Sept. 22	49	4.2	638	67	0.9	8.3	8.4
	Sept. 23	49	5.4	664	53	1.1	8.9	8.1
	Sept. 24	48	3.5	604	41	0.4	8.9	7.3
	Sept. 25	48	4.1	538	55	0.2	5.8	6
	Sept. 26	48	4.8	458	57	0.4	6.7	6
	Sept. 27	45	4.8	583	81	0.4	7.2	7
	Sept. 28	48	3.3	583	49	0.5	7.0	6.9
	Sept. 29	46	5.0	601	47	0.6	7.2	8
	Sept. 30	40	4.1	504	53	0.5	7.4	7.2
	Oct. 01	41	3.6	502	80	1.4*	7.2	7.2
	Oct. 02	41	4.8	522	66	1.9*	8.4	7.2
		46	4.3	554	59	0.5	7.5	7
11	Oct. 03	43	3.2	574	62	1.1*	7.4	8
	Oct. 04	42	3.8	518	62	0.6	6.8	7.4
	Oct. 05	45	3.5	527	22	0.5	7.0	7.4
	Oct. 06	47	3.6	507	65	0.5	6.8	6.8
	Oct. 07	47	3.4	491	41	0.3	9.8*	7.4
	Oct. 08	43	3.2	504	47	0.6	6.8	6.8
	Oct. 09	43	3.8	535	53	0.5	7.2	7.2
	Oct. 10	44	3.7	555	41	0.5	6.8	6.8
	Oct. 11	44	4.1	528	33	0.4	7.4	8.6*
	Oct. 12	43	2.9	559	33	0.2	6.8	6.9
	Oct. 13	45	3.9	546	53	0.1	7.2	6.9
	Oct. 14	44	3.6	483	37	0.3	6.8	7
	Oct. 15	43	3.5	513	51	0.5	7.2	7
		44	3.5	526	46	0.3	7.0	7
12	Oct. 17	45	4.3	488	58	0.3	5.6	5.6
	Oct. 18	41	4.1	510	35	0.3	5.1	3.8
	Oct. 19	44	4.8	559	29	0.3	4.1	5.4
	Oct. 20	38	4.2	553	70	0.4	5.3	4.8
	Oct. 21	39	3.7	559	51	0.4	5.2	5.7
	Oct. 22	45	3.3	487	38	0.8*	5.4	5.2
	Oct. 23	37	3.6	475	47	0.4	4.7	5
	Oct. 24	40	3.5	535	70	0.4	5.1	4.8
	Oct. 25	43	3.3	543	95*	0.5	6.1	5.3
	Oct. 26	43	3.5	504	33	0.3	5.2	5.2
	Oct. 27	24*	2.4	531	62	0.5	5.9	4.1
	Oct. 28	43	2.5	538	60	0.5	6.0	4.7
	Oct. 29	41	3.9	486	44	0.6	5.7	5.7
	Oct. 30	41	3.2	480	27	0.5	4.5	3.9
	Oct. 31	41	3.2	488	55	0.7	5.7	3.8
		41	3.6	517	49	0.4	5.3	5

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
13	01-Nov	53	4.1	475	41	0.7*	10.5	10.4
	02-Nov	51	3.3	502	47	1.1	10.3	8.6
	03-Nov	45	3.5	469	55	0.8*	8.8	9.6
	04-Nov	45	3.5	477	63	1.5	10.2	9.3
	05-Nov	51	3.5	465	37	2.8	11.2	10.4
	06-Nov	50	5.5*	500	53	4.4*	13.2	12.2
	07-Nov	44	4.3	479	51	2.1	11.1	12.3
	08-Nov	45	3.9	479	53	1.6	11.0	11.1
	09-Nov	46	3.4	483	33	1.4	10.6	10.2
	10-Nov	45	2.9	506	43	3.0	13.1	11.5
	11-Nov	46	3.2	508	43	1.7	11.6	11.4
	12-Nov	47	3.4	492	43	1.4	9.6	11.3
	13-Nov	46	3.4	498	35	2.2	10.6	11.2
	15-Nov	48	11.5*	530	59			4.3*
16-Nov	47	7.4*	522	53			7.9	
17-Nov	40*	2.7	430*	33	2.1		8.1	
		47	3.5	492	46	1.9	10.9	10
14	18-Nov	46	3.1	539	35	3.1		8.7
	19-Nov	46	2.9	526	39	3.2		11.9
	20-Nov	47	3.7	502	41	3.1		12
	21-Nov	47	2.7	520	53	2.0		11.4
	22-Nov	47	5*	526	45	1.0		11.7
	23-Nov	47	3.0	551	55	1.0		12
	24-Nov	46	3.9	545	45	8.8	16.4	18.35
	25-Nov	47	3.6	530	56	9.2	17.7	17.7
	26-Nov	46	3.4	485	39	8.7	18.2	18.3
	27-Nov	48	2.9	526	58	7.8	15.3	16.68
	28-Nov	48	3.1	551	33	8.5	16.8	17.81
	29-Nov	47	2.7	559	47	9.6	16.7	16.68
	30-Nov	48	4.0	559	64*	7.9	15.0	16.57
	01-Dec	46	3.1	469	45	4.6	12.6	13.87
02-Dec	47	2.9	530	51	6.3	13.8	13.87	
03-Dec	41	2.7	462*	39	3.5	10.8	12.18	
04-Dec	49	4.3	514	37	3.0	10.6	11.16	
		47	3.3	527	45	5.4	14.7	14
15	05-Dec	46	3.2	530	47	1.4	8.9*	10.04*
	06-Dec	43	2.9	539	47	0.5	5.5	6.72
	07-Dec	43	2.0	547	27*	0.5	5.5	5.47
	08-Dec	43	2.9	532	41	0.5	5.5	5.47
	09-Dec	46	4.4*	498	37	0.5	5.3	5.25
	10-Dec	45	2.9	496	45	0.5	5.6	5.59
	11-Dec	47	3.1	526	57	0.5	5.6	5.59
	12-Dec	45	3.4	557	53	0.5	5.8	5.8
	13-Dec	44	2.5	520	51	0.5	5.7	5.7
	14-Dec	43	2.9	565	66	2.8*	4.2	5.59
		45	2.9	531	49	0.6	5.4	6

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale acitvated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
16	08-Jan	38	3.7	472	32	3.9	5.1	5.5
	09-Jan	36	3.2	470	47	3.1	4.5	5.5
	10-Jan	37	3.7	500	43	4.0	4.3	6.93
	11-Jan	36	3.3	452	32	3.4	4.9	5.8
		37	3.5	474	39	3.6	4.7	6
17	12-Jan	41*	3.2	429	24	3.1	10.1	10.07
	13-Jan	46	3.9	502	58	2.8	10.8	10.78
	14-Jan	46	3.8	462	44	2.7	9.8	10.48
	15-Jan	49	2.5*	516	54	2.1	8.7	9.36
	16-Jan	46	3.5	474	42	2.2	9.0	9.01
	17-Jan	47	3.6	530	44	2.1	9.0	9
	18-Jan	47	4.1	502	36	0.8	8.3	8.3
	19-Jan	49	4.2	498	34	0.7	8.3	8.3
	20-Jan	49	3.3	484	54	0.5	8.0	8.2
	21-Jan	49	3.9	446	39	0.6	8.0	8
	22-Jan	46	3.7	433	41	1.5	7.8	7.74
	23-Jan	48	4.3	481	39	1.4	7.7	7.98
	24-Jan	48	3.4	479	60	1.0	8.1	8.1
25-Jan	48	3.6	495	81*	0.4	7.7	8.42	
		48	3.7	481	44	1.6	8.7	9
18	26-Jan	49*	3.4	483	80	1.1	7.9*	7.88*
	27-Jan	35	2.5	442	52	0.6	5.5	5.49
	28-Jan	37	2.6	486	68	0.2	5.1	5.38
	29-Jan	38	3.5	465	45*	0.7	5.0	5.06
	30-Jan	40	4.3	516	75	0.8	4.9	5.14
	31-Jan	37	3.7	437	85	1.5	5.7	5.47
	01-Feb	38	3.7	453	71	2.8*	5.4	6.35
	02-Feb	38	3.6	435	75	0.6	5.3	5.34
	03-Feb	37	4.3	443	79	0.7	5.3	5.34
	04-Feb	38	3.6	419	65	0.1	5.6	5.57
	05-Feb	37	3.4	396	63		5.6	5.57
06-Feb	37	3.6	447	73	0.3	5.4	4.88	
07-Feb	22*	2.8	552*	78	0.3	5.2	4.99	
		37	3.5	450	72	0.6	5.3	5
19	08-Feb	40*	3.4	468	53	0.2	4.5	5.64
	09-Feb	46	4.1*	489	65	0.2	4.6	5.64
	11-Feb	46	3.8	548	76	0.4	4.8	5.41
	12-Feb	47	3.6	454	65	0.4	5.1	5.07
	13-Feb	49	2.9	468	51	0.3		5.64
	14-Feb	46	3.6	469	59	0.2		5.67
	15-Feb	45	3.1	492	53	0.2	5.6	5.73
	16-Feb	45	2.8	494	51	0.1	5.3	5.96
	17-Feb	44	2.9	485	63	1.0	7.3	7.29
	18-Feb	44	3.3	504	45	1.4	7.5	8.07
	19-Feb	46	2.9	535	81	1.4	7.7	7.73
20-Feb	45	2.7	510	35*	0.6	6.7	7.55	
21-Feb	42	3.0	476	60	4.5*	10.3*	10.26*	
		45	3.2	492	59	0.6	5.9	6

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** test rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
20	22-Feb	51	3.4	468	41	6.2	12.1	12.07
	23-Feb	47	2.9	534	35	6.0	13.9	13.9
	24-Feb	48	3.8	405	51	4.9	11.6	13.05
	25-Feb	48	3.8	499	45	6.1	13.4	13.72
	26-Feb	48	3.4	497	41	6.5	13.9	13.85
	27-Feb	49	3.4	514	53	7.0	15.1	15.64
	28-Feb	51	2.9	522	47	6.5	14.3	14.64
	29-Feb	51	3.4	500	38	6.9	14.0	14.01
	01-Mar	50	3.8	494	37	7.0	13.4	14.01
	02-Mar	48	3.5	471	61	5.7	13.5	13.54
	03-Mar	47	3.2	479	61	5.4	12.2	12.2
	04-Mar	49	3.2	492	57	5.1	12.0	12.32
	05-Mar	50	4.2*	530	61	5.0	11.5	12.29
		49	3.4	500	48	6.0	13.1	13
21	06-Mar	51	3.6	498	31	5.1*	11.7*	12.29*
	07-Mar	45	4.3	467	37	3.1*	10.2*	10.74*
	08-Mar	52	4.1	483	57	2.5*	8.8	9.91
	09-Mar	47	3.8	475	35	3.5*	8.0	8.72
	10-Mar	48	3.4	447	51	0.9	7.7	7.65
	11-Mar	48	4.1	455	57	0.3	6.5	6.93
	12-Mar	51	4.8	531	39	0.6	7.8	7.75
	13-Mar	56	5.8*	546	58	0.5	7.4	7.86
	14-Mar	58	3.4	536	62	1.2	8.0	8.04
	15-Mar	53	3.4	496	54	1.7	7.9	7.92
	16-Mar	55	3.6	546	50	1.4	8.2	8.16
	17-Mar	53	2.7	513	44	0.9	8.2	8.39
	18-Mar	53	4.0	523	58	1.7	7.7	7.94
19-Mar	53	4.3	529	51	2.5*	8.9	9.03	
		52	3.8	503	49	1.0	7.5	8
22	04-Apr	56	2.4	493	39	6.4*	15.2*	15.18*
	05-Apr	58	3.2	466	32	9.8	19.5	19.52
	06-Apr	62*	3.4	475	41	10.3	19.3	19.52
	07-Apr	59	3.1	485	35	9.7	20.4	20.44
	08-Apr	57	2.9	458	35	8.2	19.4	19.41
	09-Apr	57	2.4	464	45	9.4	20.2	20.24
	10-Apr	58	3.8	458	41	10.5	19.8	20
	11-Apr	59	3.1	505	45	9.6	20.1	20.12
	12-Apr	56	2.9	480	31	9.4	19.0	19.41
		56	3.0	476	39	9.6	19.7	20
23	13-Apr	52	2.9	477	30	8.9	15.9	17.56
	14-Apr	50	2.5	443	22	8.6	15.8	15.75
	15-Apr	58	2.7	488	32	6.5	15.3	15.75
	16-Apr	57	2.9	526	36	5.6	14.9	15.41
	17-Apr	54	3.5	472	28	5.3	14.8	14.8
	18-Apr	54	3.1	490	35	5.4	15.6	16.4
	19-Apr	59	3.2	519	27	6.1	15.6	16.46
	20-Apr	61	3.6	536	58*	5.7	17.1	17.07
	21-Apr	59	3.6	457	35	6.4	17.0	17.31
	22-Apr	61	3.8	538	35	7.5	18.2	18.35
	23-Apr	61	3.8	525	51	9.0	20.9*	20.9*
		57	3.2	483	33	8.8	16.0	16

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
24	24-Apr	64*	2.5	482	31	10.9*	21.6*	21.58*
	25-Apr	58	2.9	482	33	6.2	17.0	19.44*
	26-Apr	54	3.2	519	53	4.1	13.6	15.16
	27-Apr	53	3.7	480	47	3.2	12.7	12.9
	28-Apr	55	3.9	463	42	2.8	13.7	13.66
	29-Apr	52	3.2	475	44	3.4	13.7	14.3
	30-Apr	53	2.9	475	54	1.1	12.0	12.49
	01-May	52	3.1	493	44	2.3	11.4	11.78
	02-May	49	2.7	505	46	0.3	9.5	10.43
	03-May	52	3.0	521	43	0.0	9.4	9.86
	04-May	53	2.8	479	47	0.9	9.9	10
	05-May	53	3.5	479	67*	1.2	10.9	10.13
	06-May	54	2.7	473	43	3.9	13.9	12.62
	07-May	58	3.0	516	37	7.3	17.3	16.97
08-May	52	3.8	437*	41	7.9	17.2	17.35	
		53	3.1	488	43	3.2	13.0	13.0
25	09-May	66	3.0	534	43	6.6	18.2	19.09
	10-May	70*	4.0	561	49	5.2	18.0	18.4
	11-May	50	3.1	526	39	4.8	13.3	14.43
	12-May	46	2.9	477	39	3.1	11.3	10.73
	13-May	48	2.5	505	41	3.3	12.3	11.13
	14-May	51	4.0	531	49	3.4	13.6	12.19
	15-May	47	3.2	424	53	4.3	12.7	13.63
	16-May	46	2.8	440	30*	5.8	12.7	13.59
	17-May	51	3.4	483	55	4.9	13.4	13.42
	18-May	49	3.2	501	45	7.0	16.1	14.88
	19-May	53	3.9	496	51	4.5	13.1	14.5
		51	3.3	498	46	4.9	14.1	14.1
26	20-May	54	2.3	475	41	7.4*	10.7*	12.83*
	21-May	72*	4.8*	668*	65	13.1	23.7	19.74
	22-May	53	3.6	453	67	9.7	20.3	21.41
	23-May	58	4.0	486	55	12.0	22.0	22.01
	24-May	58	3.2	451	41	14.1	25.0	24.49
	25-May	56	3.1	463	39	14.1	24.5	24.48
	26-May	56	2.9	418	47	13.5	23.9	23.9
	27-May	60	3.2	422	49	12.5	23.2	23.77
	28-May	59	3.2	455	76*	13.0	23.1	23.6
	29-May	60	3.4	462	47	13.5	24.2	24.72
	30-May	61	2.0	466	55	13.1		24.52
	31-May	64	2.9	491	53	12.2	24.2	24.27
		58	3.1	458	51	12.8	23.4	23.4

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C3-cont.

Daily COD, TKN and nitrates concentration results for the parent laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	TKN (mgN/l)		COD (mgCOD/l)		NITRATES (mgN/l)		
		Influent	Effluent	Influent	Effluent	Anoxic	Aerobic	Effluent
27	01-Jun	55	2.9	515	39	11.2*	13.2*	19.17*
	02-Jun	51	3.2	546	77*	8.3*	5.8	13.07
	03-Jun	40	3.6	420	45		5.9	8.41
	04-Jun	44	2.8	434	45		7.8	7.01
	05-Jun	46	2.5	481	57	2.0	9.3	9.25
	06-Jun	42	2.4	471	53	1.5	9.5	9.51
	07-Jun	45	2.7	446	37	1.3	9.5	9.58
	08-Jun	47	2.4	465	41	2.1	10.7	10.73
	09-Jun	44	2.5	384*	43	4.0	11.8	11.55
	10-Jun	47	3.6	478	62	3.9	12.0	12.54
	11-Jun	45	2.7	472	43	4.1	12.5	12.45
	12-Jun	53	3.7	488	51	3.2	11.5	11.93
	13-Jun	50	3.4	456	38	3.2	12.1	12.79
	14-Jun	62*	13*	550	45	10.1*	17.9*	17.88*
		47	3.0	479	48	2.8	9.8	11
28	15-Jun	54	3.5	478	35	6.4	14.4	16.71
	16-Jun	60	2.7	489	37	7.0	17.4	17.36
	17-Jun	60	3.1	486	41	8.1	20.0	19.96
	18-Jun	58	2.4	505	76*	9.3	20.1	20.09
	19-Jun	64	2.3	484	37	7.9	19.2	19.57
	20-Jun	74	3.8	475	78*	5.5	16.5	18.4
	21-Jun	52	3.9	487	47	5.5	14.6	15.5
	22-Jun	55	2.8	489	45	5.9	17.5	17.48
	23-Jun	50	2.5	461	35	5.2	15.7	15.72
	24-Jun	53	3.9	475	39	5.3	15.6	15.6
	25-Jun	62	2.7	446	29	4.5	15.3	15.47
	26-Jun	47	2.5	461	62	5.2	13.9	13.85
	27-Jun	51	3.1	458	33	4.1	14.0	14.1
		57	3.0	478	40	6.2	16	17

shaded values mean values for the wastewater batch

* test rejected as an outlier at 95% confidence interval

** test rejected due to system operational problems

Table C4

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory -scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
1	March 30	2688	2282	3165	209	131	27.6	7.72
	March 31	2709	2285	3145	220	131	27.6	7.68
	April 01	2727	2299	3145	230	130	28.0	7.53
	April 02	2759	2313		248	138	27.1	7.53
	April 03	2924	2470	3226	227	130	33.7	7.49
	April 04	2972	2478	3407	239	121	33.7	7.55
	April 05	2932	2503	3387	239	152	25.2	7.52
	April 06	2954	2487	3407	220	129	27.7	7.6
	April 07	2733	2355	3185	203	136	22.9	7.68
	April 08	2985	2521	3367	242	143	31.4	7.48
	April 09	2853	2397	3189	228	142	28.1	7.6
	April 10	2792	2359	3475	235	144	29.1	7.73
	April 11	2901	2460	3332	217	154	25.3	7.56
April 12	2704	2310	3230	217	165*	26.1	7.67	
			2394		227		28.1	7.6
2	April 13	2848	2413	3230	220	157	31.2	7.68
	April 14	2843	2435	3291	214	156	25.9	7.56
	April 15	2818	2411	3413	227	149	24.2	7.61
	April 16	2802	2352	3413	220	153	23.6	7.67
	April 17	2829	2459	3291	214	142	23.9	7.63
	April 18	2592	2282	3127	207	167	24.1	7.62
	April 22	2054**	1810**	2412**	204**	144**	24.1**	7.55
	April 23	1960**	1725**	2330**	174**	174**	29.5**	7.58
	April 24	2025**	1763**	2146**	199**	193**	22.2**	7.78
	April 25	2064**	1815**	2371**	184**	187**	29.9**	7.65
			2392	3294	217		25.6	7.63
3	April 26	1982	1738	2330*	155	184	17.5*	7.54
	April 27	1797*	1623*	2187*	141*	197	16.5*	7.64
	April 28	2204	1914	2657	157	172	20.8	7.64
	April 29	2212	1939	2591	171	155	23.4	7.78
	April 30	2276	2049	2611	171	137	26.9	7.88
	May 01	2280	1974	2509	175	132	23.5	7.88
	May 02	2229	2012	2489	182	149	23.4	7.74
	May 03	2150	1862	2672	165	140	26.3	7.65
	May 04	2097	1818	2632	175	138	25.0	7.52
	May 05	2283	2055	2672	175	127	23.1	7.92
	May 06	2189	1920	2774	189	158	25.2	7.58
	May 07	2328	2041	2815	193	147	26.9	7.48
	May 08	2289	2029	2817	196	158	27.1	7.34
	May 09	2288	2032	2817	195	157	25.4	7.52
	May 10	2311	2029	2857	206	158	26.5	7.66
	May 11	2197	1904	2857	189	163	28.3	7.56
	May 12	2267	1995	2676	189	150	26.2	7.76
May 13	2208	1943	2716	189	154	26.6	7.75	
May 14	2124	1819	2656	192	192	26.0	7.56	
			1948	2695	181		25.2	7.63

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
4	June 20	2190	1886	2596	158*	201	24.7	7.7
	June 21	2290	1968	2698	185	193	22.0	7.61
	June 22	2252	1902	2862	183	200	22.0	7.7
	June 23	2418	2028	2719	188	207	24.1	7.46
	June 24	2382	2071	2800	206	203	25.2	7.56
	June 25	2295	1845	2596	203	195	29.1	7.58
	June 26	2255	1898	2616	200	190	25.5	7.62
	June 27	2221	1924	2854	200	166*	29.0	7.68
		1953	2718	195		25.7	7.62	
5	June 28	2832	2458	2813	207	163*	29.8	7.59
	June 29	2572	2184	2631	207	165*	28.3	7.6
	July 03	2187**	1885**	2550**	155**	143**	28.3**	7.6
	July 04	2106**	1820**	2672**	165**	121**	29**	7.7
	July 05	2086**	1764**	2307**	174**	113*	29.7**	7.53
	July 06	2249**	1913**	2585**	179**	105**	29.4**	7.53
	July 07	1925**	1651**	2362**	188**	121**	29.1**	7.53
	July 08	2056**	1807**	2464**	179**	127**	29.7**	7.61
	July 09	1821**	1583**	2056**	167**	120**	28.4**	7.68
	July 10	1659**	1421**	2016**	242**	127**	27**	7.62
	July 11	1791**	1567**	2036**	187**	115*	27.2**	8.03*
	July 12	1737**	1517**	2117**	174**	112**	27.9**	7.88
	July 13	2419	2140	2810	197	121	26.3	7.73
	July 14	2923	2536	3278	262*	118	32.6	7.89
	July 15	2738	2380	3312	221	126	32.1	7.66
	July 16	2762	2423	3231	209	107	31.8	7.66
	July 17	2627	2259	3109	216	108	30.9	7.64
July 18	2681	2340	3048	200	120	30.2	7.73	
July 19	2629	2282	3170	195	114	29.2	7.7	
July 20	2415	2061	2987	161	138	27.7	7.78	
		2306	3037	261		29.9	7.66	
6	July 21	2376	2054	2967	164	112	33.8	7.85*
	July 22	2184	1896	2744	130	105	31.3	7.62
	July 23	2099	1794	2908	139	111	28.5	7.72
	July 24	2884*	2455*	3420	153	114	29.4	7.55
	July 25	2697	2315	3236	130	121	30.4	7.68
	July 26	2596	2238	2908	146	134	34.3	7.6
	July 27	2465	2121	3174	140	123	33.7	7.64
	July 28	2195	1936	2540	125	124	32.7	7.65
	July 29	1984	1693	2171*	183	136	32.0	7.7
	July 30	2034	1748	2417	179	137	29.0	7.51
	July 31	2455	2108	2908	213	123	29.3	7.51
	August 1	2317	1983	2728	193	121	27.5	7.51
	August 2	2232	1926	2769	199	119	28.5	7.61
August 3	2201	1872	2667	174	118	29.2	7.61	
		1876	2876	162		30.6	7.62	

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSV) and pH results for the laboratory -scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC		
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSV (ml/g)	OUR (mgO/l/h)	pH	
7	August 4	2211	1923	2647	189	104	25.9	7.88	
	August 5	2179	1991	2667	200	100	25.2	7.76	
	August 6	2125	1835	2565	178	120	24.2	7.52	
	August 7	2342	2020	2810	220	119	25.8	7.74	
	August 8	2479	2150	2769	231	112	25.4	7.82	
	August 9	2298**	1955**	2894**	197**	115**	26.1**	7.96	
	August 10	2081**	1804**	2188**	223**	122**	23.5**	7.67	
	August 11	1882**	1656**	2387**	188**	121**	23.4**	7.86	
	August 12	1743**	1555**	1923**	154**	116**	29.1**	8.05*	
	August 13	1593**	1433**	2044**	168**	126**	24.3**	7.75	
	August 14	1640**	1445**	2490**	148**	173**	24.3**	7.55	
	August 15	2624	2264	3178	199	133	30.6	7.62	
	August 16	2778	2439	3097	214	119		7.9	
	August 17	2663	2310	3203	172	113		7.68	
	August 18	2591	2326	3244	179	112	30.2	7.46	
	August 19	2301	2043	3101	174	117	31.0	7.68	
	August 20	2320	2014	3019	168	109	28.8	7.75	
	August 21	2245	1988	2917	160	111	27.3	7.66	
	August 22	2162	1912	2693	140	105	24.7	7.63	
			2094	2916	185		27.2	7.72	
	8	August 23	2185	1908	2754	130*	105	21.3*	7.94
		August 24	2055	1761	2672	210	101	22.0*	7.82
August 25		2056	1859	2841	217	102	21.8*	8	
August 26		2116	1850	2800	218	108	24.7	7.64	
August 27		2198	1898	3066	184	100	24.4	7.74	
August 28		2240	1945	3127	200	93	25.5	7.62	
August 29		2212	1962	2923	188	102	26.0		
August 30		2196	1936	3107	178	93	27.0		
Sept. 01		2170	1908	2759	175	84	30.7	7.67	
Sept. 02		2194	1988	3203	213	86	27.9		
Sept. 03		2154	1911	2998	172	84	27.5	7.77	
Sept. 04		2078	1890	3121	168	85	27.6	7.71	
Sept. 05		1943*	1707*	2652	154	82	27.9	7.69	
Sept. 06		2272	1997	4162*	185	85	29.2	7.81	
		1911	2925	186		27.1	7.77		
9	Sept. 07	2112	1860	3346*	174	86	30.07*	7.81	
	Sept. 08	1947	1728	2407	172	69	28.6	7.69	
	Sept. 09	1726	1643	2386	188	73	27.9	7.75	
	Sept. 10	1880	1676	2672	153*	72	27.3	7.58	
	Sept. 11	1849	1614	2260	169	62	26.2	7.51	
	Sept. 12	1893	1638	2811	182	79	26.0	7.69	
	Sept. 13	1828	1576	2240	178	76	25.9	7.68	
	Sept. 14	1848	1576	2402	178	82	23.8	7.55	
	Sept. 15	1981	1669	2565	175	77	24.6	7.54	
	Sept. 16	1911	1713	2464	162	76	24.8	7.71	
	Sept. 17	1742	1570	2484	162	63	23.6	7.62	
	Sept. 18	1948	1665	2438	183	78	25.3	7.61	
	Sept. 19	1907	1646	2459	178	103	26.0	7.81	
	Sept. 20	2255*	1908*	3170*	221*	84	28.1	7.98	
		1661	2472	175		28.0	7.68		

shaded values

mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory-scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
10	Sept. 21	2311	1988	3007	213	86	27.5	7.91
	Sept. 22	2354	2053	3231	207	78	24.2	7.91
	Sept. 23	2166	1976	3414	223	81	28.3	7.87
	Sept. 24	2626	2283	3211	211	92	27.5	7.76
	Sept. 25	2769	2392	3481	225	92	27.7	7.64
	Sept. 26	2711	2344	3785	241	90	29.1	7.69
	Sept. 27	2823	2402	3744	269	79	30.0	7.91
	Sept. 28	2698	2330	3947	227	77	28.6	7.9
	Sept. 29	2817	2426	3481	255	82	30.9	7.71
	Sept. 30	2412	2068	2674	237	77	27.0	7.72
	Oct. 01	2439	2154	3125	239	79	24.7	7.3
	Oct. 02	2576	2249	3166	223	71	25.2	7.11
		2222	3372	231		27.6	7.7	
11	Oct. 03	2308	2033	3269	225	89	26.9	7.49
	Oct. 04	2374	2065	3638	221	67	26.1	7.61
	Oct. 05	2729	2455	3380	258	81	30.5	7.68
	Oct. 06	2679	2287	3665	259	92	29.3	7.61
	Oct. 07	2990	2592	3685	256	85	30.4	7.84
	Oct. 08	2920	2488	3809	286	96	29.7	7.7
	Oct. 09	2964	2514	3645	253	99	29.4	7.59
	Oct. 10	2787	2430	3645	237	107	28.0	7.69
	Oct. 11	2752	2343	3359	248	120	27.6	7.78
	Oct. 12	2856	2443	3256	245	115	26.5	7.73
	Oct. 13	2559	2263	3549	245	110	25.4	7.81
	Oct. 14	2721	2263	3346	244	119	24.8	7.97
	Oct. 15	2660	2234	3245	242	134	21.0*	7.87
		2339	3499	248		27.9	7.73	
12	Oct. 17	2778	2358	3248	266	133	27.4	7.54
	Oct. 18	2776	2361	3146	267	127	22.4	7.76
	Oct. 19	2797	2411	3619	287	123	26.8	7.87
	Oct. 20	2752	2427	3927	246	129	26.2	7.66
	Oct. 21	2750	2411	3639	270	124	24.5	7.69
	Oct. 22	2717	2225	3105	239	124	22.0	7.97
	Oct. 23	2439	2026	3290	269	135	26.2	7.55
	Oct. 24	2507	2110	3865	238	148	22.5	7.32
	Oct. 25	1959*	1604*	2734	241	142	23.7	7.71
	Oct. 26	1574*	1124*	3218	256	175	23.7	7.8
	Oct. 27	2591	2103	3675	266	302*	25.8	7.69
	Oct. 28	2837	2396	3529	244	162	25.7	7.81
	Oct. 29	2819	2403	3833	245	125	23.9	7.74
	Oct. 30	1500*	1282*	1931*	199*	129	24.4	7.68
	Oct. 31	1880*	1618*	2348*	199*	156	23.3	7.52
		2203	3433	256		24.6	7.89	

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory -scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
13	01-Nov	1947	1635	2285	204	149	24.8	7.41
	02-Nov	1821	1562	2346	204	147	24.7	7.72
	03-Nov	1714	1504	2448	199	154	23.8	7.61
	04-Nov	2104	1444	2908	199	133	23.3	
	05-Nov	2191	1800	2621	249	180*	23.3	
	06-Nov	2049	1744	2929	209	156	22.7	
	07-Nov	1997	1743	3256	210	149	22.6*	
	08-Nov	2035	1733	3195	231	138	23.8	
	09-Nov	2104	1800	2785	209	150	23.4	
	10-Nov	2004	1726	2970	210	133	21.9*	
	11-Nov	2086	1696	2621	213	151	22.1*	
	12-Nov	1975	1752	3092	204	142	23.5	
	13-Nov	1951	1635	2929	188	137	21.3*	
	15-Nov	2056	1757	3195	224	147	23.4	
	16-Nov	1815	1554	2785	217	140	29.3*	
	17-Nov	2061	1864	2990	182	142	22.6*	
			1884	2833	210		23.7	7.58
14	18-Nov	2344	2096	3019	197	139	23.8	
	19-Nov	2310	2077	2990	221	142	23.2	
	20-Nov	2405*	2184*	2999	218	124	21.5	
	21-Nov	2318	1980	3488	242	116	23.4	
	22-Nov	2176	1822	2876	175*	110	38.2*	
	23-Nov	1979	1886	3346	206	126	28.7	
	24-Nov	2207	1967	3325	220	143	27.4	
	25-Nov	2206	1921	3146	221	138	27.2	
	26-Nov	2211	1959	3310	246	132	27.0	
	27-Nov	2279	1920	3372	237	141	27.0	
	28-Nov	2119	1845	3290	227	133	26.6	
	29-Nov	2154	1846	2899	221	146	26.5	
	30-Nov	2318	2041	3146	209	146	25.9	
	01-Dec	2136	1833	3043	235	135	24.3	
02-Dec	1999	1760	3146	210	118	25.7		
03-Dec	2038	1758	2899	216	125	22.7		
04-Dec	2100	1818	2826	328*	125	24.2		
		1908	3125	222		25.3		
15	05-Dec	2247	1922	3195	207	138	24.6	
	06-Dec	2256	1951	3256	217	137	23.5	
	07-Dec	2165	1866	2949	183	135	24.7	
	08-Dec	2183	1879	2724	230	128	25.2	
	09-Dec	2334	2048	2437	230	134	24.3	
	10-Dec	2230	1942	2970	227	128	24.3	
	11-Dec	2185	1879	2683	216	127	24.1	
	12-Dec	2287	1929	3195	216	144	24.3	
	13-Dec	2252	1968	3830*	265	138	25.5	
	14-Dec	1798*	1587*	3113	174	140	27.6*	
		1932	2947	217		24.5		
16	08-Jan	2275	1956	3461	231		25.5	7.42
	09-Jan	2312	2050	3319	235	164	26.3	7.34
	10-Jan	2332	2014	2975	235	132	23.9	7.59
	11-Jan	2365	2053	2883	224	158	27.2	7.67
		2018	3160	231		25.7	7.5	

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory -scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
17	12-Jan	2222	1925	2742	210	151	24.4	7.37
	13-Jan	2110*	1829*	2762	183*	149	25.0	7.21
	14-Jan	2295	1983	2883	211	145	25.5	7.19
	15-Jan	2290	1991	3064	216	142	25.4	7.52
	16-Jan	2459	2090	3064	234	141	26.2	7.63
	17-Jan	2493	2112	3125	241	151	26.1	7.28
	18-Jan	2376	2057	2943	224	144	26.3	7.54
	19-Jan	2331	2012	2681	217	142	25.7	7.26
	20-Jan	2475	2138	2984	232	156	25.9	7.3
	21-Jan	2523	2132	2968	231	144	26.5	7.58
	22-Jan	2411	2097	2638	216	136	26.4	7.57
	23-Jan	2334	2003	2658	210	141	25.5	7.72
	24-Jan	2302	1989	2619	231	181	26.4	7.65
	25-Jan	2214	1896	2619	211	200*	26.5	7.74
		2033	2639	222		25.8	7.47	
18	26-Jan	1943	1628	2231	192	211	24.3	7.39
	27-Jan	1900	1572	2464	181	201	20.8	7.58
	28-Jan	1804	1585	2502	209	209	19.7	7.62
	29-Jan	1927	1654	2316	193	153	23.4	7.58
	30-Jan	2000	1759	2560	189	139	24.1	7.67
	31-Jan	2057	1772	2842	174	133	24.7	7.69
	01-Feb	1876*	1447*	2052*	176	125	24.0	7.8
	02-Feb	2104	1852	2560	176	124	24.1	7.77
	03-Feb	2024	1714	2418	204	131	21.1	7.69
	04-Feb	2106	1791	2662	214	103	22.9	7.68
	05-Feb	2055	1756	2459	193	123	21.8	7.68
	06-Feb	2017	1692	2621	218	123	22.6	7.75
	07-Feb	1983	1731	2698	98*	114	21.4	7.59
		1706	2513	163		22.7	7.85	
19	08-Feb	2046	1793	2494	225	104	21.2*	7.57
	09-Feb	2029	1773	2600	227	118	24.2	7.71
	11-Feb	2016	1772	2759	217	106	23.8	7.69
	12-Feb	2038	1762	2412	241	113	23.1	7.68
	13-Feb	2101	1773	2618	217	147	23.7	7.71
	14-Feb	2058	1758	2519	234	153	23.1	7.8
	15-Feb	2123	1835	2826	218	164	23.1	7.58
	16-Feb	2048	1766	2801	220	178	22.7	7.72
	17-Feb	2059	1783	2662	223	174	22.9	7.67
	18-Feb	2135	1808	2908	216	170	23.2	7.69
	19-Feb	2020	1746	2560	210	179	24.1	7.81
20-Feb	1962	1732	2519	216	177	23.8	7.63	
21-Feb	1745*	1519*	2216*	197*	183	24.1	7.64	
		1775	2640	222		23.5	7.67	

shaded values

mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC		
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	MLCOD (mgCOD/l)	MLTKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH	
20	22-Feb	1805*	1531*	2544	220	211	24.7	7.66	
	23-Feb	1578*	1367*	2606	207	196	24.9	7.66	
	24-Feb	2224	1899	2565	185	209	25.0	7.72	
	25-Feb	2187	1912	2686	199	216	24.9	7.82	
	26-Feb	2228	1885	2673	224	153	24.4	7.66	
	27-Feb	2246	1964	3195	206	131	24.4	7.48	
	28-Feb	2410	2019	3092	227	132	24.6	7.58	
	29-Feb	2511	2139	3031	230	122	25.6	7.73	
	01-Mar	2529	2177	2970	273*	139	24.6	7.5	
	02-Mar	2534	2154	3256	241	131	22.3	7.63	
	03-Mar	2573	2178	3154	217	124	23.5	7.65	
	04-Mar	2479	2062	3031	244	121	23.4	7.45	
	05-Mar	2538	2170	3448	253	110	23.7	7.56	
		2082	2058	221		24.3	7.61		
21	06-Mar	2518	2118	3366	224	129	23.6	7.63	
	07-Mar	2428	2068	2897*	231	126	22.1*	7.67	
	08-Mar	2625	2229	3754	286	132	24.5	7.83	
	09-Mar	2711	2315	3529	235	145	26.0	7.51	
	10-Mar	2616	2220	3611	238	148	24.8	7.58	
	11-Mar	2469	2130	3386	248	143	24.7	7.71	
	12-Mar	2556	2175	3488	279	144	26.8	7.61	
	13-Mar	2535	2180	3654	288	160	26.6	7.61	
	14-Mar	2391	2101	3654	281	156	26.0	7.73	
	15-Mar	2458	2131	3405	274	120	26.0	7.75	
	16-Mar	2303	1959	3197	262	143	26.0	7.82	
	17-Mar	2337	1942	3633	267	141	27.3	7.67	
	18-Mar	2341	1961	3384	274	153	26.6	7.7	
19-Mar	2123*	1829*	3140	239	165	27.2	7.61		
		2116	347	256		25.9	7.88		
22	04-Apr	3600*	3045*	4827*	288	166	27.7	7.6	
	05-Apr	3475	2957	4522	314	173	27.2	7.65	
	06-Apr	3348	2804	4320	447*	144	27.4	7.55	
	07-Apr	3086	2640	4113	263	145	27.5	7.35	
	08-Apr	3169	2750	4296	291	157	26.9	7.55	
	09-Apr	3129	2675	4255	307	152	27.6	7.48	
	10-Apr	3183	2671	4092	288	160	26.8	7.46	
	11-Apr	3215	2696	4459	293	157	27.5	7.48	
	12-Apr	3102	2635	4215	291	165	27.7	7.21	
			2729	4284	294		27.4	7.48	
	23	13-Apr	3065	2588	4109	298	167	23.3*	7.42
		14-Apr	3100	2804	4048	349	170	23.6*	7.26
15-Apr		3182	2675	4372	321	162	28.1	7.69	
16-Apr		3184	2653	4615	280	161	27.7	7.44	
17-Apr		3172	2680	3886	287	168	25.5*	7.61	
18-Apr		3296	2763	4301	349	170	27.1	7.72	
19-Apr		3157	2681	4550	330	164	26.8	7.8	
20-Apr		3127	2617	4157	301	166	27.3	7.72	
21-Apr		3225	2715	4033	314	164	27.9	7.34	
22-Apr		3161	2678	4508	312	168	27.2	7.31	
23-Apr		3195	2693	4022	302	169	28.4	7.66	
		2688	4238	314		27.6	7.54		

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory-scale activated sludge system

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
24	24-Apr	3153	2678	3940	300	167	28.8	7.61
	25-Apr	2563	2465	3283	283	175	28.7	7.64
	26-Apr	2810*	2348*	3406	249	157	29.4	7.62
	27-Apr	2872	2458	3263	273	154	29.3	7.79
	28-Apr	2946	2517	3501	273	170	29.8	7.84
	29-Apr	2927	2490	3581	276	155	29.0	7.49
	30-Apr	3022	2534	3783	267	163	29.1	7.69
	01-May	3041	2584	3823	287	161	29.5	7.64
	02-May	3015	2551	3622	274	158	29.3	7.81
	03-May	3015	2538	3772	259	155	29.3	7.63
	04-May	3071	2585	3711	277	165	29.7	7.85
	05-May	3154	2671	3934	328	166	29.6	7.78
	06-May	3113	2599	3853	284	170	29.0	7.76
	07-May	3083	2567	3448	322	161	29.6	7.72
08-May	3104	2569	3958	319	177	28.0	7.57	
		2537	2638	3638	284		29.3	7.71
25	09-May	3147	2638	4488	307	179	32.0	7.68
	10-May	3187	2699	4388	316	164	33.8	7.75
	11-May	3068	2843	4325	295	178	30.5	7.71
	12-May	3349	2832	4366	319	163	29.2	7.62
	13-May	3321	2803	4137	291	159	28.9	7.58
	14-May	3348	2805	4401	314	166	29.2	7.57
	15-May	3548*	2946*	4786	330	157	26.0	7.89
	16-May	3356	2788	4360	304	160	25.7	7.87
	17-May	3220	2704	4766	308	153	24.8	7.72
	18-May	3334	2763	4421	294	169	26.2	7.81
19-May	3377	2801	4511	319	148	26.5	7.68	
		2747	4450	300		28.4	7.71	
26	20-May	3363	2820	4389	288	150	26.8	7.92
	21-May	3401	2858	4511	300	159	37.2*	7.78
	22-May	3403	2854	4958*	301	135	28.3	7.96
	23-May	3372	2853	4531	304	140	27.6	7.79
	24-May	3312	2774	4547	316	137	27.9	7.73
	25-May	3506	2960	4506	290	133	28.3	7.48
	26-May	3478	2947	4219	260	141	28.6	7.56
	27-May	3406	2870	4116	319	122	27.8	7.36
	28-May	3387	2863	4219	261	128	28.0	7.52
	29-May	3383	2870	4058	293	125	28.6	7.75
	30-May	3385	2836	4320	326	128	26.0	7.61
	31-May	3388	2827	3853	321	129	27.6	7.67
		2881	4297	303		27.9	7.88	

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C4-cont.

Daily MLTSS, MLVSS, MLCOD, MLTKN, OUR, DSVI and pH results for the laboratory -scale activated sludge system.

Sew. Batch No.	Dates of Test	MIXED LIQUOR					AEROBIC	
		MLTSS (mgTSS/l)	MLVSS (mgVSS/l)	COD (mgCOD/l)	TKN (mgN/l)	DSVI (ml/g)	OUR (mgO/l/h)	pH
27	01-Jun	3721	3143	5111	318	127	25.9	7.61
	02-Jun	3767	3162	5293	323	127	21.0	7.72
	03-Jun	4150*	3485*	5284	336	124	25.0	7.73
	04-Jun	3947	3321	5181	344	127	23.3	7.9
	05-Jun	3942	3311	5059	346	121	23.4	7.87
	06-Jun	3946	3254	4772	340	126	23.2	7.58
	07-Jun	3812	3209	4690	350	121	22.9	7.69
	08-Jun	3929	3293	4895	329	123	25.3	7.82
	09-Jun	3759	3150	4679	343	125	23.4	7.94
	10-Jun	3711	3141	4596	346	134	23.3	7.87
	11-Jun	3686	3102	4843	308	127	24.0	7.86
	12-Jun	3614	3047	4699	347	127	25.2	7.84
	13-Jun	3574	3001	4535	312	135	24.7	7.72
	14-Jun	3852	3268	4579	318	135	35.9*	7.84
		3185	4873	333		23.9	7.79	
28	15-Jun	3238*	2729*	4763	267*	122	26.0	7.78
	16-Jun	3616	3083	4844	294	133	26.7	7.86
	17-Jun	3939	3331	5151	385	132	27.8	7.89
	18-Jun	3867	3274	5171	363	130	26.4	7.82
	19-Jun	3836	3254	5233	302	126	27.1	7.78
	20-Jun	4155	3511	5428	385	141	27.7	7.92
	21-Jun	4003	3402	5448	379	141	25.7	8.06
	22-Jun	3995	3382	5202	342	137	25.8	8.07
	23-Jun	3883	3303	4893	350	135	24.5	8.1
	24-Jun	3836	3282	5017	329	136	24.5	7.84
	25-Jun	4006	3401	5037	325	139	24.9	7.69
	26-Jun	3878	3289	5058	309	152	23.9	7.81
	27-Jun	3677	3113	5089	365	159	22.1*	7.74
		3302	5103	344		25.9	7.87	

shaded values mean values for wastewater batch

* test rejected as an outlier at 95% confidence interval

** data rejected due to system operational problems

Table C5 Summary of the parent system COD and N mass balances and wastewater and mixed liquor fractions for the various wastewater batches.

Sewage Batch No.	MASS BALANCE (%)		WASTEWATER (mgCOD/mgCOD)		FRACTIONS		MIXED LIQUOR	
	COD	N	Unbiodeg. Soluble fs,us	Unbiodeg. particulat fs,up	COD/VSS (fcv) (mgCOD/mgVSS)	TKN/VSS (fn) (mgN/mgVSS)		
1	84	90	0.08	0.18	1.37	0.09		
2	79	94	0.08	0.20	1.38	0.09		
3	74	92	0.09	0.08	1.38	0.09		
4	88	93	0.11	0.12	1.39	0.10		
5	95	87	0.10	0.15	1.32	0.09		
6	91	81	0.08	0.11	1.46	0.08		
7	85	88	0.07	0.10	1.39	0.09		
8	86	83	0.09	0.06	1.53	0.10		
9	92	85	0.14	0.07	1.49	0.11		
10	92	98	0.11	0.12	1.52	0.10		
11	97	100	0.09	0.17	1.50	0.11		
12	94	91	0.09	0.17	1.50	0.11		
13	80	111	0.09	0.06	1.68	0.12		
14	79	113	0.09	0.08	1.64	0.12		
15	86	77	0.09	0.08	1.53	0.11		
16	105	63	0.08	0.15	1.57	0.11		
17	91	93	0.09	0.13	1.40	0.11		
18	97	90	0.16	0.12	1.47	0.11		
19	88	86	0.12	0.08	1.49	0.13		
20	83	92	0.10	0.12	1.44	0.11		
21	97	85	0.10	0.16	1.64	0.12		
22	81	92	0.08	0.11	1.57	0.11		
23	80	90	0.07	0.08	1.59	0.12		
24	84	98	0.09	0.07	1.43	0.11		
25	87	100	0.09	0.10	1.62	0.11		
26	85	96	0.11	0.14	1.50	0.11		
27	87	94	0.10	0.17	1.53	0.10		
28	85	99	0.08	0.19	1.55	0.10		

APPENDIX D

CONSTRUCTION AND INTERPRETATION OF STATISTICAL PLOTS FOR DATA ANALYSIS

TABLE OF CONTENTS

- D.1 INTRODUCTION
- D.2 CONSTRUCTION OF STATISTICAL PLOT
- D.3 INTERPRETATION OF STATISTICAL PLOT
- D.4 TEST FOR STATISTICAL SIGNIFICANCE OF THE DIFFERENCES
BETWEEN TWO MEAN VALUES
- D.5 ILLUSTRATION BY AN EXAMPLE

Fig D1 Example of statistical probability plot for a number of heterotrophic active biomass (mgCOD/ℓ) derived from a batch test.

CONSTRUCTION AND INTERPRETATION OF STATISTICAL PLOTS FOR DATA ANALYSIS

D.1 INTRODUCTION

Data from different tests could not be compared directly on a daily basis because of the variability in results from all the tests, due to variations in multitude of factors that influence the data. Therefore a graphical approach was used to evaluate the data (Velz, 1950), to interpret the trends and compare the results between two test methods.

For a particular batch of wastewater, the data obtained from the different test methods were statistically analysed using a graphical procedure, to determine the mean, sample standard deviation, and standard deviation of the mean for the data set. This information then could be used to evaluate whether the difference between the means from two data sets is statistically significant at a selected confidence level, or not.

D.2 CONSTRUCTION OF STATISTICAL PLOT

The experimental data is plotted using the procedure below:

- Arrange the data (n in number) in order of ascending magnitude.
- Assign a serial number " m " to each of the values (1,2,3,4..... n)
- Compute the y-axis plotting the position of each serial value, as the probability equal to or less than from the expression $[m/(n+1)]$. The x-axis plotting position is the actual value for the data
- The probability curve is linearized and plotted; for this investigation the transformed rank probability method (Scientific Tables, 1975) was used to linearize the probability curve, see Fig D 1. Alternatively, probability paper can be used on which the y-axis has been linearized.

D.3 INTERPRETATION OF THE STATISTICAL PLOT

The data plotted can give an indication of whether the data is normally distributed or not:

- If a straight line can be fitted to the plot it indicates that the data have a normal distribution.
- If a straight line can not be fitted to the plot, the data are not normally distributed.

If the data are normally distributed it indicates that a multitude of factors have each had an independent small influence on the measurements; if the data are not normally distributed it indicates that one factor has had a dominating influence.

From the above, provided a straight line can be fitted to the distribution (i.e. the data are normally distributed), it is possible to determine graphically (refer to Fig D 1) :

- The mean of the data plotted - this is determined as the x-value where the straight line of the distribution intercepts a vertical line extended from $y = 5$.
- The standard deviation of the sample, which provides a measure of the variation of the data - this is the difference between the mean (i.e. the x-value that gives $y = 5$) and the x-value that gives $y = 4$ (or $y = 6$).

D.4 TEST FOR STATISTICAL SIGNIFICANCE OF THE DIFFERENCES BETWEEN TWO MEAN VALUES

Visual comparison of two data (or data sets) is a common method of appraisal, to determine whether they differ. However, observed differences or similarities may not be significant as these may arise solely by chance. Statistics defines the expected variations due to chance, to determine whether the observed differences between two data have arisen by chance alone or are significant. In the graphical method, by plotting of two or more series of data on the same probability plot, a quick visual appraisal of similarities and differences can be obtained. To test whether the visual differences in the two series of data are statistically significant, a mathematical significant test is done as follows:

- Plot the two or more distributions to test for normality as described above.
- If normal, obtain the mean (m) and the sample standard deviation (σ) of each series.
- Compute standard deviation of each mean:

$$SD(\text{mean}) = (\sigma/\sqrt{n})$$
 where n = number of data points.
- Compute the standard deviation of the difference between the two means :

$$SD(\text{difference}) = \sqrt{\{(SD \text{ mean1})^2 + (SD\text{mean2})^2\}}$$
- Compute the absolute value (i.e. positive) of the difference between the two means :

$$\text{mean}(\text{difference}) = | \text{mean1} - \text{mean2} |$$
- Decide upon a confidence level for the test for significance, 95% certainty or 99% or any other level desired.
- Apply the test for statistical significance of the difference.

For example, if 95% is selected as the confidence level, subtract from the difference between the two means [$\text{mean}(\text{difference})$], twice the standard deviation of the difference between the two means [$SD(\text{difference})$], i.e. [$\text{mean}(\text{difference}) - 2*SD(\text{difference})$] - if positive number is obtained it can be concluded that the difference between the two means is statistically significant at the selected level of confidence; if a negative value is obtained, then the difference between the two means was by chance alone, and it can be concluded that the apparent difference between the two means is **NOT** statistically significant.

D.5 ILLUSTRATION BY AN EXAMPLE

An example plot is given in Fig D 1.

The mean of a set of values from an experiment is read off from the statistical graph as the value of x that gives $y = 5$, in this case:

from the graph the mean = 18mgCOD/l

The standard deviation of a set of values is calculated from the difference between the x -value that gives $y = 5$ and the x -value that gives $y = 6$, OR, from the difference between the x -value that gives $y = 5$ and the x -value that gives $y = 4$, as shown in Fig D 1, i.e. from graph:

the x -value at $y = 6 = 22.6\text{mgCOD/l}$

the x-value at $y = 4 = 13.4\text{mgCOD}/\ell$

\therefore the standard deviation (σ) = $22.6 - 18$ OR $18 - 13.4 = 4.6\text{mgCOD}/\ell$

The standard deviation of the mean is the standard deviation divided by the square root of the number of values in the data set. In this case:-

number data in set (n) = 12

\therefore SD mean = $4.6/\sqrt{12} = 1.33\text{mgCOD}/\ell$

Say a second set of 10 data is analysed as above to give:

mean = $16\text{mgCOD}/\ell$

then standard deviation (σ) = $5.1\text{mgCOD}/\ell$

Standard deviation of the mean is calculated:

SD mean = $5.1/\sqrt{10} = 1.61\text{mgCOD}/\ell$

Now, comparing the data from the two sets:

$$\begin{aligned}\text{SD(difference)} &= \sqrt{1.33^2 + 1.61^2} \\ &= 2.09\text{mgCOD}/\ell\end{aligned}$$

$$\text{mean(difference)} = |18 - 16| = 2\text{mgCOD}/\ell$$

Selecting a 95% confidence interval:

$$\begin{aligned}\text{test} &= \text{mean(difference)} - 2 * \text{SD(difference)} \\ &= 2 - 2.09 \\ &= -2.18\end{aligned}$$

Since the resultant value is negative, it can be concluded that the two means are not significantly different at the 95% confidence interval.

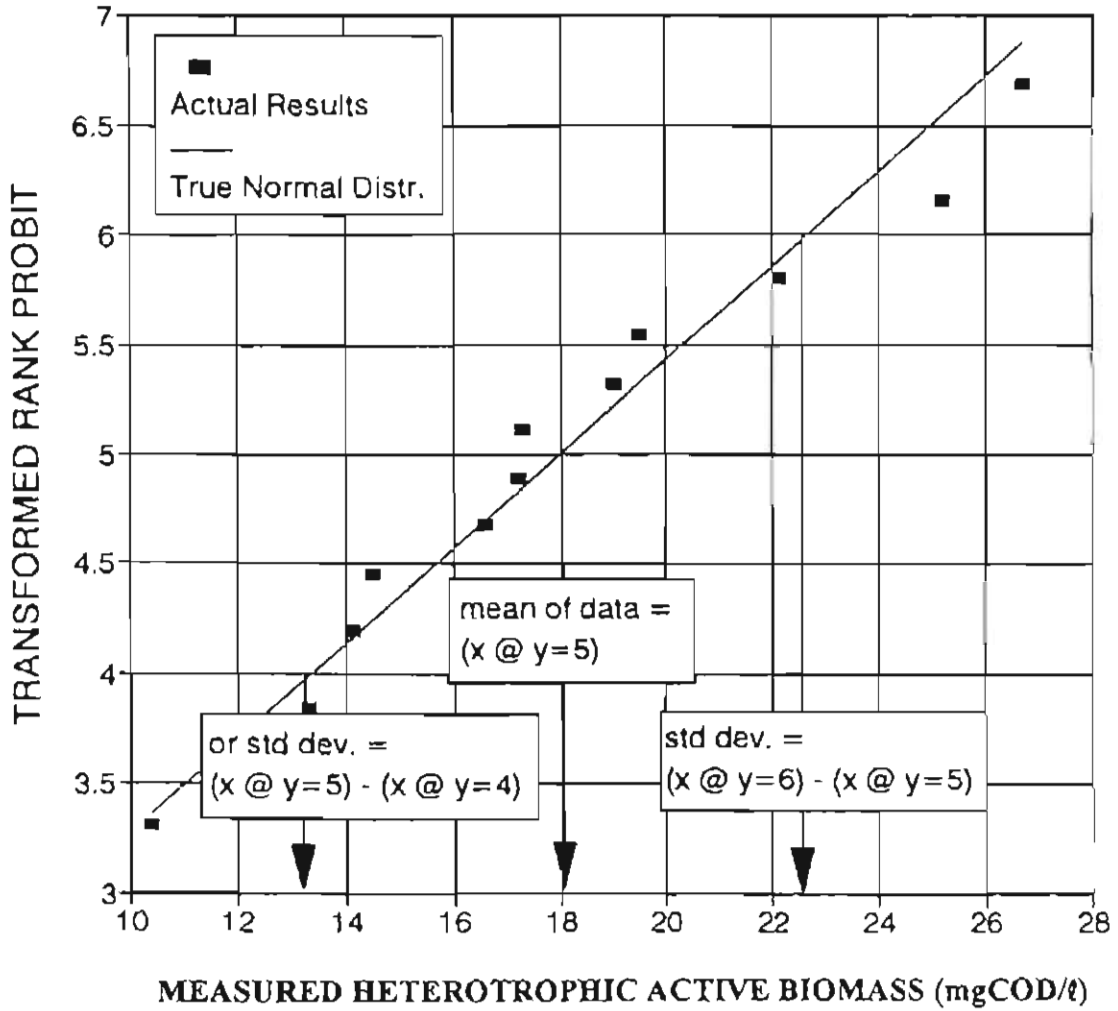


Fig D 1

Example of a statistical probability plot for a number of measured heterotrophic active biomass derived from the batch test.

APPENDIX E

COMPREHENSIVE DATA FOR INORGANICS

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Table E1 Daily parent system unfiltered and filtered influent data for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
1	March 30	850	455	495	710	279	431
	March 31	1009	459	550	750	284	466
	April 01	903	477	428	664	299	365
	April 02	918	497	421	646	309	337
	April 03	1050	535	515	771	368	403
	April 04	1016	553	463	788	393	395
	April 05	870	539	331	617	313	304
	April 06	1055	498	556	839	310	529*
	April 07	970	618	352	872	519*	353
	April 08	977	571	406	721	362	359
	April 09	896	517	379	681	347	334
	April 10	858	420	438	634	256	378
	April 11	984	595	389	775	417	358
April 12	944	499	445	741	338	403	
		957	517	440	729	329	375
2	April 13	1014	581	433	806	407	398
	April 14	991	561	430	789	413	376
	April 15	941	563	378	742	430	312
	April 16	939	507	432	755	386	369
	April 17	1015	617	398	883	490	373
	April 18	1000	635	365	859	548	311
	April 22	982	660	322*	881	562	319
	April 23	895	450	445	685	293	392
	April 24	1045	660	385	870	487	383
April 25	952	525	427	717	353	364	
		977	576	410	800	437	360
3	April 26	1008	645	383	885	540	345
	April 27	976	624	352	777	419	358
	April 28	1041	688	373	832	518	314
	April 29	1090	565	425	874	465	409
	April 30	1104	678	426	886	535	351
	May 01	1406*	731	675*	972	561	411
	May 02	944	683	281	781	547	234
	May 03	1149	754	395	1004	633	371
	May 04	971	529	442	1105	883	422
	May 05	1226	823*	403	1001	691	310
	May 06	888	480	408	1076	758	318
	May 07	1044	727	317	891	825	266
	May 08	830	560	270	820	659	161*
	May 09	1168	699	469	984	613	371
	May 10	1147	624	523	1173	726	447
May 11	958	581	377	796	494	302	
May 12	1286	682	604	1251*	769	482	
May 13	1182	670	512	1057	617	440	
May 14	941	523	418	727	385	342	
		1053	640	408	924	601	361

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches: total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
4	June 20	895	565	330	872	504	368
	June 21	895	579	316	606	446	160*
	June 22	1026	585	441	858	485	373
	June 23	918	562	356	724	397	327
	June 24	969	592	377	784	446	338
	June 25	951	512	439	769	407	362
	June 26	895	512	383	745	410	335
	June 27	1082	613	469	907	523	384
		954	565	389	783	452	355
5	June 28	1058	690	368	868	550	318
	June 29	940	542	398	798	486	312
	July 03	930	549	381	794	484	310
	July 04	940	631	309	778	535	243
	July 05	978	564	414	830	496	334
	July 06	1002	621	381	900	552	348
	July 07	967	556	411	884	523	361
	July 08	1103	728	377	1055	715*	340
	July 09	979	582	397	883	593	290
	July 10	1059	643	416	946	607	339
	July 11	1451*	686	765*	1380*	709*	671*
	July 12	981	595	386	889	588	321
	July 13	929	637	292	854	649	205*
	July 14	980	613	367	903	603	300
	July 15	989	634	355	935	657	278
	July 16	983	657	326	821	594	227
	July 17	1011	628	383	860	528	332
July 18	852	480	372	927	597	330	
July 19	949	582	367	885	589	296	
July 20	1063	472*	591	1165	535	630*	
		984	611	384	893	504	310
6	July 21	1306	593	713	1225	507	718
	July 22	858	496	362	857	534	323
	July 23	930	443	487	792	360	432
	July 24	864	408	456	811	391	420
	July 25	1131	538	593	1015	472	543
	July 26	1067	525	542	968	487	481
	July 27	1164	552	612	1034	473	561
	July 28	1199	627	572	1171	628	543
	July 29	875	74*	801*	1238	509	729
	July 30	975	549	426	903	524	379
	July 31	906	461	445	861	458	403
	August 1	933	469	464	827	410	417
	August 2	1106	434	672	982	346	636
	August 3	1216	488	728	1177	487	690
		1038	506	544	990	470	520

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches, total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT			
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)	
7	August 4	1122	467	655	1006	418	588	
	August 5	882	442	440	720	361	359	
	August 6	851	442	409	680	353	327	
	August 7	1010	498	512	817	395	422	
	August 8	1172	521	651	1076	457	619	
	August 9	1065	501	564	846	430	416	
	August 10	806	436	370	662	355	307	
	August 11	1257	503	754	1120*	420	700*	
	August 12	1039	467	572	901	417	484	
	August 13	849	511	338	751	428	323	
	August 14	820	445	375	666	352	314	
	August 15	1060	498	562	888	445	421	
	August 16	1081	489	582	943	465	478	
	August 17	933	535	398	765	487	298	
	August 18	697	473	224	593	409	184	
	August 19	839	442	397	725	416	309	
	August 20	946	466	480	877	420	457	
	August 21	835	465	370	705	424	281	
	August 22	809	416	393	738	389	347	
			951	476	476	796	413	385
	8	August 23	1017	394	623	933	396	537
		August 24	1152*	433	719*	1058*	438	620*
August 25		946	484	482	836	484	352	
August 26		926	521	405	818	520	298	
August 27		812	395	417	705	358	347	
August 28		726	425	301	622	368	254	
August 29		784	441	343	799	419	380	
August 30		1051	468	583	961	433	528	
Sept. 01		769	441	328	701	384	317	
Sept. 02		1002	482	520	890	490	400	
Sept. 03		856	466	370	752	432	320	
Sept. 04		742	478	263	573	383	190	
Sept. 05		891	543*	348	808	514	294	
Sept. 06		885	458	427	805	429	376	
		878	453	418	785	432	353	
9	Sept. 07	937	476	461	848	478	370	
	Sept. 08	931	502	429	866	497	369	
	Sept. 09	987	456	531	869	441	428	
	Sept. 10	1091	513	578	658	398	260	
	Sept. 11	793	488	305	739	489	250	
	Sept. 12	958	438	520	897	446	451	
	Sept. 13	831	366	465	854	430	424	
	Sept. 14	810	423	387	744	398	346	
	Sept. 15	856	452	404	889	476	413	
	Sept. 16	948	454	494	906	464	442	
	Sept. 17	705	366*	337	658	378	280	
	Sept. 18	849	464	385	768	467	301	
	Sept. 19	1054	440	614	958	445	513	
	Sept. 20	1127	476	651	1082*	421	661*	
		920	465	469	820	445	373	

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches, total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS)

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
10	Sept. 21	1050	488	584	920	447	473
	Sept. 22	1108	585	521	907	503	404
	Sept. 23	1010	573	437	840	472	388
	Sept. 24	904	540	364	726	470	256
	Sept. 25	758	438	320	599	342*	257
	Sept. 26	997	589	408	777	436	341
	Sept. 27	1069	459	610*	930	360	570*
	Sept. 28	1005	494	511	926	456	470
	Sept. 29	853	545	308	662	435	227
	Sept. 30	830	461	369	863	457	206
	Oct. 01	777	488	289	837	408	229
Oct. 02	754	452	302	634	423	211	
		926	507	401	760	442	353
11	Oct. 03	860	527	333	705	405	300
	Oct. 04	884	387	487	767	352	415
	Oct. 05	984	585*	399	900	532	368
	Oct. 06	881	410	471	741	377	364
	Oct. 07	968	517	441	806	445	361
	Oct. 08	756	407	349	608	327	281
	Oct. 09	763	451	312	559	345	214
	Oct. 10	894	454	440	802	391	411
	Oct. 11	961	476	465	828	361	466
	Oct. 12	941	438	503	849	417	432
	Oct. 13	1018	460	558	863	498	354
	Oct. 14	1029	415	614*	885	389	496
	Oct. 15	747	434	313	563	398	165
	Oct. 16	716	390	326	530	346	184
		385	444	417	743	395	344
12	Oct. 17	965	470	495	905	434	474
	Oct. 18	875	393	482	689	309	381
	Oct. 19	930	580	350	784	477	307
	Oct. 20	868	489	379	888	402	286
	Oct. 21	870	521	349	641	266	355
	Oct. 22	769	424	345	575	299	276
	Oct. 23	573*	314	259	443*	251	192
	Oct. 24	907	471	436	724	316	408
	Oct. 25	835	384	451	699	275	424
	Oct. 26	717	253*	484	755	298	457
	Oct. 27	1105*	502	603*	863*	428	535
	Oct. 28	822	446	373	742	343	396
	Oct. 29	831	463	368	733	395	338
	Oct. 30	732	433	299	600	336	264
	Oct. 31	898	534	385	763	442	321
		646	459	387	718	353	361

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT			
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)	
13	01-Nov		613		732	443	289	
	02-Nov	820	526	294	673	424	249	
	03-Nov	782	533	249	727	478	249	
	04-Nov	580	410	170	424	290	134	
	05-Nov	768	510	258	610	414	196	
	06-Nov	686	436	250	518	311	207	
	07-Nov	559	389	190	415	258	157	
	08-Nov	581	543	38*	453	462		
	09-Nov	584	393	191	460	256	202	
	10-Nov	593	353	240	483	227	256	
	12-Nov	393	186*	208	486	372	114	
	13-Nov	461	257	204	646	441	205	
	15-Nov	514	202	222	337	144	193	
	16-Nov	709	409	300	531	270	261	
	17-Nov	625	429	196	391	186	205	
			618	434	229	525	332	208
	14	18-Nov	675	498	177	533	348	185
19-Nov		618	375	243	437	251	186	
20-Nov		622	299*	323	473	173	300	
21-Nov		621	478	143	440	347	93*	
22-Nov		706	470	236	399	142	257	
23-Nov		588	440	148	334	249	85*	
24-Nov		581	366	215	411	215	196	
25-Nov		636	412	224	372	190	182	
26-Nov		798	476	322	599	317	282	
27-Nov		742	452	290	537	261	276	
28-Nov		713	520	193	436	306	130	
29-Nov		704	503	201	392	224	168	
30-Nov		621	428	193	413	270	143	
01-Dec		762	496	266	542	313	229	
02-Dec		643	437	206	417	222	195	
03-Dec		776	531	245	606	349	257	
04-Dec		924*	556	368*	636	269	367	
		675	465	227	469	262	233	
15	05-Dec	749	534	215	475	295	180	
	06-Dec	698	522	176	396	240	156	
	07-Dec	676	495	181	400	243	157	
	08-Dec	727	512	215	401	242	159	
	09-Dec	607	430	177	385	226	159	
	10-Dec	805	473	332*	565	235	330	
	11-Dec	749	465	284	528	245	283	
	12-Dec	671	443	228	428	264	164	
	13-Dec	641	472	169	384	262	122	
	14-Dec	482*	310*	172	426	340*	86	
			703	483	202	439	250	160

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
16	08-Jan	650	367	283	461	210	251
	09-Jan	644	364	280	454	198	256
	10-Jan	535	356	179	322	173	148
	11-Jan	520	371	149	345	228	117
		387	365	223	395	282	183
17	12-Jan	480	338	142	330	209	121
	13-Jan	708	422	285	531	238	293
	14-Jan	777	423	354	588	281	307
	15-Jan	600	442	158	357	227	130
	16-Jan	789	473	316	586	268	298
	17-Jan	581	360	201	323	151	172
	18-Jan	594	439	155	341	238	103
	19-Jan	859	508	351	544	250	294
	20-Jan	862	480	382	593	286	307
	21-Jan	788	437	351	583	264	319
	22-Jan	740	478	262	550	320	230
	23-Jan	829	531	298	588	321	267
	24-Jan	480	272*	218	510	309	201
25-Jan	916	623*	295	649	361	288	
		714	444	299	594	256	238
18	26-Jan	949*	508	441*	646	283	363*
	27-Jan	783	500	283	577	287	290
	28-Jan	699	475	224	505	326	179
	29-Jan	828	578	251	588	358	230
	30-Jan	817	535	282	649	422	227
	31-Jan	887	558	329	652	358	294
	01-Feb	869	522	347	687	385	322
	02-Feb	801	566	235	581	367	214
	03-Feb	862	510	352	645	351	294
	04-Feb	730	427	303	528	487	41*
	05-Feb	707	426	281	612	370	242
	06-Feb	803	506	297	657	390	267
	07-Feb	800	510	290	615	387	226
		798	509	290	611	366	258
19	08-Feb	815	436	379	765	452	313
	09-Feb	815	476	339	839	318	321
	11-Feb	775	457	318	655	403	252
	12-Feb	830	483	347	717	427	290
	13-Feb	744	418	326	679	367	312
	14-Feb	642*	328*	313	675	430	245
	15-Feb	771	453	318	678	410	268
	16-Feb	704	395	309	697	470	227
	17-Feb	789	519	270	617	358	259
	18-Feb	817	470	347	660	381	279
	19-Feb	788	461	327	672	402	270
	20-Feb	784	510	254*	607	412	195*
	21-Feb	805	477	328	704	421	283
		785	483	327	674	404	277

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
20	22-Feb	706	458	248	558	312	244
	23-Feb	849	552	297	839	427	212
	24-Feb	842	576	266	712	465	247
	25-Feb	727	450	277	618	389	229
	26-Feb	773	456	317	649	417	232
	27-Feb	801	527	274	632	414	218
	28-Feb	772	454	318	606	332	274
	29-Feb	846	428	418*	737	376	361
	01-Mar	872	520	352	753	473	280
	02-Mar	713	420	293	605	360	245
	03-Mar	817	461	356	693	406	287
	04-Mar	744	378	366	620	305	315
05-Mar	812	477	335	730	431	299	
		790	474	308	658	393	265
21	06-Mar	839	439	400	734	372	362
	07-Mar	724	378	346	690	359	331
	08-Mar	714	376	338	712	370	342
	09-Mar	823	444	379	742	384	358
	10-Mar	681	369	312	612	320	292
	11-Mar	721	381	340	649	358	291
	12-Mar	833	464	369	771	403	368
	13-Mar	802	372	430	761	308	453*
	14-Mar	795	448	347	811	468	343
	15-Mar	676	371	305	580*	283	297
	16-Mar	783	391	372	641	276	365
	17-Mar	792	378	414	670	273	397
18-Mar	802	448	354	721	358	363	
19-Mar	839	417	422	732	368	364	
		772	405	386	711	350	344
22	04-Apr	851	304	347	506	216	290
	05-Apr	632	412	220	600	418*	182
	06-Apr	782	354	428	637	197	440*
	07-Apr	880	398	282	451	167	284
	08-Apr	898	394	304	531	240	291
	09-Apr	875	341	334	475	170	305
	10-Apr	847	370	277	449	203	248
	11-Apr	721	419	302	542	216	326
12-Apr	795	430	385	660	286	374	
		898	388	318	539	212	287

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches: total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
23	13-Apr	741	350	391	592	181	411
	14-Apr	749	384	365	581	215	368
	15-Apr	738	371	367	532	177	355
	16-Apr	856	362	494	694	225	469
	17-Apr	800	393	407	832	264	368
	18-Apr	784	368	418	808	230	378
	19-Apr	615*	382	233*	448*	233	215
	20-Apr	759	404	355	571	247	324
	21-Apr	772	366	406	618	230	388
	22-Apr	817	440	377	633	265	368
	23-Apr	874	447	427	662	297	365
		789	388	400	612	233	364
24	28-Apr	990	538	452	758	301	457
	29-Apr	870	412	458	701	271	430
	30-Apr	889	461	428	707	293	414
	01-May	927	441	486	735	300	435
	02-May	925	481	444	762	342	420
	03-May	943	457	486	782	319	463
	04-May	949	414	535	795	308	487
	05-May	900	423	477	719	297	422
	06-May	906	413	493	708	266	440
	07-May	995	487	528	784	303	481
08-May	981	352*	629*	925*	364	561	
		934	451	478	745	305	495
25	09-May	1123	796	327	924	594	330
	10-May	1079	577	502	856	404	452
	11-May	771	463	308	568*	255	313
	12-May	970	424	546	827	349	478
	13-May	1108	529	579	908	372	536
	14-May	1051	455	596	928	382	546
	15-May	946	381	565	808	271	537
	16-May	1179	428	751*	1086	350	736*
	17-May	774	417	357	729	380	349
	18-May	873	389	484	840	388	452
19-May	1112	450	682	934	354	580	
		998	483	493	862	373	458

Table E1-cont.

Daily parent system unfiltered and filtered influent data for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED INFLUENT			FILTERED INFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
26	20-May	1045	480	565	950	488	482
	21-May	1227*	571*	656*	951	458	492
	22-May	830	393	437	822	392	430
	23-May	756	466	290	636	384	252
	24-May	790	361	429	644	278	366
	25-May	788	409	359	608	328	282
	26-May	912	444	488	569	241	328
	27-May	897	401	496	688	193	475
	28-May	899	479	420	609	233	376
	29-May	955	494	461	664	248	418
	30-May	909	428	481	683	229	434
31-May	1007	477	530	747	262	485	
		888	439	449	711	309	402
27	01-Jun	1108	556	552	755	270	485
	02-Jun	1544*	543	1001*	1288*	295	973*
	03-Jun	858	417	441	826	229	397
	04-Jun	847			688	444*	224
	05-Jun	792	452	340	595*	247	348
	06-Jun	1041	556	485	785	344	441
	07-Jun	975	491	484	770	330	440
	08-Jun	1008	500	508	775	317	458
	09-Jun	871	455	516	844	347	497
	10-Jun	1035	554	481	816	378	438
	11-Jun	1019	503	516	829	386	443
	12-Jun	1008	474	534	802	332	470
	13-Jun	1122	464	658	942	359	583
	14-Jun	988	545	454	770	367	403
		983	501	498	782	323	433
28	15-Jun	1342	530	812	1151	390	761
	16-Jun	947	543	404	635	289	346
	17-Jun	956	456	500	864	427	437
	18-Jun	1138	476	662	952	321	631
	19-Jun	1279	598	681	1011	412	599
	20-Jun	1231	672*	559	849	374	475
	21-Jun	1070	379	691	837	213	624
	22-Jun	843	472	371	642	339	303
	23-Jun	620	354	286	420	177	243
	24-Jun	783	487	276	496	252	244
	25-Jun	791	412	379	563	192	371
	26-Jun	914	462	452	780	333	447
	27-Jun	697	346	351	488	183	325
		969	459	493	745	299	447

Table E2 Daily parent system unfiltered and filtered effluent results for the various wastewater batches: total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
1	March 30	636	217	419	615	198	416
	March 31	737	268	469	714	237	477*
	April 01	716	273	443	706	251	455
	April 02	700	345	355	644	288	356
	April 03	734	319	415	702	298	404
	April 04	761	357	404	735	326	409
	April 05	680	244	416	645	252	393
	April 06	710	342	368	707	319	388
	April 07	840*	531*	309	808*	470*	338
	April 08	728	372	356	712	379	333
	April 09	677	356	321	657	324	333
	April 10	631	289	362	634	278	358
	April 11	756	344	412	737	429	308
April 12	741	372	369	763	398	365	
		707	314	387	690	396	372
2	April 13	834	431	403	841	417	424
	April 14	811	436	375	840	437	403
	April 15	858	508	348	845	489	356
	April 16	845	446	399	843	449	394
	April 17	837	545	392	926	552	374
	April 18	910	808	304	926	645	281
	April 22	851	533	318	901	595	306
	April 23	633*	446	187*	628*	435	193*
	April 24	862	494	368	895	502	393
	April 25	753	369	384	732	382	350
		851	481	366	861	490	365
3	April 26	973	585	388	1023	651	372
	April 27	859	535	324	862	527	335
	April 28	802*	504	298	936	630	306
	April 29	927	584	363	935	577	358
	April 30	922	524	398	640*	219*	421
	May 01	1031	607	424	1074	847	427
	May 02	1038	641	397	846	432*	414
	May 03	1028	703	325	1054	714	340
	May 04	1073	782	311	994	861	333
	May 05	1105	752	353	1072	737	335
	May 06	1090	727	383	1073	674	399
	May 07	947	639	308	929	635	294
	May 08	928	695	233	908	685	223*
	May 09	902	622	280	902	626	276
	May 10	969	577	392	949	560	389
May 11	901	547	354	938	575	363	
May 12	1111	689	422	1129	735	394	
May 13	1088	608	480	1108	658	450	
May 14	933	539	394	932	552	380	
		990	622	358	981	638	366

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
4	June 20	977*	614*	363	714	433	281
	June 21	620	396	224	689	320	369
	June 22	815	481	354	670	367	303
	June 23	666	319	347	689	371	318
	June 24	740	447	293	728	405	323
	June 25	735	375	360	744	411	333
	June 26	760	391	369	748	379	369
	June 27	769	438	331	817*	504*	313
		729	404	330	712	384	326
5	June 28	887	550	337	853	520	333
	June 29	798	444	354	896	583	333
	July 03	725	415	310	791	486	305
	July 04	760	504	256	746	502	244
	July 05	740	412	328	807	478	329
	July 06	856	500	356	857	504	353
	July 07	808	447	361	856	504	352
	July 08	971	628	343	990	645	345
	July 09	817	496	321	813	536	277
	July 10	881	542	339	899	560	339
	July 11	1021	598	423	975	619	356
	July 12	1099*	580	519	1095*	586	509*
	July 13	940	599	341	926	640	286
	July 14	885	585	300	869	594	275
	July 15	919	627	292	968	685	283
	July 16	784	514	270	840	579	261
July 17	854	528	326	858	548	308	
July 18	852	530	322	891	565	326	
July 19	805	490	315	826	515	311	
July 20	940	463	477	895	452	443*	
		855	523	345	871	554	312
6	July 21	1039	526	513	1062	551	511
	July 22	1021	581	440	1006	558	448
	July 23	846	464	382	808*	440	369
	July 24	823	419	404	843	449	394
	July 25	941	495	446	885	451	434
	July 26	1009	431	578	1021	477	544
	July 27	1039	514	525	1011	502	509
	July 28	1172	839*	533	1251	887*	564
	July 29	1145	489	656	1139	484	655
	July 30	1145	553	592	1189	583	606
	July 31	891	507	384	894	491	403
	August 1	895	458	437	909	506	403
	August 2	953	452	501	937	442	495
	August 3	1133	531	602	1186	568	618
		1004	484	500	1026	600	467

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT			
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)	
7	August 4	1061*	555*	506	1052	531	521	
	August 5	945	441	504	958	475	483	
	August 6	857	452	405	868	461	407	
	August 7	798	357	439	826	420	408	
	August 8	989	478	511	976	470	508	
	August 9	839	380	459	910	448	462	
	August 10	886	441	445	863	441	422	
	August 11	907	419	488	972	486	486	
	August 12	1035	516	519	1035	491	544	
	August 13	863	447	416	914	510	404	
	August 14	768	419	349	753	399	354	
	August 15	845	457	388	884	503	381	
	August 16	871	473	398	893	472	421	
	August 17	902	495	407	935	557*	378	
	August 18	733	495	238	708	473	235*	
	August 19	689	423	268	702	448	254	
	August 20	792	447	345	794	459	335	
	August 21	753	405	348	787	443	344	
	August 22	751	420	331	773	443	330	
			846	443	408	874	455	413
	8	August 23	812	405	407	842	454	388
		August 24	867	448	519	968	447	521*
August 25		945	454	491	977	510	467	
August 26		873	514*	359	928	530	398	
August 27		749	368	381	803	437	366	
August 28		711	389	322	725	420	305	
August 29		691	396	293	738	452	286	
August 30		768	421	347	807	473	334	
Sept.01		691	335	356	732	380	352	
Sept.02		739	448	291	777	481	296	
Sept.03		622	407	415	857	456	402	
Sept.04		664	407	257	665	384	281	
Sept.05		734	489	245	751	497	254	
Sept.06		729	409	320	749	417	332	
		778	414	357	809	453	343	
9	Sept.07	787	410	377	793	422	371	
	Sept.08	934	547*	387	934	542	392	
	Sept.09	844	505	339	840	505	335	
	Sept.10	841	472	369	920	544	378	
	Sept.11	771	487	284	784	519	265	
	Sept.12	771	467	314	769	440	329	
	Sept.13	870	425	445	906	452	454	
	Sept.14	864	398	466	846	398	448	
	Sept.15	878	497	381	909	526	383	
	Sept.16	808	458	350	815	473	342	
	Sept.17	754	437	317	752	438	314	
	Sept.18	774	445	329	782	462	320	
	Sept.19	900	497	403	866	481	385	
	Sept.20	976*	384	592*	992*	380	612*	
		830	452	386	840	470	363	

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
10	Sept. 21	886	408	478	872	414	458
	Sept. 22	930	514*	416	923	525	398
	Sept. 23	908	465	441	860	463	397
	Sept. 24	836	484	352	822	473	349
	Sept. 25	690	344	346	695	362	333
	Sept. 28	740	434	306	751	455	296
	Sept. 27	803	375	428	808	398	412
	Sept. 28	928	478	450	944	492	452
	Sept. 29	744	438	306	734	431	303
	Sept. 30	741	476	285	734	491	243
	Oct. 01	688	433	255	664	391	273
Oct. 02	669	384	285	693	444	249	
		797	429	361	792	445	327
11	Oct. 03	604	389	235	602	386	236
	Oct. 04	708	381	347	701	337	364
	Oct. 05	790	430	360	794	434	360
	Oct. 08	710	404	308	800	423	377
	Oct. 07	765	410	355	739	453	286
	Oct. 08	703	319	384	735	376	358
	Oct. 09	637	308	329	582	343	239
	Oct. 10	689	371	318	713	418	295
	Oct. 11	731	343	388	748	377	371
	Oct. 12	824	434	390	806	427	378
	Oct. 13	818	316	502*	840	496	344
	Oct. 14	845	362	483*	855	388	487*
	Oct. 15	705	325	380	730	457	273
Oct. 16	610	354	256	618	414	202	
		724	365	337	733	406	314
12	Oct. 17	681	381	300	777	442	335
	Oct. 18	639	348	291	627	372	255
	Oct. 19	711	437	274	738	459	279
	Oct. 20	707	381	326	688	428	260
	Oct. 21	693	322	371	637	273	364
	Oct. 22	662	301	361	711	360	351
	Oct. 23	478*	225	253	518	283	235
	Oct. 24	508	222	284	496*	185*	311
	Oct. 25	686	326	360	714	363	351
	Oct. 26	693	280	413	707	306	401
	Oct. 27	827	275	552*	838	311	525*
	Oct. 28	782	408	374	825	379	446
	Oct. 29	723	368	355	690	347	343
	Oct. 30	634	318	316	603	312	291
	Oct. 31	748	493*	255	715	461	254
		692	328	324	699	364	320

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT			
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)	
13	01-Nov	692	443	249	636	325	331*	
	02-Nov	681	434	247	730	468	262	
	03-Nov	666	424	242	618	420	198	
	04-Nov	565	390	175	622	383	239	
	05-Nov	529	359	170	538	371	167	
	06-Nov	494	292	202	498	308	190	
	07-Nov	531	397	134	567	404	183	
	08-Nov	572	462	110	554	481	93*	
	09-Nov	430	222	208	418	211	207	
	10-Nov	523	314	209	367	225	142	
	12-Nov	632	313	319	257*	89*	168	
	13-Nov	393	233	160	432	216	216	
	15-Nov	394	242	152	361	197	164	
	16-Nov	410	216	194	411	213	198	
	17-Nov	381	188	193	514	334	180	
			526	320	198	519	324	192
	14	18-Nov	590	403	187	458	254	204
19-Nov		490	312	178	446	295	151	
20-Nov		368	161*	207	364	124*	240	
21-Nov		452	300	152	468	280	188	
22-Nov		414	200	214	413	168	245	
23-Nov		417	310	107	416	272	144	
24-Nov		446	265	181	461	347	114	
25-Nov		471	285	176	409	224	185	
26-Nov		809	362	247	510	343	167	
27-Nov		606	365	241	606*	325	281	
28-Nov		466	352	114	538	364	174	
29-Nov		526	365	161	444	284	160	
30-Nov		451	270	181	413	318	95*	
01-Dec		502	350	152	534	324	210	
02-Dec		493	268	225	538	316	222	
03-Dec		543	324	219	479	302	177	
04-Dec	675*	391*	284*	567	341	226		
		490	316	184	465	297	218	
15	05-Dec	678*	425	253	497	217	280	
	06-Dec	456	377	79*	457	297	180	
	07-Dec	529	387	142	336	167	169	
	08-Dec	528	356	172	475	315	160	
	09-Dec	463	363	100*	320	159	161	
	10-Dec	434	278*	156	433	264	169	
	11-Dec	518	323	195	485	180	305	
	12-Dec	566	347	219	488	237	251	
	13-Dec	582	352	230	384	262	122	
	14-Dec	433	362	71*	418	251	167	
		501	366	195	428	225	195	

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
16	08-Jan	415	162	253	432	184	248
	09-Jan	413	155	258	480	244	236
	10-Jan	381	176	205	458	292	166
	11-Jan	308	160	148	365	206	159
		379	163	216	424	232	202
17	12-Jan	303*	185	138	255*	142	113*
	13-Jan	332	142	190	392	213	179
	14-Jan	482	221	261	487	225	262
	15-Jan	482	254	228	408	186	222
	16-Jan	451	213	238	458	247	211
	17-Jan	524	282	242	404	157	247
	18-Jan	452	246	206	480	282	198
	19-Jan	492	272	220	446	208	240
	20-Jan	574	295	279	585	349	236
	21-Jan	612	284	328	572	231	341*
	22-Jan	604	330	274	599	363	238
	23-Jan	587	344	243	535	322	213
	24-Jan	569	533*	36*	601	352	249
25-Jan	575	338	237	484	213	271	
		518	281	246	496	249	230
18	26-Jan	593	218*	375	663	336	327
	27-Jan	592	319	273	540	273	267
	28-Jan	526	305	221	594	366	228
	29-Jan	612	373	239	550	313	237
	30-Jan	535	320	215	571	378	193
	31-Jan	622	323	299	597	312	285
	01-Feb	649	328	321	702	382	320
	02-Feb	640	380	280	657	393	264
	03-Feb	577	301	278	679	400	279
	04-Feb	580			541	262	279
05-Feb	542	279	263	632	382	250	
06-Feb	553	312	241	548	303	245	
07-Feb	508	281	227	562	357	205	
		579	320	268	603	343	260
19	08-Feb	623	340	283	599	344	255
	09-Feb	582	286	296	661	366	295
	11-Feb	632	310	322	550	289	281
	12-Feb	629	328	301	687	383	324
	13-Feb	641	319	322	600	271	329
	14-Feb	585	306	279	616	345	271
	15-Feb	563	306	257	503	251	252
	16-Feb	530	275	255	597	345	252
	17-Feb	619	343	276	546	268	278
	18-Feb	609	314	295	636	344	292
	19-Feb	631	352	279	604	308	296
20-Feb	534	308	226*	519	332	187*	
21-Feb	643	361	282	579	317	262	
		602	319	267	592	317	282

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
20	22-Feb	587	308	279	692	419	273
	23-Feb	590	396	194*	556	348	208
	24-Feb	636	365	271	651	401	250
	25-Feb	631	373	258	590	316	274
	26-Feb	588	319	289	618	377	241
	27-Feb	673	436	237	595	361	234
	28-Feb	578	286	292	596	311	285
	29-Feb	608	307	301	600	287	313
	01-Mar	690	395	295	724	408	316
	02-Mar	700	394	306	663	369	294
	03-Mar	593	327	266	628	348	280
04-Mar	645	340	305	591	274	317	
05-Mar	648	350	298	696	401	295	
		628	354	281	631	355	275
21	06-Mar	751	394	357	883	342	341
	07-Mar	615	300	315	638	326	312
	08-Mar	693	370	323	635	340	295
	09-Mar	646	323	323	645	299	346
	10-Mar	686	360	326	639	302	337
	11-Mar	578	287	291	591	295	296
	12-Mar	713	404	309	658	338	318
	13-Mar	532	265	267	686	317	369
	14-Mar	796	458	338	746	398	348
	15-Mar	566	278	288	644	293	351
	16-Mar	451	114*	337	626	275	351
17-Mar	555	220	335	573	230	343	
18-Mar	552	186	364	657	305	352	
19-Mar	586	273	313	656	344	312	
		623	317	320	648	315	334
22	04-Apr	438	110*	328	551	200	351
	05-Apr	456	186	270	570	295*	275
	06-Apr	537	195	342	486	117	369
	07-Apr	527	182	345	463	123	340
	08-Apr	495	237	256	451	152	299
	09-Apr	509	200	309	455	144	311
	10-Apr	494	237	257	442	187	255
	11-Apr	499	187	312	456	182	274
12-Apr	566	250	316	494	189	305	
		572	209	304	485	162	308

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches; total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
23	13-Apr	578	217	359	567	152	415
	14-Apr	621	230	391	555	212	343
	15-Apr	449	124	325	489	162	307
	16-Apr	606	222	384	537	166	371
	17-Apr	566	188	378	590	197	393
	18-Apr	641	266	375	587	201	386
	19-Apr	476	184	292	486	169	317
	20-Apr	561	246	315	505	188	319
	21-Apr	487	153	334	510	155	355
	22-Apr	614	297	317	564	215	349
23-Apr	612	271	341	632	295*	337	
		564	218	347	548	184	354
24	28-Apr	688	362	326	617	239	378
	29-Apr	665	276	389	638	281	377
	30-Apr	761	324	437	718	300	418
	01-May	687	300	387	679	266	413
	02-May	778	370	408	757	337	420
	03-May	719	252	467	724	280	444
	04-May	601	307	494	749	289	460
	05-May	703	287	416	736	310	428
	06-May	805	388	419	761	329	432
	07-May	792	337	455	824	363	461
08-May	857*	413	544*	801	263	538*	
		740	320	420	728	294	423
25	09-May	875	484	391	864	325	539
	10-May		470		830	368	461
	11-May	707	322	385	685	255	430
	12-May	789	418	371	740	335	405
	13-May	826	361	465	836	379	457
	14-May	936	383	553	913	390	523
	15-May	645	292	553	922	328	594
	16-May	981	341	640	993	365	628
	17-May	866	338	528	971	421	550
	18-May	791	348	443	781	304	477
19-May	840	344	496	870	380	490	
		848	373	483	855	350	505

Table E2-cont.

Daily parent system unfiltered and filtered effluent results for the various wastewater batches: total solids (TS), total volatile solids (TVS), total inorganic solids (TIS), total dissolved solids (TDS), volatile dissolved solids (VDS) and inorganic dissolved solids (IDS).

Sew. Batch No.	Dates of Test	UNFILTERED EFFLUENT			FILTERED EFFLUENT		
		TS (mgTS/l)	TVS (mgTVS/l)	TIS (mgTIS/l)	TDS (mgTDS/l)	VDS (mgVDS/l)	IDS (mgIDS/l)
26	20-May	932	372	560	900	343	557
	21-May	925	381	544	930*	367	563
	22-May	854	347	507	824	303	521
	23-May	789	463*	326	724	309	325
	24-May	677	312	365	676	333	343
	25-May	689	363	326	716	405	311
	26-May	582	242	340	985	224	461
	27-May	655	239	416	648	260	388
	28-May	734	325	409	744	326	418
	29-May	650	268	362	675	293	382
	30-May	738	284	454	723	251	472
	31-May	736	300	436	730	297	433
		747	314	420	732	317	431
27	02-Jun	1018	361	657*	1029	327	702*
	03-Jun	1016	352	664*	1047*	354	693*
	04-Jun	764	279	485	779	292	487
	05-Jun	703	287	406	710	282	418
	06-Jun	804	402	402	774	388	386
	07-Jun	758	313	445	768	337	431
	08-Jun	818	337	481	828	466*	362
	09-Jun	879	390	489	865	385	480
	10-Jun	881	419	462	878	425	453
	11-Jun	851	341	510	866	378	488
	12-Jun	820	355	465	855	396	459
	13-Jun	827	323	504	858	362	496
	14-Jun	817	346	471	828	344	484
			843	347	465	837	357
28	15-Jun	929	423	506	806	422	484
	16-Jun	926	415	511	913	410	503
	17-Jun	841	401	440	872	407	465
	18-Jun	846	380	466	868	390	478
	19-Jun	1025	418	607	1032	414	618
	20-Jun	980	406	574	1019	421	598
	21-Jun	804	251	553	802	262	520
	22-Jun	958	418	540	970	408	562
	23-Jun	589	214	375	564	192	372
	24-Jun	664	342	322	674	363	311
	25-Jun	549	249	300	541	195	346
	26-Jun	779	388	391	764	413	351
	27-Jun	649	238	411	633	233	400
		611	330	461	612	350	462

Table E3 Summary of the parent system unfiltered influent wastewater solids statistical data for the various wastewater batches; total solids (TS), total inorganic solids (TIS) and total volatile solids (TVS).

Sew. Batch No.	Dates of Test	Statistical data for unfiltered influent solids									
		TS (mgTS/l)			TIS (mgTIS/l)			TVS (mgTVS/l)			No. of tests
		Mean	std. dev of sample	No. of tests	Mean	std. dev. of sample	No. of tests	Mean	std. dev. of sample	No. of tests	
1	30Mar-12Apr	957	63	14	440	69	14	517	57	14	
2	13Apr-25Apr	977	45	10	410	29	9	576	69	10	
3	26Apr-14May	1053	124	18	408	86	18	640	77	17	
4	20Jun-27Jun	954	69	8	389	56	8	565	36	8	
5	29Jun-20Jul	984	58	19	384	60	19	611	59	19	
6	21Jul-3Aug	1038	150	14	544	116	13	506	65	13	
7	4Aug-22Aug	951	149	18	476	133	18	475	33	19	
8	23Aug-06Sept.	878	108	13	416	109	13	453	36	13	
9	07Sept-20Sept	920	120	14	469	103	14	458	38	13	
10	21Spt-02Oct.	926	128	12	401	101	11	507	56	12	
11	03Oct-16Oct	885	105	14	417	83	13	444	43	13	
12	17Oct-31Oct	848	77	12	387	70	14	459	68	14	
13	01Nov-17Nov	618	123	14	229	41	13	434	101	14	
14	18Nov-04Dec.	675	69	16	227	54	16	465	54	16	
15	05Dec-14Dec	703	61	9	202	38	9	483	35	9	
16	08Jan-11Jan	587	69	4	223	69	4	365	6	4	
17	12Jan-25Jan	714	144	14	269	81	14	444	56	12	
18	26Jan-07Feb	799	61	12	290	40	12	509	47	13	
19	08Feb-21Feb	785	36	12	327	26	12	463	35	12	
20	22Feb-05Mar	790	56	13	308	39	12	474	56	13	
21	06Mar-19Mar	772	58	14	366	39	14	405	36	14	
22	04Apr-12Apr	698	58	9	318	60	9	380	41	9	
23	13Apr-23Apr	789	48	10	400	41	10	388	31	11	
24	24Apr-08May	934	42	10	479	35	9	451	40	9	
25	09May-19May	999	143	11	493	122	10	483	119	10	
26	20May-31May	888	95	11	449	77	11	439	44	11	
27	01Jun-14Jun	983	98	13	498	71	12	501	47	13	
28	15Jun-27Jun	969	230	13	493	175	13	460	77	13	

Table E4 Summary of the parent system filtered influent solids statistical data for the various wastewater batches; total dissolved solids (TDS), inorganic dissolved solids (IDS) and volatile dissolved solids (VDS).

Sew. Batch No.	Dates of Test	Statistical data for filtered influent solids									
		IDS (mgIDS/l)					VDS (mgVDS/l)				
		Mean	std. dev. of sample tests	No. of tests	Mean	std. dev. of sample tests	No. of tests	Mean	std. dev. of sample tests	No. of tests	Mean
1	30Mar-12Apr	729	76	14	375	43	13	329	47	13	
2	13Apr-25Apr	800	70	10	360	33	10	437	85	10	
3	26Apr-14May	924	128	18	361	66	18	591	110	19	
4	20Jun-27Jun	783	97	8	355	22	7	452	47	8	
5	29Jun-20Jul	893	92	19	310	36	17	564	51	18	
6	21Jul-3Aug	990	159	14	520	133	14	470	75	14	
7	4Aug-22Aug	798	129	18	385	111	18	413	38	19	
8	23Aug-06Sept.	785	114	13	353	97	12	432	53	14	
9	07Sept-20Sept	820	96	13	373	82	13	445	36	14	
10	21Spt-02Oct.	768	130	12	313	102	11	442	38	11	
11	03Oct-16Oct	743	129	14	345	103	14	399	59	14	
12	17Oct-31Oct	715	85	18	361	91	15	353	71	15	
13	01Nov-17Nov	526	124	19	208	50	14	332	108	18	
14	18Nov-04Dec.	409	90	69	233	65	68	262	63	69	
15	05Dec-14Dec	439	63	56	180	73	48	250	21	58	
16	08Jan-11Jan	396	72	24	193	71	24	202	23	24	
17	12Jan-25Jan	504	114	78	238	78	75	266	54	76	
18	26Jan-07Feb	611	53	74	253	43	73	365	53	74	
19	08Feb-21Feb	674	42	72	277	29	70	404	40	72	
20	22Feb-05Mar	658	71	74	265	43	73	393	54	76	
21	06Mar-19Mar	711	57	79	344	33	79	350	54	79	
22	04Apr-12Apr	539	78	54	287	56	50	212	39	53	
23	13Apr-23Apr	612	47	58	364	62	60	233	35	60	
24	24Apr-08May	745	36	57	455	43	60	306	28	57	
25	09May-19May	862	69	59	458	103	58	373	87	57	
26	20May-31May	711	130	46	402	82	48	309	94	46	
27	01Jun-14Jun	782	81	37	433	84	36	323	50	42	
28	15Jun-27Jun	745	224	38	447	171	39	299	92	35	

Table E5 Summary of the parent system unfiltered effluent wastewater statistical data for the various wastewater batches; total solids (TS), total inorganic solids (TIS) and total volatile solids (TVS).

Sew. Batch No.	Dates of Test	Statistical data for unfiltered effluent solids											
		TS (mgTS/l)			TIS (mgTIS/l)			TVS (mgTVS/l)					
		Mean	std. dev of sample	No. of tests	Mean	std. dev. of sample	No. of tests	Mean	std. dev. of sample	No. of tests			
1	30Mar-12Apr	707	43	13	387	46	14	314	53	13			
2	13Apr-25Apr	851	53	9	366	35	9	481	69	10			
3	26Apr-14May	990	81	18	358	51	17	622	80	19			
4	20Jun-27Jun	729	66	7	330	49	7	404	49	7			
5	29Jun-20Jul	855	80	19	345	64	18	523	66	20			
6	21Jul-3Aug	1004	116	14	500	87	14	494	48	13			
7	4Aug-22Aug	846	91	18	409	82	18	443	41	18			
8	23Aug-06Sept.	778	94	14	357	81	13	414	40	13			
9	07Sept-20Sept	830	57	13	366	52	13	452	40	13			
10	21Spt-02Oct.	797	88	12	361	77	12	429	47	12			
11	03Oct-16Oct	724	77	14	337	51	13	365	42	14			
12	17Oct-31Oct	692	75	14	324	50	14	328	64	14			
13	01Nov-17Nov	526	109	15	198	52	14	329	94	15			
14	18Nov-04Dec.	490	70	16	184	41	16	316	52	16			
15	05Dec-14Dec	501	56	9	195	41	7	366	29	9			
16	08Jan-11Jan	379	50	4	216	51	4	163	9	4			
17	12Jan-25Jan	518	80	13	246	46	12	260	63	13			
18	26Jan-07Feb	579	45	13	268	46	11	320	32	11			
19	08Feb-21Feb	602	39	13	287	21	13	319	25	13			
20	22Feb-05Mar	628	49	13	281	22	12	354	44	13			
21	06Mar-19Mar	623	95	14	320	26	14	317	77	13			
22	04Apr-12Apr	502	37	9	304	34	9	209	27	8			
23	13Apr-23Apr	564	65	11	346	33	11	218	52	11			
24	24Apr-08May	740	53	10	420	47	10	329	50	11			
25	09May-19May	846	77	10	483	88	10	373	61	11			
26	20May-31May	747	110	12	420	82	12	314	49	11			
27	01Jun-14Jun	843	91	13	465	36	11	347	40	13			
28	15Jun-27Jun	811	156	13	461	97	13	349	81	13			

Table E6 Summary of the parent system filtered effluent statistical data for the various wastewater batches; total dissolved solids (TDS), inorganic dissolved solids (IDS) and volatile dissolved solids (VDS).

Sew. Batch No.	Dates of Test	Statistical data for filtered effluent solids											
		TDS (mgTDS/l)				IDS (mgIDS/l)				VDS (mgVDS/l)			
		Mean	std. dev	No. of sample tests		Mean	std. dev.	No. of sample tests		Mean	std. dev.	No. of sample tests	
1	30Mar-12Apr	690	46	13	373	42	13	306	67	13			
2	13Apr-25Apr	861	60	9	365	47	10	490	84	10			
3	26Apr-14May	981	86	18	366	48	18	638	63	17			
4	20Jun-27Jun	712	30	7	326	31	8	384	37	7			
5	29Jun-20Jul	871	64	18	312	34	18	554	62	20			
6	21Jul-3Aug	1053	132	13	497	92	14	500	50	14			
7	4Aug-22Aug	874	103	19	413	76	18	465	32	18			
8	23Aug-06Sept.	809	95	14	343	60	12	453	44	14			
9	07Sept-20Sept	840	63	13	363	53	13	470	52	14			
10	21Spt-02Oct.	792	94	12	347	76	12	445	48	12			
11	03Oct-16Oct	733	86	14	314	62	13	406	47	12			
12	17Oct-31Oct	699	85	14	320	61	15	364	64	14			
13	01Nov-17Nov	519	111	15	192	33	13	324	98	14			
14	18Nov-04Dec.	466	58	66	193	43	66	297	51	68			
15	05Dec-14Dec	429	64	54	195	61	55	235	57	54			
16	08Jan-11Jan	434	50	23	202	46	24	232	47	24			
17	12Jan-25Jan	496	75	74	230	27	70	249	73	78			
18	26Jan-07Feb	603	57	74	260	40	74	343	46	71			
19	08Feb-21Feb	592	53	68	282	26	71	317	40	69			
20	22Feb-05Mar	630	50	74	275	34	74	355	47	77			
21	06Mar-19Mar	648	41	81	334	23	82	315	39	79			
22	04Apr-12Apr	485	46	52	309	38	54	162	32	52			
23	13Apr-23Apr	547	47	64	354	34	62	184	23	61			
24	24Apr-08May	728	63	62	423	29	58	294	38	63			
25	09May-19May	855	94	64	505	69	66	350	46	65			
26	20May-31May	732	73	52	431	84	54	317	57	52			
27	01Jun-14Jun	837	79	43	449	45	34	357	41	41			
28	15Jun-27Jun	812	166	39	462	100	39	350	90	39			

Table E7 Summary of the parent system reactor solids statistical data with the % inorganic solids recovery for the various wastewater batches; total suspended solids (TSS), organic/volatile suspended solids (VSS) and inorganic suspended solids (ISS).

Sew. Batch No.	Dates of Test	REACTOR SOLIDS												%Inorganic Solids Recovery
		TSS (mgTSS/l)			VSS (mgVSS/l)			ISS (mgISS/l)			No. of tests	No. of sample tests		
		Mean	std. dev of sample	No. of tests	Mean	std. dev. of sample	No. of tests	Mean	std. dev. of sample	No. of tests				
1	30Mar-12Apr	2815	105	11	2378	86	11	437	27	11				93
2	13Apr-25Apr	2441	381	10	2392	65	6	337	86	10				94
3	26Apr-14May	2217	87	18	1949	93	18	269	26	18				92
4	20Jun-27Jun	2293	83	7	1961	68	7	332	33	7				90
5	29Jun-20Jul	2310	401	20	2306	149	10	310	57	20				94
6	21Jul-3Aug	2296	213	13	1976	186	13	320	33	13				95
7	4Aug-22Aug	2224	335	19	2094	187	13	271	59	19				89
8	23Aug-06Sept.	2163	72	12	1911	61	12	251	37	13				89
9	07Sept-20Sept	1890	100	13	1661	78	13	237	62	14				81
10	21Spt-02Oct.	2559	218	12	2222	167	12	350	40	11				95
11	03Oct-16Oct	2735	177	13	2339	169	14	376	64	14				86
12	17Oct-31Oct	2714	130	12	2293	149	13	401	62	14				89
13	01Nov-17Nov	2013	102	15	1684	118	16	293	53	14				93
14	18Nov-04Dec.	2194	124	17	1908	106	16	281	43	16				88
15	05Dec-14Dec	2238	54	9	1932	56	9	306	23	9				105
16	08Jan-11Jan	2321	38	4	2018	45	4	303	27	4				104
17	12Jan-25Jan	2363	102	13	2033	78	13	322	28	13				98
18	26Jan-07Feb	1994	88	12	1709	85	12	281	37	13				98
19	08Feb-21Feb	2053	48	12	1775	28	12	274	32	13				92
20	22Feb-05Mar	2356	226	12	2051	118	11	341	46	11				97
21	06Mar-19Mar	2484	124	13	2116	108	13	362	38	14				93
22	04Apr-12Apr	3212	133	8	2729	108	8	491	46	9				101
23	13Apr-23Apr	3168	61	11	2664	56	9	500	20	11				91
24	24Apr-08May	3023	104	14	2557	66	14	474	34	14				91
25	09May-19May	3305	130	11	2747	71	10	541	37	10				102
26	20May-31May	3397	51	12	2861	51	12	538	10	12				98
27	01Jun-14Jun	3789	128	13	3185	102	13	602	30	13				97
28	15Jun-27Jun	3891	147	12	3302	120	12	589	29	12				98

Table E8 Summary of statistical significance test on the difference between the parent system mean influent and mean effluent unfiltered total solids (TS) for the various wastewater batches.

Sew. Batch No.	Date of Test	UNFILTERED INFLUENT AND EFFLUENT TS							Conclusion
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance			
1	30Mar-12Apr	16.9	12.0	20.7	250.3	208.8	stat. signif.		
2	13Apr-25Apr	14.2	17.7	22.7	126.0	80.6	stat. signif.		
3	26Apr-14May	29.2	19.0	34.9	62.7	-7.1	stat. insignif.		
4	20Jun-27Jun	24.5	24.9	34.9	224.6	154.8	stat. signif.		
5	29Jun-20Jul	13.4	18.4	22.8	129.0	83.5	stat. signif.		
6	21Jul-3Aug	40.1	31.1	50.8	34.1	-67.4	stat. insignif.		
7	4Aug-22Aug	35.1	21.6	41.2	105.6	23.2	stat. signif.		
8	23Aug-06Sept.	29.8	25.2	39.0	99.8	21.7	stat. signif.		
9	07Sept-20Sept	32.2	15.9	35.9	89.3	17.5	stat. signif.		
10	21Spt-02Oct.	37.1	28.2	46.6	129.3	36.1	stat. signif.		
11	03Oct-16Oct	28.0	20.6	34.7	160.9	91.5	stat. signif.		
12	17Oct-31Oct	22.2	20.0	29.9	155.4	95.6	stat. signif.		
13	01Nov-17Nov	32.9	28.1	43.3	92.0	5.4	stat. signif.		
14	18Nov-04Dec.	17.3	17.5	24.6	185.1	135.9	stat. signif.		
15	05Dec-14Dec	20.4	18.7	27.7	201.6	146.2	stat. signif.		
16	08Jan-11Jan	34.7	25.0	42.7	208.0	122.5	stat. signif.		
17	12Jan-25Jan	38.4	22.2	44.4	195.6	106.9	stat. signif.		
18	26Jan-07Feb	17.7	12.3	21.6	219.8	176.6	stat. signif.		
19	08Feb-21Feb	10.4	10.9	15.0	183.2	153.1	stat. signif.		
20	22Feb-05Mar	15.4	13.7	20.6	162.1	120.8	stat. signif.		
21	06Mar-19Mar	15.5	25.5	29.8	148.9	89.2	stat. signif.		
22	04Apr-12Apr	19.4	12.3	23.0	195.6	149.6	stat. signif.		
23	13Apr-23Apr	15.0	19.7	24.8	224.5	174.9	stat. signif.		
24	24Apr-08May	13.3	16.8	21.4	194.2	151.4	stat. signif.		
25	09May-19May	43.0	24.4	49.5	153.1	54.2	stat. signif.		
26	20May-31May	28.5	31.7	42.6	141.3	56.0	stat. signif.		
27	01Jun-14Jun	27.1	25.2	37.0	140.5	66.5	stat. signif.		
28	15Jun-27Jun	63.7	43.3	77.0	157.8	3.9	stat. signif.		

Table E9 Summary of statistical significance test on the difference between the parent system mean influent and mean effluent unfiltered total inorganic solids (TIS) for the various wastewater batches.

Sew. Batch No.	Date of Test	UNFILTERED INFLUENT AND EFFLUENT TIS							Conclusion
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance			
1	30Mar-12Apr	18.5	12.7	22.4	53.3	8.4	stat. signif.		
2	13Apr-25Apr	9.7	11.2	14.8	44.7	15.1	stat. signif.		
3	26Apr-14May	20.2	12.0	23.5	49.2	2.3	stat. signif.		
4	20Jun-27Jun	19.7	18.6	27.1	58.8	4.6	stat. signif.		
5	29Jun-20Jul	13.8	15.4	20.7	38.7	-2.6	stat. insignif.		
6	21Jul-3Aug	32.1	23.2	39.6	44.5	-34.8	stat. insignif.		
7	4Aug-22Aug	31.3	19.2	36.7	67.6	-5.8	stat. insignif.		
8	23Aug-06Sept.	30.2	23.3	38.1	58.8	-17.5	stat. insignif.		
9	07Sept-20Sept	27.4	14.5	31.0	102.4	40.4	stat. signif.		
10	21Spt-02Oct.	30.3	23.1	38.1	40.5	-35.8	stat. insignif.		
11	03Oct-16Oct	23.1	13.7	26.8	79.4	25.7	stat. signif.		
12	17Oct-31Oct	18.6	12.8	22.6	63.0	17.9	stat. signif.		
13	01Nov-17Nov	11.2	14.0	18.0	31.0	-4.9	stat. insignif.		
14	18Nov-04Dec.	13.5	5.0	14.4	42.7	13.9	stat. signif.		
15	05Dec-14Dec	12.6	5.9	13.9	6.9	-21.0	stat. insignif.		
16	08Jan-11Jan	34.5	10.5	36.0	6.8	-65.3	stat. insignif.		
17	12Jan-25Jan	21.8	5.3	22.4	23.7	-21.1	stat. insignif.		
18	26Jan-07Feb	11.7	5.4	12.9	22.0	-3.7	stat. insignif.		
19	08Feb-21Feb	7.6	2.5	8.0	39.5	23.5	stat. signif.		
20	22Feb-05Mar	11.1	2.5	11.4	26.8	4.0	stat. signif.		
21	06Mar-19Mar	10.5	3.0	10.9	45.9	24.1	stat. signif.		
22	04Apr-12Apr	19.9	4.9	20.5	13.6	-27.3	stat. insignif.		
23	13Apr-23Apr	12.8	4.2	13.5	53.6	26.5	stat. signif.		
24	24Apr-08May	11.6	6.1	13.1	58.9	32.7	stat. signif.		
25	09May-19May	38.7	11.5	40.4	10.1	-70.7	stat. insignif.		
26	20May-31May	23.1	11.9	25.9	28.2	-23.7	stat. insignif.		
27	01Jun-14Jun	20.5	6.0	21.4	32.5	-10.2	stat. insignif.		
28	15Jun-27Jun	48.4	15.6	50.9	31.4	-70.3	stat. insignif.		

Table E10 Summary of statistical significance test on the difference between the parent system mean influent and mean effluent unfiltered, total volatile solids (TVS) for the various wastewater batches.

Sew. Batch No.	Date of Test	UNFILTERED INFLUENT AND EFFLUENT TVS							Conclusion
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance			
1	30Mar-12Apr	15.2	14.6	21.1	203.0	160.9	stat. signif.		
2	13Apr-25Apr	21.8	21.8	30.9	94.5	32.8	stat. signif.		
3	26Apr-14May	18.8	18.4	26.3	18.1	-34.4	stat. insignif.		
4	20Jun-27Jun	12.9	18.6	22.6	161.1	115.9	stat. signif.		
5	29Jun-20Jul	13.6	14.9	20.1	88.8	48.5	stat. signif.		
6	21Jul-3Aug	17.9	13.3	22.3	12.5	-32.1	stat. insignif.		
7	4Aug-22Aug	7.6	9.6	12.2	32.6	8.2	stat. signif.		
8	23Aug-06Sept.	10.1	11.0	15.0	39.2	9.2	stat. signif.		
9	07Sept-20Sept	10.4	11.0	15.2	5.9	-24.5	stat. insignif.		
10	21Spt-02Oct.	16.1	13.4	21.0	78.0	36.1	stat. signif.		
11	03Oct-16Oct	11.9	11.1	16.3	79.6	46.9	stat. signif.		
12	17Oct-31Oct	18.2	17.2	25.0	131.1	81.0	stat. signif.		
13	01Nov-17Nov	27.0	24.2	36.3	105.2	32.6	stat. signif.		
14	18Nov-04Dec.	13.4	13.1	18.7	148.8	111.4	stat. signif.		
15	05Dec-14Dec	11.8	9.6	15.2	117.1	86.7	stat. signif.		
16	08Jan-11Jan	3.2	4.5	5.5	201.3	190.2	stat. signif.		
17	12Jan-25Jan	16.1	17.4	23.7	183.8	136.3	stat. signif.		
18	26Jan-07Feb	12.9	9.7	16.2	189.2	156.9	stat. signif.		
19	08Feb-21Feb	10.2	7.0	12.3	143.8	119.2	stat. signif.		
20	22Feb-05Mar	15.5	12.2	19.7	120.1	80.6	stat. signif.		
21	06Mar-19Mar	9.6	21.4	23.4	88.5	41.6	stat. signif.		
22	04Apr-12Apr	13.8	9.7	16.8	171.0	137.3	stat. signif.		
23	13Apr-23Apr	9.4	15.8	18.4	169.9	133.1	stat. signif.		
24	24Apr-08May	13.2	15.1	20.0	122.2	82.1	stat. signif.		
25	09May-19May	37.6	18.3	41.8	109.8	26.2	stat. signif.		
26	20May-31May	13.2	14.8	19.8	125.4	85.7	stat. signif.		
27	01Jun-14Jun	13.0	11.1	17.1	153.5	119.2	stat. signif.		
28	15Jun-27Jun	21.5	22.4	31.0	110.1	48.1	stat. signif.		

Table E11 Summary of statistical significance test on the difference between the parent system mean influent and mean effluent filtered total dissolved solids (TDS) for the various wastewater batches.

Sew. Batch No.	Date of Test	FILTERED INFLUENT AND EFFLUENT TDS						
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance	Conclusion	
1	30Mar-12Apr	20.4	12.7	24.1	39.1	-9.0	stat. insignif.	
2	13Apr-25Apr	22.2	20.2	30.0	61.0	1.0	stat. signif.	
3	26Apr-14May	30.1	20.4	36.3	57.3	-15.3	stat. insignif.	
4	20Jun-27Jun	34.2	11.3	36.0	71.4	-0.6	stat. insignif.	
5	29Jun-20Jul	21.0	15.0	25.8	22.2	-29.5	stat. insignif.	
6	21Jul-3Aug	42.4	36.7	56.1	62.3	-49.9	stat. insignif.	
7	4Aug-22Aug	30.5	23.6	38.5	76.3	-0.7	stat. insignif.	
8	23Aug-06Sept	31.5	25.4	40.5	23.6	-57.3	stat. insignif.	
9	07Sept-20Sept	26.7	17.4	31.9	20.2	-43.6	stat. insignif.	
10	21Sept-02Oct	37.6	27.0	46.3	23.3	-69.4	stat. insignif.	
11	03Oct-16Oct	34.5	22.9	41.4	10.4	-72.4	stat. insignif.	
12	17Oct-31Oct	20.1	22.7	30.3	16.5	-44.2	stat. insignif.	
13	01Nov-17Nov	28.5	28.7	40.4	6.7	-74.1	stat. insignif.	
14	16Nov-04Dec	10.8	7.1	12.9	56.9	31.1	stat. signif.	
15	05Dec-14Dec	8.5	8.7	12.1	9.5	-14.8	stat. insignif.	
16	08Jan-11Jan	14.8	10.4	18.0	38.3	2.2	stat. signif.	
17	12Jan-25Jan	12.9	8.8	15.6	7.6	-23.6	stat. insignif.	
18	26Jan-07Feb	6.2	6.7	9.1	8.2	-10.0	stat. insignif.	
19	08Feb-21Feb	4.9	6.4	8.1	82.1	65.9	stat. signif.	
20	22Feb-05Mar	8.3	5.9	10.1	27.2	7.0	stat. signif.	
21	06Mar-19Mar	6.4	4.6	7.9	63.0	47.3	stat. signif.	
22	04Apr-12Apr	10.7	6.4	12.4	53.7	28.8	stat. signif.	
23	13Apr-23Apr	6.1	5.8	8.5	64.8	47.9	stat. signif.	
24	24Apr-08May	4.7	8.0	9.3	17.2	-1.5	stat. insignif.	
25	09May-19May	9.0	11.8	14.8	6.6	-23.1	stat. insignif.	
26	20May-31May	19.2	10.1	21.7	20.6	-22.7	stat. insignif.	
27	01Jun-14Jun	13.3	12.1	18.0	54.7	18.8	stat. signif.	
28	15Jun-27Jun	36.4	26.6	45.0	66.9	-23.1	stat. insignif.	

Table E12 Summary of statistical significance test on the difference between the parent system mean influent and mean effluent filtered inorganic dissolved solids (IDS) for the various wastewater batches.

Sew. Batch No.	Date of Test	FILTERED INFLUENT AND EFFLUENT IDS						Conclusion
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance		
1	30Mar-12Apr	12.1	11.5	16.7	1.6	-31.7	stat. insignif.	
2	13Apr-25Apr	10.5	14.8	18.1	4.8	-31.5	stat. insignif.	
3	26Apr-14May	15.4	11.3	19.2	5.2	-33.2	stat. insignif.	
4	20Jun-27Jun	8.2	10.8	13.6	29.2	2.0	stat. signif.	
5	29Jun-20Jul	8.7	8.0	11.8	2.0	-21.7	stat. insignif.	
6	21Jul-3Aug	35.6	24.5	43.2	23.0	-63.4	stat. insignif.	
7	4Aug-22Aug	26.1	18.0	31.7	28.0	-35.4	stat. insignif.	
8	23Aug-06Sept.	28.0	17.4	33.0	10.2	-55.8	stat. insignif.	
9	07Sept-20Sept	22.7	14.7	27.0	10.2	-43.8	stat. insignif.	
10	21Spt-02Oct.	30.9	21.9	37.9	34.5	-41.2	stat. insignif.	
11	03Oct-16Oct	27.5	17.2	32.4	30.3	-34.6	stat. insignif.	
12	17Oct-31Oct	23.5	15.9	28.4	41.4	-15.3	stat. insignif.	
13	01Nov-17Nov	13.3	9.3	16.3	16.5	-16.0	stat. insignif.	
14	18Nov-04Dec.	7.9	5.3	9.5	39.6	20.5	stat. signif.	
15	05Dec-14Dec	10.5	8.2	13.3	15.3	-11.4	stat. insignif.	
16	08Jan-11Jan	14.5	9.4	17.3	9.0	-25.5	stat. insignif.	
17	12Jan-25Jan	9.0	3.2	9.5	7.5	-11.5	stat. insignif.	
18	26Jan-07Feb	5.1	4.6	6.8	6.6	-7.1	stat. insignif.	
19	08Feb-21Feb	3.5	3.1	4.7	5.7	-3.6	stat. insignif.	
20	22Feb-05Mar	5.0	3.9	6.4	10.5	-2.2	stat. insignif.	
21	06Mar-19Mar	3.7	2.5	4.5	10.4	1.5	stat. signif.	
22	04Apr-12Apr	8.0	5.2	9.5	21.5	2.5	stat. signif.	
23	13Apr-23Apr	8.0	4.4	9.1	10.4	-7.7	stat. insignif.	
24	24Apr-08May	5.5	3.8	6.7	32.5	19.0	stat. signif.	
25	09May-19May	13.5	8.5	15.9	47.0	15.1	stat. signif.	
26	20May-31May	11.8	11.4	16.4	29.5	-3.3	stat. insignif.	
27	01Jun-14Jun	14.0	7.7	16.0	16.6	-15.4	stat. insignif.	
28	15Jun-27Jun	27.4	16.0	31.7	14.7	-48.7	stat. insignif.	

Table E13 Summary of statistical significance test on the difference between the parent system mean influent and mean effluent filtered volatile dissolved solids (VDS) for the various wastewater batches.

Sew. Batch No.	Date of Test	FILTERED INFLUENT AND EFFLUENT VDS						
		SDmean Influent	SDmean Effluent	SD difference	Mean difference	Test of significance	Conclusion	
1	30Mar-12Apr	13.1	18.5	22.6	22.9	-22.4	stat. insignif.	
2	13Apr-25Apr	26.9	26.6	37.8	53.4	-22.2	stat. insignif.	
3	26Apr-14May	25.1	15.3	29.4	46.4	-12.4	stat. insignif.	
4	20Jun-27Jun	16.8	13.9	21.8	68.5	25.0	stat. signif.	
5	29Jun-20Jul	12.1	13.8	18.3	9.6	-27.1	stat. insignif.	
6	21Jul-3Aug	20.0	13.4	24.1	29.7	-18.5	stat. insignif.	
7	4Aug-22Aug	8.8	7.6	11.6	52.5	29.3	stat. signif.	
8	23Aug-06Sept.	14.1	11.7	18.4	20.6	-16.1	stat. insignif.	
9	07Sept-20Sept	9.7	14.0	17.0	25.3	-8.8	stat. insignif.	
10	21Sept-02Oct.	11.4	13.8	17.9	2.3	-33.5	stat. insignif.	
11	03Oct-16Oct	15.8	13.4	20.7	7.5	-34.0	stat. insignif.	
12	17Oct-31Oct	18.3	17.1	25.0	11.3	-38.7	stat. insignif.	
13	01Nov-17Nov	25.5	26.1	36.5	7.9	-65.1	stat. insignif.	
14	18Nov-04Dec.	7.5	6.1	9.7	35.8	16.3	stat. signif.	
15	05Dec-14Dec	2.7	7.7	8.2	15.7	-0.6	stat. insignif.	
16	08Jan-11Jan	4.7	9.7	10.7	29.3	7.8	stat. signif.	
17	12Jan-25Jan	6.1	8.3	10.3	16.8	-3.8	stat. insignif.	
18	26Jan-07Feb	6.2	5.5	8.3	22.6	6.1	stat. signif.	
19	08Feb-21Feb	4.8	4.8	6.8	86.8	73.2	stat. signif.	
20	22Feb-05Mar	6.2	5.4	8.2	37.5	21.1	stat. signif.	
21	06Mar-19Mar	6.1	4.4	7.5	35.4	20.4	stat. signif.	
22	04Apr-12Apr	5.3	4.4	6.9	50.1	36.3	stat. signif.	
23	13Apr-23Apr	4.6	2.9	5.4	49.6	38.8	stat. signif.	
24	24Apr-08May	3.7	4.7	6.0	11.5	-0.5	stat. insignif.	
25	09May-19May	11.5	5.7	12.9	22.6	-3.2	stat. insignif.	
26	20May-31May	13.9	7.9	16.0	7.3	-24.6	stat. insignif.	
27	01Jun-14Jun	7.7	6.4	10.0	33.5	13.6	stat. signif.	
28	15Jun-27Jun	15.5	14.4	21.2	51.1	8.7	stat. signif.	

