THE COD/VSS RATIO OF THE VOLATILE SOLIDS IN THE ACTIVATED SLUDGE PROCESS

by

W. D. Schroeter (B.Sc., Cape Town)

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DECLARATION

I, Wolfgang D. Schroeter, hereby declare that this thesis is my own work and that it has not been submitted for a degree at another university.

signature removed

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SYNOPSIS

In the kinetic analysis of the activated sludge process behaviour, a vital requirement is that a COD balance near unity is obtained. The COD/VSS ratio of the mixed liquor forms an integral part of such a balance by reason that the practice has arisen, prompted by convenience, to determine the VSS rather than the COD of the mixed liquor and to convert the VSS to COD by accepting a COD/VSS ratio. Evidently good experimental COD recoveries will depend on the correctness of the COD/VSS ratio.

Dold, Ekama and Marais (1980), in an analysis on the dynamic behaviour of the aerobic activated sludge process, observed that no COD balances on their experimental data near unity were possible for a 2,5 day and 20 day sludge age at 12°C. They hypothesized that under the conditions above a possible cause for the lack in COD balances was that the COD/VSS ratio was higher than that 'normal' at the longer sludge ages at 20°C *i.e.* COD/VSS = 1,48 $\mathrm{mgCOD.mgVSS^{-1}}$; then, in a mass balance if the lower value was used the apparent loss of COD recovery would be observed. Such a high COD/VSS ratio could very likely arise from an accumulation of solidified fats (derived from the influent) at the lower temperature *i.e.* 12°C. Upon solidification, these fats could be relatively resistant to biodegradation thereby leading to a substantial accumulation on the sludge mass. As the average COD/VSS ratio of fats is of the order of 2,6 $\mathrm{mgCOD.mgVSS^{-1}}$ it is clear that, upon accumulation, these could increase the COD/VSS ratio. At 20°C, it was hypothesized that the fats, most probably, are in an emulsified form and therefore amenable to biodegradation; a substantial accumulation of fats is therefore not expected at this temperature. To test the above hypothesis, aerobic activated sludge units at a 20, 8 and 3 day sludge age at 12°C and 20°C treating a raw domestic effluent were operated and tested. These experiments indicated a slight increase in the COD/VSS ratio at a 3 day sludge age at 12°C (relative to the other units) but insufficient to explain the discrepancies in the COD balances observed by Dold *et al.* (1980).

During the above experiments it was established that a significant error (up to 30 percent) in the COD balance can occur due to oxygen transfer from the atmosphere into the liquid mass giving rise to an under estimation of the 'true' oxygen consumption rate of the mixed liquor. By sealing the liquid surface from contact with the atmosphere during an oxygen consumption rate measurement, (particularly at the short sludge ages and low temperatures) good COD recoveries were achieved. It was concluded that the most likely cause for the discrepancies between the observed and predicted response in Dold *et al*'s (1980) experiments was due to this error in the oxygen consumption rate measurement; this was verified by repeating the experiments under the same conditions, after Dold *et al.* (1980), and obtaining COD mass balances of close to 100 percent.

To enquire whether fats could be a significant factor in raising the COD/VSS ratio value above that of 'normal' activated sludge (treating a 'normal' municipal effluent) at the short sludge ages, a set of experiments was inaugurated at a 3 day sludge age at both 12°C and 20°C - two units treating only raw domestic sewage and the other two treating raw domestic sewage spiked with up to 33 percent of influent COD by mass with oleic acid. It was observed that the COD/VSS ratio for the units treating artificially added fat (in the form of oleic acid) increased above the ratio in the units treating only raw domestic sewage thereby indicating that high concentrations of fat can increase the COD/VSS ratio under these conditions. However, with the 'normal' fat concentrations expected in a municipal effluent, the effect on the COD/VSS ratio should be negligible for sludge ages of 3 days and longer between temperatures of 12°C and 20°C; a COD/VSS ratio of 1,48 mgCOD.mgVSS^{-1}, as proposed by Ekama and Marais (1978) appears to be acceptable for the design of activated sludge processes at 3 days sludge age or longer and temperatures ranging from 12°C to 20°C.

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B.1 ENERGY MASS BALANCES - THEORY

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
b'_h	Death rate constant for active sludge (d^{-1}).
b_n	Death rate constant for nitrifiers (d^{-1}).
COD	Chemical Oxygen Demand, a measure of the carbonaceous material concentration ($mgCOD.\ell^{-1}$).
f'	Inert residue in the death regeneration approach.
f_{bs}	Ratio of easily biodegradable (soluble) to total biodegradable material in the influent ($mgCOD.mgCOD^{-1}$).
f_{ma}	Maximum fraction of substrate that can be stored on the active sites. (Maximum ratio of stored material/active sludge) ($mgVSS.mgVSS^{-1}$).
f_n	Mass fraction of nitrogen in the organic sludge ($mgN.mgVSS^{-1}$).
f_{na}	Ratio of ammonia to total TKN in the influent ($mgN.mgN^{-1}$).
f_{ns}	Ratio of stored organic nitrogen to stored slowly biodegradable organic material ($mgN.mgCOD^{-1}$).
f_{oa}	Organic nitrogen fraction of the nitrogen released by active heterotrophic organism death ($mgN.mgN^{-1}$).
f_{os}	Organic nitrogen fraction of the nitrogen required for heterotrophic cell synthesis ($mgN.mgN^{-1}$).
f_{sn}	Free and saline ammonia fraction in the influent TKN ($mgN.mgN^{-1}$).
f_{un}	Unbiodegradable soluble TKN fraction in the influent ($mgN.mgN^{-1}$)
f_{up}	Unbiodegradable particulate influent COD fraction ($mgVSS.mgCOD^{-1}$)
f_{us}	Unbiodegradable soluble influent COD fraction ($mgCOD.mgCOD^{-1}$).
K_a	Particulate substrate adsorption rate constant ($\ell.mgVSS^{-1}.d^{-1}$).
K_{mp}	Maximum specific substrate utilization rate constant for stored slowly biodegradable COD in an aerobic environment ($mgCOD.mgVSS^{-1}.d^{-1}$).

Symbol	Description
K_{ms}	Maximum specific substrate utilization rate constant for easily biodegradable COD (mgCOD.mgVSS^{-1}.d^{-1}).
K_n	Half saturation value for nitrification (mgN.ℓ^{-1}).
K_{ns}	Substrate utilization rate constant for nitrification (mgN.mgX_n^{-1}-d^{-1}).
K_r	Conversion rate of organic nitrogen to free and saline ammonia (ℓ.mgVSS^{-1}.d^{-1}).
K_{sp}	Half saturation coefficient for heterotrophic cell synthesis from slowly biodegradable COD (mgCOD.mgVSS^{-1}).
K_{ss}	Half saturation coefficient for heterotrophic cell synthesis from easily biodegradable COD (mgCOD.ℓ^{-1}).
MO	Mass of oxygen required daily (mgO.d^{-1}) subscript c refers to carbonaceous material degradation subscript n refers to nitrification.
MS	Mass of COD input daily (mgCOD.d^{-1}) subscript b refers to biodegradable material subscript t refers to total COD.
MX	Mass of sludge in an activated sludge process (mgVSS) subscript a refers to active organism mass subscript e refers to endogenous residue subscript i refers to inert material subscript n refers to nitrifiers subscript v refers to volatile solids.
N	General parameter for nitrogen concentration (mgN.ℓ^{-1}) subscript a refers to ammonia concentration subscript n refers to nitrate concentration subscript ne refers to effluent nitrate concentration subscript o refers to organic nitrogen concentration subscript pi refers to particulate unbiodegradable material concentration in the influent subscript s refers to influent TKN concentration required for synthesis subscript te refers to total soluble effluent nitrogen concentration

Symbol	Description
	subscript ti refers to influent TKN concentration
	subscript u refers to unbiodegradable soluble nitrogen concentration.
O	General parameter for oxygen consumption rate (mgO.ℓ^{-1}.hr^{-1})
	subscript c refers to oxidation of carbonaceous material
	subscript n refers to nitrification
	subscript t refers to total oxygen consumption rate
P	COD equivalence of organic sludge: COD/VSS ratio (mgCOD.mgVSS^{-1}).
Q	General parameter for flow rate (ℓ.d^{-1})
	subscript e refers to effluent flow
	subscript i refers to influent flow.
q	Sludge waste flow (ℓ.d^{-1}).
R	General parameter for retention time (d)
	subscript h refers to hydraulic retention time
	subscript s refers to solids retention time (sludge age).
S	General parameter for COD concentration (mgCOD.ℓ^{-1})
	subscript b refers to total biodegradable material
	subscript bp refers to biodegradable particulate material
	subscript bs refers to biodegradable soluble material
	subscript t refers to total carbonaceous material
	subscript u refers to unbiodegradable soluble material.
T	Temperature (°C).
TKN	Total Kjeldahl Nitrogen concentration (mgN.ℓ^{-1}).
V	General parameter for volume (ℓ)
	subscript t refers to total process volume
	subscript aer refers to aerobic reactor volume.
VSS	Volatile suspended solids concentration (mgVSS.ℓ^{-1}).
X	General parameter for sludge concentration (mgVSS.ℓ^{-1})
	subscript a refers to active organisms
	subscript e refers to endogenous residue
	subscript i refers to inert material

Symbol	Description
	subscript ii refers to inert material in influent subscript n refers to nitrifiers subscript s refers to stored material subscript v refers to total volatile solids.
Y_h	Yield coefficient for active heterotrophic sludge ($mgVSS.mgCOD^{-1}$).
Y_n	Yield coefficient for nitrifiers ($mgVSS.mgN^{-1}$).
μ_n	Specific growth rate of nitrifiers (d^{-1}).
μ_{nm}	Maximum specific growth rate of nitrifiers (d^{-1}).

Additional Subscripts

e	refers to effluent concentration
T or 20	refers to temperature (°C)
i	refers to influent concentration
p or 7,2	refers to pH of mixed liquor

CHAPTER ONE

INTRODUCTION

In the analysis of activated sludge process behaviour a vital requirement to forming any valid conclusion is that a COD mass balance is obtained. Under constant daily cyclic loading conditions the total mass of COD in the influent per day must equal the mass of COD in the effluent per day plus the mass of COD in the waste flow per day and the mass of oxygen utilized per day.

In performing a balance the practice has arisen, prompted by practical convenience, to determine the VSS rather than the COD of the wasted sludge and to convert the VSS to COD by accepting a COD/VSS ratio. Evidently the accuracy of the COD balance will depend on the correctness of the COD/VSS ratio.

Estimates of the COD/VSS ratio have been developed both theoretically and experimentally. Theoretically the estimates have been based on hypothesizing a stoichiometric chemical composition for the microorganism protoplasm. Depending on the composition hypothesized a range of COD/VSS ratio values have been proposed, from 1,07 to 1,48. Experimentally numerous COD/VSS ratios have been determined on the MLVSS of full and laboratory scale activated sludge plants. These have shown a similar wide range of values, from 1,07 to 1,77.

With regard to the experimental COD/VSS ratio a number of hypotheses have been advanced for the different values obtained, of which two appear to merit a more detailed consideration. The first hypothesis is as follows: The sludge mass consists of principally three volatile fractions (1) active organism, (2) endogenous residue and (3) inert material derived from the unbiodegradable particulate organic material in the influent. The chemical composition of each of these fractions very likely differs from others. For a plant operating at say a long or a short sludge age the relative magnitudes of the three fractions differ substantially and the COD/VSS ratio should in consequence also differ. However, using the same influent and operating plants over a range of sludge ages from 3 to 20 days at 20°C have indicated that there is virtually no difference in the COD/VSS ratios. This hypothesis therefore does not appear to explain the different COD/VSS ratios observed satisfactorily.

The second hypothesis is that there are fractions of organic material in the influent that give rise to the observed COD/VSS ratio. This explanation finds support from the following observation. The COD/VSS ratio of the MLVSS derived from an influent from one source may differ significantly from that from another source. Moreover even for the same influent source and the same sludge age at a low temperature the COD/VSS ratio may differ from that at a higher temperature. Such behavioural patterns could be explained via the physical behaviour of the sludge treating influents with certain characteristics: In the general activated sludge model the biodegradable influent COD is divided into two categories (1) a rapidly biodegradable COD and (2) a slowly biodegradable particulate COD. The particulate COD requires adsorption and storage on the active organism mass prior to undergoing extracellular enzymatic breakdown into smaller molecular units in order to pass through the cytoplasmic membrane of the organism. At short sludge ages of 3 days or less the mass of stored COD per unit mass of organisms is predicted to be quite high for reason that the rate of enzymatic breakdown is relatively slow. If the adsorbed material has a COD/VSS ratio greater than that of the organism and inert mass then the COD/VSS ratio of the MLVSS should be affected at the shorter sludge ages. However, earlier experimental evidence has shown that at 20°C using the same influent the difference in the COD/VSS ratio between long and short sludge ages was hardly detectable. In contrast, at 12°C changes in the COD/VSS ratio between the long and short sludge ages have been noted on a number of occasions. In terms of the stored COD hypothesis as presented in the general model, if the stored material has a high COD/VSS ratio then the behavioural pattern would be explained if the stored material changes its physical nature between 20°C and 12°C, for example, if the material is a liquid or an emulsion at the higher temperature and solid at the lower temperature. A material that seems to have these characteristics is a fat, for example, some fats at 20°C are in an emulsified form and hence more readily attacked by enzymes even if stored; at 12°C, should some of the fats solidify the fatty material can be degraded only on the exposed surface and the accumulation of adsorbed particulate fat can be substantial. Furthermore the COD/VSS ratio of fats is of the order of 2,6 and therefore a large accumulation of fat on the sludge mass could be expected to have a significant effect on the COD/VSS ratio of the mixed liquor.

To resolve this uncertainty regarding the COD/VSS ratio of the mixed liquor, an investigation was proposed to establish the causes for the variability of the COD/VSS ratio. As a first objective, the effect of varying operating conditions such as sludge age and temperature on the COD/VSS ratio for activated sludge treating the same domestic wastewater, had to be established. And, as a second objective, the effect of long-chain fatty acids in the influent on the COD/VSS ratio had to be checked.

A third objective was to determine the causes for poor COD mass balances achieved in earlier investigations at 12°C by Dold, Ekama and Marais (1980). Here it was hypothesized that a possible cause was unwanted oxygen transfer from the atmosphere into the liquid during an oxygen consumption rate test on the aerobic reactors, particularly at the lower temperatures. In the event that the cause for the poor balances could be identified and suppressed it was proposed to repeat earlier experiments of Dold *et al*. (1980) on the dynamic response observed on 24-hour square wave cyclically loaded single reactor aerobic activated sludge units for 2,5 and 20 day sludge ages at 12°C and thereby check the predictive power of the general theory.

CHAPTER TWO

LITERATURE REVIEW

2.1 OILS AND GREASE IN DOMESTIC WASTEWATERS

The significance of 'oils and greases' in wastewaters has been a subject of wide concern to sanitary engineers. Greases are known to create operational problems in the efficient operation of waste collection and treatment facilities. They can accumulate in sewers causing clogging of wastewater conduits, interfere in biological treatment processes, for example by coating the sludge particles thereby inhibiting oxygen transfer, and also are responsible for unsightly scum formations in digesters and at outfalls. Because grease is insoluble in water and often in a solid form it is relatively resistant to biodegradation (in contrast to carbohydrates and proteins) and a significant fraction may pass through a treatment plant [Loehr and Higgins (1965)].

Notation

In the context of wastewater terminology 'oils and greases' in wastewaters have been defined as synonomous to 'lipids' [Standard Methods (1971)]. The general biochemical term 'lipids' is a collective term used to describe a group of substances which are characterised by their solubility in organic solvents such as ether, benzene, chloroform and the like. These substances are not necessarily related chemically but are grouped together on the basis of their solubility [Awapara (1968)].

Chemical composition

Neutral lipids are actual or potential esters of fatty acids; they have been classified as follows: (1) *simple lipids* which are fatty acid esters with glycerol, (2) *compound lipids* which are fatty acid esters with alcohol plus other radicals, and (3) *derived lipids* which are hydrolytic derivations of the first two groups but still showing the characteristics of a lipid. There are several other classes of lipids known but these are of a limited quantitative significance in wastewaters and will therefore not be considered here [Hrudey (1981)].

The fatty acids formed from oils and greases are generally of a long straight chain configuration and are either saturated or unsaturated. A saturated fatty acid contains only single bonds between adjacent carbon atoms; the most stable configuration is thought to be a zig-zag line formation. An unsaturated fatty acid will contain either double or triple bonds between some carbon atoms; the general configuration when double bonds are present seems to be a *cis* (stepped) formation [Awapara (1968)].

The solubility of fatty acids in water is dictated by the length of the hydrocarbon chain (often called the tail) and the presence of a carboxyl group (called the head). The carboxyl group is hydrophilic (water-liking) and is therefore responsible for the solubility of the fatty acid; as the hydrocarbon chain length increases the solubility of the fatty acid decreases [Awapara (1968)].

It is interesting to note that the melting point of an unsaturated fatty acid is lower than that of the corresponding saturated fatty acid, for example oleic acid (with one double bond) is a liquid at room temperature (say 20°C) whereas its saturated analogue, stearic acid, is a solid [Awapara (1968)]. A list of the most commonly found long-chain fatty acids in wastewaters together with their formula and melting points is shown in Table 2.1.

Sources of oils and grease

Loehr and Kukar (1965) and Loehr and de Navarra (1969) discussed the main sources of oils and greases in wastewaters. These include faeces, kitchen wastes and industrial wastes such as those from meat packing houses, dairies and oil refineries. Faeces are estimated to contain from 4 to 23 percent grease consisting of approximately 38 percent total fatty acids, 33 percent total fatty acid esters and 29 percent neutral fat. Kitchen wastes contribute unused fats from foods and the soaps resulting from a reaction with predominant cations in a wastewater.

Table 2.1: Long-chain fatty acids found in wastewaters [taken from Awapara (1968)].

Fatty acid	Formula	Melting point (°C)
Lauric	$CH_3(CH_2)_{10}CO_2H$	43,6
Myristic	$CH_3(CH_2)_{12}CO_2H$	58,0
Palmitic	$CH_3(CH_2)_{14}CO_2H$	62,9
Stearic	$CH_3(CH_2)_{16}CO_2H$	69,9
Oleic	$CH_3(CH_2)_7CH{=}CH(CH_2)_7CO_2H$	13,0
Linoleic	$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7CO_2H$	-5,0

Concentrations in sewage

Several investigators such as Mahlie (1940), Viswanathan, Beera Bai and Pillai (1962), Hunter and Heukelekian (1965), Loehr and Kukar (1965), Loehr and de Navarra (1969), Farrington and Quinn (1973) and Lordi and Lue-Hing (1976) have reported that a major fraction of the organic content of domestic wastewaters can be attributed to oils and greases. Mahlie (1940) reported concentrations of grease in wastewaters generally varying from 16 $mg.\ell^{-1}$ to about 1480 $mg.\ell^{-1}$ with a range of 40 to 100 $mg.\ell^{-1}$ for domestic wastewaters and the higher values occuring from laundry, wool-scouring and meat packing wastes. Bowerman and Dryden (1962) reported an average grease concentration of 60 $mg.\ell^{-1}$ whereas Loehr and de Navarra (1969) measured an average grease concentration of about 147 $mg.\ell^{-1}$ in a domestic wastewater.

The Cape Town City Engineer's Department provided experimental data on some typical total fat concentrations in the main outfall sewer as measured over a 24-hour cycle (on 2-hour grab samples) at the Mitchell's Plain Sewage Works (the collection site for wastewater used in this investigation). A total fat analysis on the raw domestic sewage shows an average total fat concentration of about 450 $mg.\ell^{-1}$ for this particular sewage. Figures 2.1 and 2.2 reflect

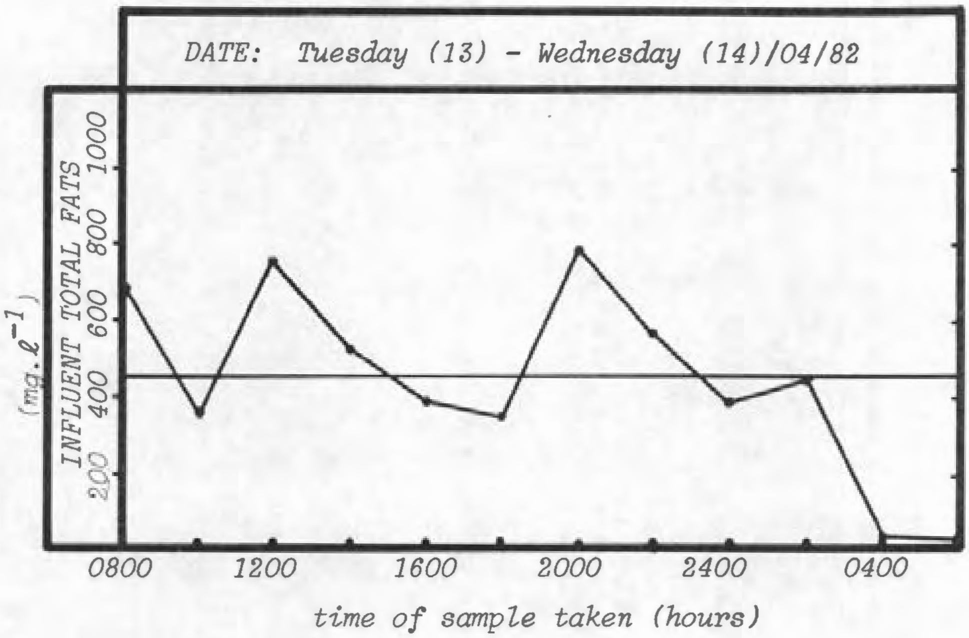


Figure 2.1: Typical fat concentrations measured during weekdays for raw domestic sewage at the Mitchell's Plain Sewage Works (from City Engineer, C.T.)

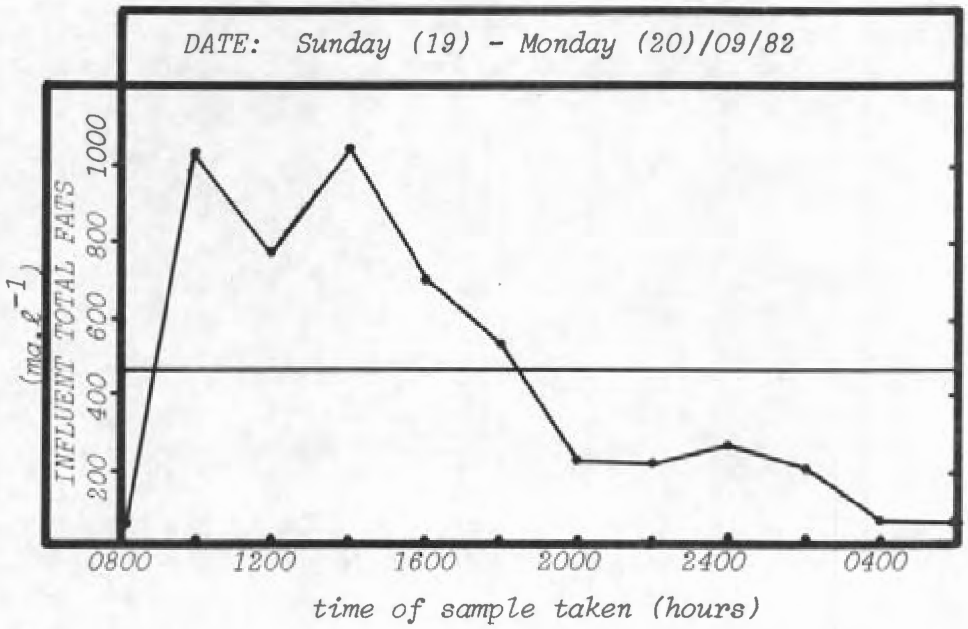


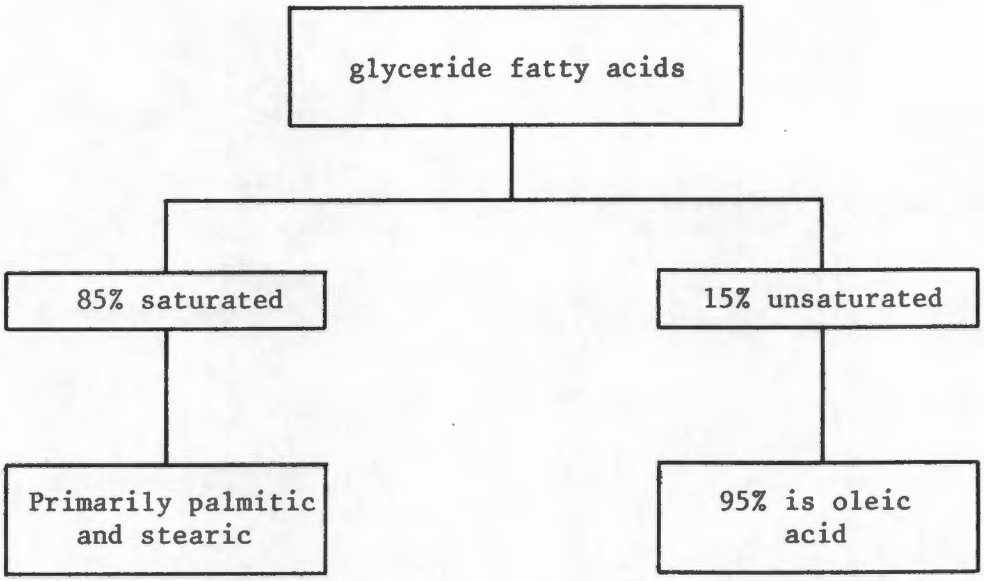
Figure 2.2: Typical fat concentrations measured during weekends for raw domestic sewage at the Mitchell's Plain Sewage Works (from City Engineer, C.T.)

typical 24-hour variations for an average weekday and weekend respectively. The data indicates inordinately high concentrations of fats and oils, to a degree that probably makes this sewage atypical and probably arises from the purely domestic nature of this influent. The very high concentrations on Sunday mornings reflect the working habits of the residents. On weekdays, the working members are employed outside the drainage area of the sewer system; Sundays are spent at home. This is supported by the influent COD measurements; on Saturdays and Sundays the average COD concentration is approximately twice that on weekdays.

Hunter and Heukelekian (1965) presented a summary of data collected during various studies; some important conclusions that were drawn from these studies are: (1) about 23 to 52 percent of the organic matter in domestic wastes can be attributed to grease, (2) about 56 to 67 percent of grease present in a domestic sewage is in a suspended form and must therefore be removed by biological action in a normal sewage treatment plant, (3) from 34 to 80 percent of particulate grease is in the form of glyceride fatty acids and (4) that the saturated fatty acids constitute over 85 percent of the total fatty acids present.

With regard to (3) and (4) above the principal constituents of glycerides and soaps (or alkali salts of fatty acids) are the long-chain saturated fatty acids - lauric, myristic, palmitic and stearic acids - and the long-chain unsaturated fatty acids - oleic and linoleic acids. Viswanathan *et al.* (1962), Heukelekian and Mueller (1963), Hunter and Heukelekian (1965) and Loehr and Roth (1968) reported that the saturated fatty acids in domestic sewage and also sewage sludges are primarily palmitic and stearic acids with lesser amounts of myristic and lauric acids while oleic acid accounts for more than 95 percent of the unsaturated fatty acids present.

To summarise, the glyceride fatty acids in wastewaters can be broken down into the following percentage fractions:



Biodegradability

Several investigators reported studies on the biodegradability of lipids, amongst them Gaffney and Heukelekian (1958), Loehr and Roth (1968), Malaney and Gerhold (1969), Kramer (1971) and Novak and Kraus (1973). Gaffney and Heukelekian (1958) studied the aerobic metabolism of the lower fatty acids and observed significant lag periods in the oxygen consumption rate at high substrate concentrations; they noted that seed adaptation reduced the lag periods in the oxygen consumption rate and suggested that these lag periods may be due to a lack of appropriate enzyme systems which can metabolize the fatty acids.

Loehr and Roth (1968) used activated sludge from a full scale plant to investigate the degradation of sodium and calcium salts of various fatty acids. Using the fatty acid salts as the only carbon source they measured the oxygen consumption rate of the microorganisms in a Warburg apparatus. From this study they drew the following conclusions: (1) the sodium salts were metabolized at a faster rate than the calcium salts, (2) the shorter chain fatty acids were metabolized faster than the long-chain ones and (3) the unsaturated fatty acids were more biodegradable than the saturated fatty acids. They attributed these relative rates of metabolism to the increased water solubilities of sodium salts, short-chain and unsaturated fatty acids. Using various concentrations of the same fatty acid salts they also showed that these compounds could be metabolized at relatively high concentrations.

Malaney and Gerhold (1969) studied the biodegradation of a wide range of aliphatic compounds by activated sludge. The conclusions drawn from their study generally coincided with those by Loehr and Roth (1968). Novak and Kraus (1973) conducted experiments very similar to Loehr and Roth (1968) and Malaney and Gerhold (1969); but in addition measured substrate degradation rates. They concluded that the substrate degradation rates for the long-chained fatty acids to be an order of magnitude less than for other biodegradable substrates as reported by Lawrence and McCarty (1970); the relative degradation rates for the unsaturated long-chain fatty acids were all essentially the same whereas the degradation rates for the saturated long-chain fatty acids seemed to depend on their solubility in water.

Response to oils and grease

Concern over the response of activated sludge to oils and grease in wastewater has led several investigators [Loehr and Kukar (1964), Loehr and Higgins (1965), Loehr and de Navarra (1969), McCarty, Hahn, Dermoth and Weaver (1972), Anderson, Benson, Loften and Satchell (1973), Farrington and Quinn (1973), Mulligan and Sheridan (1975), Lordi and Lue-Hing (1976), Young (1979) and Hrudey (1981, 1982)] to evaluate activated sludge processes treating lipid containing wastes at full and laboratory scale. Generally all these studies have demonstrated the capability of activated sludge to treat high concentrations of emulsified lipids and provide removal efficiencies in excess of 80 percent.* In particular, Loehr and de Navarra (1969) observed, from a series of studies, average grease removal efficiencies of 45 percent (with respect to the primary clarifier influent) by primary treatment, 74 percent (with respect to the primary clarifier effluent) by secondary treatment and 84 percent (with respect to the primary

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*The authors did not define what they meant by removal efficiency.

clarifier influent) for overall plant treatment. The authors above generally did not supply details on the activated sludge process design parameters but as the data was collected in the United States of America, the sludge ages are expected to be short (less than 10 days). With regard to sludge ages normal in South Africa (longer than 10 days), the oxidation of fats should be more complete.

Failure of activated sludge processes treating industrial wastes under lipid overloading conditions were reported by Hydroscience (1971) and Banerji, Robson and Hyatt (1974). A dramatic increase in effluent turbidity was observed; these observations were explained on the basis that lipids possess a specific gravity of less than 1,0, consequently high concentrations of lipids enmeshed in the sludge floc could reduce the specific gravity of the floc to such an extent that the settleability of the sludge was impaired. Another hypothesis suggested that the sludge floc could be coated with hydrophobic (water dis-liking) material and thereby limit the oxygen transfer efficiency.

In contrast, studies conducted by Hrudey (1981, 1982) on meat packing plant wastes demonstrated that (1) more than 80 percent of available lipids (up to 320 $mg.\ell^{-1}$) were adsorbed onto the sludge floc within 20 minutes, (2) the settling characteristics of the sludge improved as the lipid concentration in the mixed liquor solids increased (up to about 500 $mg.\ell^{-1}$) and (3) the mixed liquor oxygen consumption rate was not significantly affected by the lipid loading. Hrudey (1982) concluded that as the lipid concentrations encountered in industrial wastes are likely to be above those normally encountered in domestic wastewaters, it seems that the biological behaviour of an activated sludge process treating domestic wastes will not be adversely affected by the presence of oils and greases.

To summarize, some of the more important conclusions drawn from the various studies reported above are as follows:

(1) a major fraction (from 23 to 52 percent) or organic matter in domestic wastewaters can be attributed to grease

(2) about 56 to 67 percent of grease present in a domestic sewage

is in a non-settleable form and therefore must be removed biologically in a normal treatment plant

(3) about 34 to 80 percent of particulate grease is constituted of glyceride fatty acids

(4) the major fraction (more than 85 percent) of glyceride fatty acids is constituted of long-chain fatty acids such as palmitic, stearic and oleic acid

5) oils and greases, while biodegradable, are less amenable to enzymatic breakdown than compounds such as carbohydrates and proteins and

(6) in general, activated sludge can accept high concentrations of emulsified lipids and provide removal efficiencies in excess of 80 percent for a normal domestic wastewater.

2.1.1 Selection of fat for laboratory study

In proposing an experimental investigation into the effect of long-chain fatty acids on the COD/VSS ratio it is necessary to select a fatty acid that is likely to show the effect of such substances on the COD/VSS ratio most readily.

Stoichiometrically, the long-chain fatty acids such as palmitic, stearic and oleic acid have a COD/VSS ratio of 2,88, 2,93 and 2,84 respectively. It is therefore clear that if these long-chain fatty acids constitute an appreciable fraction of the biodegradable particulate fraction in an influent they could have a significant effect on the COD/VSS ratio of the mixed liquor.

The most suitable long-chain fatty acid would appear to be oleic acid for the following reasons: (1) it is a common unsaturated long-chain fatty acid in sewage, (2) any effects on the COD/VSS ratio observed due to the addition of oleic acid to an influent can be expected to also hold true for the long-chain saturated fatty acids because oleic acid is more soluble in water and (3) oleic acid has a melting point of 13°C, therefore it would be in an emulsified form at 20°C and hence more prone to enzymatic breakdown; at 12°C however it will be in a solid state and therefore more resistant to biodegradation.

2.2 THE COD/VSS RATIO OF ACTIVATED SLUDGE

In 1952 Hoover and Porges postulated a stoichiometric formulation in microbial protoplasm treating dairy wastes in terms of its principal constituents as $C_5H_7NO_2$. Eckenfelder and Weston (1956) used this formulation to determine the Theoretical Oxygen Demand (TOD) to oxydize a unit mass of protoplasm to carbon dioxide, water and ammonia as follows:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3$$

Stoichiometrically, the TOD can be shown to be

$$TOD = 1{,}42.(\text{unit mass of } C_5H_7NO_2)$$

Assuming that the TOD is closely approximated by the Chemical Oxygen Demand (COD) and the microbial mass by the Volatile Settleable Solids (VSS) of the mixed liquor, they concluded that

$$COD/VSS = 1{,}42$$

Based on experimental results other empirical stoichiometric formulations have been proposed for microbial protoplasm by Sawyer (1956), Symons and McKinney (1958), Speece and McCarty (1964) and Burkhead and McKinney (1968). In particular, Burkhead and McKinney (1968) selected a series of pure and mixed substrates of carbohydrates, amino acids and short-chain fatty acids and showed that the microbial composition of activated sludge (1) varies with the nature of the substrate undergoing treatment and (2) depends on the food to microorganism ratio. The carbohydrate substrates yielded microbial protoplasm compositions of $C_5H_9NO_3$ and $C_5H_{11}NO_4$ while the non-carbohydrate substrates yielded compositions of $C_5H_7NO_2$ and $C_5H_9NO_3$; the substrate used to represent domestic sewage yielded a microbial protoplasm composition of $C_5H_{11}NO_4$. A summary of the various empirical formulations for microbial sludge with their corresponding theoretical COD/VSS ratios is shown in Table 2.2.

Several investigators, among them Burkhead and McKinney (1968), Rickert and Hunter (1972), Marsden and Giloi (1973) and Gujer and Jenkins (1975) experimentally determined the COD of the mixed liquor. Burkhead and McKinney (1968) measured values for the COD/VSS

Table 2.2: Theoretical COD/VSS ratios for various empirical formulations for microbial sludge.

Bacterial Formulation	COD/VSS Ratio	Reference
$C_5H_7NO_2$	1,42	Hoover and Porges (1952)
$C_7H_{10}NO_3$	1,48	Sawyer (1956)
$C_5H_8NO_2$	1,47	Symons and McKinney (1958)
$C_5H_9NO_3$	1,22	Speece and McCarty (1964)
$C_5H_7NO_2$	1,42	Burkhead and McKinney (1968)
$C_5H_9NO_3$	1,22	"
$C_5H_{11}NO_4$	1,07	"

ratio ranging from 1,07 to 1,77 for activated sludge. Rickert and Hunter (1972) reported an average COD/VSS ratio for domestic sewage of 1,73. Gujer and Jenkins (1975) measured COD/VSS ratios for aerobic activated sludge treating domestic sewage in a range of 1,38 to 1,50 with a measured mean of 1,44 at 20°C. Marsden and Giloi (1973) at the University of Cape Town measured COD/VSS ratio on a number of sludges. They found the average COD/VSS ratio for activated sludge treating various wastes to range from 1,43 to 1,48. From this investigation and simulations on the activated sludge process, Ekama and Marais (1978) concluded that a COD/VSS ratio of 1,48 mgCOD. mgVSS^{-1} for activated sludge treating domestic wastewaters gave rise to good COD balances. Table 2.3 shows a summary of the experimentally measured COD/VSS ratios reported by the various researchers.

2.3 IMPLICATIONS OF A VARIABLE COD/VSS RATIO ON THE GENERAL MODEL

If the hypothesis is correct that long-chain fatty acids in a wastewater increase the COD/VSS ratio of activated sludge substantially, the implication of variations in the COD/VSS ratio is such that the theoretical predictions of the general model will be affected if a wrong COD/VSS ratio is assumed. This observation is

Table 2.3: Experimentally measured COD/VSS ratios.

Microbial Sludge (treating)	COD/VSS Ratio		Reference
	range	mean	
carbohydrates	1,07-	-	Burkhead and McKinney (1968)
non-carbohydrates	-1,77	-	"
domestic sewage	1,45-2,03	1,73	Rickert and Hunter (1972)
activated sludge (Bellville)	1,01-1,75	1,43	Marsden and Giloi (1973)
laboratory CMAS units (R_s = 3-30 days)	1,14-2,16	1,48	"
aerobic digestor sludge	0,98-3,16	1,45	"
activated sludge (Athlone)	1,24-1,62	1,45	"
Wine distillery waste	0,75-1,88	1,43	"
Aerobic activated sludge	1,38-1,50	1,44	Gujer and Jenkins (1975)

supported by the following considerations of substrate utilization in the activated sludge process:

In the theory on the kinetics of the activated sludge process as presented in the general model by Dold *et al.* (1980), the influent COD is divided into four components: (1) an unbiodegradable soluble COD, (2) an unbiodegradable particulate COD, (3) an easily biodegradable soluble COD and (4) a slowly biodegradable particulate COD fraction. Of particular interest are the unbiodegradable particulate and the biodegradable particulate COD fractions as these are enmeshed and adsorbed on the sludge mass and therefore are likely to affect the COD/VSS ratio of the mixed liquor depending on their relative chemical compositions.

As a solidified form of long-chained fatty acids is more likely at 12°C than at 20°C, the adsorption and storage of these on the organism mass can be expected to increase the COD/VSS ratio more readily at the lower temperature because the solidified fatty acids will be relatively resistant to biodegradation. Hence, effectively, the unbiodegradable particulate COD fraction in the influent can be expected to increase at the lower temperature as well.

As a consequence of the increased unbiodegradable particulate COD fraction (assuming the soluble COD fractions to remain the same at 12°C and 20°C), the biodegradable particulate COD fraction in the influent must decrease. This implies that less active organism mass can be synthesized from the biodegradable COD available (assuming the yield constant and death rate constant to remain relatively constant at 12°C and 20°C). Consequently, the carbonaceous oxygen consumption rate decreases.

From the above considerations it is clear therefore that the 'correct' design of an activated sludge process largely depends on the correctness of the COD/VSS ratio. Nonetheless, the general model describing the dynamic response behaviour of the aerobic activated sludge process as presented by Dold *et al.* (1980) has proved to be a very useful mathematical tool in the evaluation of kinetic constants by simulation of experimental data.

CHAPTER THREE

EXPERIMENTAL APPARATUS AND METHODOLOGY

The experimental phase forms an integral part of and is the most important stage in any laboratory investigation. To ensure that consistent and reliable data is obtained at all times it is vital that attention be directed towards appropriate design of equipment and details of experimental control and methods of testing. If these are neglected the effort is largely wasted because the data will be unreliable and very likely inappropriate.

3.1 APPARATUS

A schematic layout of a laboratory-scale single-reactor aerobic completely mixed activated sludge unit is shown in Figure 3.1.

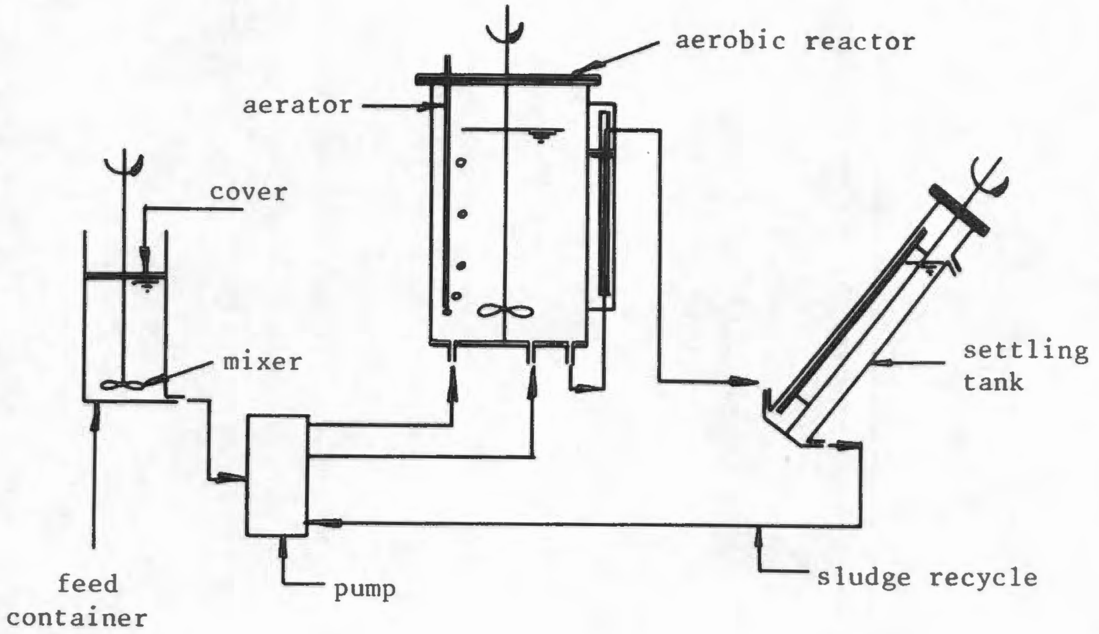


Figure 3.1: Schematic layout of laboratory-scale single-reactor activated sludge process.

3.1.1 Aeration Reactor

The reactors are of different sizes, depending on the volume of mixed liquor required and range from 3 to 15ℓ. All reactors are made of transparent perspex and of a cylindrical construction. A drawing of a reactor as used in this investigation is shown in Figure 3.2.

The mixed liquor inside the reactor is kept in suspension and completely mixed independent of aeration mixing by means of a paddle stirrer fixed on a stainless steel spindle driven by an electric motor at 28 rpm mounted on the lid of the reactor. The size of the paddle, the location of the stirrer on the driving spindle and the number of stirrers fixes the stirring energy. The intensity and its point of input must be controlled to induce sufficient mixing in the mass of the liquid yet prevent turbulence at the liquid surface as high surface renewal may cause oxygen transfer from the atmosphere into the liquid during an oxygen consumption rate test. Vertical baffle plates are mounted on the inside of the reactor walls to improve the mixing action and to prevent the formation of a vortex.

The mixed liquor is kept in an aerobic state by a porous stone aerator fixed to the end of a fine perspex tube connected to an air pump. For easy control of the dissolved oxygen concentration in the mixed liquor it must be possible to adjust the depth of the porous stone in the reactor by sliding the perspex tube up and down in the liquid mass through a close fitting hole in the reactor lid and/or to adjust the air flow.

The influent sewage enters the aeration reactor through an inlet located in the base of the reactor. The mixed liquor from the settling tank is recycled into the aeration reactor via a separate inlet also in the base. In short sludge age units, of 3 days or less, sludge wastage should be at short intervals throughout the day. To accomplish this a third outlet is provided in the base connected to a pump that is activated at set times (for details of operation, see later).

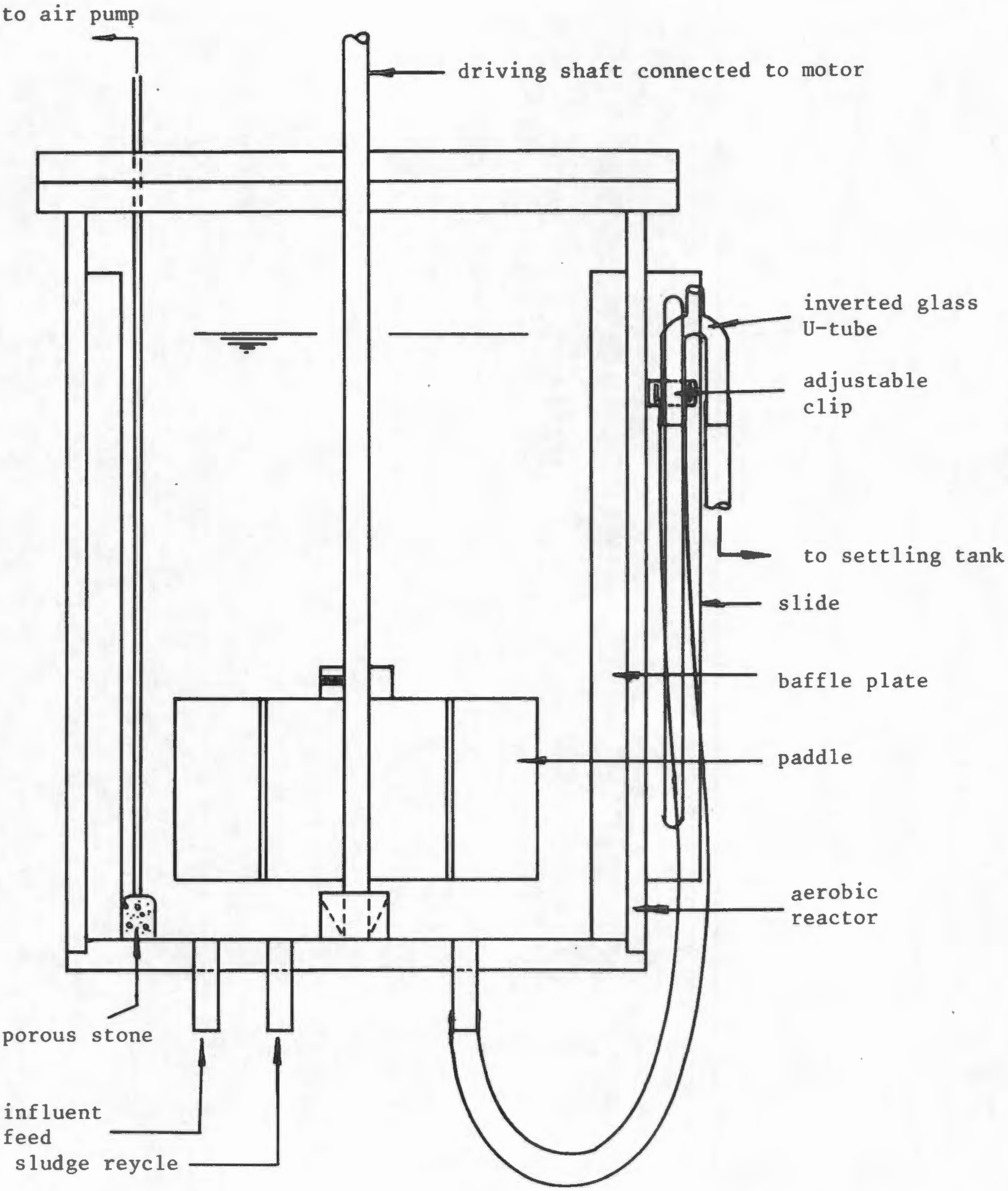


Figure 3.2: Typical experimental reactor.

The mixed liquor passes from the aerobic reactor via a soft plastic tube to the outlet which is an inverted U-tube with an air bleed. The U-tube is bolted to a slide fixed to the side of the reactor. The outlet level defines the volume of liquid in the reactor. The volume of liquid for any level of outlet is marked on the outside of the reactor.

3.1.2 Settling Tank

A drawing of the settling tank is shown in Figure 3.3. The settling tank is made of a 80 mm diameter perspex tube. A windscreen wiper and a bottom wiper are attached to a central stainless steel shaft which is driven by an electric motor at 1,3 rpm mounted on the lid of the settling tank. The electric motor is activated for a few seconds every one to two minutes by an electronic on-off timer; this causes the wiper blades to sweep the sides and bottom of the settler clean and prevents lumps of sludge to remain in the settler. These lumps, if allowed to develop, cause formation of nitrogen gas bubbles (due to denitrification) and eventually are dislodged and rise to the surface and discharged in the overflow. The mixed liquor from the aerobic reactor enters the settling tank at the bottom and the thickened sludge is withdrawn also at the bottom. The unit is set at an angle of about 60° to the horizontal as this is the angle for optimal separation of the settleable solids from the liquid.

3.1.3 Feed Container and Effluent Bucket

The feed container is made of a 450 mm diameter plastic pipe with a flat plastic bottom welded to it. The volume of the feed container is 20ℓ. The outlet is on the side at the bottom of the container. The contents of the container are gently mixed by a paddle stirrer fixed to a stainless steel rod and driven by an electric motor at 20 rpm. The motor is mounted on a steel bracket that spans the top of the container. The contents are kept at a low temperature of about 5°C to 8°C by placing the feed container in an open refrigerator. To minimise absorption of oxygen from the air a plastic-lined styrine cover floats on the liquid in the container.

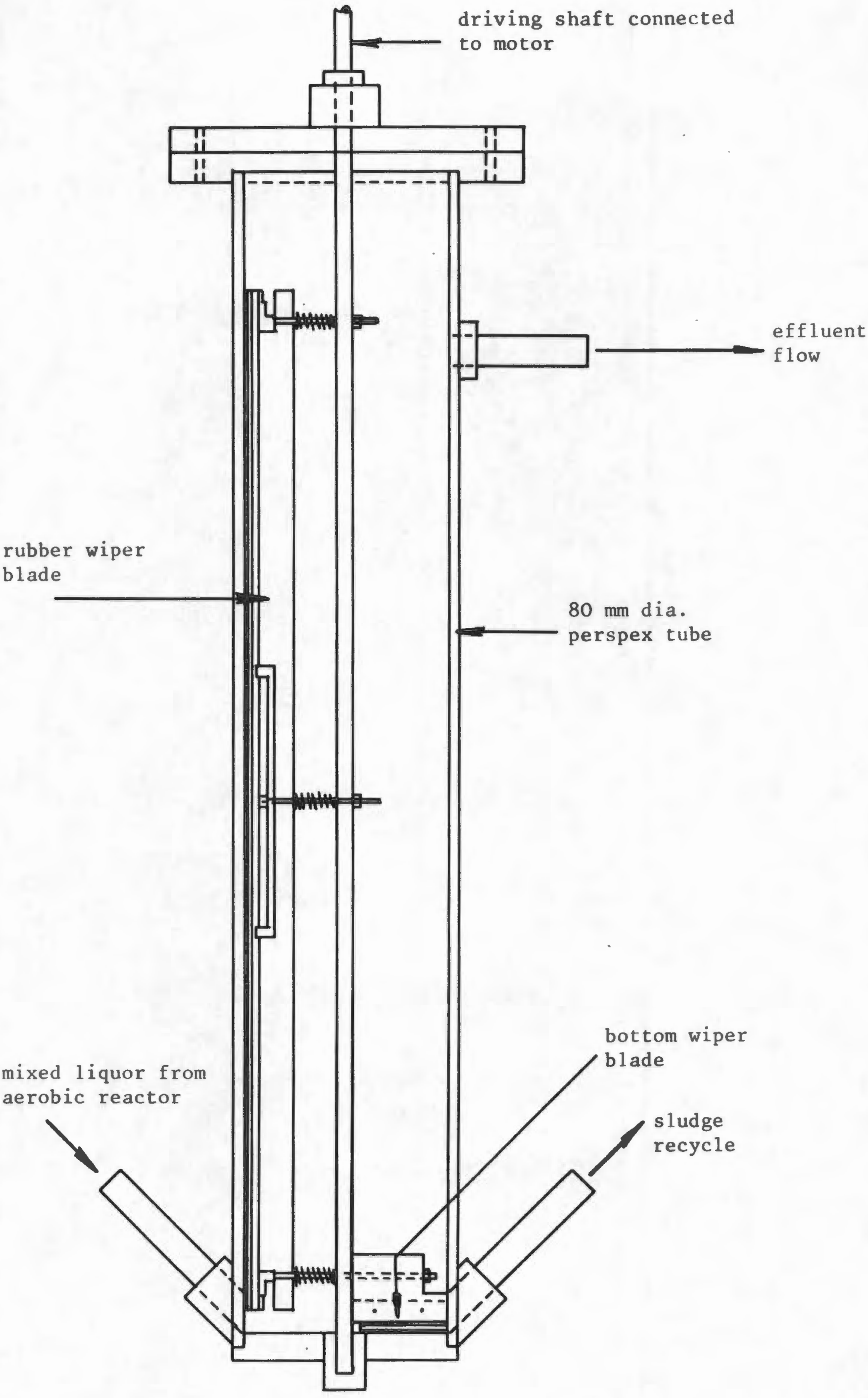


Figure 3.3: Typical experimental settling tank.

The effluent bucket is an ordinary 20ℓ white plastic bucket. This allows for quick visual inspection of the general effluent quality in the bucket.

3.1.4 Pumps

The pumps are of the peristaltic type and of a local design. Each pump can accommodate 8 channels of flow. The drive tubing is made of silicon rubber and stretches around the drive rollers. By increasing or releasing the tension of the tubing the delivery in each tube can be slightly adjusted to obtain equal flow rates in the different channels. The pump itself is activated by an electronic on-off timer; by setting the timer to different on-off times, a wide range of flow rates can be accommodated.

3.1.5 Connecting tubing

The connecting tubes are of soft, transparent plastic with diameters ranging from about 8 mm to 15 mm. The tubes must be soft to facilitate for easy cleaning by squashing. It is important to keep the connecting tube lengths as short as possible to minimise the retention time of the mixed liquor during its passage through the tube, to reduce possible side wall effects. The diameter of tube may be important; if the tube diameter is too small, the free flow from reactor to settler may be inadequate and there is a build-up of the liquid level in the discharging reactor. Conversely, if the tube diameter is too large settlement of the mixed liquor tends to occur and block the tube.

3.1.6 General

The aerobic reactors and the settling tanks are mounted on a vertical board, each reactor either being bolted directly to the board or placed on a support bolted to the board. The vertical board is bolted to an open unit frame mounted in turn on a horizontal frame with wheels, thus providing for mobility of the complete unit within the laboratory. A wide metal tray is placed on the horizontal frame just above the floor below the units and the pumps. This tray catches any sludge which may be lost from reactors due to blockages in the connecting tubes or when a tube on a pump splits.

The sludge then can be returned into the reactors without undue loss of experimentation time.

3.2 MAINTENANCE AND CONTROL

3.2.1 General Maintenance

The reactors are brushed twice a day with a test tube brush to remove sludge sticking to the walls of reactors and paddle stirrers; at the same time all tubing is gently tapped with a hard object to loosen sludge sticking to the inside of the tubes. The cleaning operation is preferably done 2 hours before any sampling on the units so as not to upset the steady state condition in the reactors. The aerobic reactors, settling tanks and all the tubing is washed in hot water at regular intervals of five to six weeks. This is necessary as some organism growths on the walls are so firmly attached that brushing does not remove these completely. During the time hot water cleaning is undertaken the mixed liquor must be kept aerated. The feed containers and feed tubes to the reactors are brushed each day and are washed with hot water every two to three days. For accuracy it is advisable to wash the feed tubes and the feed container daily when performing 24-hour tests as organism growth in the tubes may affect the COD of the influent delivered to the unit. The silicon tubing on the pumps normally lasts between ten and twelve weeks; it is therefore advisable to replace these every second time the complete unit is washed (at 10 week intervals).

3.2.2 Control

Close control of a laboratory-scale activated sludge unit is probably the most important factor in obtaining good continuous and representative data; without proper control the unit never really reaches 'true' steady or ideal dynamic state conditions. Energy mass balances on the daily data, done every day, provide an excellent criterion for judging how well a laboratory-scale activated sludge unit is being controlled.

Sewage is collected every ten to fourteen days in a 1000ℓ trailer tanker at one of the main sewer outfalls available. The time at which sewage is collected is important - it should be collected at the same time of day and preferably on the same week day. This ensures that the organic load in the sewage is more or less of the same composition and concentration. It was established during the course of this investigation that a good time to pump sewage at the Mitchell's Plain Sewage Works outside Cape Town is on Tuesdays, Wednesdays or Thursdays between 13.30 and 15.00 hours.

The sewage is stored in two 400ℓ stainless steel tanks at 4°C in a cold room. While pumping the sewage into the containers in the cold room the contents of the trailer tank are thoroughly mixed by air sparging. The sewage is pumped into the two containers by discharging to each tank cyclicly a few minutes at a time to ensure uniformity in both tanks. Before making use of this batch of sewage, a representative sample from both stainless steel tanks is taken and tested for COD and TKN concentrations. Usually the batch would be one with a TKN to COD ratio of 0,10 $mgN.mgCOD^{-1}$.

It is essential that an activated sludge unit receives *the same mass of COD every day*. The sewage in the cold room usually will have a COD concentration higher than that selected for the feed to the laboratory-scale activated sludge unit. Therefore, the daily feed is diluted with tap water to give the selected COD concentration for the feed. Occasionally, the stored sewage may have a lower COD concentration than required in the feed. To cope with these, the volume of feed must be increased to ensure that the same total mass of COD is fed to the unit every day.

At the termination of the daily feed period, before the new daily batch of feed is put into the feed container, it is advisable to wash the remainder of batch from the previous day into a beaker and to discharge this directly into the reactor. This ensures not only that the batch has been fed completely but also that possible microorganism growth in the remainder does not innoculate the new batch and, perhaps, affect the COD in this batch.

When running a laboratory-scale completely mixed activated sludge unit care must be taken that the dissolved oxygen concentration in the aerobic reactor always remains between about 1,5 and 2,0 $mgO.\ell^{-1}$. When operating a single-reactor aerobic activated sludge unit at short sludge ages it is good practice to keep the dissolved oxygen concentration in the mixed liquor above 3,0 $mgO.\ell^{-1}$ - experience indicates that this tends to discourage the excessive growth of filamentous organisms.

The sludge age of a unit is established by 'hydraulic control': If a sludge age of 20 days is required one twentieth of the total volume of mixed liquor in the reactor is drawn off every day. No attempt is made to control the sludge concentration; under steady state conditions (with hydraulic control of the sludge age) the sludge concentration will establish its steady state value automatically. Sludge draw-off is done once a day for sludge ages longer than 15 days, twice a day (half in the morning and half at night) for sludge ages between 8 days and 15 days and on a semi-continuous basis (at regular intervals) for sludge ages less than 8 days. For the short sludge age units a peristaltic pump activated by electronic on-off timers for a few seconds every ten to twenty minutes was used during this investigation. The pump was set to deliver a little less waste flow than required over a 24-hour cycle; the balance was drawn off directly from the reactor to ensure that the correct mass of mixed liquor was wasted daily. Intermittent on-off draw-off was employed for it was found that if the draw-off is continuous the flow rate is so low that sludge settles out in the draw-off tube, sometimes causing the liquid to be filtered through the blocking sludge so that the sludge itself is not drawn off.

3.3 METHODS OF TESTING

Sampling and testing of all the units was done on a daily basis. The following tests were performed:

(1) a COD and TKN test on an unfiltered influent sewage sample

(2) a COD and TKN test on all the unfiltered effluent samples

(3) a NO_3^- (nitrate) test on all the filtered effluent samples

(4) a COD test on the sludge mass in every unit

(5) a volatile suspended solids (VSS) test on the sludge mass in every unit

(6) an oxygen consumption rate test on every unit

(7) pH measurements of the mixed liquor in all units.

3.3.1 General

Tests, to determine the COD, TKN and VSS concentrations of samples, were conducted in accordance with the procedures as laid down in 'Standard Methods for the Examination of Water and Wastewater, 13th Edition, 1971'. The NO_3^- concentration of samples was determined by using a Technicon Auto-Analyzer; procedures were as laid down in 'Industrial Methods 33.68 and 35.69 W Test Techniques for Technicon Auto-Analyzers'. The pH of the mixed liquor was determined with a Radiometer type 29 pH-meter and pH-probe.

3.3.2 COD of the mixed liquor (COD/VSS ratio test)

This test is performed to establish the COD of the mixed liquor in the single-reactor aerobic activated sludge unit (the COD/VSS ratio of the mixed liquor). The procedure for this test is as follows:

(1) The following apparatus should be cleaned and dried thoroughly:

- (a) one crucible
- (b) one 500 ml beaker
- (c) macerator bowl and lid
- (d) two centrifuge bowls

(2) Measure out exactly 500 ml of distilled water in a volumetric flask.

(3)

(a) For a reactor VSS of less than 1800 $mgVSS.\ell^{-1}$ pipette out 100 ml of reactor mixed liquor into each of the two centrifuge bowls.

(b) For a reactor VSS of more than 1800 $mgVSS.\ell^{-1}$ pipette out 50 ml of reactor mixed liquor into each of the centrifuge bowls.

Centrifuge the two samples for about 20 minutes and pour off the supernatant from each.

(4) Transfer the one sample of solids to the crucible and conduct a VSS test on the sample in the normal manner.

(5) Pour approximately 250 ml of the distilled water in the volumetric flask into an *empty* squash bottle. Use *this* squash bottle to wash the remaining sample of solids from the centrifuge bowl into the macerator bowl. Pour the remaining contents of *this* squash bottle into the macerator bowl. Place the lid onto the bowl and macerate thoroughly for two minutes.

(6) Pour the contents of the macerator bowl into the 500 ml beaker. Use the remaining 250 ml of distilled water in the volumetric flask to wash any solids adhering to the macerator bowl and lid into the 500 ml beaker.

(7) Pipette one 10 ml aliqout from the 500 ml beaker into a COD flask using a pipette with a sufficiently large inlet hole so as to avoid filtering action. Before the aliqout is taken stir the beaker contents thoroughly. Use this sample for the COD determination.

(8) Calculation procedure:

Three data values are provided by the experimental procedure. These are:

(a) a COD value ($\text{mgCOD}.\ell^{-1}$)

(b) the crucible (plus contents) mass before and after ignition (grams)

The COD/VSS ratio is then given by the following formula:

(a) For MLVSS < 1800 $\text{mgVSS}.\ell^{-1}$

$$P = \frac{\text{COD} * 0{,}5 * 10}{\Delta M * 10000} \qquad 3.1$$

(b) For MLVSS > 1800 $\text{mgVSS}.\ell^{-1}$

$$P = \frac{\text{COD} * 0{,}5 * 20}{\Delta M * 10000} \qquad 3.2$$

where P = COD/VSS ratio ($\mathrm{mgCOD.mgVSS}^{-1}$)

COD = COD of mixed liquor ($\mathrm{mgCOD.\ell}^{-1}$)

ΔM = (crucible mass before ignition) - (crucible mass after ignition) (in grams).

3.3.3 Oxygen consumption rate test

This test demands special mention because this parameter is most sensitive to environmental changes and to changes in the control of a unit.

3.3.3.1 General

It is vital that nothing is done to a unit that might disturb steady state conditions before this test is performed. Never, for example, brush out reactors or adjust the feed rate shortly before this test is to be performed.

The oxygen probe and meter are connected to an electronic chart recorder. While calibrating the oxygen probe in oxygen saturated tap water, the range of the recorder is checked and set to correspond with readings given by the oxygen meter. After this, the test is performed *in the reactor*. The oxygen probe is placed in the mixed liquor and the dissolved oxygen concentration is increased from about 2,0 $\mathrm{mgO.\ell}^{-1}$ to about 6,0 $\mathrm{mgO.\ell}^{-1}$ by extra sparging with air. The air supply to the mixed liquor is cut off, but the *sewage feed and the mechanical stirrer are allowed to continue*. The change of dissolved oxygen concentration in the mixed liquor is recorded on the chart recorder; the oxygen consumption rate is then given by the slope of the dissolved oxygen concentration versus time recording.

When doing an oxygen consumption rate test for short sludge age units at low temperatures (say 3 days and 12°C) it is strongly advised to cover the complete liquid surface in the reactor with a flat piece of polystyrene. This prevents oxygen transfer from the atmosphere into the liquid due to turbulence in the mixed liquor. At low temperatures oxygen transfer can be appreciable causing the 'true' oxygen consumption rate of the mixed liquor to be underestimated by up to 30 percent.

3.3.3.2 Biodegradable soluble substrate concentration (S_{bs}) determination

To determine the easily biodegradable soluble substrate concentration in a sewage, it is necessary to operate a short sludge age single-reactor completely mixed aerobic activated sludge unit under square-wave dynamic loading conditions. The total volume of feed is fed to the unit during the first 12 hours of a 24 hour cycle and the oxygen consumption rates are monitored for a period of at least 2 hours before to 2 hours after feed termination. Oxygen consumption rates should be performed at one-half hour intervals before feed termination. At feed termination a continuous oxygen consumption rate test must be performed as follows: Just before feed termination, increase the dissolved oxygen concentration in the mixed liquor to about 7,5 to 8,0 $mgO.\ell^{-1}$ by additional sparging with air. All aeration is stopped while the feed and the mechanical stirrer are allowed to continue. The electronic chart recorder is switched on. When the dissolved oxygen concentration has dropped to about 6,5 $mgO.\ell^{-1}$, the feed into the reactor is switched off by putting a clamp on the feed line. The recycle flow from the settler and the mechanical stirrer are allowed to continue; the chart recorder also is run continuously. When the dissolved oxygen concentration has dropped to about 1,5 $mgO.\ell^{-1}$, the test is completed. It will be apparent from the recorder chart that a change in the slope of the recorded line occurs immediately after the feed into the aerobic reactor is stopped. The change in the two slopes of the oxygen consumption rate line just before and after feed termination provides information whereby the easily biodegradable soluble substrate concentration, S_{bs}, in the influent can be calculated (see below).

After feed termination the oxygen consumption rates should be monitored for at least another two hours at 15 minute intervals. It is important to perform this sequence of oxygen consumption rate measurements for the determination of the S_{bs} concentration over a period of at least four hours as this will establish a general trend which allows for the *only check* on the step change in the oxygen consumption rate *at* feed termination.

The easily biodegradable soluble COD fraction, S_{bs}, is calculated as follows: Performing a mass balance in terms of COD around the aerobic reactor for the oxygen utilized by micro-organism synthesis from S_{bs} gives

$$Q(1-P.Y_h)S_{bs} = \Delta O_c.V.24$$

or

$$S_{bs} = \frac{\Delta O_c.V.24}{Q(1-P.Y_h)} \qquad 3.3$$

where S_{bs} = easily biodegradable soluble substrate concentration in the influent (mg COD.ℓ^{-1})

ΔO_c = step change in the oxygen consumption rate at feed termination (mgO.ℓ^{-1}.hr^{-1})

V = volume of mixed liquor in the reactor (ℓ)

Q = influent flow rate (ℓ.d^{-1})

P = COD/VSS ratio (mgCOD.mgVSS^{-1})

Y_h = specific yield coefficient for heterotrophic organisms (mgVSS.mgCOD^{-1}).

CHAPTER FOUR

DATA COLLECTION AND ANALYSIS

4.1 INTRODUCTION

The project was subdivided into two separate tasks, to enquire into the causes for:

(1) the changes in the COD/VSS ratio of the mixed liquor, and

(2) differences in the observed response and that predicted by the general model for the single-reactor aerobic activated sludge process at 2,5 and 20 day sludge ages under daily square-wave cyclic flow and load conditions at 12°C.

4.2 COD/VSS RATIO OF ACTIVATED SLUDGE

4.2.1 Exploratory investigation

At the commencement of this investigation there was no clarity with regard to which environmental factors, if any, affected the COD/VSS ratio of activated sludge treating a raw domestic sewage. Consequently, the first set of experiments were of an exploratory nature to determine which combination of temperature and sludge age had the greater effect on the COD/VSS ratio of activated sludge treating a raw domestic sewage from the Mitchell's Plain Sewage Works outside Cape Town.

To have as diverse a set of environmental conditions as possible, six single-reactor aerobic activated sludge units, three at 12°C and three at 20°C with sludge ages at each temperature of 3,8 and 20 days, were operated under constant flow and load conditions, all six units treating the same influent sewage. The experimental apparatus for each unit has been described in detail in Chapter 3. A summary of the experimental design parameters is shown in Table 4.1. The influent TKN concentration could not be specified as it tends to vary with each particular batch of raw sewage.

Table 4.1: Experimental design parameters for the 3,8 and 20 day sludge age units at both 12°C and 20°C treating raw domestic sewage.

Sludge age (days)	Volume (liters)	Flow ($\ell.d^{-1}$)	Average influent COD ($mgCOD.\ell^{-1}$)
3	3,0	10,0	500
8	6,0	10,0	500
20	8,0	10,0	500

The six aerobic units were run for 52 days and tested as set out in Chapter 3. The daily measured results plotted on a time basis are shown in Figures 4.1 to 4.6; the numerical data is recorded in Appendix A, Tables A.1 to A.6.

Before proceeding to analyse this data kinetically, it was essential to determine, within our understanding of the meaning of the COD, whether the measured data was consistent, in other words whether adequate COD recoveries were obtainable on the measured process response data.

COD and N balances

COD and N balances were performed on all the measured daily data as shown in Figures 4.1 to 4.6 and plotted in Figures 4.7 to 4.9. A summary of the average percentage COD and N recoveries for the 3,8 and 20 day sludge age units at both 12°C and 20°C using the *measured COD/VSS ratios* is given in Table 4.2.

From Table 4.2 [and Figures 4.7(b), 4.8(b) and 4.9(b)] it is clear that generally good N recoveries were achieved for all six aerobic units. In contrast, the COD balances showed considerable variation. No COD balances near unity were obtainable for the 3 day sludge age unit at 12°C [see Table 4.2 and Figure 4.7(a)]. For the remaining five aerobic units, good percentage COD recoveries were achieved; these are plotted in Figures 4.7(a), 4.8(a) and 4.9(a) (see also Table 4.2).

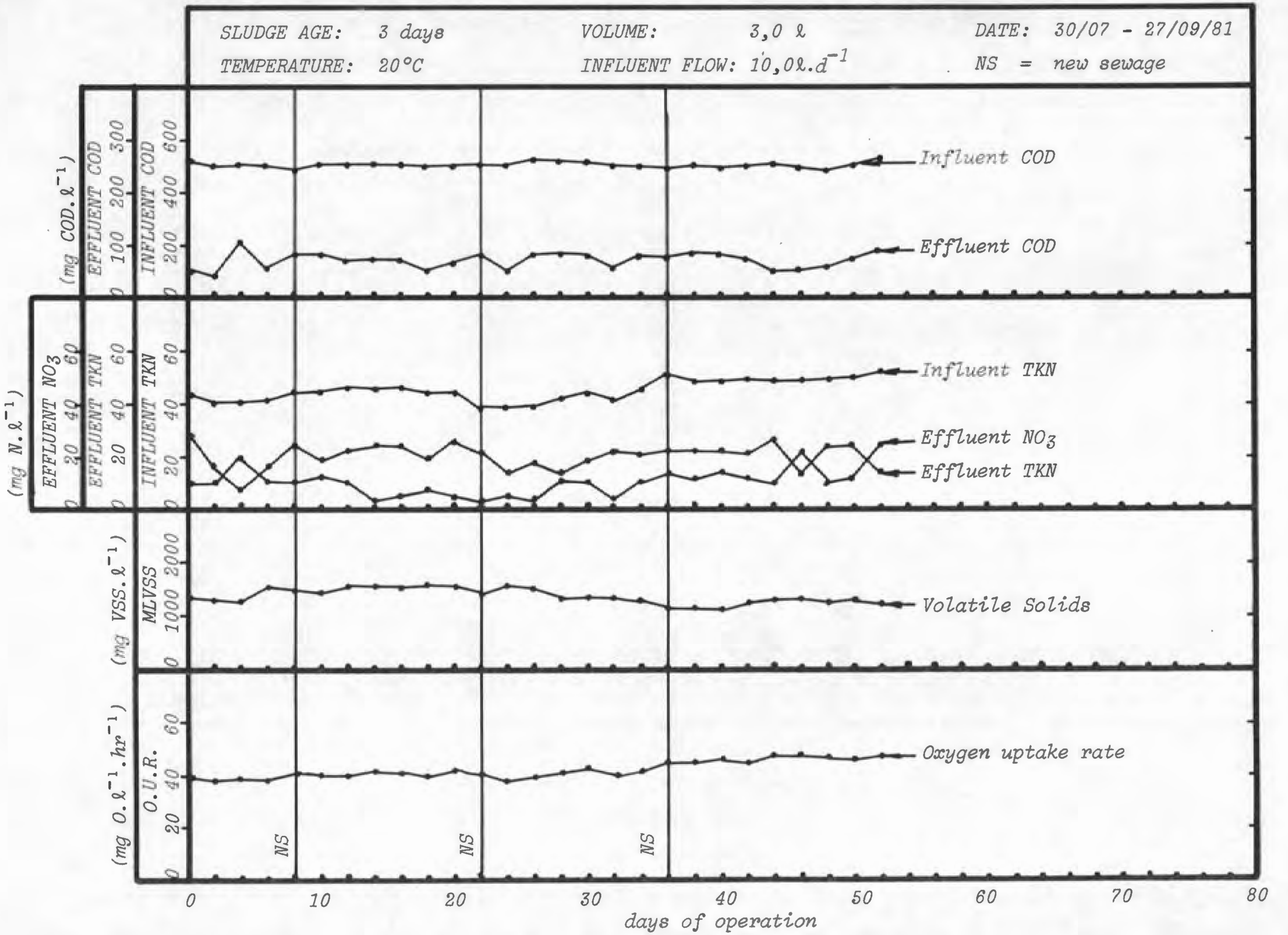


Figure 4.1: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage.

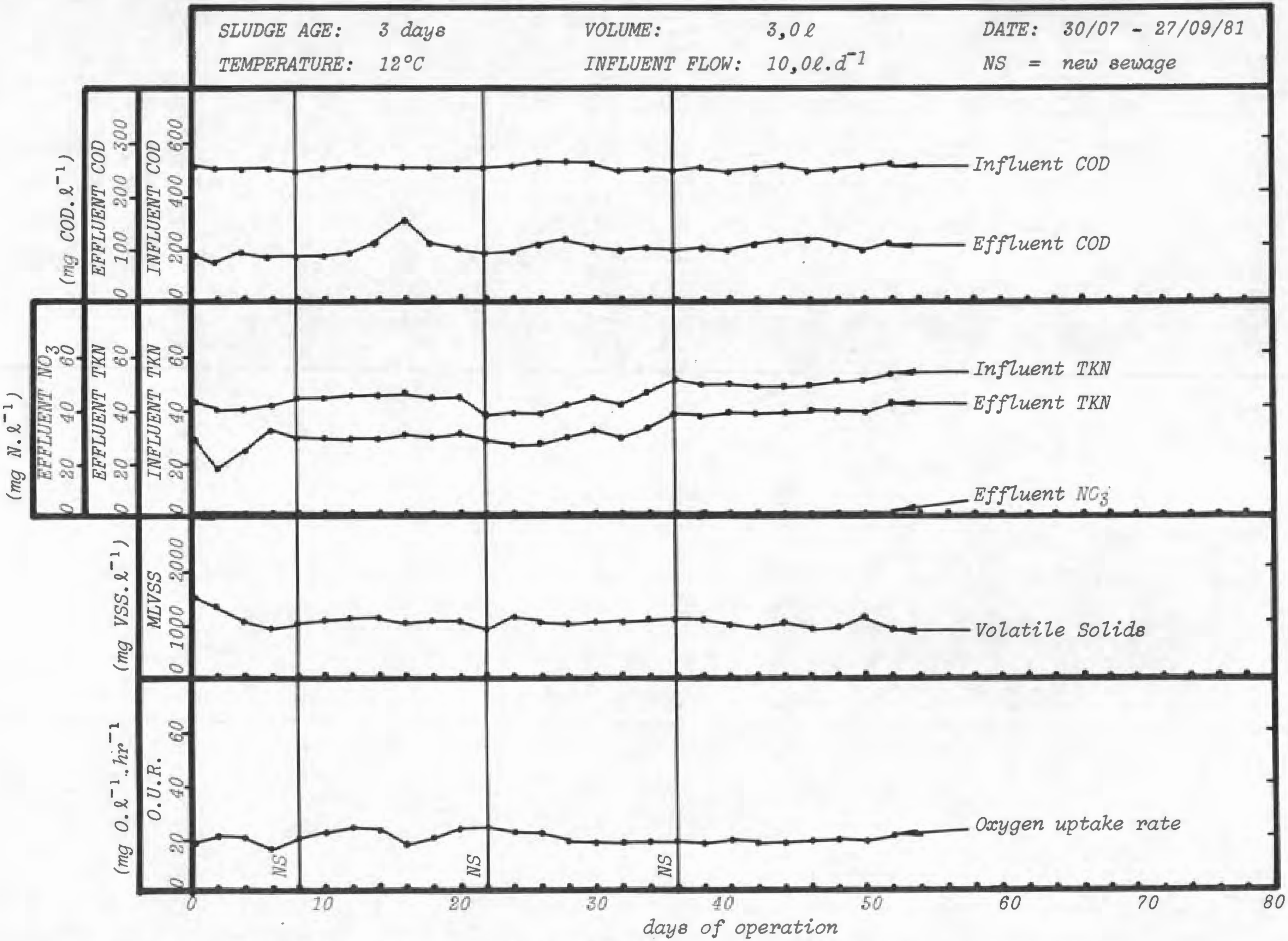


Figure 4.2: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage.

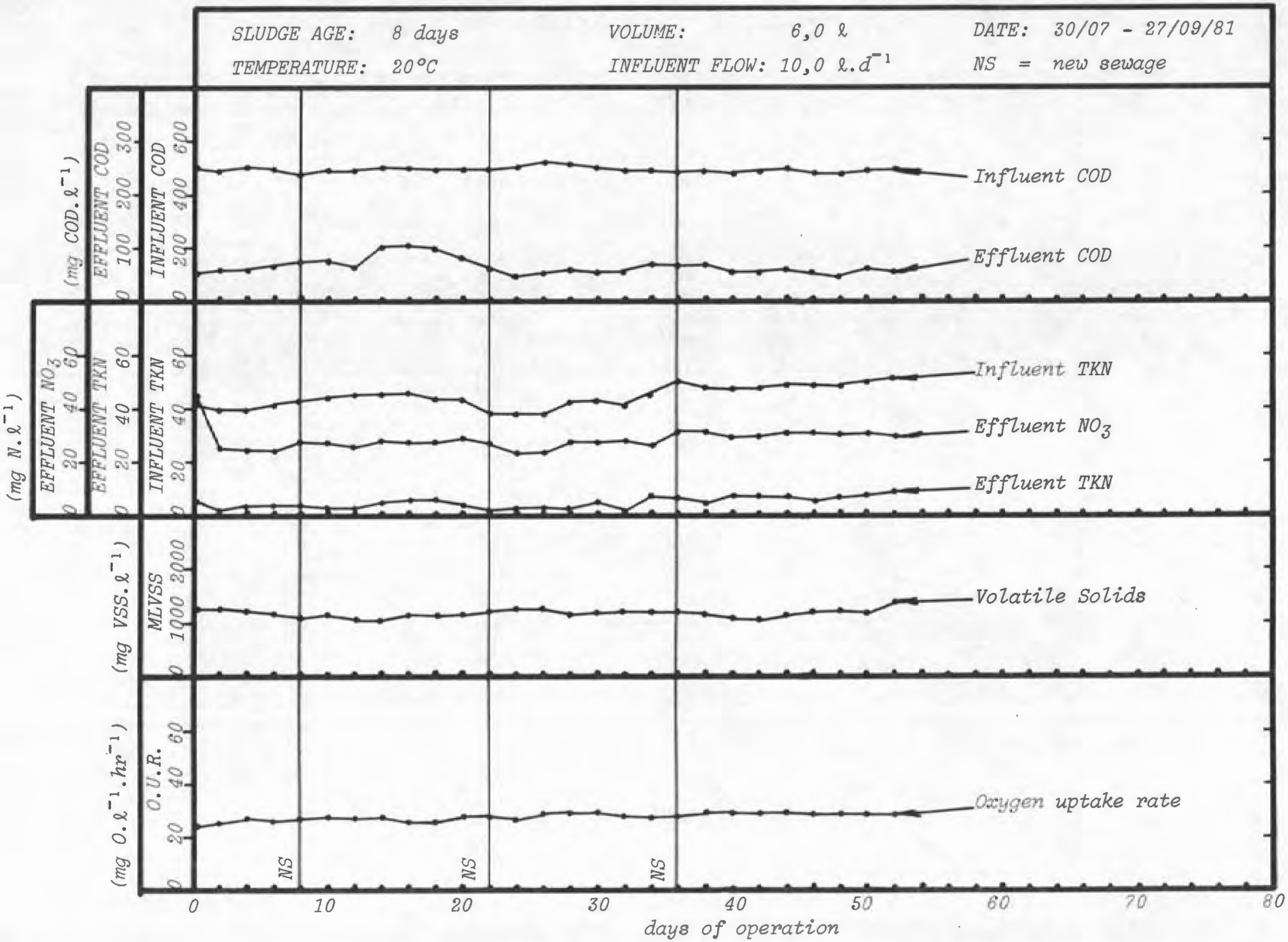


Figure 4.3: Daily Performance of the 8 day sludge age unit at 20°C treating domestic sewage.

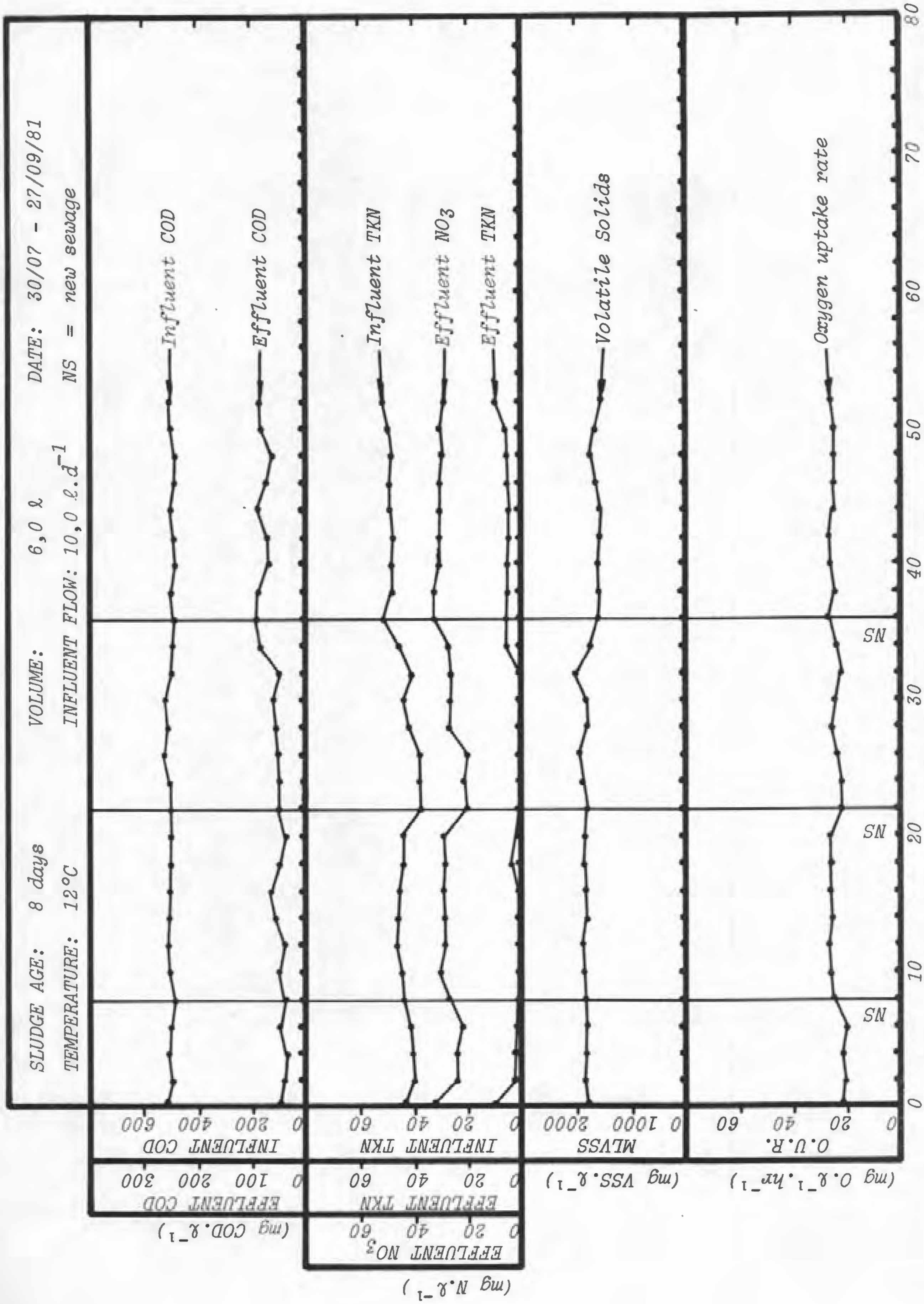


Figure 4.4: Daily Performance of the 8 day sludge age unit at 12°C treating domestic sewage.

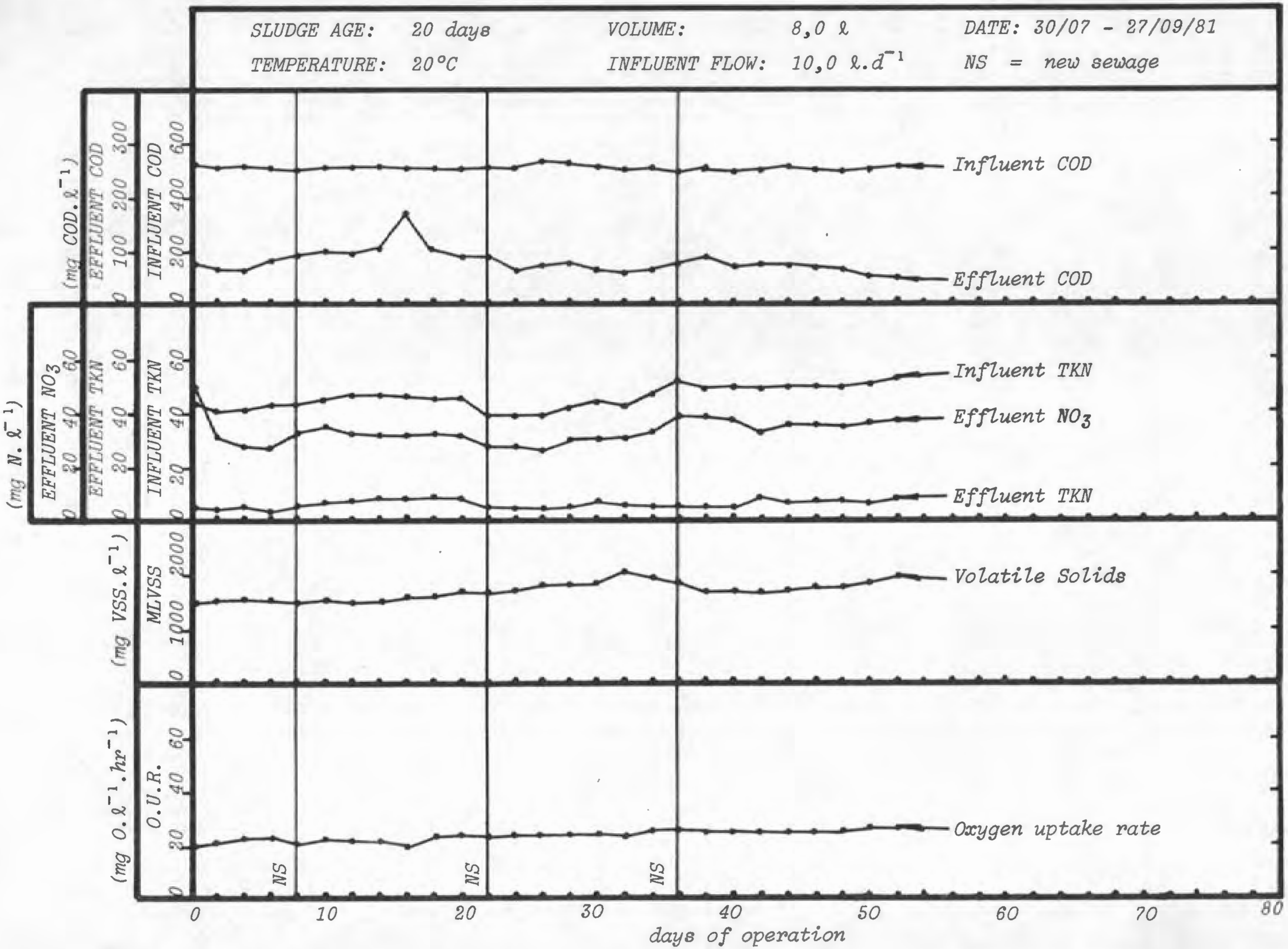


Figure 4.5: Daily Performance of the 20 day sludge age unit at 20°C treating domestic sewage.

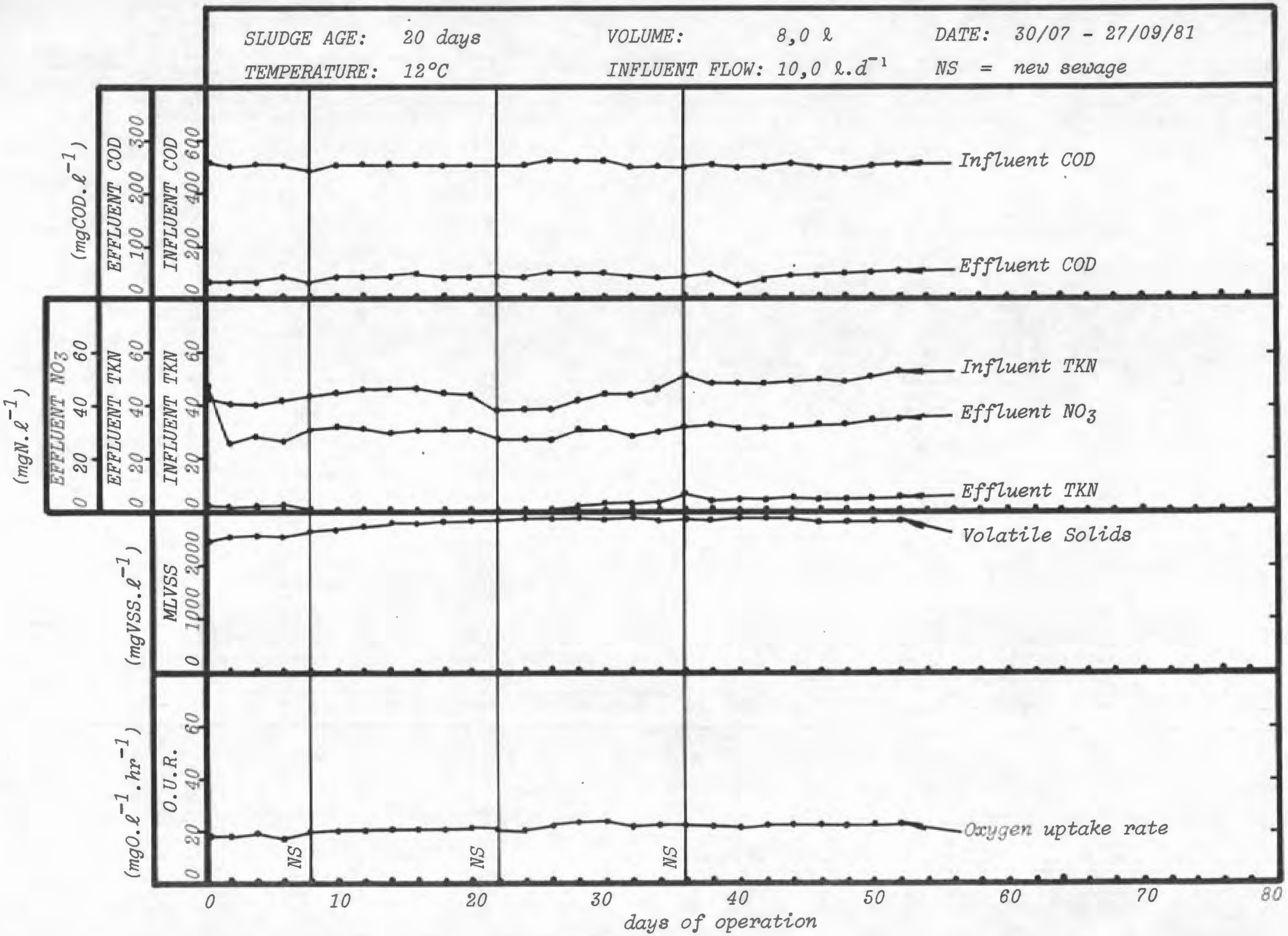


Figure 4.6: Daily Performance of the 20 day sludge age unit at 12°C treating domestic sewage.

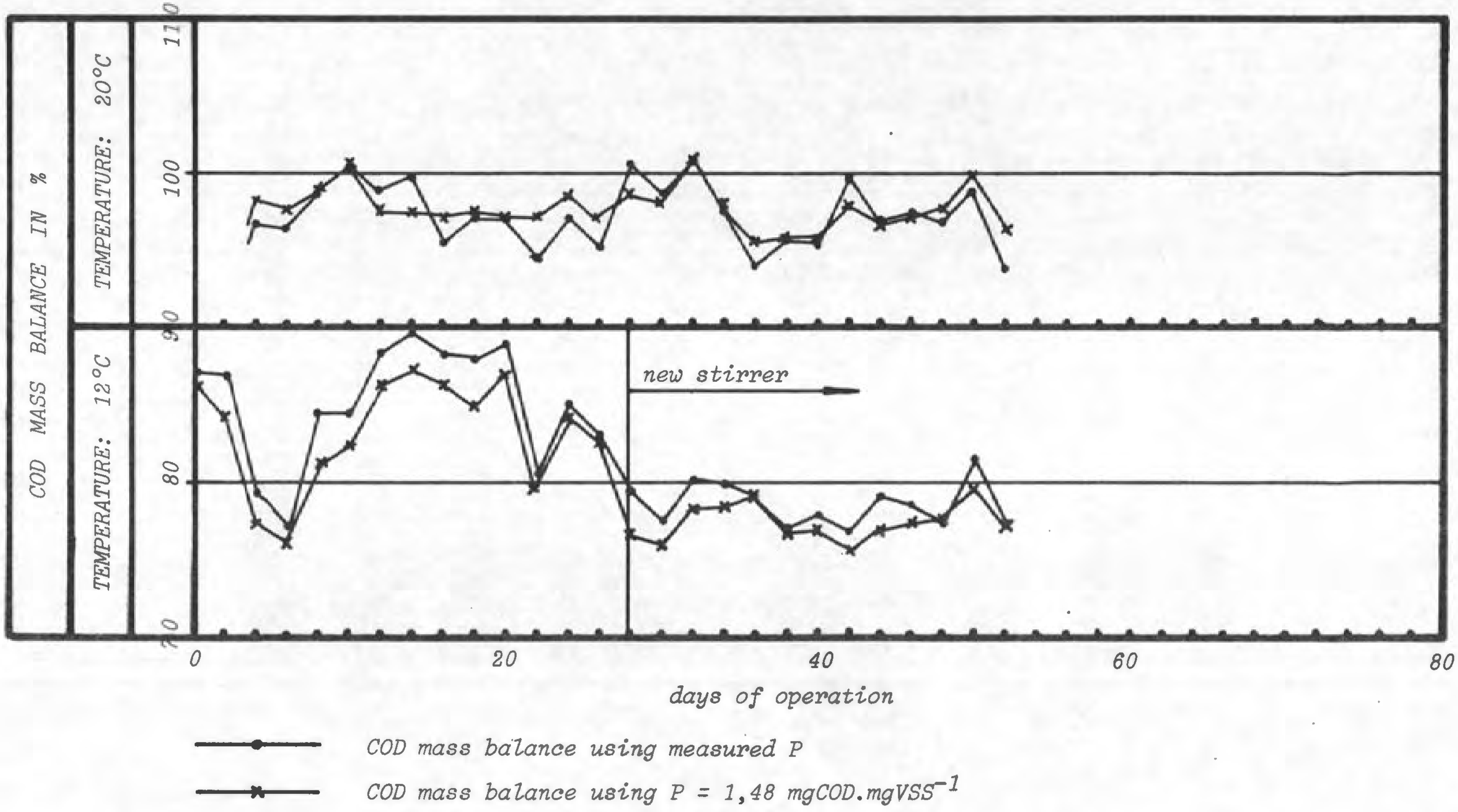


Figure 4.7(a): COD mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C treating domestic sewage.

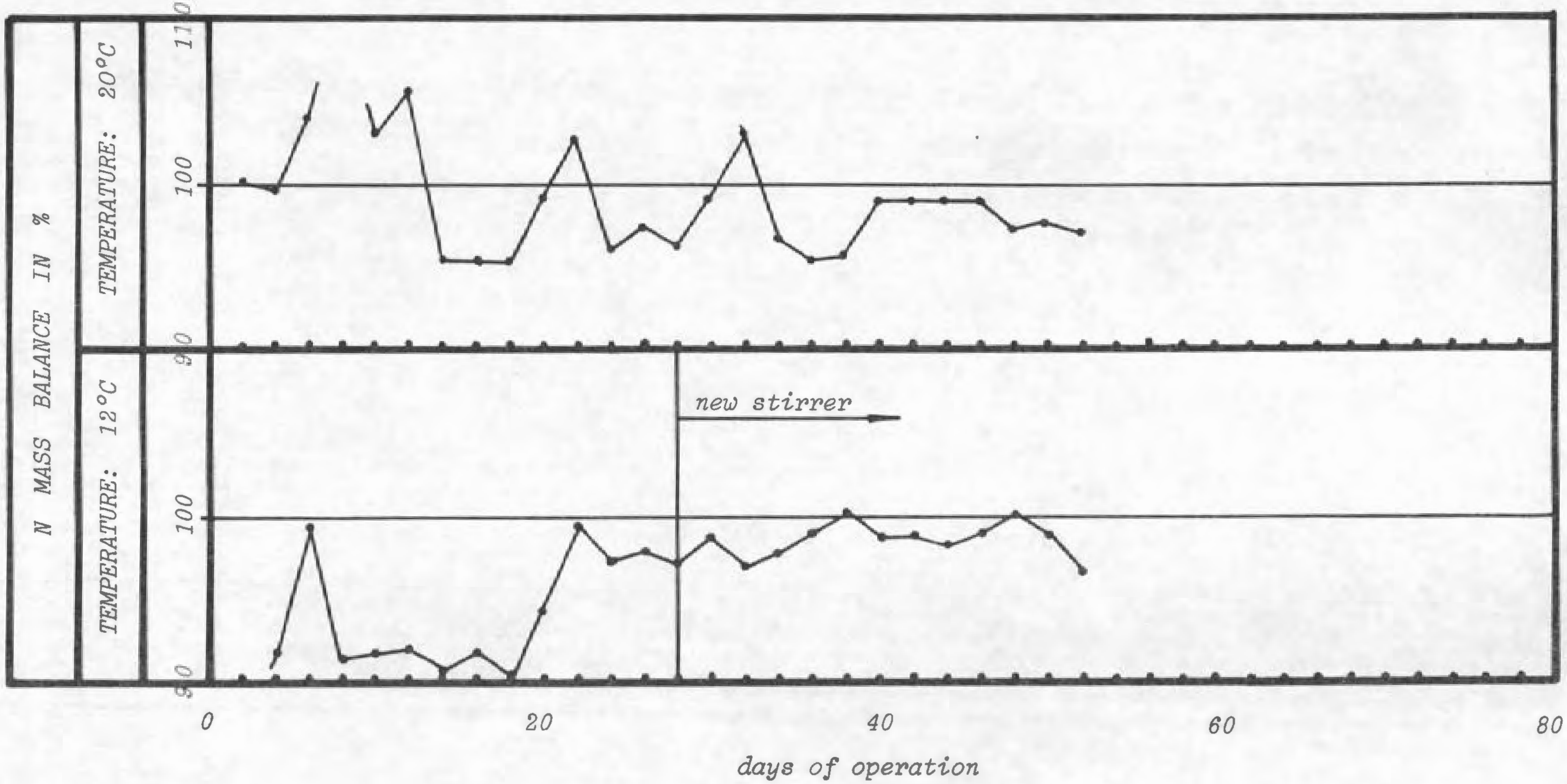


Figure 4.7(b): N mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C treating domestic sewage.

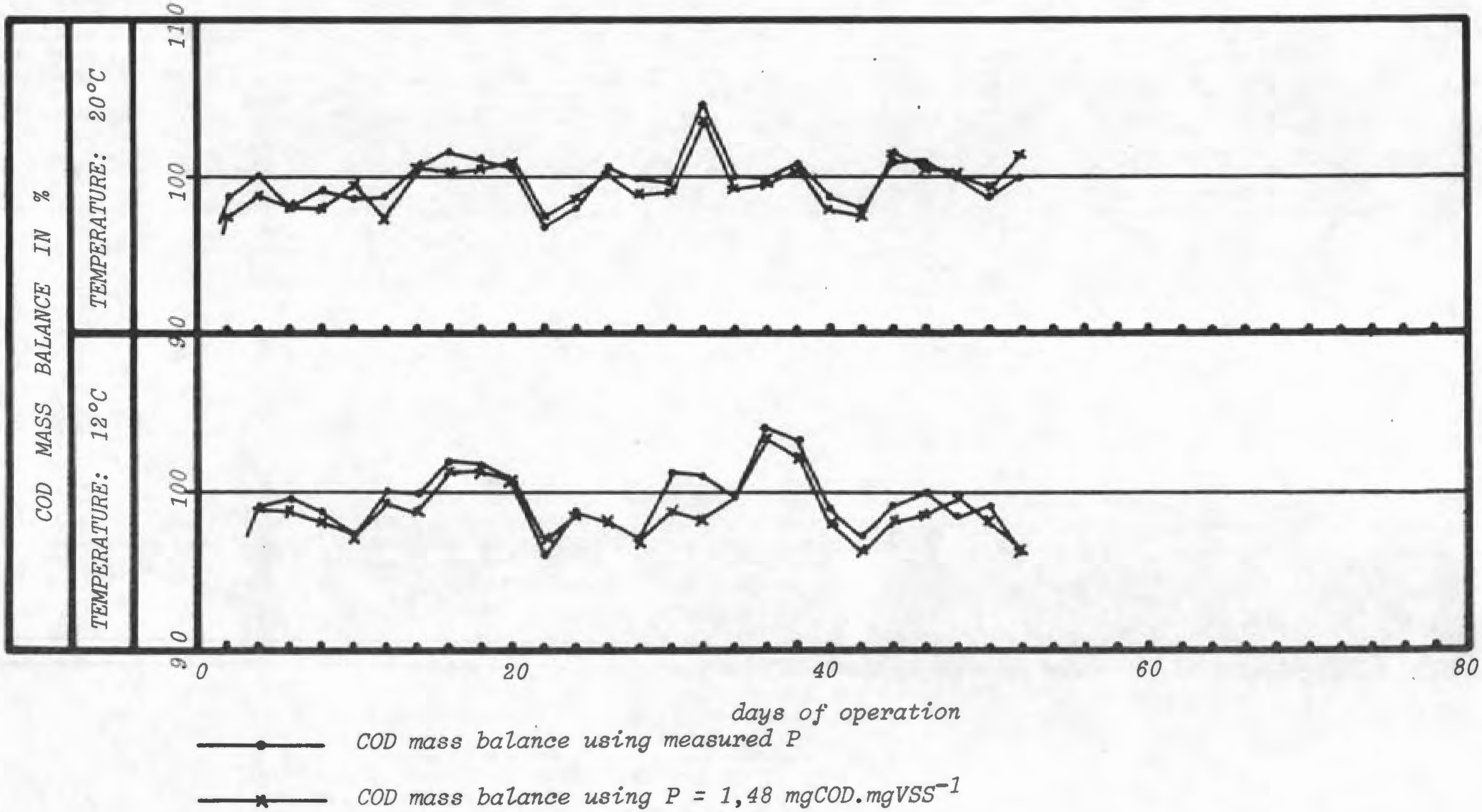


Figure 4.8(a): COD mass balances on daily measured data for the 8 day sludge age units at 20°C and 12°C treating domestic sewage.

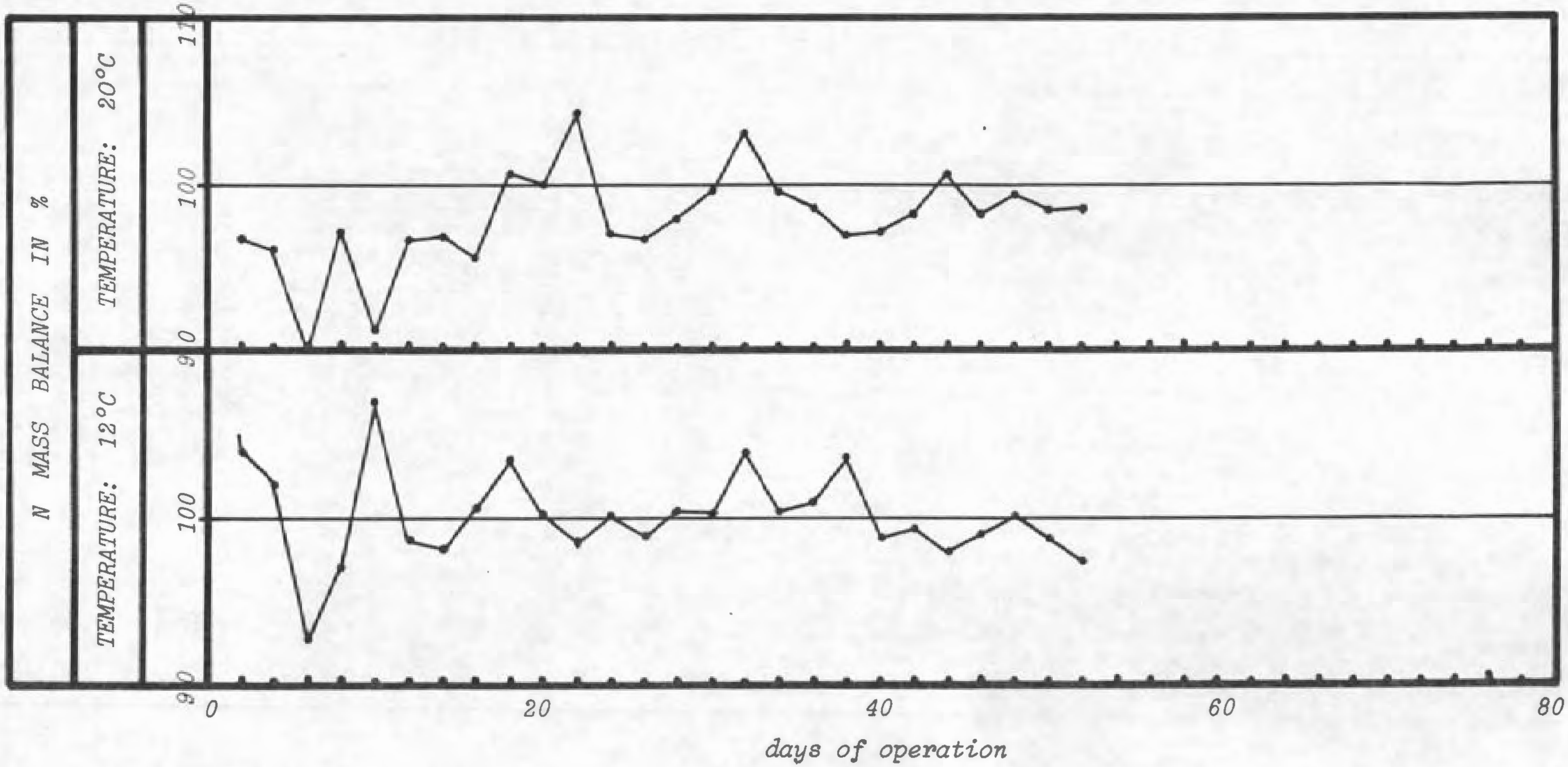


Figure 4.8(b): N mass balances on daily measured data for the 8 day sludge age units at 20°C and 12°C treating domestic sewage.

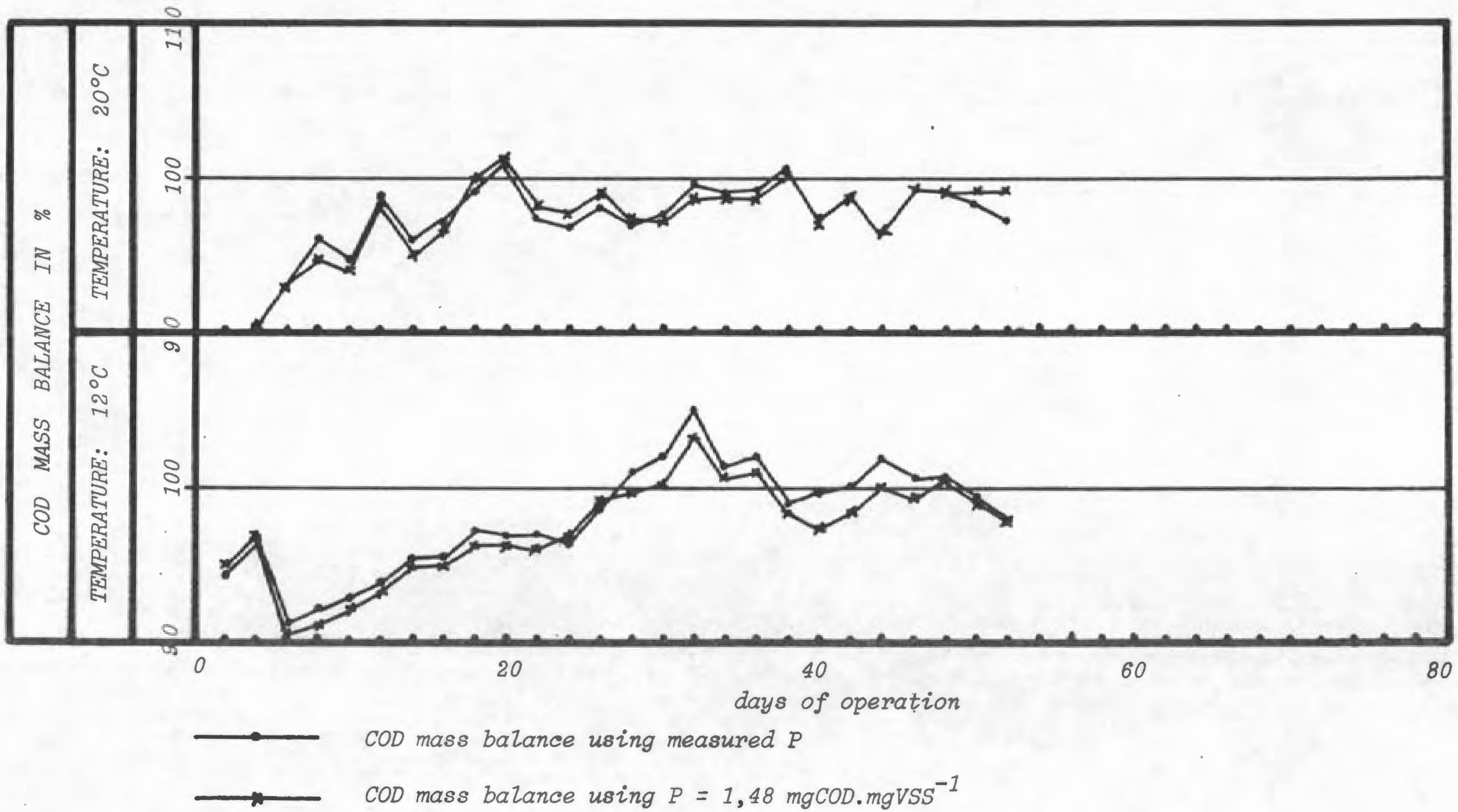


Figure 4.9(a): COD mass balances on daily measured data for the 20 day sludge age units at 20°C and 12°C treating domestic sewage.

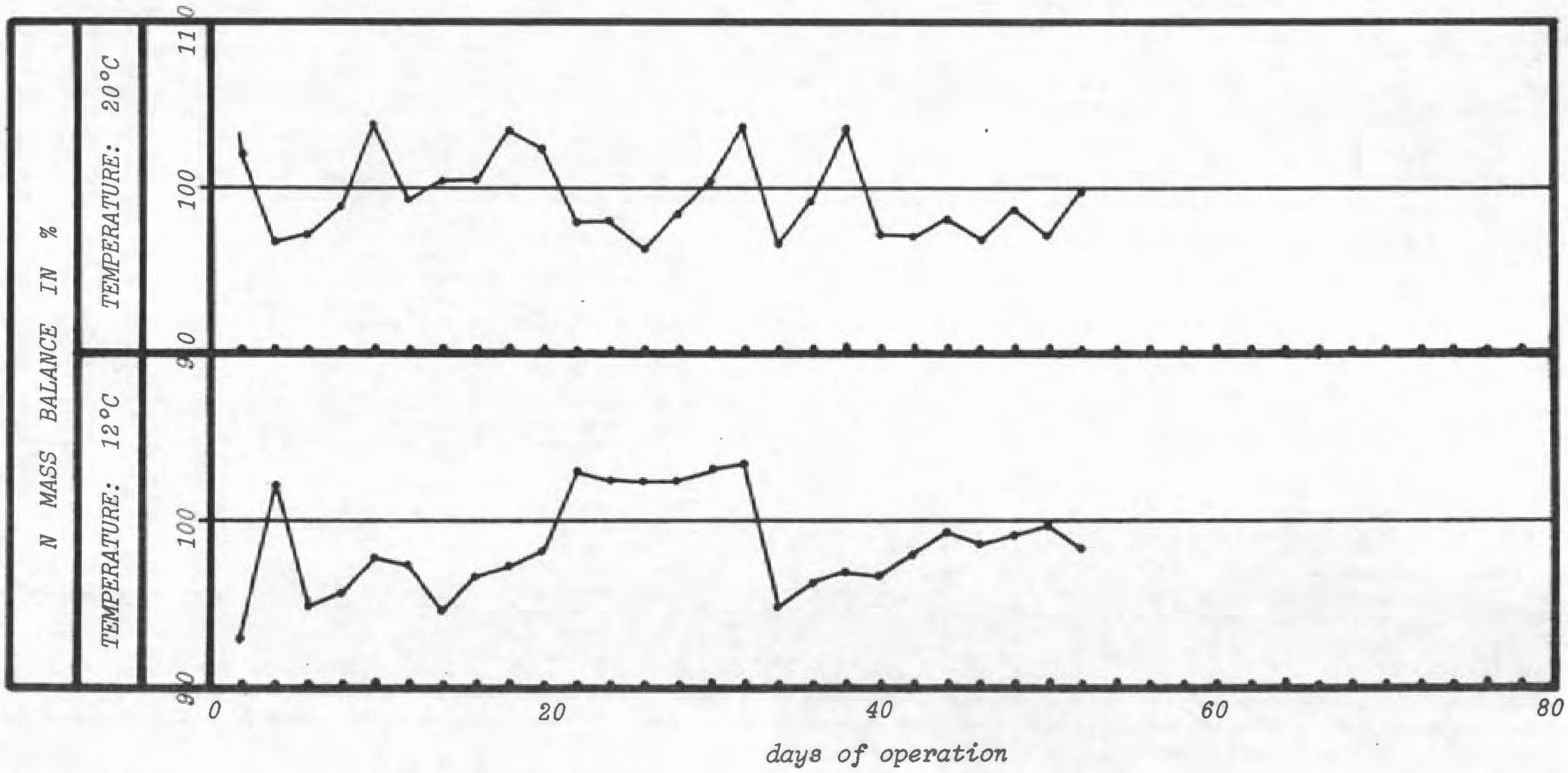


Figure 4.9(b): N mass balances on daily measured data for the 20 day sludge age units at 20°C and 12°C treating domestic sewage.

Table 4.2: Average percentage COD and N recoveries for the 3,8 and 20 day sludge age units at 12°C and 20°C.

Sludge age (days)	Average COD recovery (%)		Average N recovery (%)	
	12°C	20°C	12°C	20°C
3	81,7	97,4	96,6	99,3
8	99,6	99,9	100,2	97,5
20	99,4	98,4	99,2	99,4

Leaving out the 3 day sludge age unit at 12°C for the moment, the lack of good COD recoveries during the initial operating period on the other units can be explained by accepting that the units initially were not at steady state and would take some time to achieve steady state conditions whereafter good COD balances could be expected and indeed were observed. With regard to the 3 day sludge age unit at 12°C, this unit displayed an opposite effect - after about the twenty eighth day of operation the average percentage COD recoveries showed a sudden decrease to values of 80 percent and less.

There was no point in continuing the investigation, particularly at the lower temperature where the hypothesis on the effect of the long-chain fatty acids appears to be critically relevant, if the causes for the poor COD balances in the 3 day sludge age unit at 12°C could not be satisfactorily identified and corrected. Two possible causes for the poor COD balances were advanced, either (1) the COD is an inappropriate kinetic parameter in terms of which a balance is not always obtainable or, (2) a suspect experimental measurement procedure was being employed.

(1) The COD test gives a measure of the electrons available for transfer in a wastewater (in terms of oxygen) by oxidizing the organic compounds to carbon dioxide and water with a strong oxidizing agent, chromic acid. The test value only reflects the electron release in oxidation of the carbonaceous compounds as

ammonia present in a wastewater will not be oxidized. Hence, provided all the organic material is oxidized then theoretically, an electron balance in terms of oxygen should be possible. Some organic materials such as aromatic hydrocarbons and pyridines are biodegradable but are not digested in the test under any circumstances. Fatty acids (such as acetate) and also straight chain alcohols are extremely difficult to oxidize in the test; to ensure their breakdown silver sulphate is added as a catalyst. However, the silver sulphate will react with chlorides, iodides and bromides to produce precipitates which will diminish the effect of the silver sulphate; to overcome this, mercuric sulphate is added to the sample before refluxing. The mercuric sulphate will react with the chloride ion forming a soluble mercuric chloride complex thereby greatly reducing its propensity to react with the silver. Pyridines are unlikely in a wastewater of mainly domestic origin. Consequently there was no reason to suspect that the COD measurement was the cause for a low COD balance. This conclusion was supported further when the data showed that good COD balances were obtained on all the remaining five aerobic units. The cause also could not have arisen from errors in the nitrification oxygen demand in the units as good N balances were achieved for all the units irrespective of whether nitrification occurred or not. Consequently the cause for the error was sought in the experimental sampling and testing procedure.

(2) With regard to the possibility of suspect experimental techniques, during the course of this particular set of experiments, a larger paddle stirrer had been installed in the 3 day sludge age unit that gave the poor COD balances. An examination of the plot of the COD balances indicates that the average percentage COD recovery deteriorated from the time the larger paddle was installed [see Figure 4.7(a)] - it was concluded that the oxygen consumption rate measurement in this particular unit was in error, probably due to oxygen entering the reactor contents during an oxygen consumption rate test because of turbulence at the liquid-air interface. To correct for this in future experiments the liquid surface was totally covered with a flat piece of polystyrene while doing the oxygen consumption rate

measurement. This modification in the procedure to determine oxygen consumption rates was very successful - in all experiments thereafter COD recoveries, in excess of 95 percent, were recorded.

From the discussion above it is evident that the error introduced by oxygen transfer during an oxygen consumption rate measurement can cause serious errors in the measured response. To prevent this the paddle stirrer must be located such that the surface renewal is minimised, or, the surface must be protected from contact with the air by placing a cover on it. Attention should also be given to the shape and size of the reactor - in a cylindrical reactor the dimensions of the reactor should be such that the depth:diameter of the liquid mass is not less than 2:1 in order to minimise the exposed surface area and induce turbulence at the surface yet allow stirring with sufficient mixing in the mass of the mixed liquor. Generally the problems with the oxygen consumption rate measurement are more severe at the lower temperatures because the oxygen saturation concentration is high so that the driving force for the solubility of oxygen at a low oxygen concentration in the reactor is correspondingly higher than at higher temperatures. However, with the above precautions, and provision for secluding oxygen transfer during an oxygen consumption rate measurement, the error should be negligible.

In this set of experiments, consistent filamentous sludge bulking problems were experienced in the 3 day sludge age unit at 20°C. To improve settleability, a flocculating and coagulating agent, ferric chloride, was added at a concentration of 110 mg Fe^{3+} per liter influent feed. Due to the substantial amount of chloride added, some doubt existed around the measured COD concentrations (in spite of good percentage COD recoveries). Although the COD test provides against the effect of chlorides, to ensure that the chloride effect was as small as possible, an alternative flocculating and coagulating agent, ferric sulphate at a concentration of 110 mg Fe^{3+} per liter influent feed, was used.

The above discussion considered in detail the deviations in the COD balances observed and provided substansive evidence as to their causes. It is clear, therefore, that provided the proper precautions are taken, the elimination of these causes should make COD recoveries near 100 percent possible.

Kinetic Response Analysis

In doing the kinetic analysis it was decided to use the data recorded for each of the six aerobic units. As the cause for the poor COD balances for the 3 day sludge age unit at 12°C was satisfactorily determined, it was reasonable to assume that the process response parameters (except the oxygen consumption rates) were descriptive of the operating conditions (during the period when these showed relative daily stability). For the remaining five units, data yielding COD and N recoveries within a target range of 95 to 105 percent only, was used. Selecting the data in this fashion the mean observed response of the different units is shown in Table 4.3.

Table 4.3: Mean observed response for the 3,8 and 20 day sludge age units at 12°C and 20°C.

Temp. (°C)	Sludge age (days)	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_V $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	N_{NE} $\frac{\text{mgN}}{\ell}$
12	3	504	45,5	1085	-	110	32,6	1,0
	8	503	46,1	1773	25,5	60	4,4	27,4
	20	504	46,2	2857	22,1	44	3,3	31,0
20	3	515	47,4	1400	41,9	72	11,0	20,4
	8	516	47,1	1266	29,2	72	6,1	28,8
	20	503	46,2	1763	24,2	70	6,2	32,7

To check the observed response for the six aerobic units (as shown above in Table 4.3) against the theoretical response, the usual experimentally determined kinetic constants for raw domestic sewage [after Ekama and Marais (1978)] were used in the steady state kinetic model; these are listed in Table 4.4. The unbiodegradable soluble COD fraction, f_{us}, generally tends to be specific to a sewage source. For this sewage f_{us} = 0,08 mgCOD. $mgCOD^{-1}$ was selected, this value being indicated by the filtered effluent COD concentrations for the 20 day sludge age unit at 12°C. Using the kinetic constants in Table 4.4, the theoretical steady state response for each of the five aerobic units was calculated; this is shown in Table 4.5.

A comparison of the observed and the predicted steady state response (as reflected in Tables 4.3 and 4.5) shows no substantial difference for the various response parameters *except* the volatile suspended solids concentration X_V. The X_V observed at 20°C is lower than the predicted values, by 11 percent at a 3 day sludge age and 30 percent at a 20 day sludge age. At 12°C, the 8 and 20 day sludge age units show an insignificant difference between the experimental and predicted X_V concentrations, but the 3 day sludge age unit has an observed value 27 percent lower than predicted. It should be noted that the validity of the experimental response data is not in question for the COD (except for the 3 day unit at 12°C) and N balances were very good (see Table 4.2). The observed differences therefore cannot be sought in errors of measurement. The most likely source for the differences in the experimental and predicted response would appear to be that the wastewater characteristics were different from those accepted in the general model:

(1) A possible source for these differences between the observed and predicted X_V values at both 12°C and 20°C is that the actual unbiodegradable COD fraction, f_{up}, in the influent varies with temperature for this particular sewage. If our hypothesis is correct *i.e.* that fats at low temperatures (say 12°C) are relatively unbiodegradable (because of solidification), then the experimental response observed above would be explained theoretically in the

Table 4.4: Values of kinetic and other constants used in the steady state model to calculate the theoretical response.

Symbol	Value	Units	Temperature Dependency
Carbonaceous Material Degradation Kinetics			
Y_h	0,45	mgVSS.mgCOD^{-1}	1,000
b_{h20}*	0,24	d^{-1}	1,029
f	0,20	mgVSS.mgVSS^{-1}	1,000
K_{V20}*	0,07	ℓ.mgVSS^{-1}.d^{-1}	1,029
P	1,48	mgCOD.mgVSS^{-1}	1,000
Nitrification Kinetics			
Y_h	0,10	mgVSS.mgN^{-1}	1,000
b_{n20}*	0,04	d^{-1}	1,029
$nm20^*$	0,45	d^{-1}	1,123
K_{n20}*	1,00	mgN.ℓ^{-1}	1,123
K_{r20}*	0,015	ℓ.mgVSS^{-1}.d^{-1}	1,029
f_n	0,10	mgN.mgVSS^{-1}	1,000
Influent Wastewater Fractions			
f_{us}	0,08	mgCOD.mgCOD^{-1}	
f_{up}	0,13	mgCOD.mgCOD^{-1}	
f_{na}	0,84	mgN.mgN	

* - values at 20°C

Table 4.5: Theoretical response for the 3,8 and 20 day sludge age units at 12°C and 20°C.

Temp. (°C)	Sludge age (days)	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_V $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	N_{NE} $\frac{mgN}{\ell}$
12	3	504	45,5	1502	22,9	113	31,5	0,0
	8	503	46,1	1778	25,9	61	3,5	29,2
	20	504	46,2	2765	22,7	46	3,0	32,0
20	3	515	47,4	1576	45,6	72	4,4	27,1
	8	516	47,1	1685	27,3	72	3,2	31,1
	20	503	46,2	2530	22,4	71	3,0	32,9

model by accepting a value of f_{up} at 20°C much lower than that at 12°C.

(2) A further source of error (in the prediction) is that during this set of experiments the average *filtered* effluent COD concentration for the units was about 45 $mgCOD.\ell^{-1}$. Looking at Table 4.3 it is clear that the average *unfiltered* effluent COD concentrations (except the 20 day sludge age unit at 12°C) are substantially higher. This could indicate that some particulate material was carried over in the effluent unintentionally (due to inefficient settling); if this is true then the *nominal* sludge age would be effectively reduced as more solids are wasted than wanted in the waste flow. Accepting this explanation, the *actual* sludge age for each unit (except the 20 day unit at 12°C) was calculated. The calculation procedure is set out below:

Calculation procedure: 20 day unit at 20°C

From Table 4.3:

$$S_{TI} = 503 \text{ mgCOD}.\ell^{-1}; \quad S_{TE} = 70 \text{ mgCOD}.\ell^{-1}$$

$$S_{TE(FIL)} = 45 \text{ mgCOD}.\ell^{-1}; \quad X_V = 1763 \text{ mgVSS}.\ell^{-1}$$

Then:

$$M(X_V)_{UNIT} = X_V.V = 1763 \times 8 = 14104 \text{ mgVSS}$$

$$M(X_V)_{WASTE} = M(X_V)_{UNIT}/R_s = 14104/20 = 705{,}2 \text{ mgVSS}$$

Equivalent $M(X_V)_E$ in effluent is:

$$M(X_V)_E = (S_{TE}-S_{TE(FIL)}).(Q-q)/P$$

$$= (70-45)9{,}6/1{,}48$$

$$= 162{,}2 \text{ mgVSS}$$

Then the actual sludge age is:

$$R_s = M(X_V)_{UNIT}/M(X_V)_{WASTE} + M(X_V)_E$$

$$= 14104/(705{,}2 + 162{,}2)$$

$$= 16{,}26 \text{ days.}$$

Using $R_s = 16{,}26$ days, find f_{up} by trial and error to yield $X_v \cong 1763 \text{ mgVSS}.\ell^{-1}$:

$$X_V = \frac{Y_h.S_{TI}(1-f_{us}-f_{up})R_s(1+b_h.f.R_s)}{(1+b_h.R_s)R_h} + \frac{S_{TI}.f_{up}.R_s}{P.R_h}$$

$$= \frac{0{,}45\text{x}503(1-0{,}14-0{,}055)16{,}26(1+0{,}24\text{x}0{,}2\text{x}16{,}26)}{(1+0{,}24\text{x}16{,}26)0{,}8} + \frac{503\text{x}0{,}055\text{x}16{,}26}{1{,}48\text{x}0{,}8}$$

$$= 1725 \text{ mgVSS}.\ell^{-1}$$

then $f_{up} \cong 0{,}055 \text{ mgCOD.mgCOD}^{-1}$

Considering the above discussion, the experimental filtered effluent COD and X_V concentrations were subsequently accepted as a basis for determining the 'correct' sludge age and f_{up} value at 12°C and 20°C. After calculating the actual sludge age, the corresponding

f_{up} was determined by trial and error to give the experimentally measured X_V. Using these 'corrected' values for sludge age and f_{up}, the theoretical response was calculated for each unit and is shown in Table 4.6.

From Table 4.6, at 12°C the determined f_{up} values were about 0,15 $mgCOD.mgCOD^{-1}$ for all three aerobic units whereas at 20°C f_{up} lay in the range 0,05 to 0,08 $mgCOD.mgCOD^{-1}$. These differences between 20°C and 12°C for all sludge ages would appear to support our earlier hypothesis that the f_{up} value can increase from 20°C to 12°C due to fat solidification at the lower temperature. However, noting the increase in the f_{up} value from 20°C to 12°C one could expect (if our hypothesis that the COD/VSS ratio increases due to fat solidification is correct) that the measured COD/VSS ratios for each of the six aerobic units should give some indication of the effects that fats in an influent may have on this ratio. Accordingly the analysis of the COD/VSS ratio was undertaken.

Table 4.6: Theoretical response for the 3,8 and 20 day sludge age units at 12°C and 20°C using the actual sludge age and f_{up}

Temp (°C)	Sludge age (days)		f_{up} $\frac{mgCOD}{mgCOD}$	X_V $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	N_{NE} $\frac{mgN}{\ell}$
	Nom.	Act.						
12	3	2,20	0,14	1172	21,0	113	29,2	0,0
	8	7,47	0,15	1728	25,1	61	3,6	28,6
	20	20	0,15	2860	22,3	46	3,0	31,6
20	3	2,71	0,08	1365	47,1	72	5,0	27,2
	8	6,79	0,05	1272	29,2	72	3,5	32,2
	20	16,26	0,055	1731	23,9	71	3,2	34,3

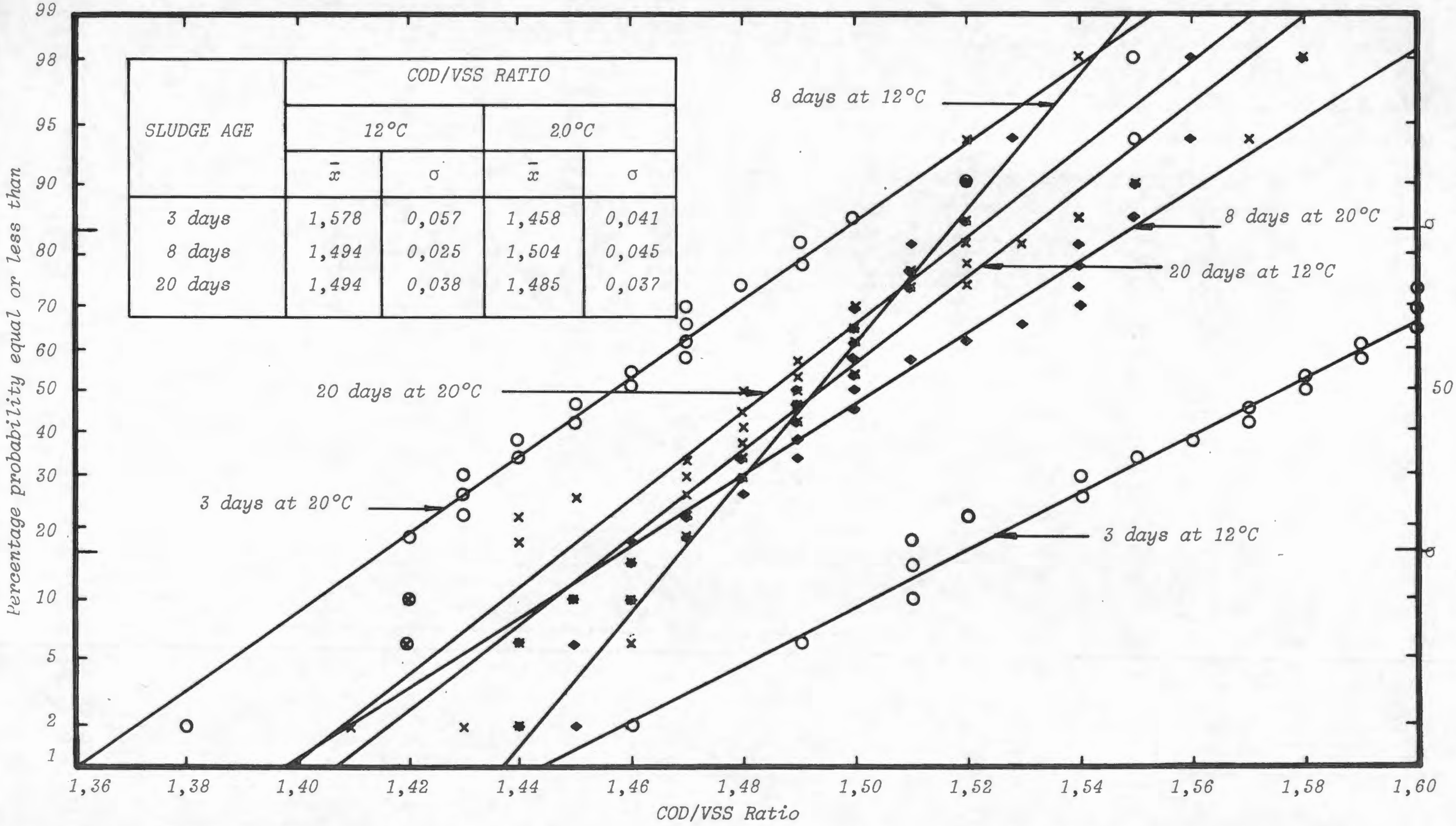
Statistical Analysis of COD/VSS ratios

The COD/VSS ratio for each unit was analysed statistically by plotting the experimentally measured COD/VSS ratios on probability paper as shown in Figure 4.10. The mean ($\bar{x}$) and standard deviation (σ) of the mean of each set of COD/VSS ratios (for each unit) was determined graphically. Table 4.7 shows a summary of this analysis.

Due to the good COD recoveries achieved for the 8 and 20 day sludge age units at both 12°C and 20°C, the reliability of the mean COD/VSS ratios was high. By applying a 'Student-t' test analysis (see Appendix C) at a 95 percent confidence level to the results as shown in Table 4.7 for the 8 and 20 day sludge age units it was concluded that the COD/VSS ratio of activated sludge treating a raw domestic sewage is *not* significantly affected at the longer sludge ages by changes in both the operating sludge age and temperature. However if the increases in f_{up} calculated at 12°C (f_{up} = 0,15 - from 0,05 at 20°C - as shown in Table 4.6) is due to solidified fats then in fact a significant quantity of fat had accumulated at 12°C. Accepting a COD/VSS ratio of 2,6 for fats there should have been a significant increase in the measured COD/VSS ratios for all the units at 12°C. The fact that this was not observed

Table 4.7: COD/VSS ratios for activated sludge treating raw domestic sewage.

Sludge age (days)	COD/VSS Ratio			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3	1,578	0,057	1,458	0,041
8	1,494	0,025	1,504	0,045
20	1,494	0,038	1,485	0,037



SLUDGE AGE	COD/VSS RATIO			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3 days	1,578	0,057	1,458	0,041
8 days	1,494	0,025	1,504	0,045
20 days	1,494	0,038	1,485	0,037

Figure 4.10: Mean and standard deviation of the COD/VSS ratio from a statistical plot.

(in the experimental COD/VSS ratios) would indicate that the fat solidification hypothesis is not supported. Despite careful examination it was not possible to find a satisfactory explanation for the low MLVSS concentration at 20°C as compared to 12°C for these units.

With regard to the validity of the mean COD/VSS ratios for the short sludge age units, the reliability was considered acceptable (as the cause for poor COD recoveries at 12°C had readily been established indicating no error in the COD and VSS determinations in these units). It is quite clear from Table 4.7 (and a 'Student-t' test analysis) that there is a significant increase in the COD/VSS ratio at the lower temperatures.

To complete the analysis, it was necessary to get an indication of the effects of changes in sludge age on the COD/VSS ratio of activated sludge treating a raw domestic sewage. From the results as reflected in Table 4.7, the changes in the COD/VSS ratio due to changes in temperature and sludge age can be determined; these are given in Table 4.8.

By applying a 'Student-t' test analysis to the results in Tables 4.7 and 4.8 it was concluded that:

Table 4.8: Changes in the COD/VSS ratio of activated sludge (treating raw domestic sewage) due to changes in temperature and sludge age.

Changes in sludge age (days)	Changes in COD/VSS Ratio	
	12°C	20°C
3 to 8	- 0,084	+ 0,046
8 to 20	0,000	- 0,019

(1) At 12°C, the COD/VSS ratio significantly increased from the longer sludge ages (8 to 20 days) to the short sludge age (3 days). This observation therefore appears to support our hypothesis that fat solidification at the lower temperature can significantly increase the COD/VSS ratio in a short sludge age unit.

(2) At 20°C, the statistical analysis indicated a significant change in the COD/VSS ratio from a 3 day sludge age to an 8 day sludge age; in contrast, there was no significant change indicated from a 3 day sludge age to a 20 day sludge age. However, a statistical analysis revealed no significant change in the COD/VSS ratio at the longer sludge ages (8 and 20 days) at either 20°C or 12°C; consequently it was accepted that there was no significant change in the COD/VSS ratio at 20°C between the short (3 days) and longer (8 and 20 days) sludge ages.

From the experiments (and conclusions) above it would appear that the COD/VSS ratio tended to be higher at the lower temperatures for the short sludge ages. However the marked differences in response as regards the MLVSS concentrations cast the whole set of experiments into doubt. A repitition of this set of experiments was indicated, but as the apparently more sensitive area (with respect to the COD/VSS ratio) was in the short sludge age region between high and low temperatures it was decided to focus further attention on this sludge age and inaugurate a new set of experiments with two 3 day sludge age units at 20°C and two 3 day sludge age units at 12°C. This set of experiments was conducted on the same sewage as the previous set, it being presumed that no appreciable changes had occurred in the characteristics of the raw domestic sewage in the interval between the two sets. A summary of the experimental design parameters is listed in Table 4.9.

All four aerobic units were tested for a period of 40 days. The daily performance of these units is plotted in Figures 4.11 to 4.14; the experimental data is recorded in Appendix A, Tables A.7 to A.10. Figures 4.11 and 4.12 reflect the daily data for the two units at 20°C and Figures 4.13 and 4.14 the daily data for the two units at 12°C. It is clear from these plots that the four units

Table 4.9: Experimental design parameters for the 3 day sludge age units at 12°C and 20°C treating raw domestic sewage.

Sludge age (days)	Volume (liters)	Flow ($\ell.d^{-1}$)	Average Influent COD
3	6,0	18,0	600

were very stable for the duration of this set of experiments. Before analysing this data kinetically, the reliability of this data was tested by checking the COD and N recoveries achieved.

COD and N balances

COD and N balances were performed on all the measured data and these are shown in Figures 4.15(a) and 4.15(b); a summary of the average COD and N recoveries (using the experimentally measured COD/VSS ratio) is given in Table 4.10.

It is clear from Figures 4.15(a) and 4.15(b) (and also Table 4.10) that good COD and N recoveries were achieved for all four units. An analysis of the kinetic response therefore could be undertaken with confidence.

Table 4.10: Average percentage COD and N recoveries for the 3 day sludge age units at 12°C and 20°C treating raw domestic sewage.

Sludge age (days)	Average COD recovery (%)		Average N recovery (%)	
	12°C	20°C	12°C	20°C
3	99,6	100,4	100,2	100,5
3	99,7	100,2	100,2	99,5

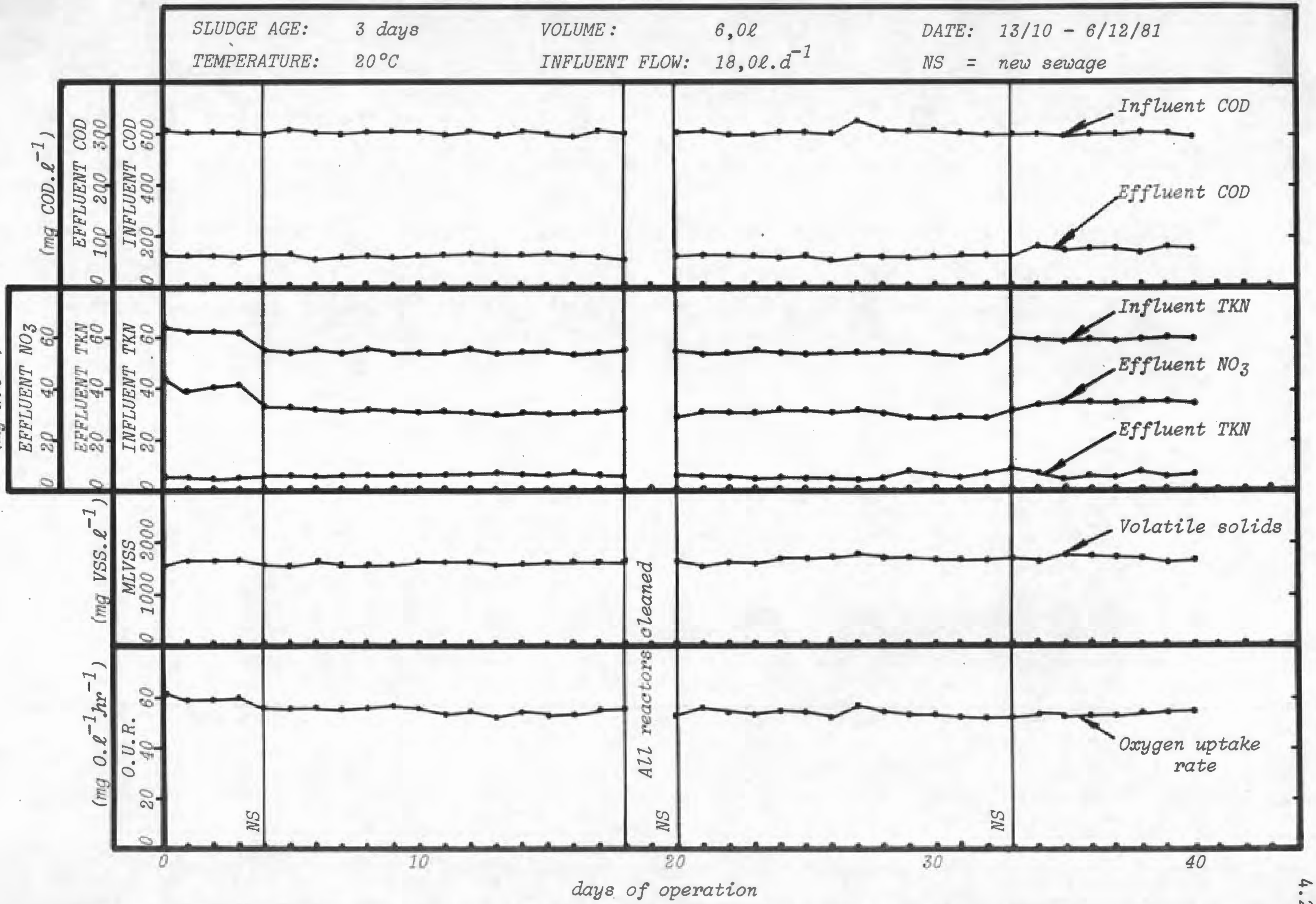


Figure 4.11: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage.

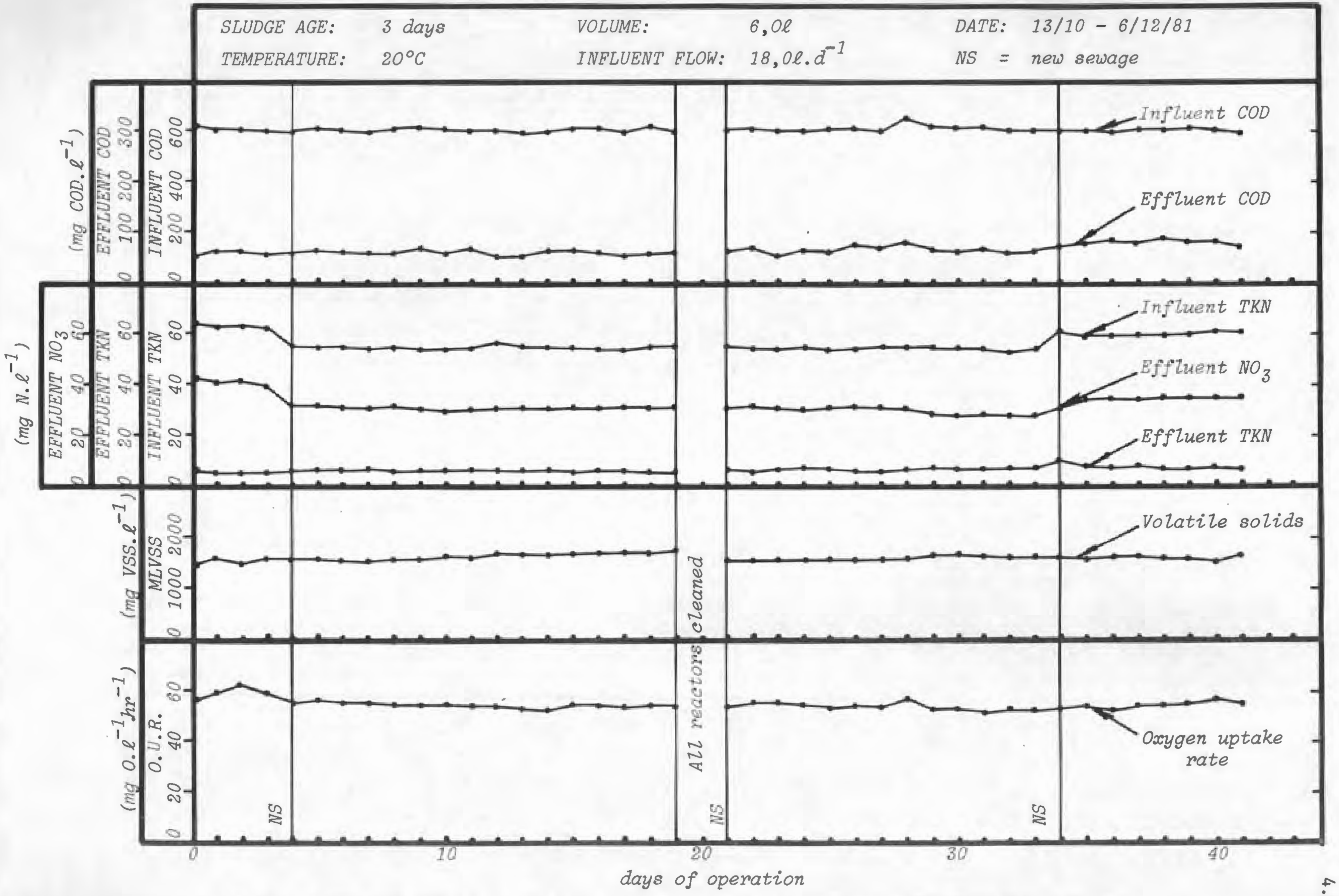


Figure 4.12: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage.

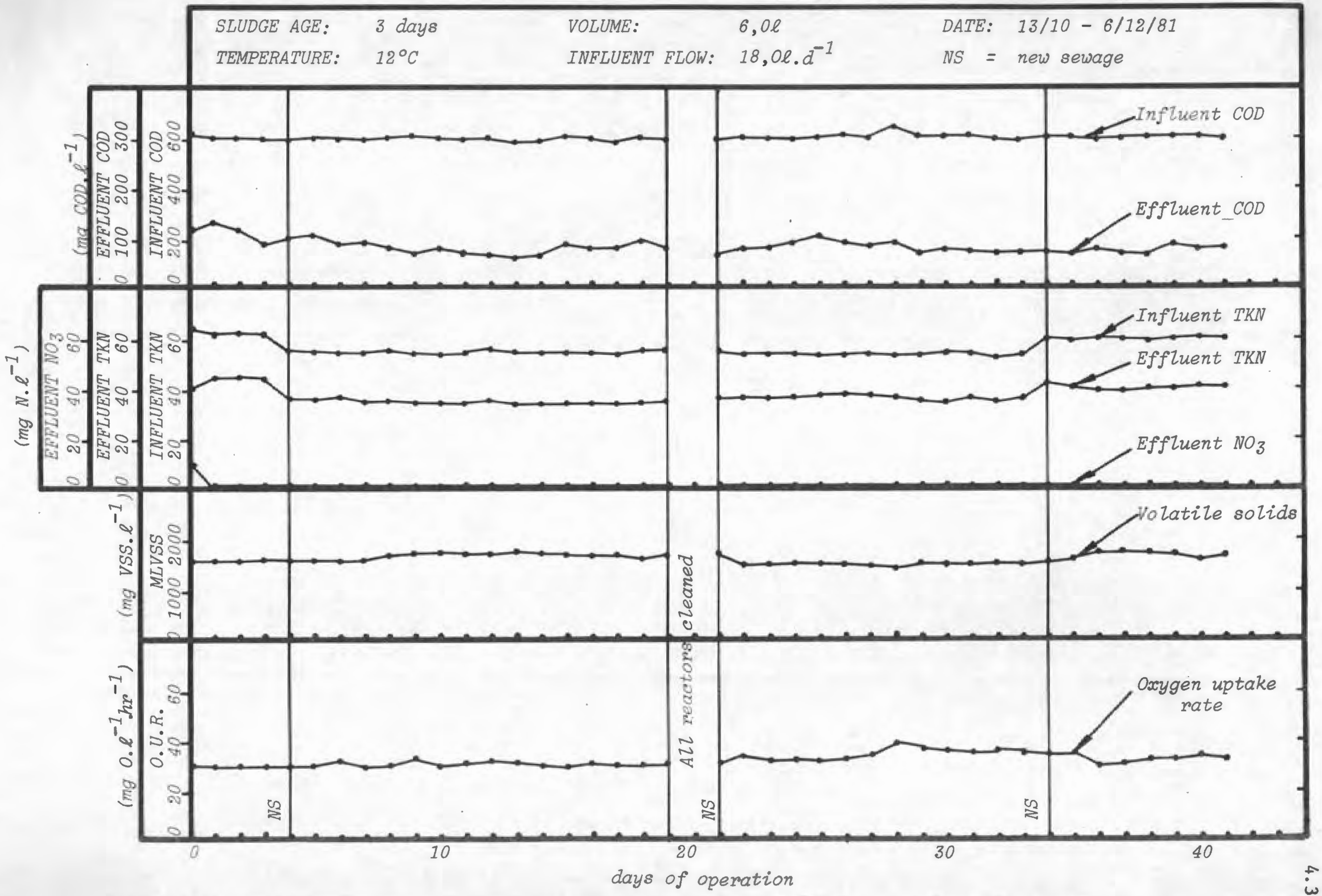


Figure 4.13: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage.

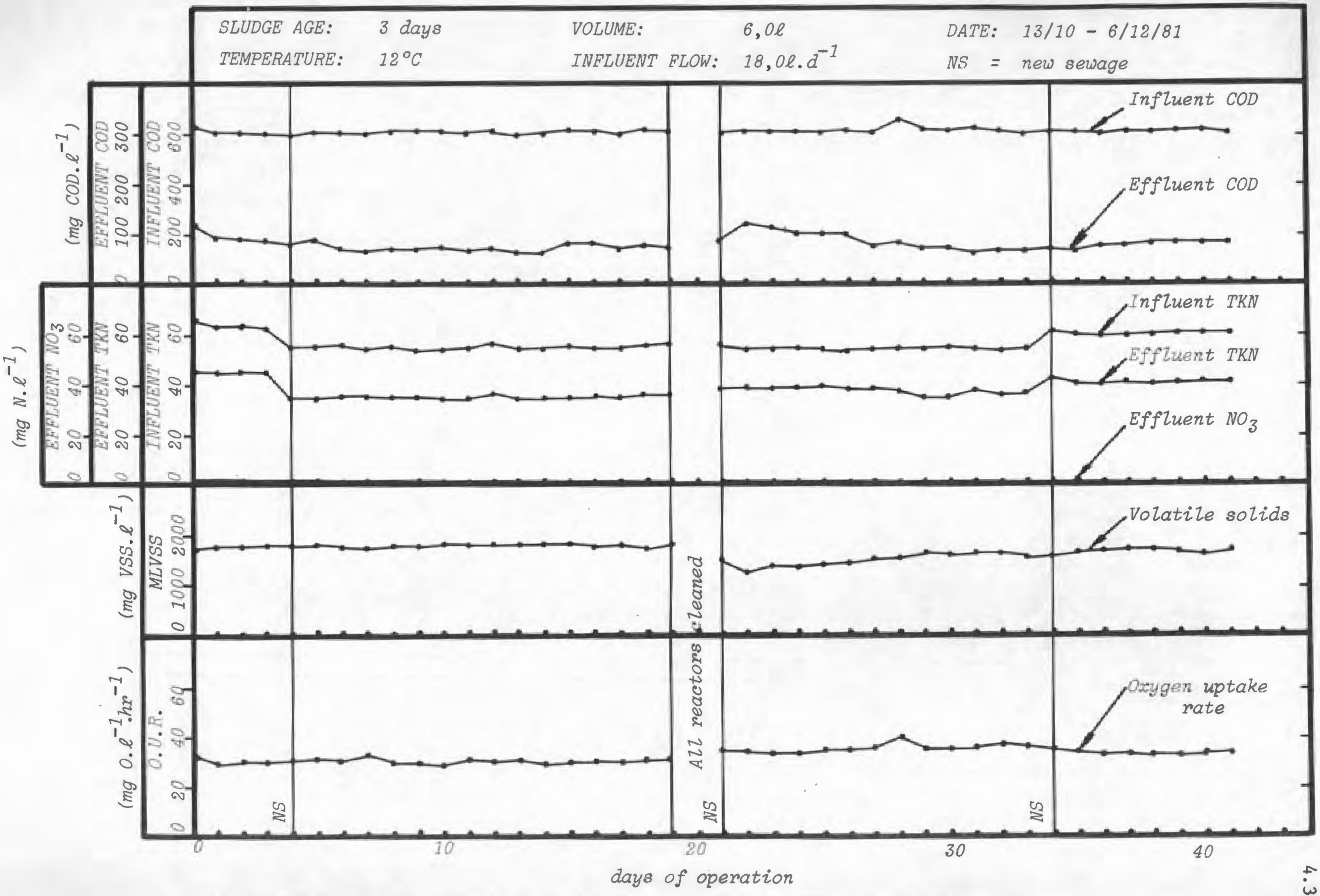


Figure 4.14: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage.

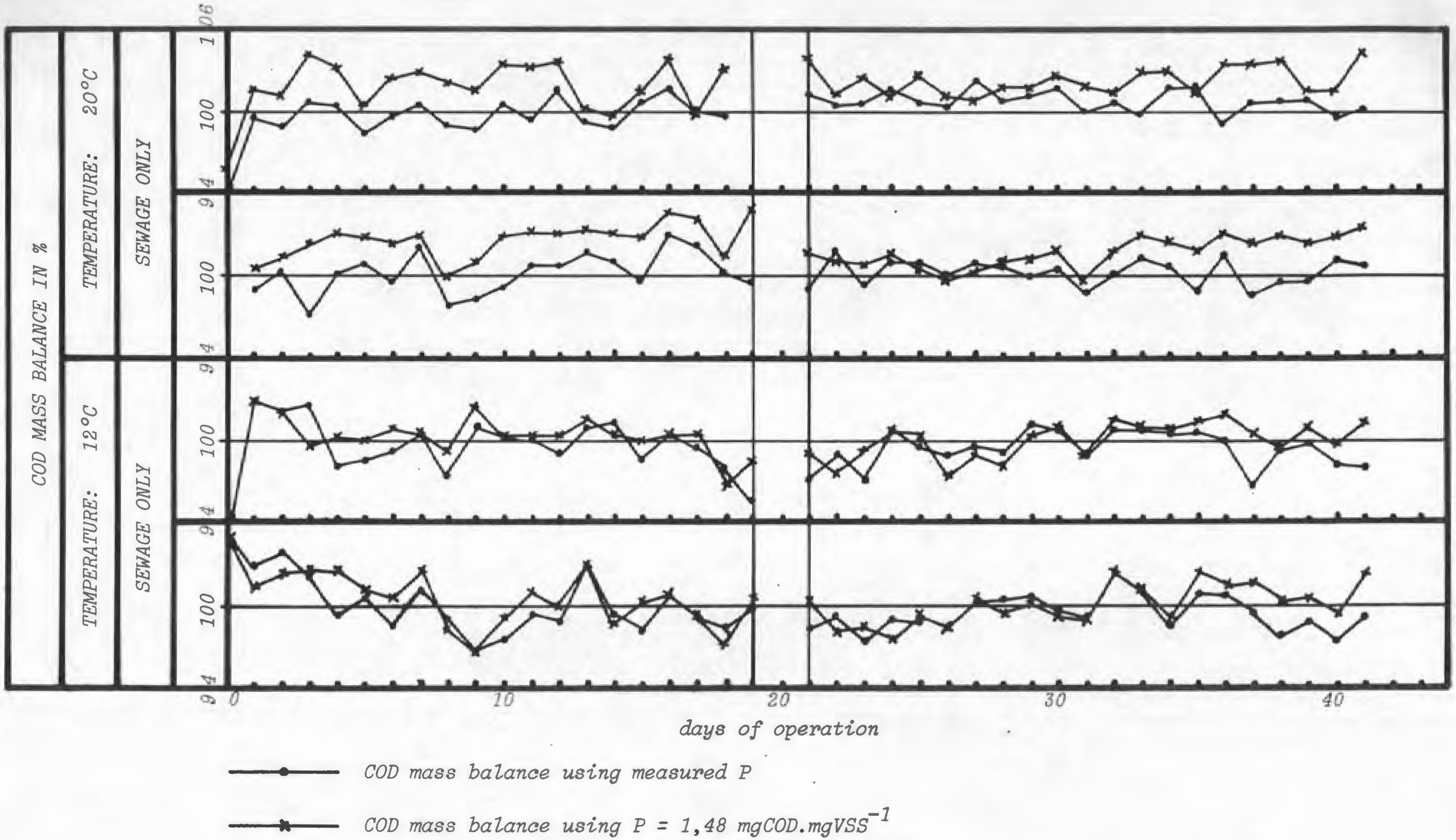


Figure 4.15(a): COD mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C treating domestic sewage.

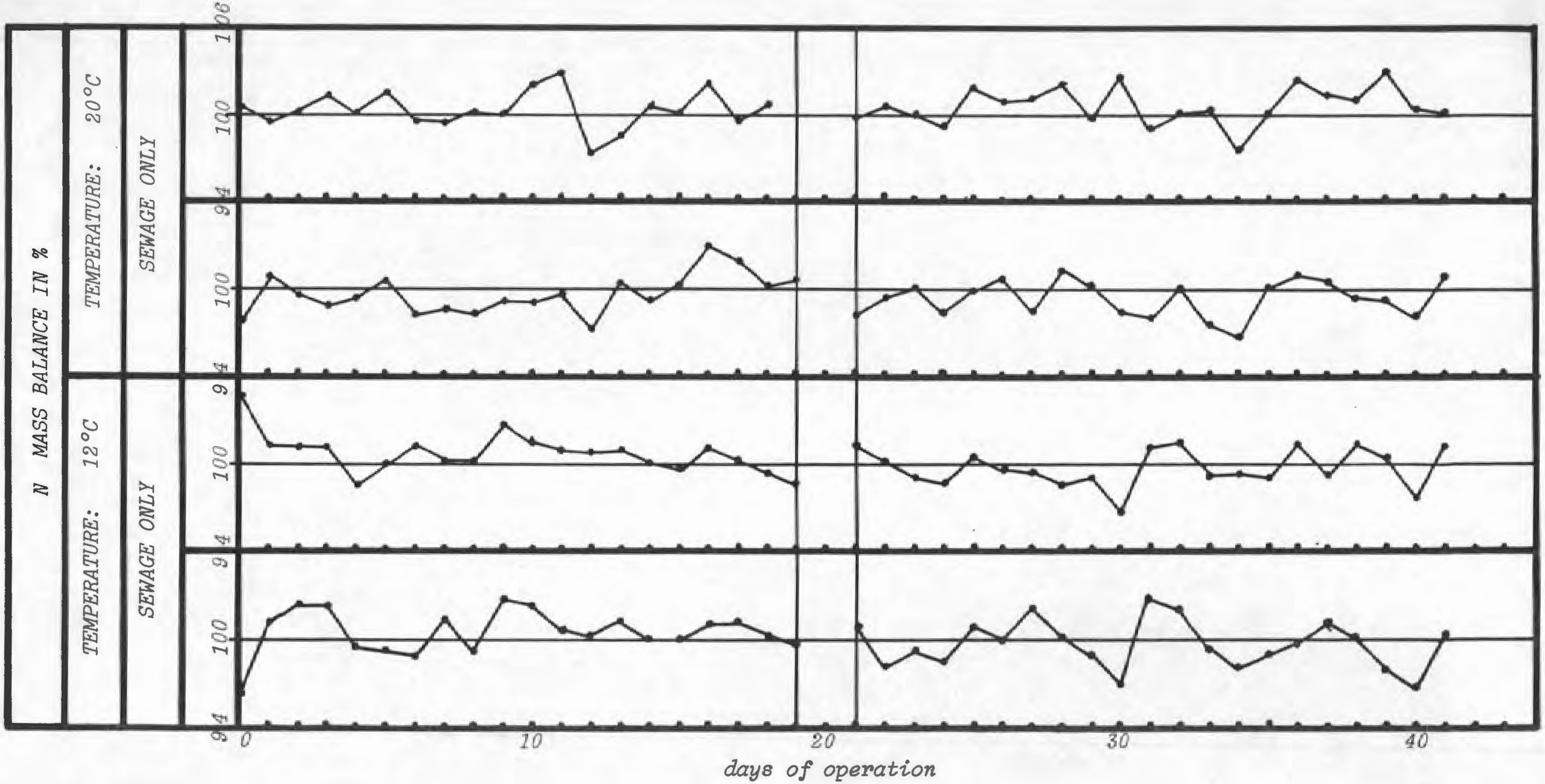


Figure 4.15(b): N mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C treating domestic sewage.

Table 4.11: Mean experimental response for the 3 day sludge age units at 12°C and 20°C.

Sludge age (days)	Temp (°C)	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_V $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell.\text{hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	N_{NE} $\frac{\text{mgN}}{\ell}$
3	12	605	56,3	1660	33,1	87	38,3	1,1
	12	605	56,3	1698	33,0	81	38,5	0,3
	20	605	56,3	1627	54,5	62	6,1	32,5
	20	605	56,3	1630	54,5	67	6,6	32,3

Kinetic Response Analysis

Making use of the experimental data for the periods that resulted in good COD and N recoveries, the mean experimental response for each unit was determined; this is reflected in Table 4.11.

From the results as shown in Table 4.11, the observed mean response for each set of units at 20°C and 12°C respectively were, for all practical purposes, identical. From the experimental COD and TKN balances (Figures 4.15(a) and 4.15(b), and also Table 4.10) the good recoveries achieved showed that the data was reliable and could form a basis for analysis of the COD/VSS ratio and the theoretical kinetic response. Making use of the kinetic constants as shown in Table 4.4, the theoretical kinetic response (with the aid of the steady state model) was calculated; as previously discussed the *actual* sludge age was determined prior to finding the correct f_{up} to give the measured X_V concentration. The results of this analysis are given in Table 4.12.

Comparing the experimentally observed and the theoretically predicted response for each unit (Table 4.11 versus Table 4.12) indicates that the response parameters show an insignificant difference. Also, the value for f_{up} remained relatively constant from 20°C to 12°C - this is in contrast to an earlier observation (see Table 4.6) indicating therefore that the substantial increase in f_{up} from 20°C to 12°C (shown in Table 4.6) remains an unexplained

Table 4.12: Theoretical response for the 3 day sludge age units at 12°C and 20°C using the actual sludge age and f_{up}.

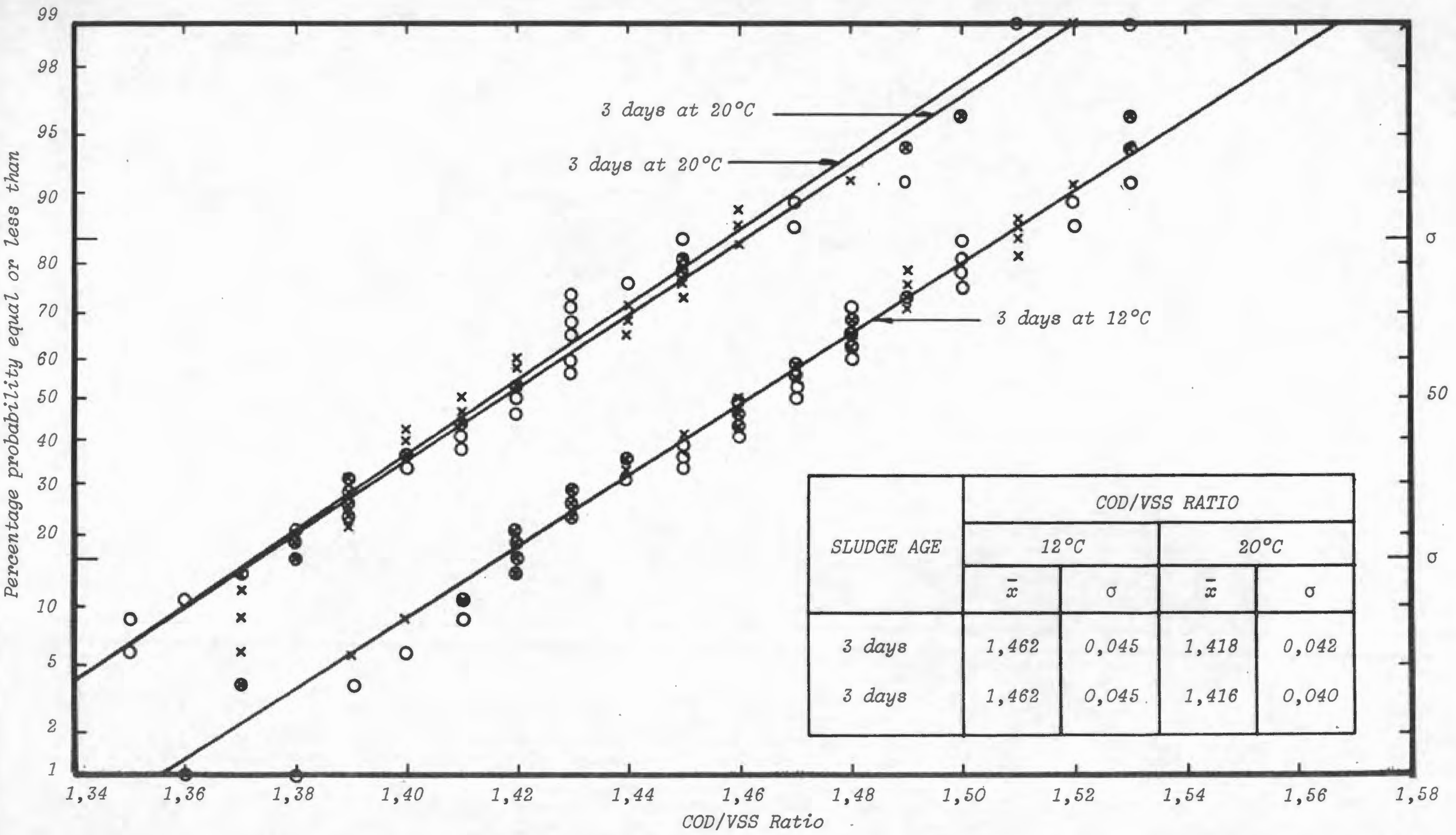
Temp (°C)	Sludge age (days)		f_{up} $\frac{mgCOD}{mgCOD}$	X_V $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	N_{NE} $\frac{mgN}{\ell}$
	Nom.	Act.						
12	3	2,66	0,085	1532	30,9	88	36,9	0,0
12		2,66	0,085	1532	30,9	88	36,9	0,0
20	3	2,80	0,08	1534	51,8	67	3,1	35,6
20		2,80	0,08	1534	51,8	67	3,1	35,6

phenomenon. Noting that good COD recoveries were achieved, the measured COD/VSS ratios therefore could be accepted as representative of the specific operating conditions. An analysis of these should give a reliable indication of the effect a change in temperature can have on the COD/VSS ratio of activated sludge at the short sludge ages.

Statistical Analysis of COD/VSS ratios

Figure 4.16 shows the daily measured COD/VSS ratios versus the percentage probability for the four single-reactor aerobic units operated at a 3 day sludge age, all units treating the same raw domestic sewage. The mean $(\bar{x})$ and corresponding standard deviation (σ) of the COD/VSS ratio for each of the four aerobic units was determined from Figure 4.16 and is given in Table 4.13.

The results in Table 4.13 illustrate that the mean COD/VSS ratio for the two units at 20°C is the same; this applies to the two units at 12°C as well. Furthermore, the COD/VSS ratio shows a distinct increase at the 3 day sludge age from a temperature of 20°C to 12°C. From a 'Student-t' test analysis it was concluded that there is a significant increase in the COD/VSS ratio at the 3 day sludge age when the temperature decreased from 20°C to 12°C. This observation was already made in the previous set of experiments (see Table 4.7). Remembering our hypothesis it should be



SLUDGE AGE	COD/VSS RATIO			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3 days	1,462	0,045	1,418	0,042
3 days	1,462	0,045	1,416	0,040

Figure 4.16: Mean and standard deviation of the COD/VSS ratio from a statistical plot.

Table 4.13: COD/VSS ratio for activated sludge treating raw domestic sewage.

Sludge age (days)	COD/VSS Ratio			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3	1,462	0,045	1,418	0,042
3	1,462	0,045	1,416	0,042

noted that the above observed increase in the COD/VSS ratio could be due to the presence of fats in the raw domestic sewage as the influent most probably already contained such substances.

Comparing the mean COD/VSS ratios measured for a 3 day sludge age in the previous and this set of experiments at both 20°C and 12°C (Table 4.7 versus Table 4.13) it is interesting to note that the mean COD/VSS ratios were higher for the previous set (at both 12°C and 20°C) than those in this set. This is illustrated in Table 4.14.

A 'Student-t' test analysis indicated a significant change in the COD/VSS ratios at both 20°C and 12°C (as shown in Table 4.14).

Table 4.14: Changes in COD/VSS ratio at a 3 day sludge age between the previous and this set of experiments.

Experiments	Changes in COD/VSS Ratio	
	12°C	20°C
from previous set to this set of	- 0,116	- 0,041

The only satisfactory explanation for the observed behaviour is as follows: The experimental COD/VSS ratios recorded during the previous set of experiments (see Table 4.7) were determined from activated sludge treating a raw domestic sewage collected at the Mitchell's Plain Sewage Works during the winter months (in contrast to the latter where it was collected during late spring). It is likely that the diet of the residents could contain a relatively higher proportion of fats during winter compared to summer. Therefore, if this explanation is acceptable, then the observations made in Table 4.14 appear to support our hypothesis that the COD/VSS ratio can increase at the short sludge ages. An interesting aspect from the results in Table 4.14 and the above discussion is that, although the relative change in the COD/VSS ratio at 20°C was less than at 12°C, there was nonetheless a significant change (probably because some fats were in an emulsified form at 20°C and therefore more amenable to biodegradation). A comparison between the mean COD/VSS ratios for the long sludge ages (8 and 20 days in Table 4.7) and the short sludge age (3 days in Table 4.13) is strictly not valid due to the observed significant changes in the COD/VSS ratio at the 3 day sludge age between the previous and this set of experiments (possibly due to changes in the sewage characteristics).

Summarizing, some of the conclusions drawn from the above investigation regarding the COD/VSS ratio of activated sludge treating raw domestic sewage were:

(1) At the longer sludge ages used in this investigation (8 to 20 days), neither the operating temperature nor the operating sludge age had any significant effects on the COD/VSS ratio.

(2) At the short sludge age (3 days) in this investigation, there is an indication that the COD/VSS ratio increases for a temperature drop from 20°C to 12°C.

(3) At 12°C, there is an indication of an increase in the COD/VSS ratio when the sludge age is shortened from 8 and 20 days to 3 days. At 20°C, this increase was not evident.

(4) Considering the effects as a whole, from a practical design point of view, the changes in the COD/VSS ratio are insignificant. The value for the ratio proposed by Ekama and Marais (1978) *i.e.* COD/VSS = 1,48 $mgCOD.mgVSS^{-1}$, for processes treating municipal effluents does not appear to be significantly different to that found here (*i.e.* 1,46 to 1,57) and seems to be reasonably representative for sludge ages ranging from 3 to 20 days and temperatures from 12°C to 20°C.

(5) Although there are indications that fats in the Mitchell's Plain sewage have an effect on the COD/VSS ratio, this effect is not definitely established because of the small changes in the COD/VSS ratio observed. Also, although the reported fat concentrations are high, there is some doubt regarding these values* so that the effect of fats is still indeterminate.

From the first three conclusions above it would appear that the most sensitive conditions to detect the effects of fats on the COD/VSS ratio are at the short sludge age (3 days) and at 12°C and 20°C. Consequently it was decided to inaugurate a new set of experiments in which the fat content of the influent to the 3 day sludge age units at 12°C and 20°C was artificially increased.

4.2.2 Effects of long-chain fatty acid addition on the COD/VSS ratio of activated sludge

To test our hypothesis that a substantial accumulation of long chained fatty acids in the sludge mass can increase the COD/VSS ratio, especially at the short sludge ages and low temperatures, oleic acid was chosen as representative because: (1) it is a common unsaturated long-chain fatty acid in domestic sewage, (2) the unsaturated long-chain fatty acids are relatively more soluble in water than their saturated analogues, thus any effects on the COD/VSS ratio noted from the presence of unsaturated long-chain fatty acids can be expected to apply to saturated long-chain fatty acids as well, and (3) oleic acid has a melting point of 13°C, in other words it would be in an

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*From Figures 2.1 and 2.2 (see Chapter 2) the mean fat concentration is of the order of 450 $mg.\ell^{-1}$. If this concentration is multiplied by 2,6 (the average COD/VSS ratio for fats) to give the equivalent COD, then this would come to $450x2,6 \cong 1200$ $mgCOD.\ell^{-1}$; yet the total COD of this sewage (as collected) did not exceed 1200 $mgCOD.\ell^{-1}$ - it is extremely unlikely that *all* the COD in this influent sewage was due to fats.

emulsified form at 20°C and therefore prone to enzymatic breakdown; at 12°C however it will be in a solid state and therefore relatively resistant to biodegradation. This should highlight the effect of fatty acids on the COD/VSS ratio of activated sludge at the lower temperatures.

The influent substrate to one of each pair of 3 day sludge age units at 12°C and 20°C respectively was supplemented by 22 percent of influent COD by mass with oleic acid (*i.e.* 4ℓ oleic acid at 600 mgCOD.ℓ$^{-1}$ plus 14ℓ raw domestic sewage at 600 mgCOD.ℓ$^{-1}$ to give a total influent substrate flow of 18ℓ at 600 mgCOD.ℓ$^{-1}$). As a control the other unit of each pair received 18ℓ of raw domestic sewage at 600 mgCOD.ℓ$^{-1}$, from the same source (the Mitchell's Plain Sewage Works) as before. Thus all four aerobic units (under constant flow and load conditions) received *the same total mass of COD daily;* the total mass of TKN varied depending on the amount of oleic acid added. A summary of the experimental design parameters is shown in Table 4.15.

Table 4.15: Experimental design parameters with and without an oleic acid addition of 22 percent of influent COD by mass.

Sludge age (days)	Volume (liters)	Influent Flow (ℓ.d^{-1})		Average Influent COD (mgCOD.ℓ$^{-1}$)	
		Sewage	Oleic Acid	Sewage	Oleic Acid
3	6,0	18,0	-	600	-
3	6,0	14,0	4,0	600	600

The four units were tested over a period of 32 days. The daily experimental data (as recorded in Appendix A, Tables A.11 to A.14) is plotted in Figures 4.17 to 4.20. Figures 4.17 and 4.19 show the daily performance of the 3 day sludge age units at 20°C and 12°C respectively which received only sewage as the influent substrate; it was necessary to operate these two units in parallel to the units that received the mixture of sewage plus oleic acid so that changes (if any) in the COD/VSS ratio due to the addition of oleic acid could be shown up. Figures 4.18 and 4.20 show the daily performance of the 3 day sludge age units at 20°C and 12°C respectively that received 22 percent of COD by mass as oleic acid.

COD and N balances

To check the reliability of the above data, COD and N balances were performed; these are plotted in Figures 4.21(a) and 4.21(b) respectively. Table 4.16 summarizes the average COD and N recoveries achieved (using the experimentally measured COD/VSS ratios).

It is clear from Figures 4.21(a) and 4.21(b) (and Table 4.16) that good COD and N recoveries were achieved; subsequently the experimental data was analysed kinetically with confidence.

Table 4.16: Average COD and N recoveries for the 3 day sludge age units at 12°C and 20°C with and without an oleic acid addition of 22 percent of COD by mass.

Sludge age (days)	Average COD recoveries (%)		Average N recoveries (%)	
	12°C	20°C	12°C	20°C
3 days (18ℓ sewage)	98,3	100,2	99,4	99,9
3 days (14ℓ sewage plus 4ℓ oleic acid)	98,6	99,5	99,8	99,1

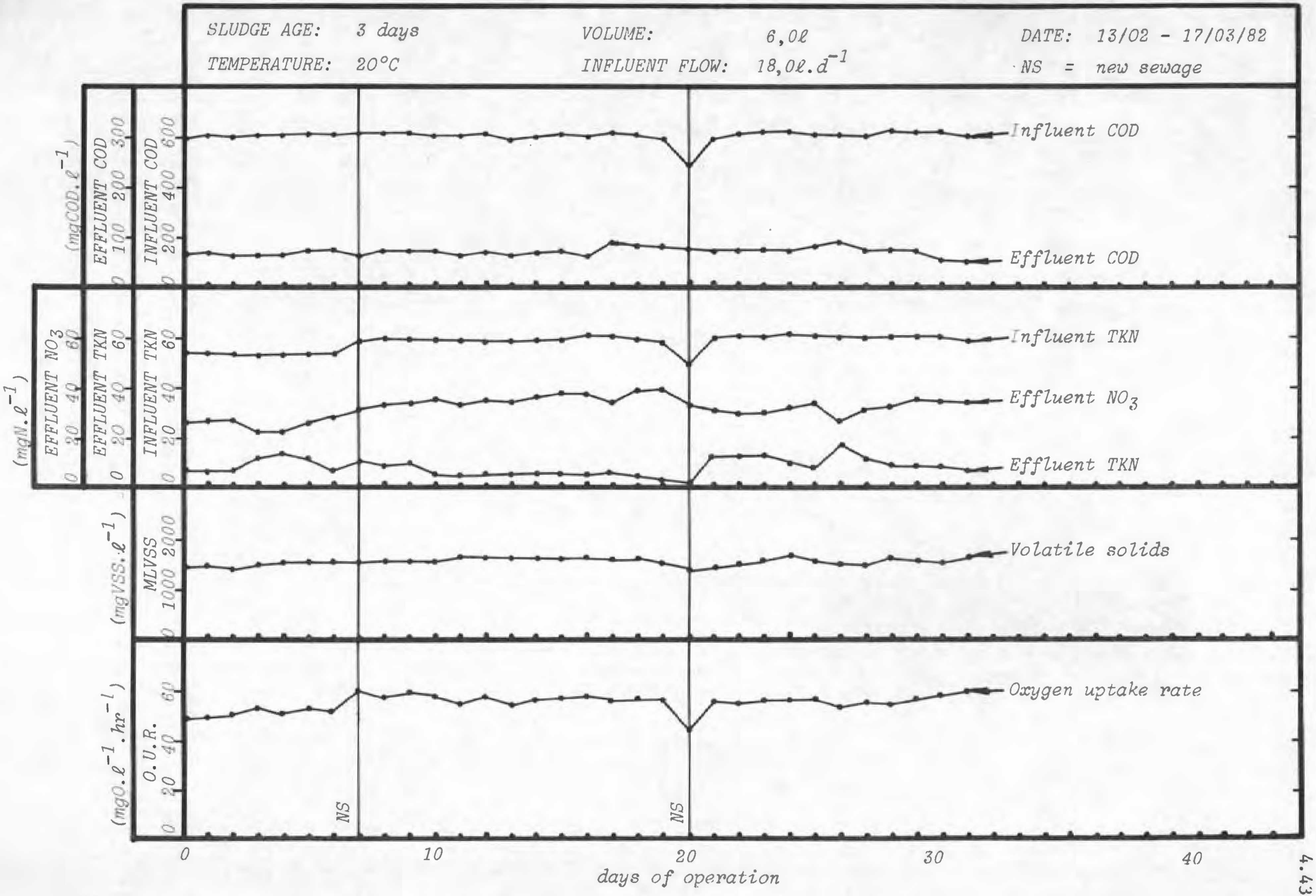


Figure 4.17: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage only.

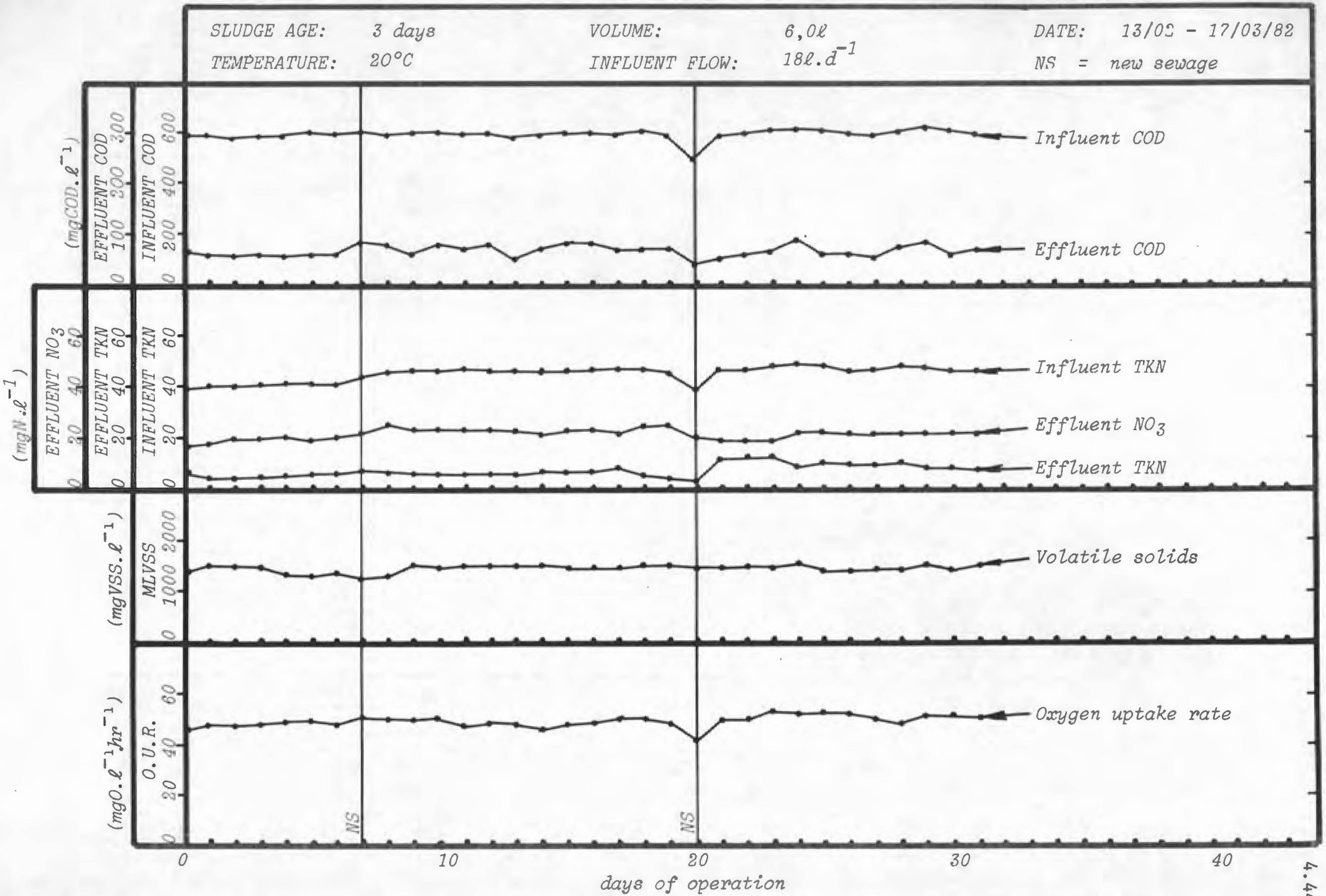


Figure 4.18: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage spiked with 22% of influent COD by mass oleic acid.

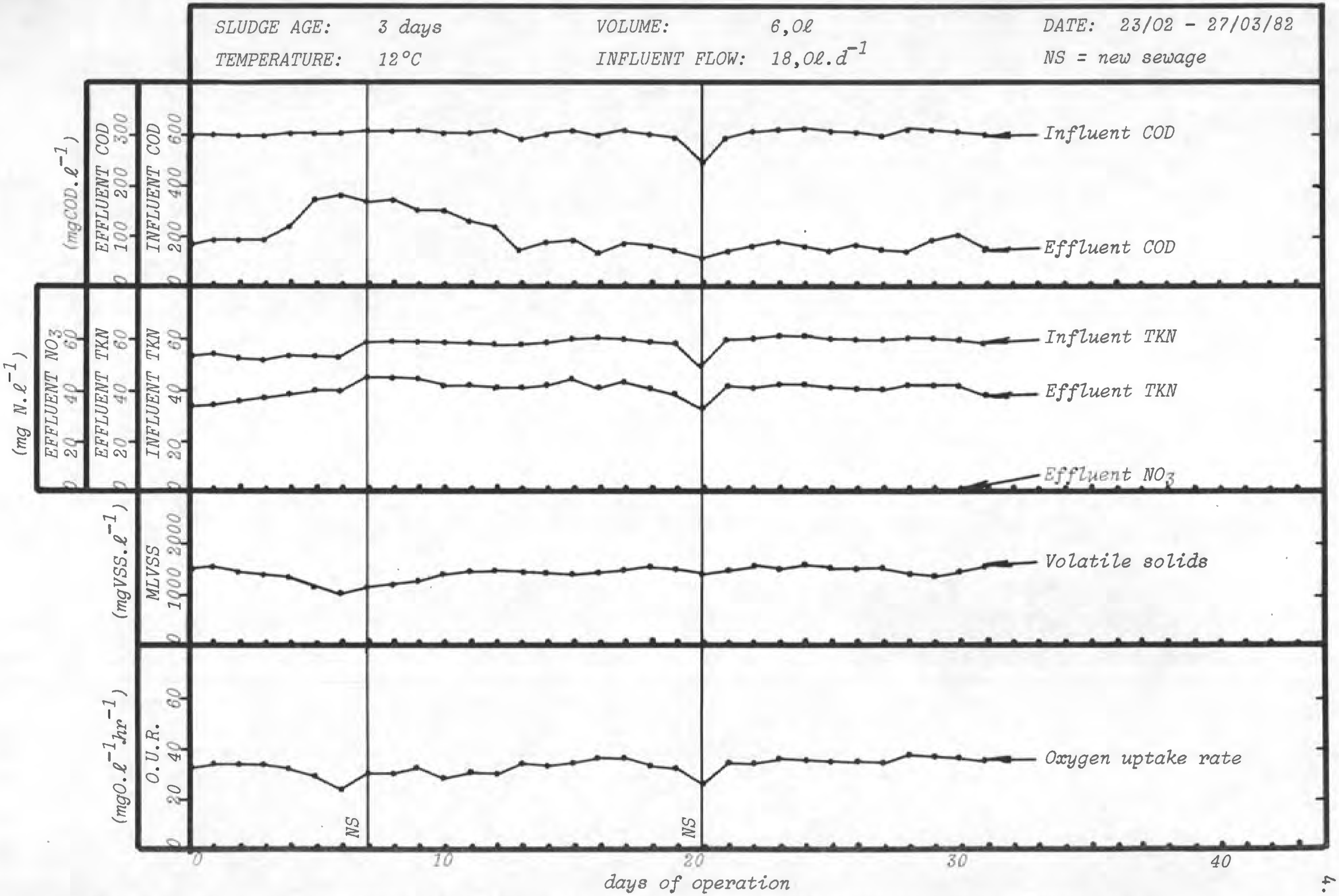


Figure 4.19: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage only.

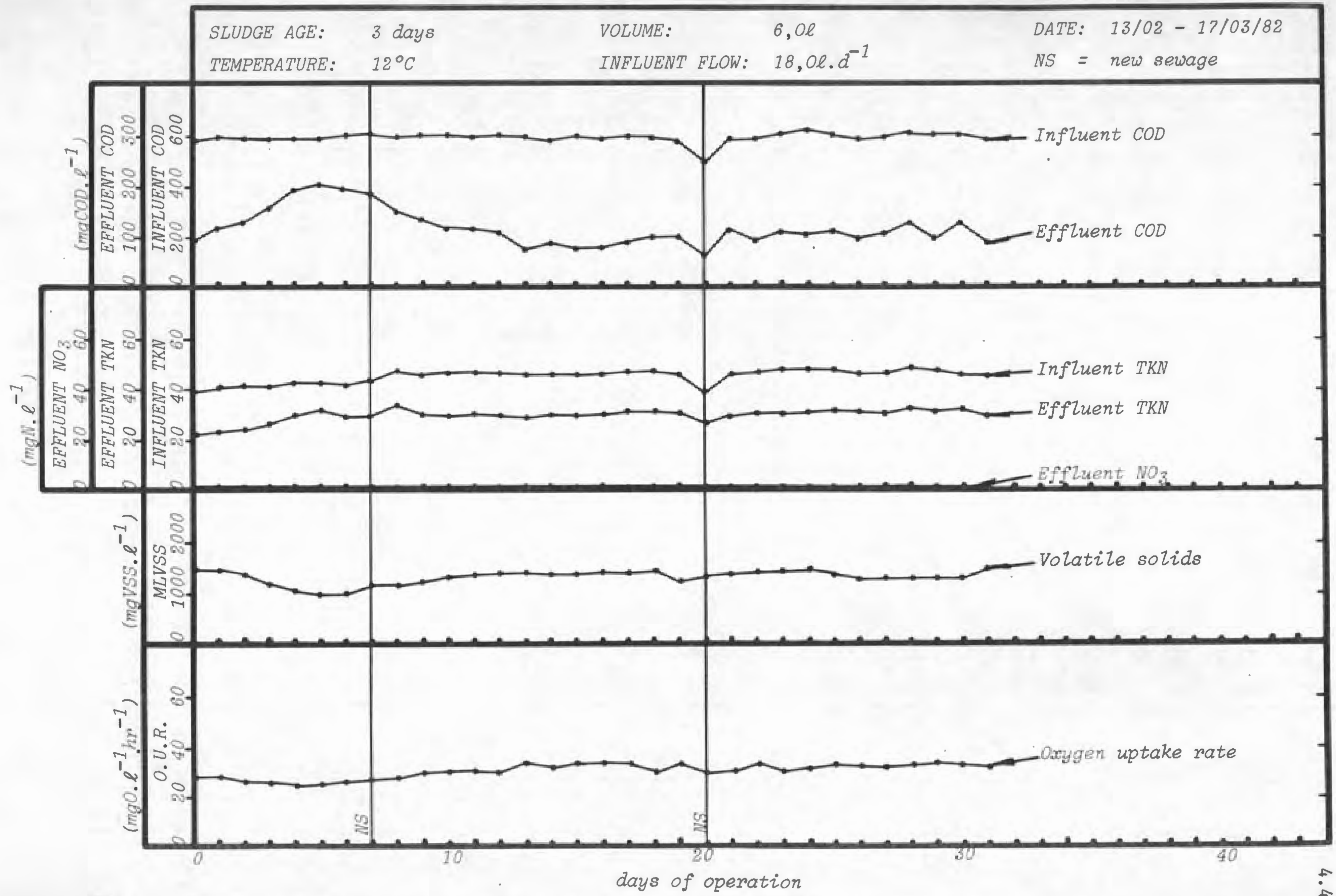


Figure 4.20: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage spiked with 22% of influent COD by mass oleic acid.

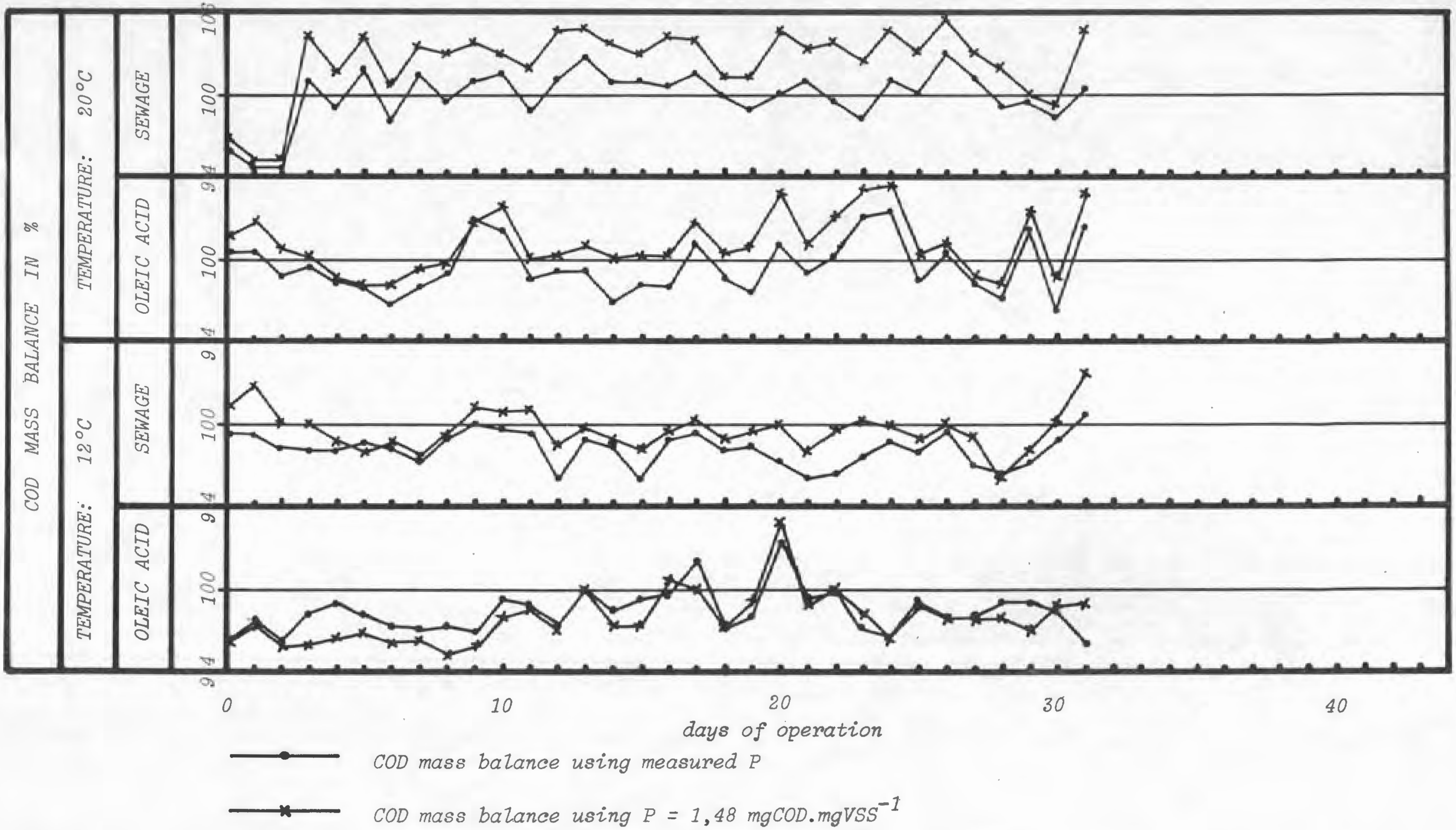


Figure 4.21(a): COD mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C with and without an oleic acid addition of 22% of influent COD by mass.

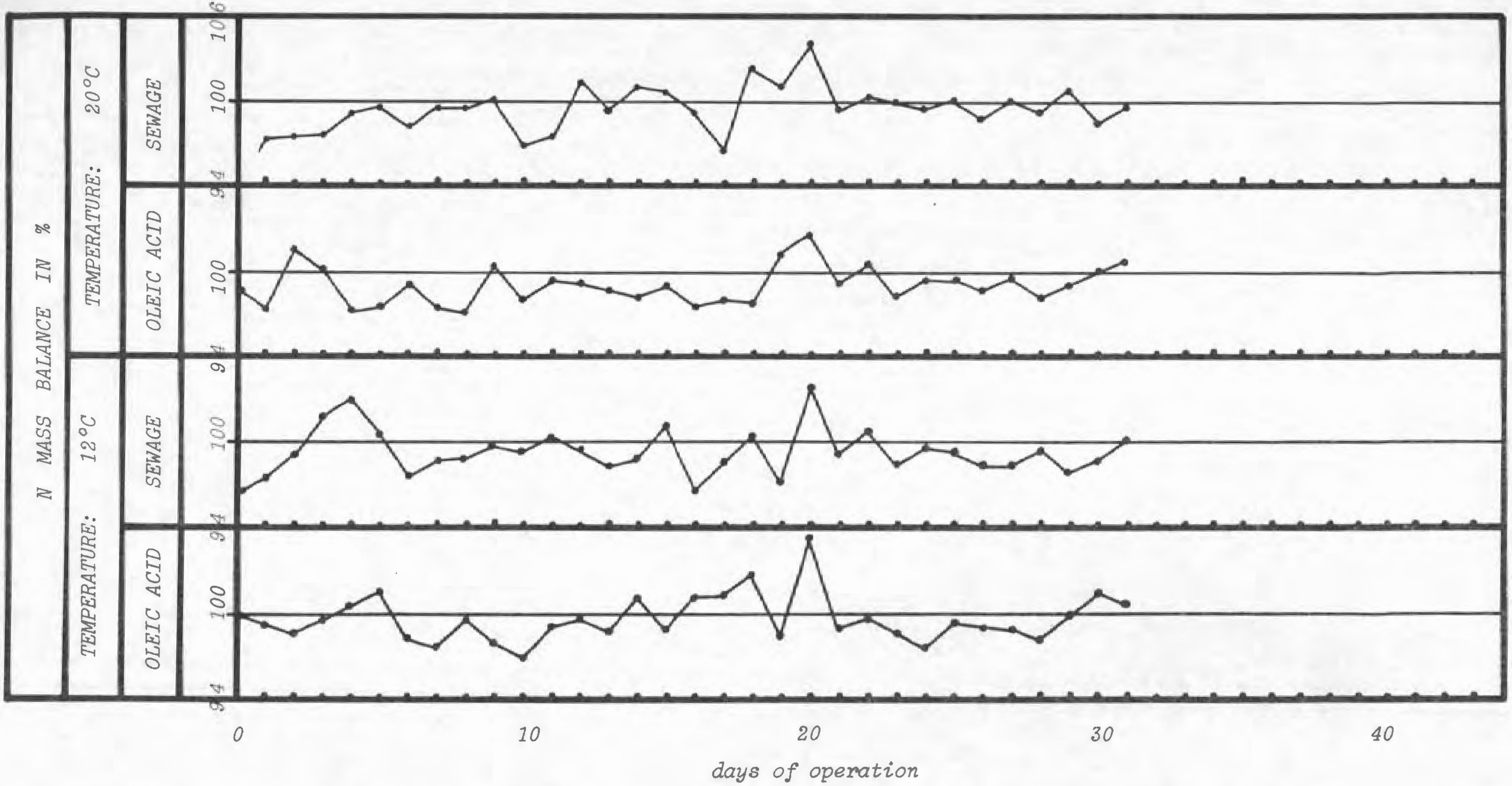


Figure 4.21(b): N mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C with and without an oleic acid addition of 22% of influent COD by mass.

Kinetic Response Analysis

The mean experimental response for each of the four units was determined from the daily data; a summary is shown in Table 4.17.

The differences in the filtered and unfiltered effluent COD concentrations (see Table 4.17) indicate a volatile suspended solids (VSS) loss in the effluent (due to inefficient settling) which in turn would affect the nominal sludge age. Accordingly the actual sludge ages were calculated from the mass of sludge abstracted per day (via the sludge waste flow) and that due to the loss of VSS per day in the effluent. After determining the actual sludge ages, the 'correct' f_{up} was calculated using the kinetic constants in Table 4.4 to yield the measured X_V; Table 4.18 summarizes this analysis.

Comparing the two units treating raw domestic sewage only at 12°C and 20°C (Table 4.18) to the units operated earlier (Table 4.12) it is clear that these units continued to behave in the same consistent manner as before; note that f_{up} remained the same as before *i.e.* f_{up} = 0,08 - 0,085. The units receiving a mixture of sewage plus oleic acid gave lower f_{up} values at both 20°C and 12°C *i.e.* f_{up} = 0,062 and 0,066 respectively.

Table 4.17: Mean observed response for the 3 day sludge age units at 12°C and 20°C with and without an oleic acid addition of 22 percent of COD by mass.

Temp. (°C)	Infl. Charac.	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_V $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	N_{NE} $\frac{mgN}{\ell}$
12	Sewage	606	57,5	1414	33,2	101	40,2	0,5
12	Oleic Acid	602	45,6	1334	32,5	115	30,2	0,5
20	Sewage	598	57,5	1519	55,0	68	8,1	31,8
20	Oleic Acid	593	45,5	1445	49,6	67	7,4	21,9

filtered effluent COD concentration ≅ 45-50 mgCOD.ℓ^{-1}

Table 4.18: Theoretical response for the 3 day sludge age units at 12°C and 20°C with and without an oleic acid addition of 22 percent of COD by mass using the actual sludge age and f_{up}.

Temp. (°C)	Infl. charac.	Sludge age (actual)	f_{up} $\frac{mgCOD}{mgCOD}$	X_V $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	N_{NE} $\frac{mgN}{\ell}$
12	Sewage	2,47	0,085	1391	33,3	105	39,1	0,0
12	Oleic Acid	2,30	0,066	1234	32,8	118	27,1	0,0
20	Sewage	2,77	0,080	1517	53,0	69	5,0	34,4
20	Oleic Acid	2,77	0,062	1471	47,1	68	4,7	23,3

Comparing all the units in Table 4.18 *i.e.* the units receiving only sewage with those receiving the mixture of sewage *and* oleic acid, the f_{up} (for the sewage plus oleic acid units) should theoretically be less than that for the units treating only sewage *if* the oleic acid was completely biodegraded, because the inert material fraction in the influent to the sewage plus oleic acid units is reduced by 22 percent by making up the total COD input partly as sewage and partly as oleic acid. Reducing the f_{up} value by 22 percent gives f_{up} = 0,062-0,066 which in fact is that observed in the units spiked with oleic acid. The theoretical X_V of the sewage plus oleic acid unit at 20°C is close to that observed experimentally indicating that little or no fat accumulated on the organism. At 12°C however, the predicted X_V concentration is about 100 mgVSS.ℓ^{-1} lower than observed. It appears, therefore, that some of the oleic acid may have accumulated as equivalent 'unbiodegradable' material on the volatile mass at the lower temperature. If this is true, then the accumulation of oleic acid on the sludge mass should affect the COD/VSS ratio in this unit; to check this, a statistical analysis of the measured COD/VSS ratios was necessary.

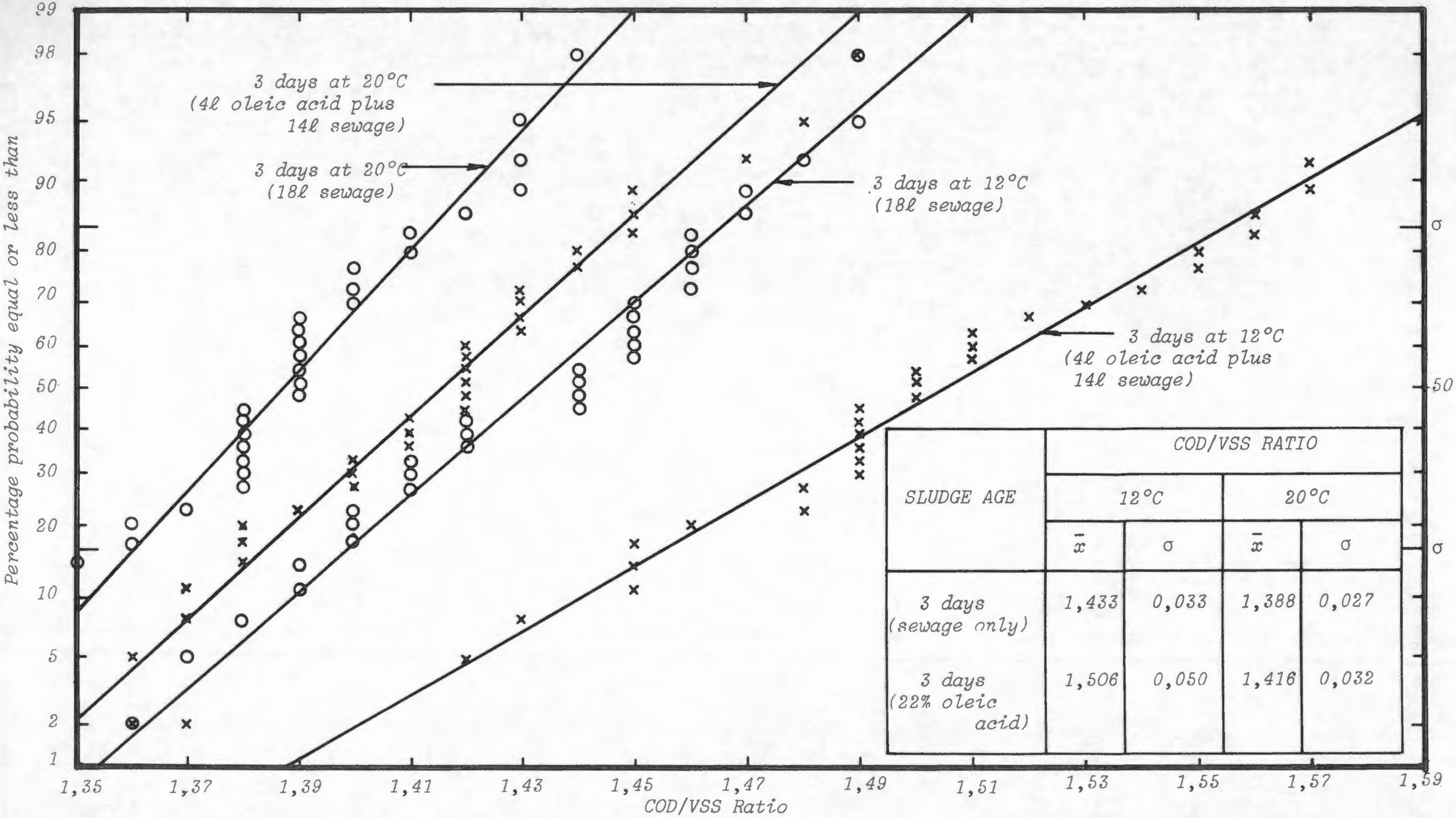
Statistical Analysis of COD/VSS ratios

Figure 4.22 reflects the daily measured COD/VSS ratios versus the percentage probability for the four single-reactor aerobic units at a 3 day sludge age - one of each pair of units at 12°C and 20°C treating 22 percent of influent COD by mass as oleic acid whereas the remaining two units treating raw domestic sewage only. The mean $(\bar{x})$ and standard deviation (σ) of the COD/VSS ratio of activated sludge treating the various substrates at 12°C and 20°C during this set of experiments is given in Table 4.19.

Noting that good COD and N recoveries were achieved, the mean COD/VSS ratios for the four units operated under the varying environmental conditions (as given in Table 4.19) were accepted as representative. A 'Student-t' test analysis showed an increase (significant at a 95 percent confidence level) in the COD/VSS ratio at both 12°C and 20°C due to the addition of oleic acid. Further, the relative increase observed at 12°C is more than at 20°C - this, very likely, can be attributed to the solidification of oleic acid at 12°C. Accepting this it should be possible, at least theoretically, to predict the

Table 4.19: Observed COD/VSS ratios of activated sludge treating raw domestic sewage, and raw domestic sewage spiked with oleic acid.

Sludge age (days)	COD/VSS Ratio			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3 days (18ℓ sewage)	1,433	0,033	1,388	0,027
3 days (14ℓ sewage plus 4ℓ oleic acid)	1,506	0,050	1,416	0,032



SLUDGE AGE	COD/VSS RATIO			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3 days (sewage only)	1,433	0,033	1,388	0,027
3 days (22% oleic acid)	1,506	0,050	1,416	0,032

Figure 4.22: Mean and standard deviation of the COD/VSS ratio from a statistical plot.

increase in the COD/VSS ratio due to the addition of oleic acid as follows:

Stoichiometrically, oleic acid has a COD/VSS ratio of 2,84; assuming that the increase in the observed over the predicted X_V concentration in the 3 day sludge age unit at 12°C treating a mixture of oleic acid and sewage (*i.e.* 100 $mgVSS.\ell^{-1}$, see Tables 4.17 and 4.18) is due to solidification of oleic acid, the COD/VSS ratio for the observed X_V can be calculated as follows:

Oleic acid is 100 x 2,84 = 284 $mgCOD.\ell^{-1}$ and
activated sludge is (1334-100)1,433* = 1768,3 $mgCOD.\ell^{-1}$

then the total COD is (1768,3 + 284) = 2052 $mgCOD.\ell^{-1}$

hence calculate the COD/VSS ratio as

$2052/1334 \cong 1{,}54\ mgCOD.mgVSS^{-1}$

Experimentally, the mean COD/VSS ratio was 1,51 $mgCOD.mgVSS^{-1}$ (see Table 4.19). These two values are quite close and appear to support the hypothesis that the presence of long-chain fatty acids can increase the COD/VSS ratio of activated sludge.

Supporting evidence for the conclusion above should be reflected in the average carbonaceous oxygen consumption rate, O_C:

The mass of oxygen required per day for carbonaceous energy removal is given by

$$M(O_C) = M(S_{TI}) - M(S_{TE}) - P.M(X_V) \qquad 4.1$$

where $M(O_C)$ = mass of oxygen required per day ($mgO.d^{-1}$)
$M(S_{TI})$ = mass of COD in the influent per day ($mgCOD.d^{-1}$)
$M(S_{TE})$ = mass of COD in the effluent per day ($mgCOD.d^{-1}$)
$M(X_V)$ = mass of sludge wasted per day ($mgVSS.d^{-1}$)
P = COD/VSS ratio.

From Equation 4.1, using the observed data given in Table 4.17,

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*Assume the COD/VSS ratio for the 'normal' activated sludge to be that measured for the parallel unit treating sewage only *i.e.* COD/VSS = 1,433 (see Table 4.19).

$$O_C = (602 \times 18) - [115 \times 16 + 45 \times 2] - [1234 \times 2 \times 1{,}433 + 100 \times 2 \times 2{,}84]/6 \times 24$$

$$= 33{,}3 \text{ mgO}.\ell^{-1}.\text{hr}^{-1}$$

The observed $O_C = 32{,}5$ mgO.ℓ^{-1}.hr^{-1}. Evidently these results are quite close, but as the relative effect of the oleic acid on the experimental VSS determination is so small, the O_C results above do not necessarily provide support for the hypothesis that oleic acid accumulated on the volatile solids.

Further, an examination of the data for the two units at 20°C shows even smaller changes than those at 12°C. It would appear therefore, that at the higher temperature (*i.e.* 20°C) and at the 3 day sludge age, no observable accumulation of oleic acid can be detected; any further analysis towards this end will, in all probability, show results completely swamped by the natural variability of the COD and VSS data.

The above analysis tends to indicate that a direct comparison of VSS concentrations and carbonaceous oxygen demands between a unit treating only sewage and that treating sewage spiked with oleic acid does not provide a sensitive method for obtaining clues towards the process response when oleic acid is added; this is due in part to the natural variability of the response parameters (as measured) swamping small changes that the oleic acid addition would bring about in these two parameters.

The effect of long-chain fatty acids appears not to be very prominent as it required oleic acid addition of substantial proportion (probably more than that expected in practice) even to indicate some difference. To check this conclusion and to ensure that the increase in the COD/VSS ratio of the mixed liquor at both 12°C and 20°C associated with the addition of oleic acid to the influent was not a chance effect, the experiment was repeated but with the oleic acid COD mass fraction increased from 22 percent to 33 percent (*i.e.* 6ℓ oleic acid at 600 mgCOD.ℓ^{-1} plus 12ℓ raw domestic sewage at

600 mgCOD.ℓ^{-1} to give a total influent of 18ℓ at 600 mgCOD.ℓ^{-1}). Two units treated the 18ℓ raw domestic sewage at 600 mgCOD.ℓ^{-1} as control. The total mass of COD delivered to each unit therefore remained the same. The total mass of TKN varied depending on the amount of oleic acid added to the influent. Table 4.20 gives a summary of the experimental design parameters for these four units operated during this set of experiments.

These units were tested over a period of 44 days. The daily experimental data collected for each unit (and recorded in Appendix A, Tables A.15 to A.18) is plotted in Figures 4.23 to 4.26. The daily performance of the two units treating only the raw domestic sewage at 20°C and 12°C is shown in Figures 4.23 and 4.25 respectively; Figures 4.24 and 4.26 reflect the daily performance of the units at 20°C and 12°C respectively treating the mixture of sewage and oleic acid. To get an indication on the reliability of the measured data, COD and N balances were performed.

Table 4.20: Experimental design parameters with and without 33 percent of influent COD by mass oleic acid addition.

Sludge age (days)	Volume (liters)	Influent Flow ($\ell.d^{-1}$)		Average Influent COD (mgCOD.ℓ^{-1})	
		Sewage	Oleic Acid	Sewage	Oleic Acid
3	6,0	18,0	-	600	-
3	6,0	12,0	6,0	600	600

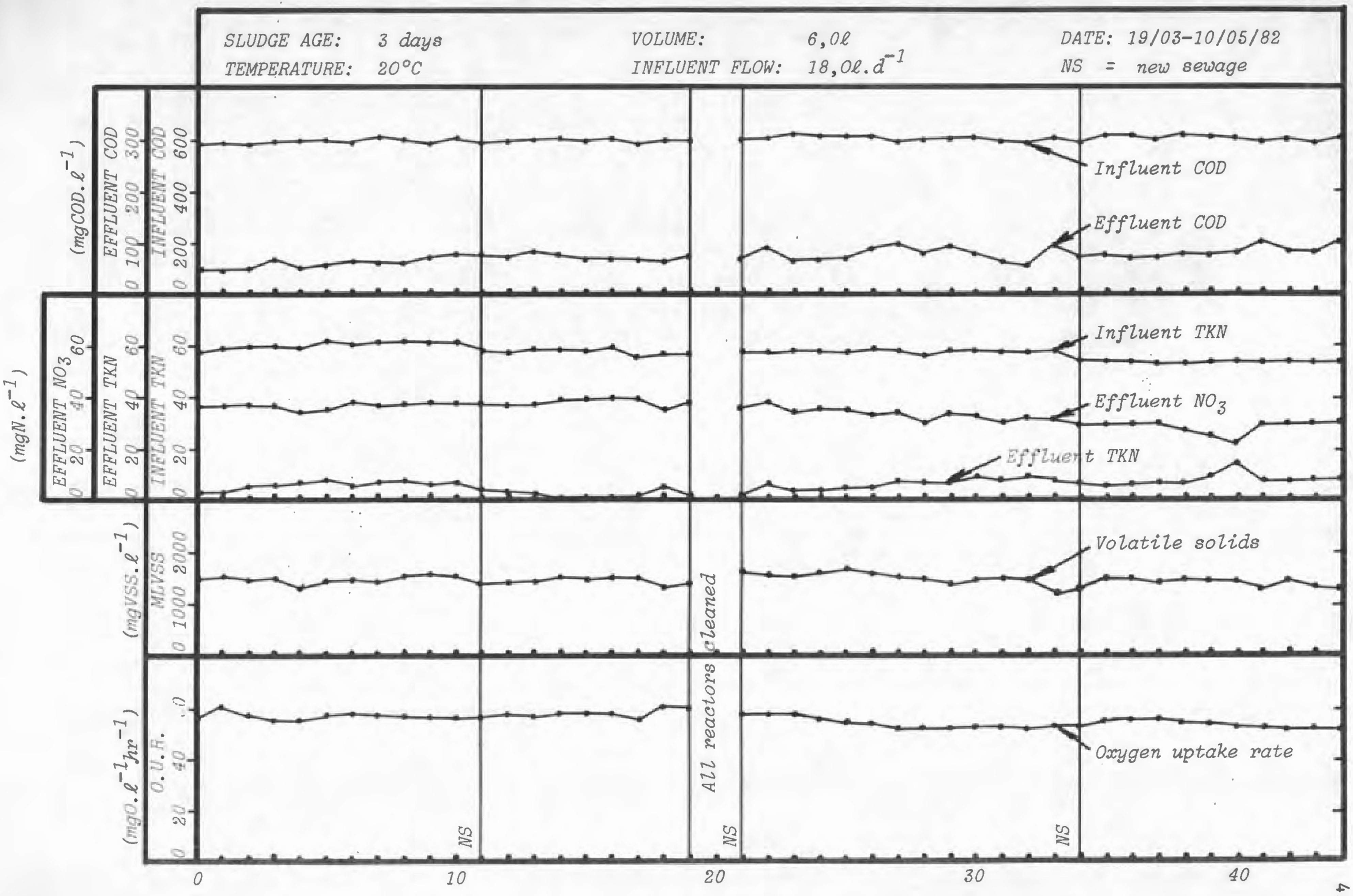


Figure 4.23: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage only.

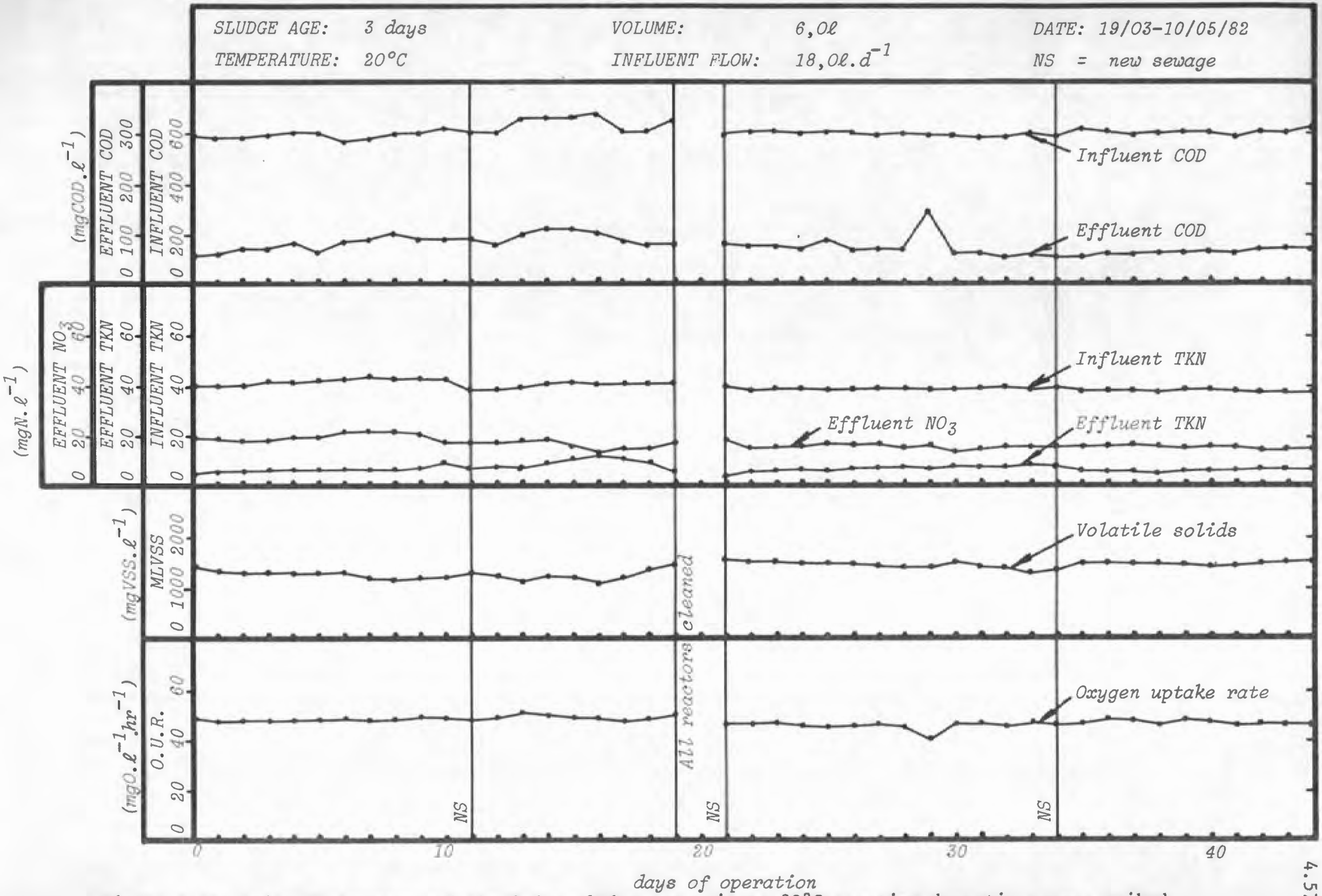


Figure 4.24: Daily Performance of the 3 day sludge age unit at 20°C treating domestic sewage spiked with 33% of influent COD by mass oleic acid.

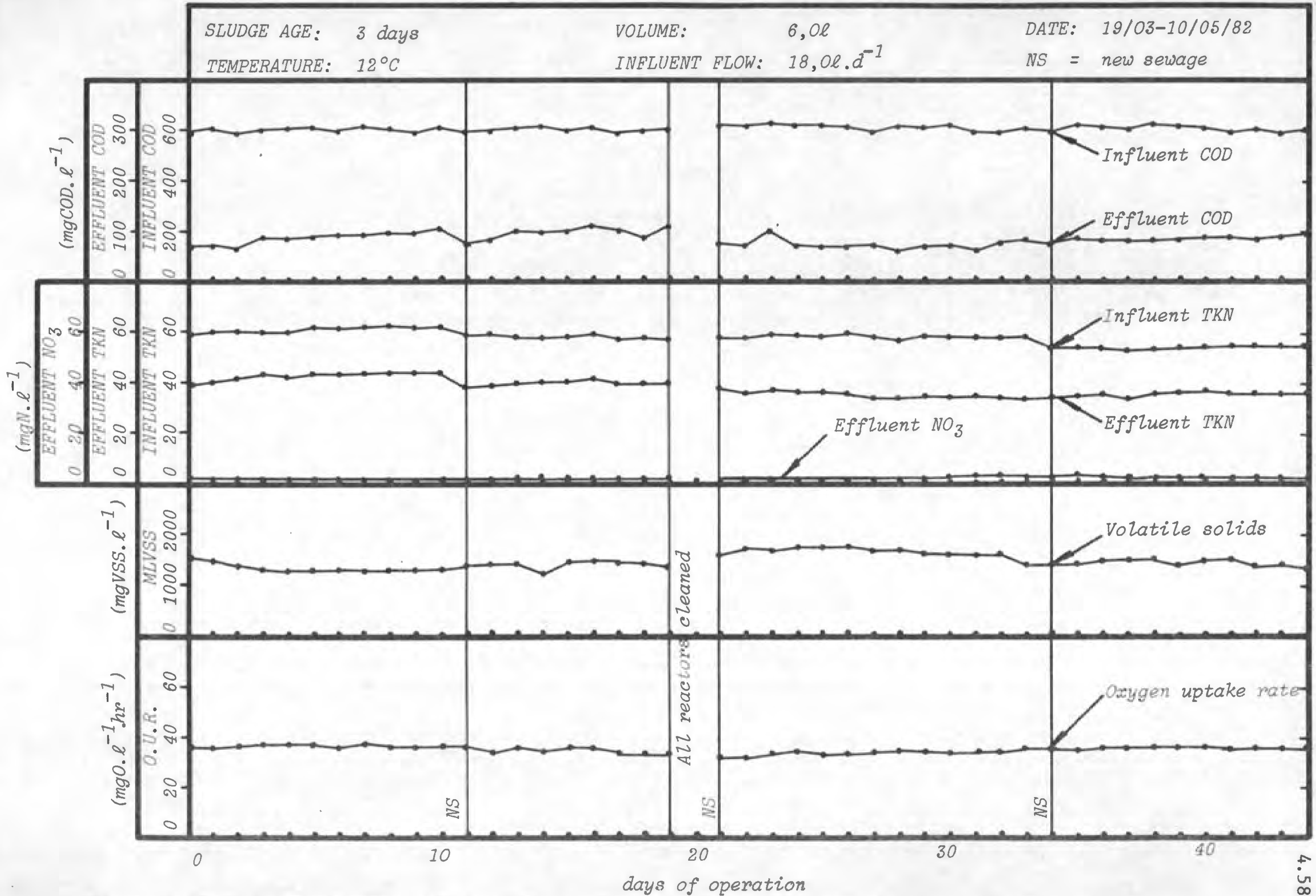


Figure 4.25: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage only.

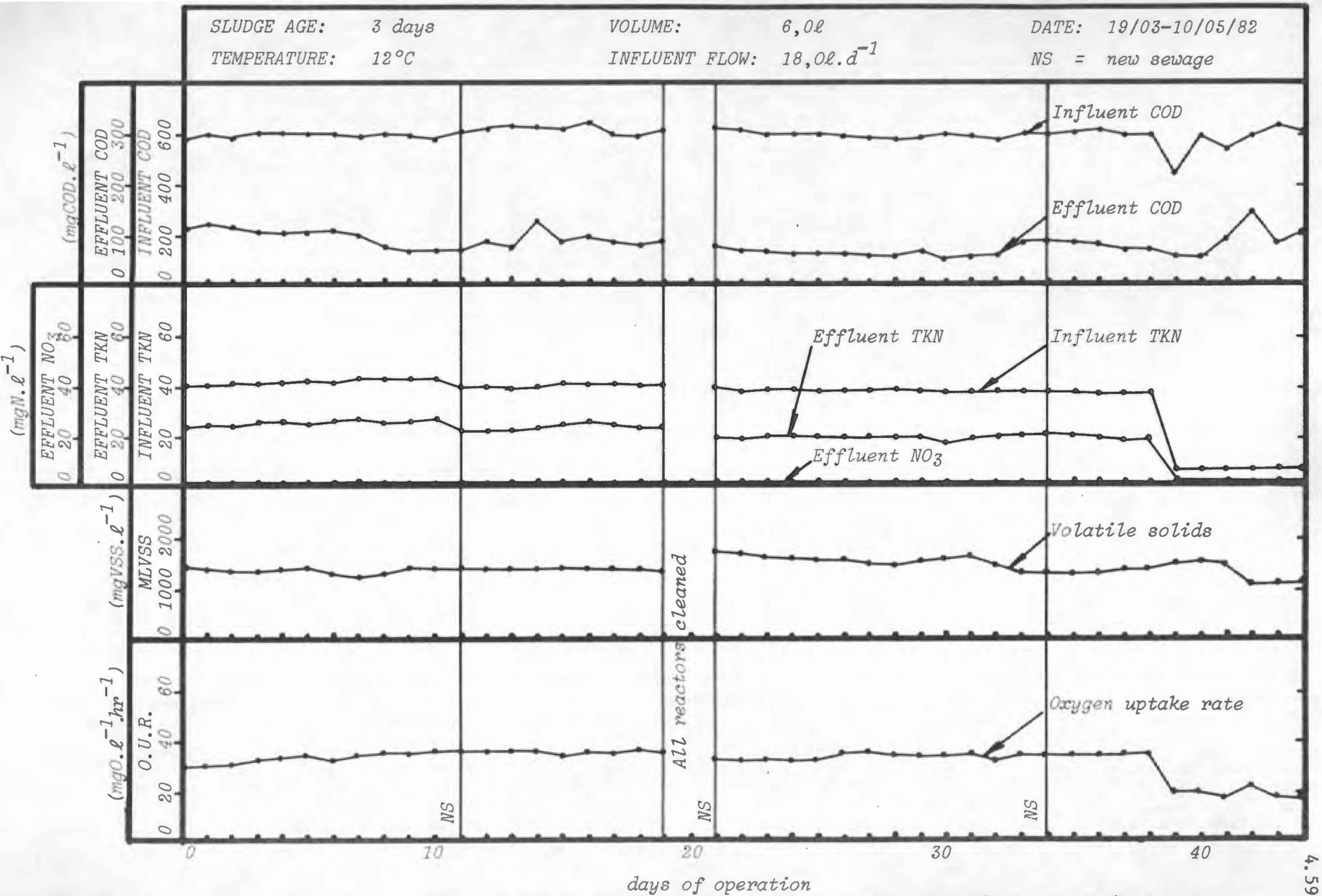


Figure 4.26: Daily Performance of the 3 day sludge age unit at 12°C treating domestic sewage spiked with 33% of influent COD by mass oleic acid.

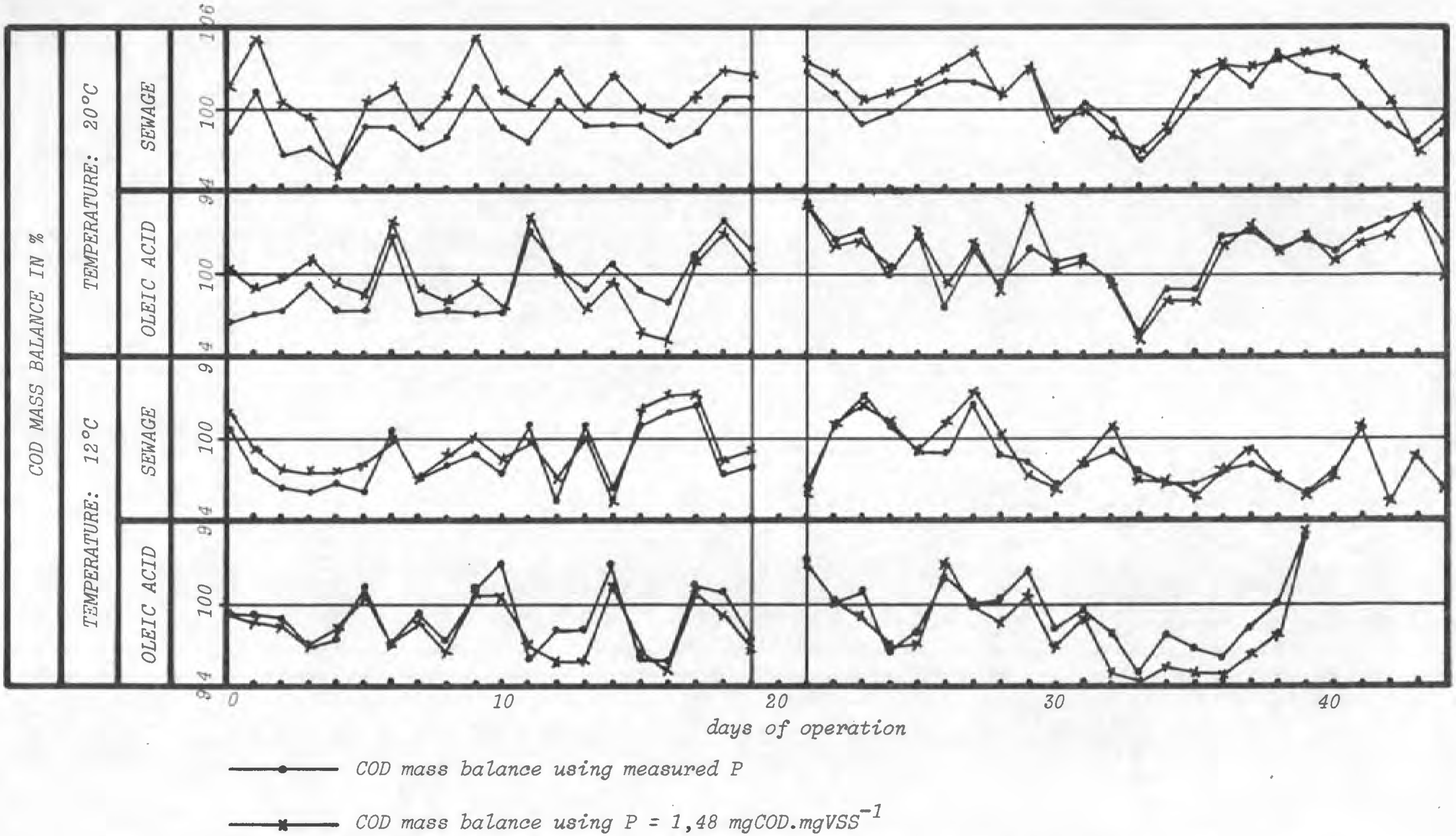


Figure 4.27(a): COD mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C with and without an oleic acid addition of 33% of influent COD by mass.

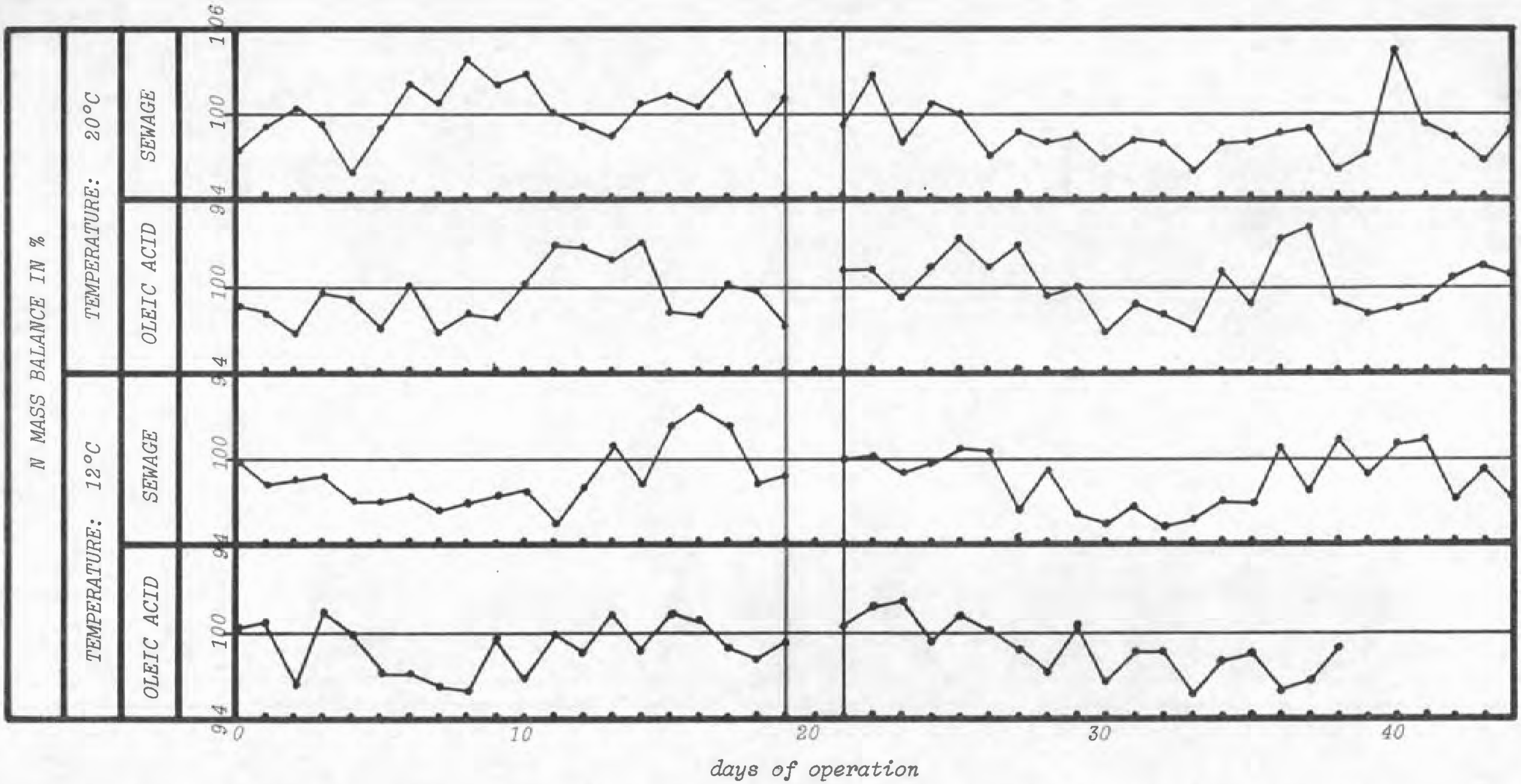


Figure 4.27(b): N mass balances on daily measured data for the 3 day sludge age units at 20°C and 12°C with and without an oleic acid addition of 33% of influent COD by mass.

COD and N balances

The daily COD and N recoveries achieved for all four units during this set of experiments are plotted in Figures 4.27(a) and 4.27(b); a summary of the mean COD and N recoveries obtained (using the experimentally determined COD/VSS ratios) is given in Table 4.21.

It is clear from Figures 4.27(a) and 4.27(b) (and Table 4.21) that good COD and N recoveries were achieved; subsequently the experimental data was analysed kinetically with confidence.

Kinetic Response Analysis

The mean experimental response for each of the four units was determined from the daily data; a summary is shown in Table 4.22.

As for previous experiments, the actual sludge age was determined (from the filtered and unfiltered effluent COD) prior to calculating the 'correct' f_{up} giving the observed X_V; this analysis is summarized in Table 4.23.

Table 4.21: Average COD and N recoveries for the 3 day sludge age units at 12°C and 20°C with and without oleic acid addition of 33 percent of COD by mass.

Sludge age (days)	Average COD recoveries (%)		Average N recoveries (%)	
	12°C	20°C	12°C	20°C
3 days (18ℓ sewage)	99,1	99,7	99,1	100,0
3 days (12ℓ sewage plus 6ℓ oleic acid)	99,4	100,3	99,5	99,4

Table 4.22: Mean observed response for the 3 day sludge age units at 12°C and 20°C with and without oleic acid addition of 33 percent of COD by mass.

Temp. (°C)	Infl. Charac.	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_V $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	N_{NE} $\frac{\text{mgN}}{\ell}$
12	Sewage	606	56,8	1475	35,4	84	38,5	2,4
12	Oleic acid	604	40,1	1445	34,4	83	22,8	1,8
20	Sewage	606	56,8	1499	56,2	77	6,5	34,8
20	Oleic acid	602	39,8	1379	47,5	77	7,3	17,1

filtered effluent COD concentration ≅ 45-50 mgCOD.ℓ^{-1}

Table 4.23: Theoretical response for the 3 day sludge age units at 12°C and 20°C with and without oleic acid addition of 33 percent of COD by mass, using the actual sludge age and f_{up}.

Temp. (°C)	Infl. Charac.	Sludge age (Act.)	f_{up} $\frac{\text{mgCOD}}{\text{mgCOD}}$	X_V $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	N_{NE} $\frac{\text{mgN}}{\ell}$
12	Sewage	2,62	0,085	1498	33,8	87	38,1	0,0
12	Oleic acid	2,63	0,054	1459	33,9	87	22,2	0,0
20	Sewage	2,69	0,080	1472	54,1	79	5,1	33,6
20	Oleic acid	2,67	0,050	1400	46,0	79	4,8	17,7

Comparing the results for the two units treating *sewage only* at 12°C and 20°C to previous experiments (Table 4.23 versus Tables 4.18 and 4.12) again it is clear that these units continued to respond in a similar fashion as before *i.e.* f_{up} remained approximately 0,08 to 0,085 $mgCOD.mgCOD^{-1}$; the oxygen consumption rates can be shown to be similarly consistent. Examining the results from the units treating sewage spiked with oleic acid at 12°C and 20°C (see Table 4.23) the equivalent f_{up} should have been f_{up} = 0,05 to 0,054 (if no oleic acid accumulated) and from Table 4.23 these values were indeed observed. The predicted X_V (on the basis that no oleic acid accumulated) is virtually identical to that observed. For this set of experiments, in contrast to the previous set *i.e.* an oleic acid addition of 22 percent of COD by mass, no oleic acid accumulation appears to be indicated. However, as pointed out from the results for the previous set of experiments (22 percent of COD by mass as oleic acid), the VSS concentration seems to be an insensitive parameter to detect the effects of fat accumulation; in contrast, the COD/VSS ratio appeared to be more sensitive. Consequently attention was directed to the measured COD/VSS ratios.

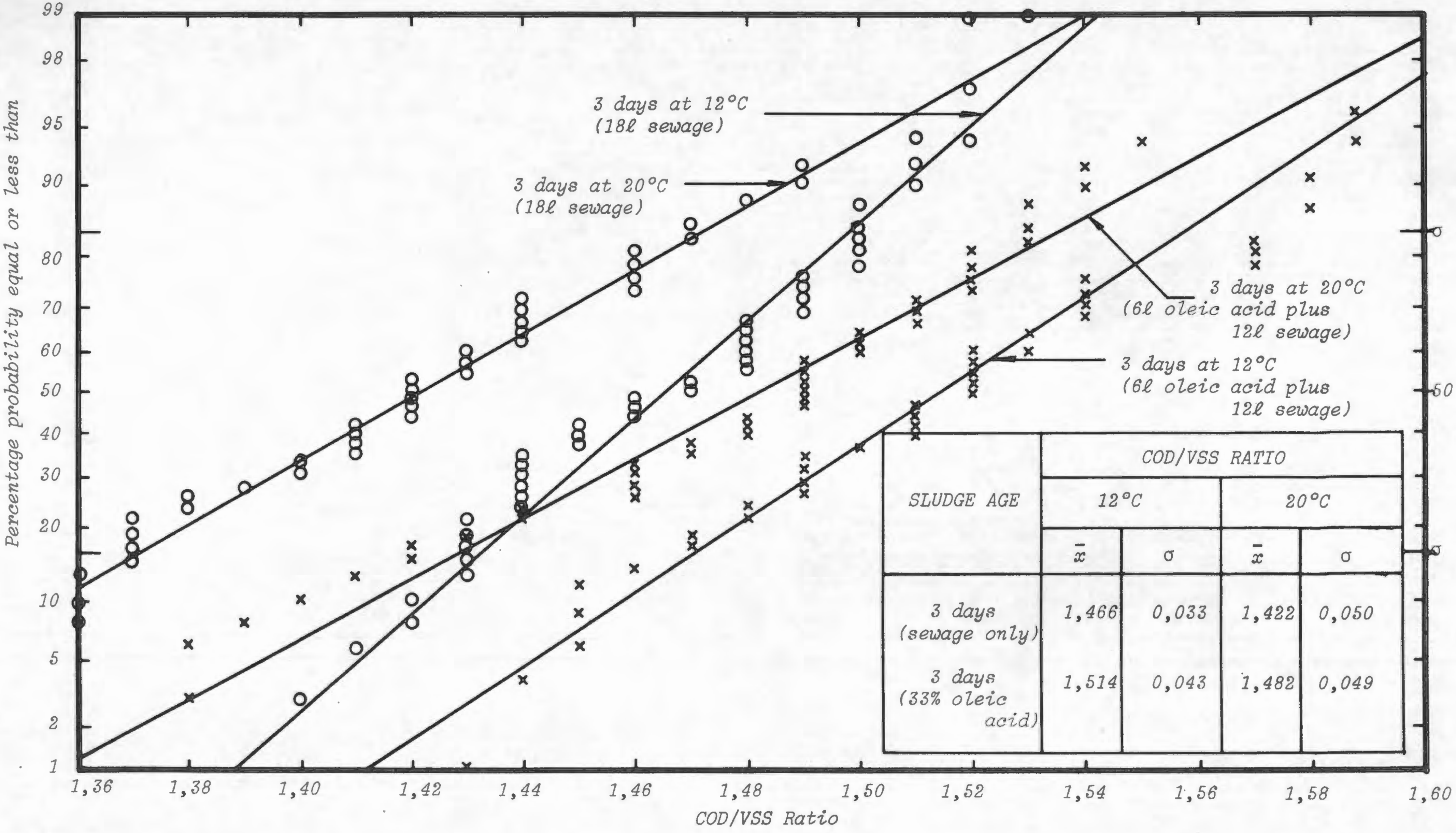
Statistical Analysis of COD/VSS ratios

Plotting the measured COD/VSS ratios of the mixed liquor versus the percentage probability for each unit - see Figure 4.28 - the mean ($\bar{x}$) and corresponding standard deviation (σ) of the COD/VSS ratio for each unit was determined graphically. Table 4.24 summarizes this analysis.

An analysis of the results shown in Table 4.24 (using the 'Student-t' test) indicates an increase in the COD/VSS ratio at both 12°C and 20°C due to the addition of oleic acid to the influent substrate (significant at a 95 percent confidence level), thereby supporting our hypothesis.

4.2.3 General Discussion

An aspect very clearly indicated from the analysis of the observed process response during the last two sets of experiments is that oleic acid, and very likely fats in general, apparently



SLUDGE AGE	COD/VSS RATIO			
	12°C		20°C	
	$\bar{x}$	σ	$\bar{x}$	σ
3 days (sewage only)	1,466	0,033	1,422	0,050
3 days (33% oleic acid)	1,514	0,043	1,482	0,049

Figure 4.28: Mean and standard deviation of the COD/VSS ratio from a statistical plot.

Table 4.24: COD/VSS ratio of activated sludge treating raw domestic sewage and raw domestic sewage spiked with oleic acid.

Sludge age (days)	COD/VSS Ratio			
	12°C		20°C	
	Sewage	Oleic Acid	Sewage	Oleic Acid
3 days (18ℓ sewage)	1,466	0,033	1,422	0,050
3 days (12ℓ sewage plus 6ℓ oleic acid)	1,514	0,043	1,482	0,049

have a relatively small effect on the COD/VSS ratio and hence on the kinetic response of the activated sludge process for waste flows derived from municipal sources. Any effects that could be induced by fats are difficult to detect from the experimental VSS concentration and oxygen consumption rate measurements and are only weakly reflected in the COD/VSS ratio. The increase in the COD/VSS ratio, at the maximum addition of oleic acid, *i.e.* 33 percent of influent COD by mass, at the most adverse temperature investigated, *i.e.* 12°C, did not appear to exceed 0,07 mgCOD.mgVSS^{-1}.

The statistical behaviour of the COD/VSS ratio indicates a ratio with a relatively low precision (*i.e.* a relatively large standard deviation) in an observed set of data points. Consequently the mean of a set attains stability only if an appreciable number of data points constitute the sample. The mean COD/VSS ratio then can lie in a range from 1,39 to 1,57 with an overall average of about 1,46. The extreme values for the COD/VSS ratio reported in the literature, *i.e.* 1,07 to 1,77, probably arose from taking too few data points to obtain a relatively stable mean. In the literature reporting experimental estimates of the COD/VSS ratio, in not a single instance was mention made of the number of data to calculate the mean COD/VSS ratio. Experience from this investigation would indicate a set with a minimum of 20 samples to obtain reasonable stability on the mean value.

4.3 THE DYNAMIC BEHAVIOUR OF THE SINGLE-REACTOR AEROBIC ACTIVATED SLUDGE PROCESS AT 12°C

Prompted by two observations, namely:

(1) that the experimental COD/VSS ratio for activated sludge treating raw domestic sewage at 12°C as measured in this study was not, for all practical purposes, appreciably different from the assumed value of 1,48 mgCOD.mgVSS^{-1} [after Ekama and Marais (1978)] and

(2) that the oxygen consumption rate measurement for the short sludge ages was responsible for the poor COD recoveries at 12°C,

the decision was taken to repeat previous experiments conducted by Dold *et al.* (1980) on the dynamic behaviour of the single-reactor aerobic activated sludge process treating raw domestic sewage at 12°C, to check the predictive power of the general mathematical model as presented by Dold *et al.* (1980).

4.3.1 Experimental design

To facilitate comparison between the data recorded in this set of experiments and that by Dold *et al.* (1980) it was decided to keep the process design parameters the same as theirs:

Four single-reactor aerobic activated sludge units were operated at 12°C; two at a 20 day and two at a 2,5 day sludge age. For each sludge age one unit was operated under steady state and the other under square-wave dynamic loading conditions. At each sludge age it was necessary to operate two units in parallel, one each under steady state and square-wave dynamic loading conditions respectively, because the recorded data on the steady state unit, for determining COD and N recoveries, provide the only experimental check on the reliability of the data recorded on the cyclic unit.

The experimental apparatus, control and testing techniques employed have been described in detail in Chapter 3. For the cyclic units the total influent feed volumes were delivered during the first 12 hours of a 24-hour cycle while for the steady state units the total influent feed volumes were delivered over a 24-hour period; the same total masses of COD and N were delivered to each set of parallel units. A summary of the experimental design parameters is given in Table 4.25.

To ensure good settling characteristics of the sludge in the 2,5 day sludge age units, ferric sulphate at a concentration of 110 mg Fe^{3+} per liter influent was bled into the reactors continuously.

All four single-reactor aerobic units were monitored for a period of at least two sludge ages to allow steady state and dynamic steady state conditions to develop. Once these conditions appeared to be achieved, tests were performed on all the units on a daily basis.

The experimental data is recorded in Appendix A, Tables A.19 and A.20 and plotted on a daily basis in Figures 4.29 and 4.30. Figure 4.29 shows plots of the daily performance of both the steady state and cyclic units at a 20 day sludge age, and Figure 4.30 the

Table 4.25: Experimental design parameters for the 20 and 2,5 day sludge age units at 12°C.

Sludge age (days)	Volume (liters)	Flow ($\ell.d^{-1}$)	Average Influent COD ($mgCOD.\ell^{-1}$)
20	12,0	14,0	600
2,5	6,73	18,0	600

daily performance of both the steady state and cyclic units at a 2,5 day sludge age prior to the 24-hour intensive tests. From the plots, the time behaviour of the MLVSS, effluent COD, TKN and NO_3^- concentrations for both the steady state and the cyclic units at each sludge age strongly suggest that all these aerobic units had attained steady states before the 24-hour intensive tests commenced. This was verified by doing material balances on COD and N (for the daily data as recorded in Figures 4.29 and 4.30) and are shown plotted in Figures 4.31 and 4.32. For both the 20 and 2,5 day sludge age units under constant flow and load conditions, very satisfactory recoveries, of between 95 and 105 percent, were obtained. From these high recoveries it was concluded that 24-hour intensive tests conducted on the cyclic units should give a reliable indication of the response behaviour to the daily square-wave dynamic loading conditions.

4.3.2 24-Hour Intensive Tests

The 24-hour intensive tests, conducted on the cyclic units at both the 20 and 2,5 day sludge ages, actually extended over a period of 26 hours. A programme summary of all the tests performed during this period, on both the cyclic and steady state units at each sludge age, is given in Table 4.26. The oxygen consumption rates for the cyclic units were measured at quarter-hour intervals for one hour after the start and termination of the feed period and at half-hour intervals during the other periods.

Five 24-hour intensive tests were conducted, two for the 20 day sludge age units and three for the 2,5 day sludge age units. Due to an experimental error, one of the 24-hour tests on the 2,5 day sludge age units had to be discarded. The results recorded for the remaining four 24-hour tests, two for a 20 day sludge age (numbered T1 and T2) and two at a 2,5 day sludge age (numbered T4 and T5) are shown plotted in Figures 4.37 to 4.40. The numerical values for the data are listed in Appendix A, Tables A.21 to A.24.

Good COD and N recoveries were achieved on the *steady state unit* data recorded *during* the 24-hour intensive tests for both the

Table 4.26: Programme of tests performed during a 24-hour intensive testing period.

TIME	Cyclic *				Steady *			
	COD	TKN	NO_3	VSS	COD	TKN	NO_3	VSS
0800	X	X	X	X	X	X	X	X
0900	X	X	X					
1000	X	X	X					
1100	X	X	X					
1200	X	X	X	X	X	X	X	X
1300	X	X	X					
1400	X	X	X					
1500	X	X	X					
1600	X	X	X	X	X	X	X	X
1700	X	X	X					
1800	X	X	X					
1900	X	X	X					
2000	X	X	X	X	X	X	X	X
2100	X	X	X					
2200	X	X	X					
2300	X	X	X					
2400	X	X	X	X	X	X	X	X
0100	X	X	X					
0200	X	X	X					
0300	X	X	X					
0400	X	X	X	X	X	X	X	X
0500	X	X	X					
0600	X	X	X					
0700	X	X	X					

* - all samples taken from the reactor

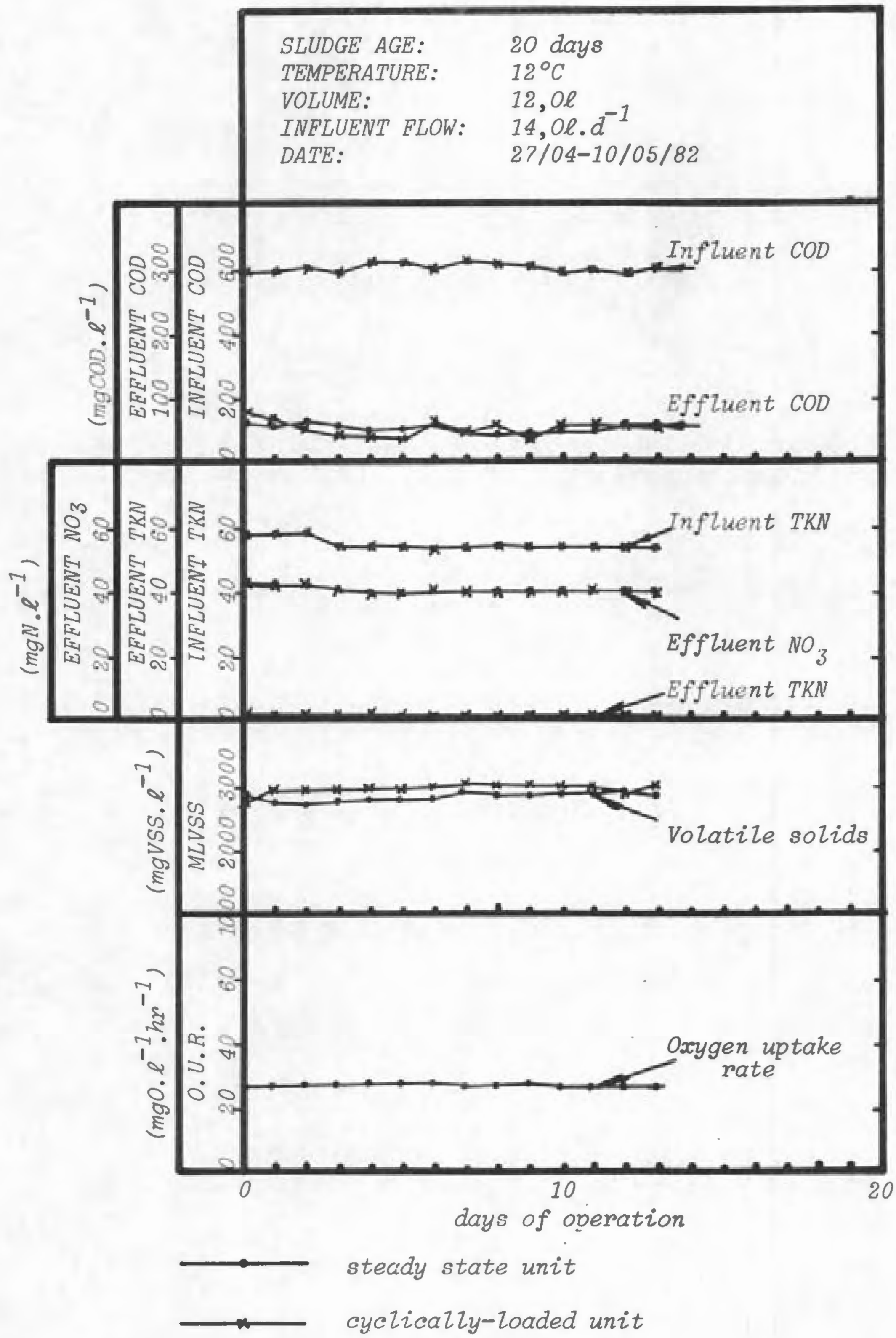


Figure 4.29: Daily Performance of the 20 day sludge age units prior to the 24-hour intensive tests.

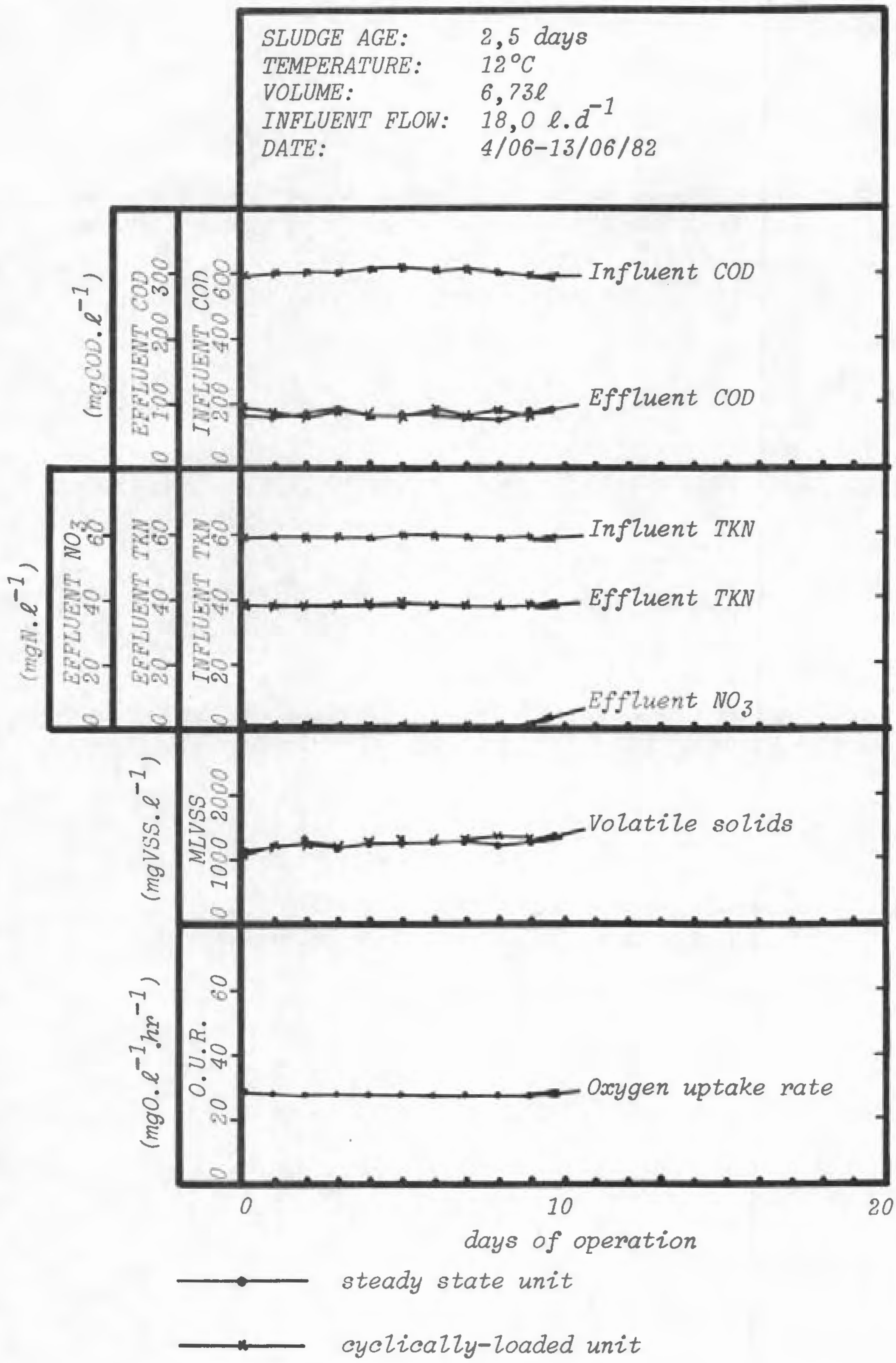


Figure 4.30: Daily Performance of the 2,5 day sludge age units prior to the 24-hour intensive tests.

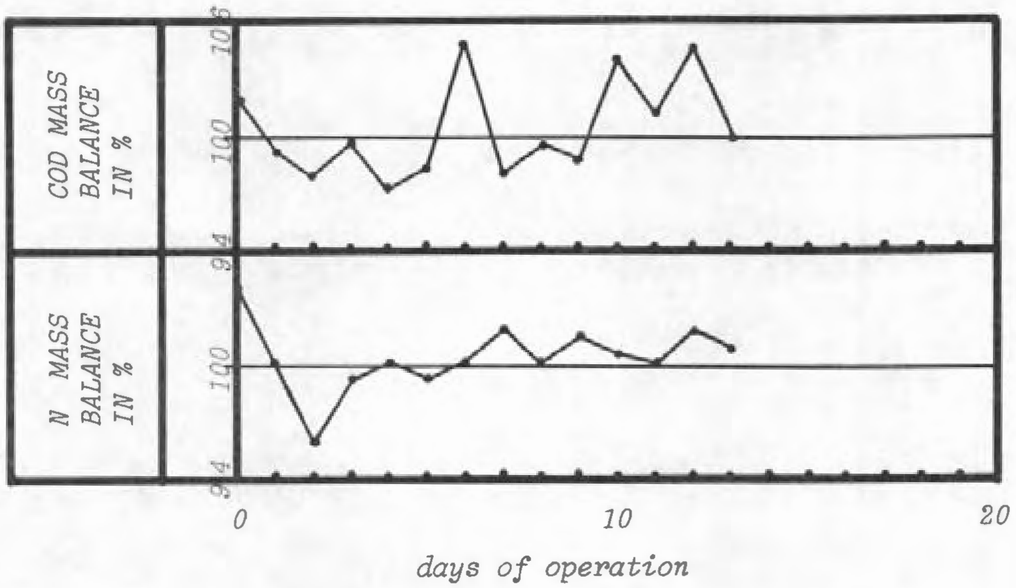


Figure 4.31: COD and N mass balances for the 20 day sludge age unit at steady state - preparation period before the 24-hour intensive tests.

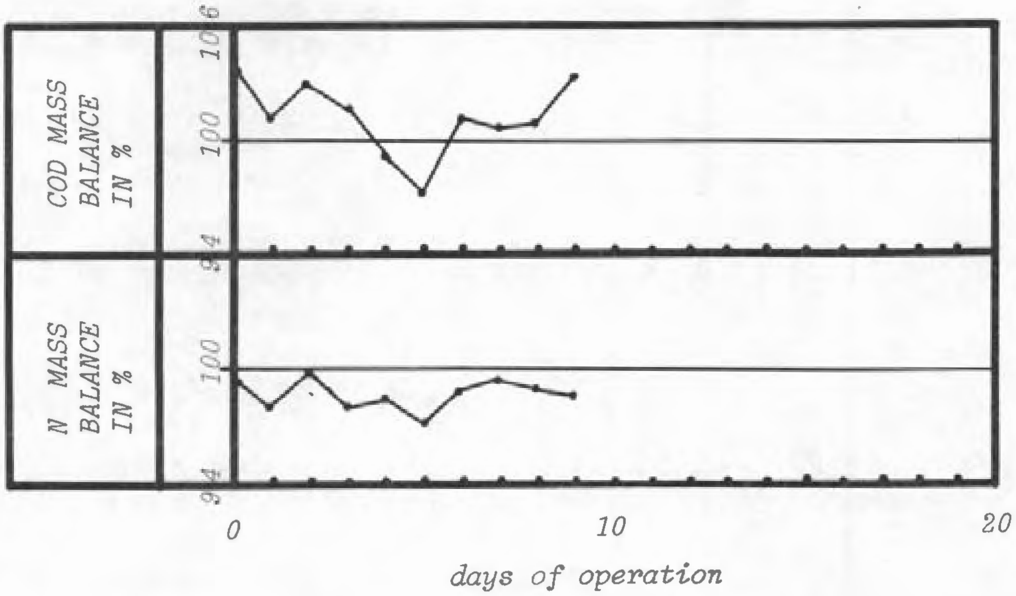


Figure 4.32: COD and N mass balances for the 2,5 day sludge age unit at steady state - preparation period before the 24-hour intensive tests.

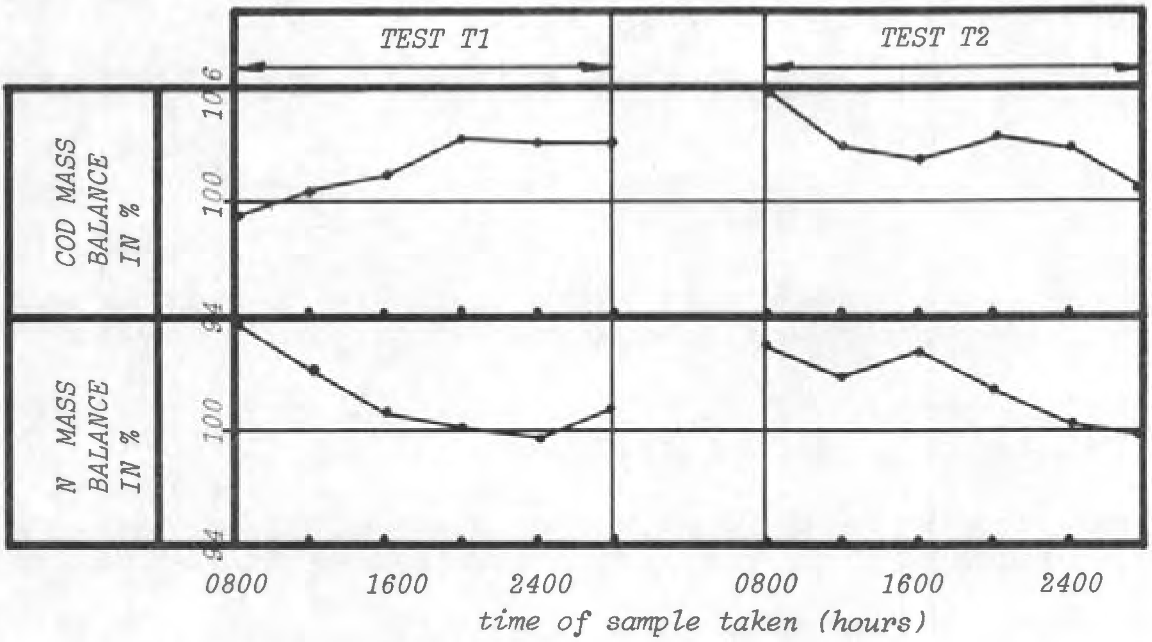


Figure 4.33: COD and N mass balances for the 20 day sludge age unit at steady state during test T1 and T2.

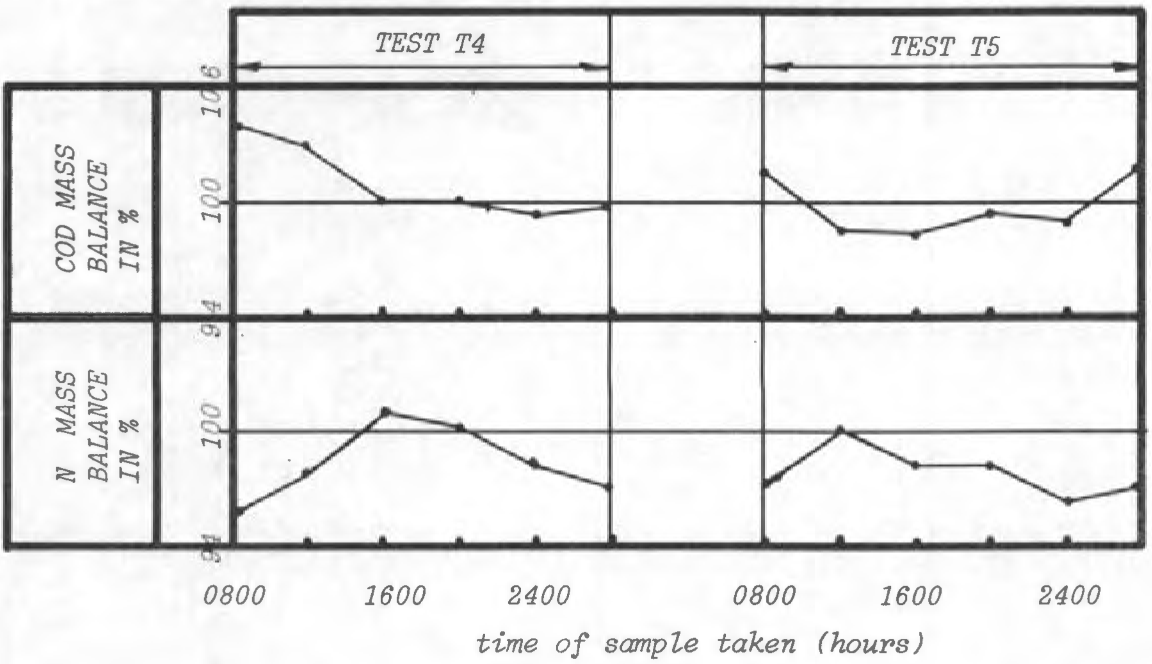


Figure 4.34: COD and N mass balances for the 2,5 day sludge age unit at steady state during test T4 and T5.

20 and 2,5 day sludge age units. These are shown in Figures 4.33 and 4.34 for the 20 day sludge age unit (T1 and T2) and the 2,5 day sludge age unit (T4 and T5) respectively.

4.3.3 Model Evaluation

The mathematical model describing the dynamic behaviour of the aerobic activated sludge process, as proposed by Dold *et al.* (1980) formed the basis for the simulations. The input to the model was programmed to receive the same cyclic input forcing waves as those imposed experimentally on the single-reactor aerobic units during each of the 24 hour tests. Using these input forcing waves the model simulates both the steady state and the dynamic response of the single-reactor aerobic activated sludge process.

In the model, initially, the kinetic constants were assumed to be identical to those used by Dold *et al.* (1980). With regard to the sewage characteristics, the unbiodegradable soluble COD fraction, f_{us}, was determined from the filtered reactor (effluent) COD concentration for the 20 day sludge age unit (at 12°C) and the easily biodegradable soluble COD fraction, f_{bs}, from the test devised to determine this constant (see Chapter 3, Section 3.3.3.2). The value for the unbiodegradable particulate COD fraction, f_{up}, was taken to be the same as that assumed by Dold *et al.* (1980). The assumed kinetic constants and sewage characteristics are listed in Table 4.27.

Examples of the simulated response, using these constants, are shown in Figures 4.35 and 4.36 for the 20 day sludge age (T1) and the 2,5 day sludge age (T4) tests. The following deviations are noted: (1) the simulated oxygen consumption rate response was lower than the observed, and (2) after feed termination, the simulated oxygen consumption rate response showed the usual behavioural pattern, a reduced rate *remaining constant* for about 3 hours before decreasing at a steady rate to a value associated with endogenous respiration; however, the observed response showed a *continuous declining* tendency.

The first deviation would arise if the actual f_{up} value of the sewage is in fact lower than that presumed by Dold *et al.* (1980)

Table 4.27: Values of kinetic constants used initially in the model for the aerobic activated sludge process (for nomenclature see List of Symbols).

Symbol	Value	Units	Temperature Dependency
Carbonaceous Material Degradation Kinetics			
K_{a20}	0,250	ℓ/mgVSS.d	1,029
K_{ms20}	20,00	mgVSS/mgCOD	1,200
K_{ss20}	5,00	mgCOD/ℓ	1,000
K_{mp20}	3,00	mgCOD/mgVSS.d	1,060
K_{sp20}	0,04	mgCOD/mgVSS	1,100
b_{h20}	0,62	d^{-1}	1,029
K_{r20}	0,023	ℓ/mgVSS.d	1,029
Y_h	0,45	mgVSS/mgCOD	1,000
f	0,08	mgVSS/mgVSS	1,000
P	1,48	mgCOD/mgVSS	1,000
f_{bs}	0,40	mgCOD/mgCOD	1,000
f_{ma}	1,00	mgVSS/mgVSS	1,000
Nitrification Kinetics			
K_{n20}	1,00	mgN/ℓ	1,123
μ_{nm20}	0,65	d^{-1}	1,123
b_{n20}	0,04	d^{-1}	1,029
f_n	0,10	mgN/mgVSS	1,000
f_{oe}	1,00	mgN/mgVSS	1,000
f_{cs}	0,00	mgN/mgCOD	1,000
Y_n	0,10	mgVSS/mgN	1,000
f_{os}	0,00	mgN/mgVSS	1,000
Influent Wastewater Fractions			
f_{us}	0,08	mgCOD/mgCOD	
f_{up}	0,13	mgCOD/mgCOD	
f_{un}	0,00	mgN/mgN	
f_{sn}	0,75	mgN/mgN	

- a lower value could arise very readily for this sewage because it is atypical in this that it is purely domestic in nature. Results from the earlier investigation into the effect of fats on the COD/VSS ratio reported in the earlier section of this Chapter for example strongly suggested that $f_{up} \cong 0{,}08$ mgCOD.mgCOD^{-1} for the raw sewage from Mitchell's Plain.

The continuous declining tendency in the observed oxygen consumption rates after feed termination could arise if the slowly biodegradable particulate COD fraction, S_{bp} (adsorbed and stored on the active organism mass), is in fact utilized at a higher rate than that assumed by Dold *et al.* (1980).

After repeated simulations by trial and error it was found that very good correspondence between experimentally measured and simulated data, on both the 20 and 2,5 day sludge age units, could be obtained if the following changes in the model constants were accepted:

Constant	Old value (after Dold *et al.*)	New value	Units
f_{up}	0,13	0,08	mgCOD.mgCOD^{-1}
K_{mp20}	3,00	6,00	mgCOD.mgVSS^{-1}.d^{-1}
K_{sp20}	0,04	0,075	mgCOD.mgVSS^{-1}

These modified values reflect (1) a lower fraction of unbiodegradable particulate material in the influent (*i.e.* $f_{up} = 0{,}08$ instead of 0,13) and (2) a higher rate of utilization of the slowly biodegradable particulate substrate than accepted for general modelling purposes [after Dold *et al.* (1980)]. The observed and simulated response for each 24-hour intensive test using the modified values of the constants are shown in Figures 4.37 to 4.40.

From the observed and simulated response plots an important new aspect is apparent: Dold *et al.* (1980) divided the influent biodegradable COD into two specific fractions, (1) a slowly biode-

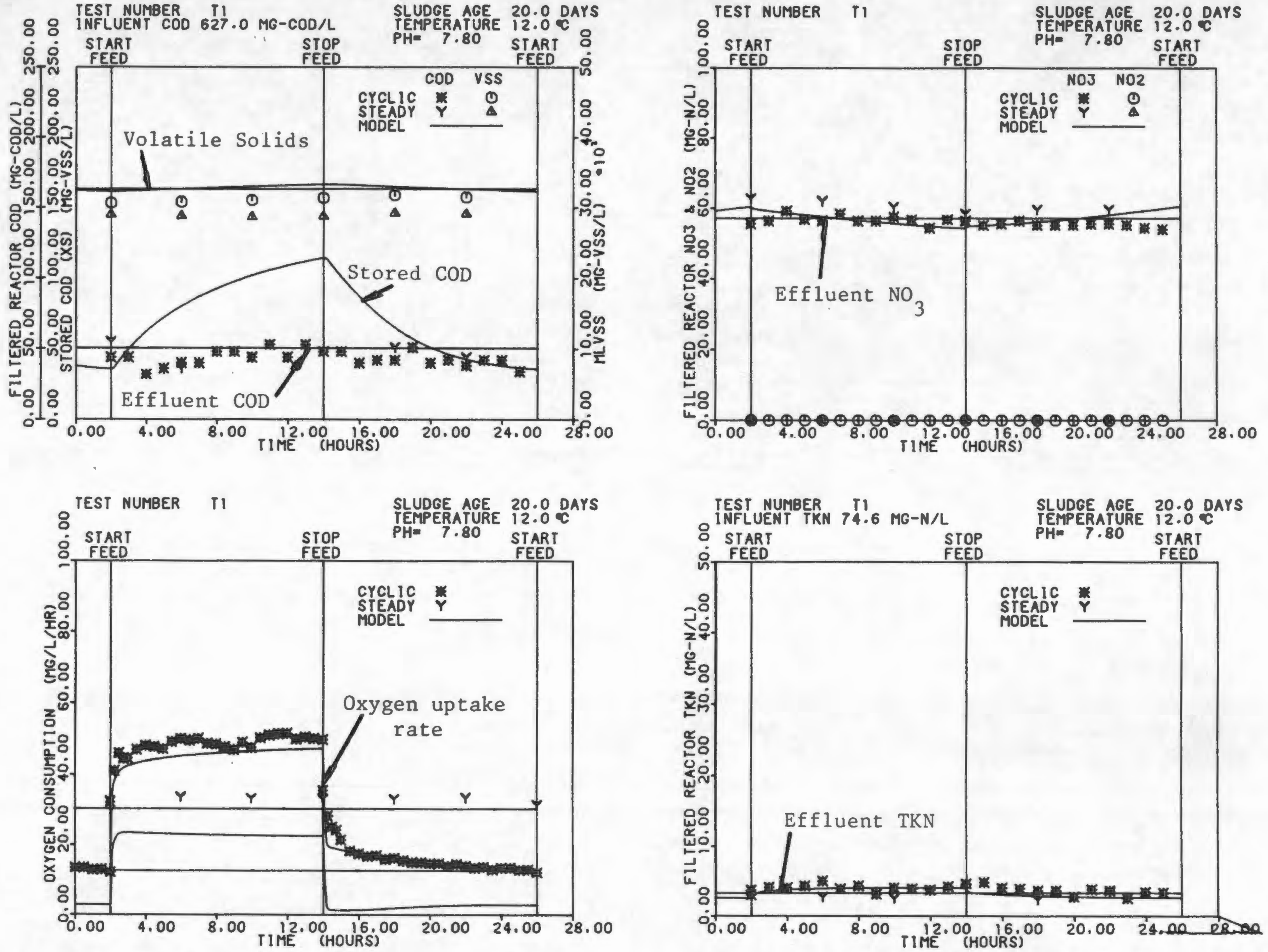


Figure 4.35: Comparison of the experimental response waves with those predicted by the mathematical model for daily square wave loading conditions at a 20 day sludge age and 12°C using the kinetic constants after Dold *et al.* (1980) (see Table 4.27).

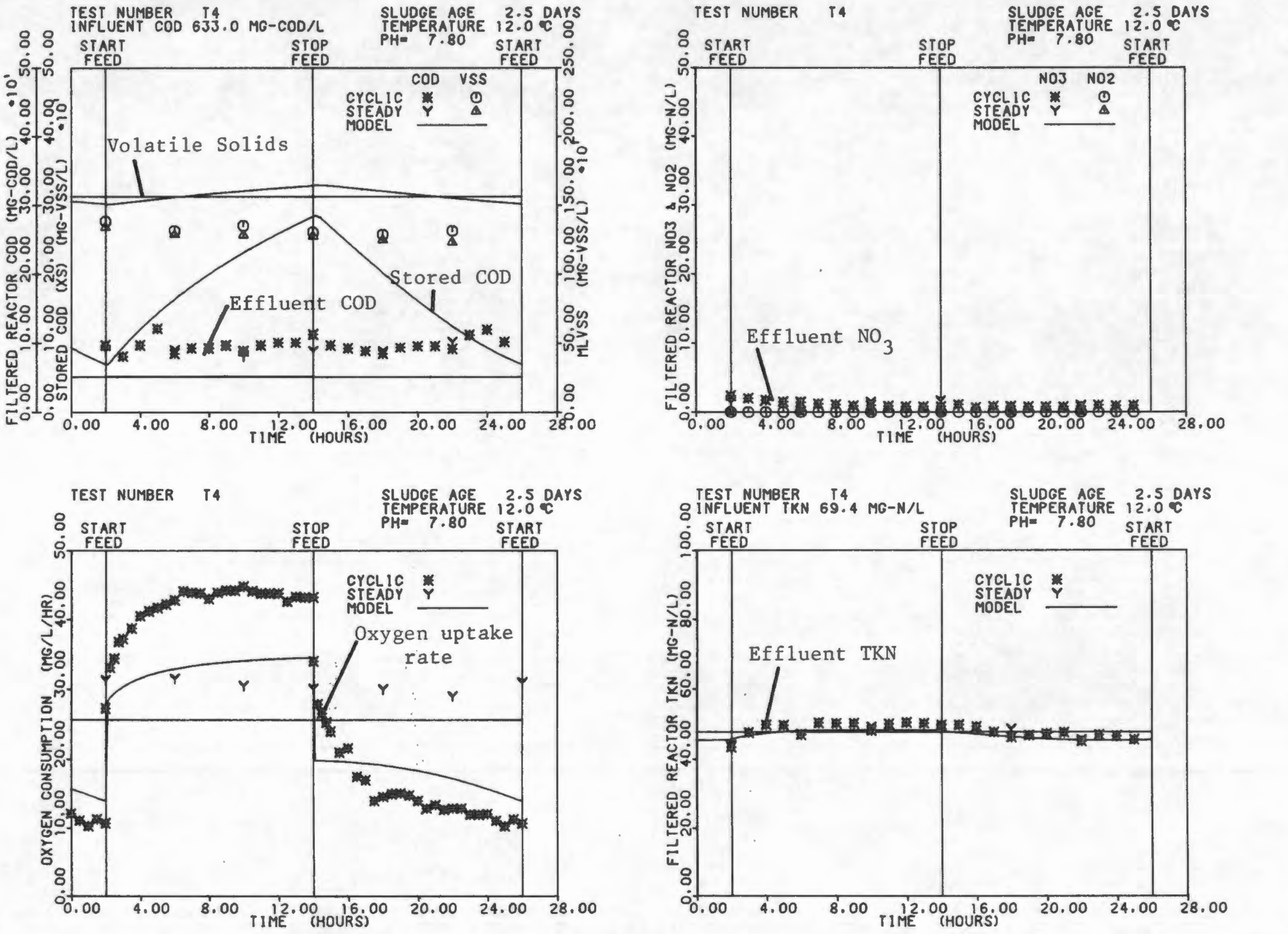


Figure 4.36: Comparison of the experimental response waves with those predicted by the mathematical model for daily square wave loading conditions at a 2,5 day sludge age and 12°C using the kinetic constants after Dold *et al.* (1980) (see Table 4.27).

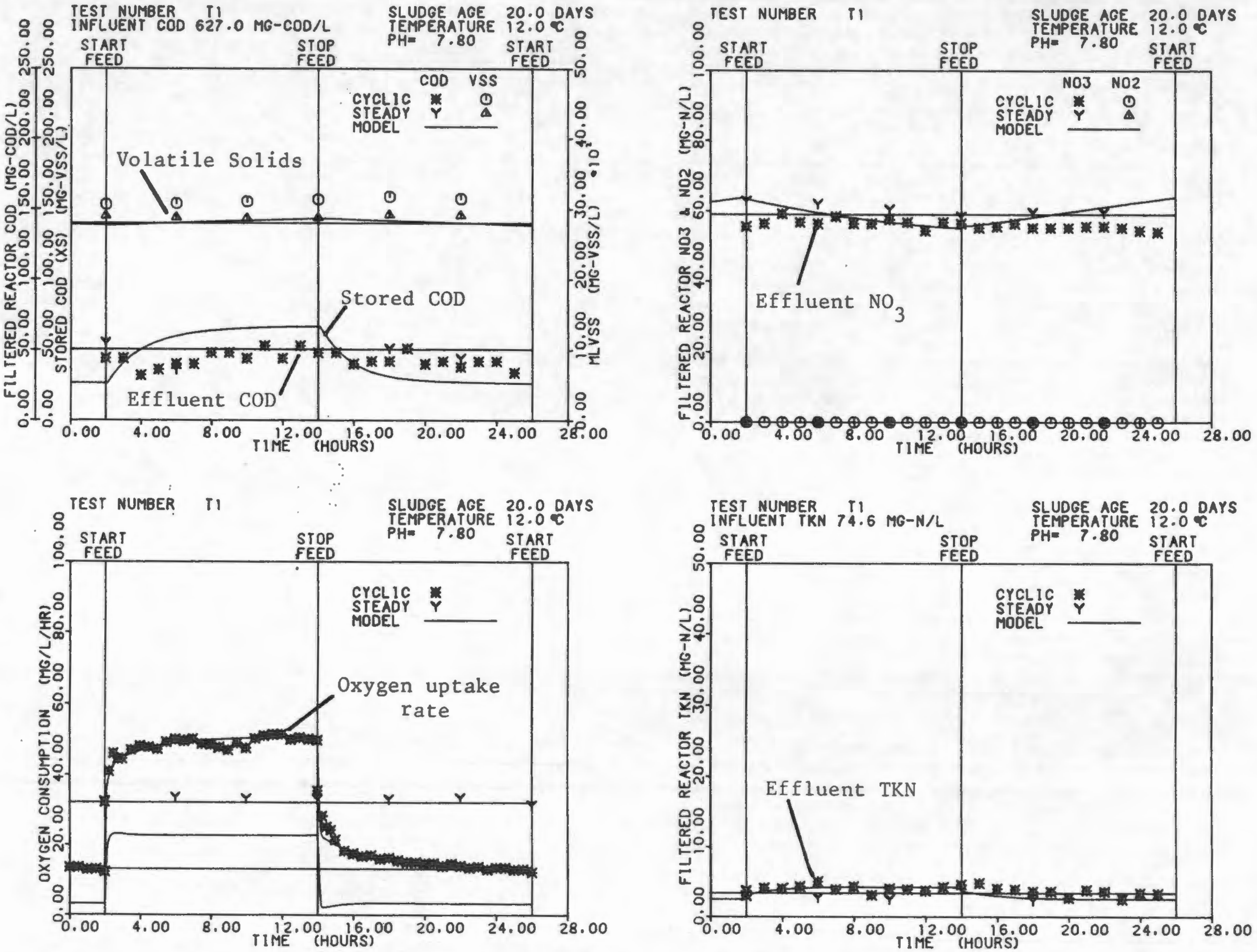


Figure 4.37: Comparison of the experimental response waves with those predicted by the mathematical model for daily square wave loading conditions at a 20 day sludge age and 12°C using the *modified* kinetic constants.

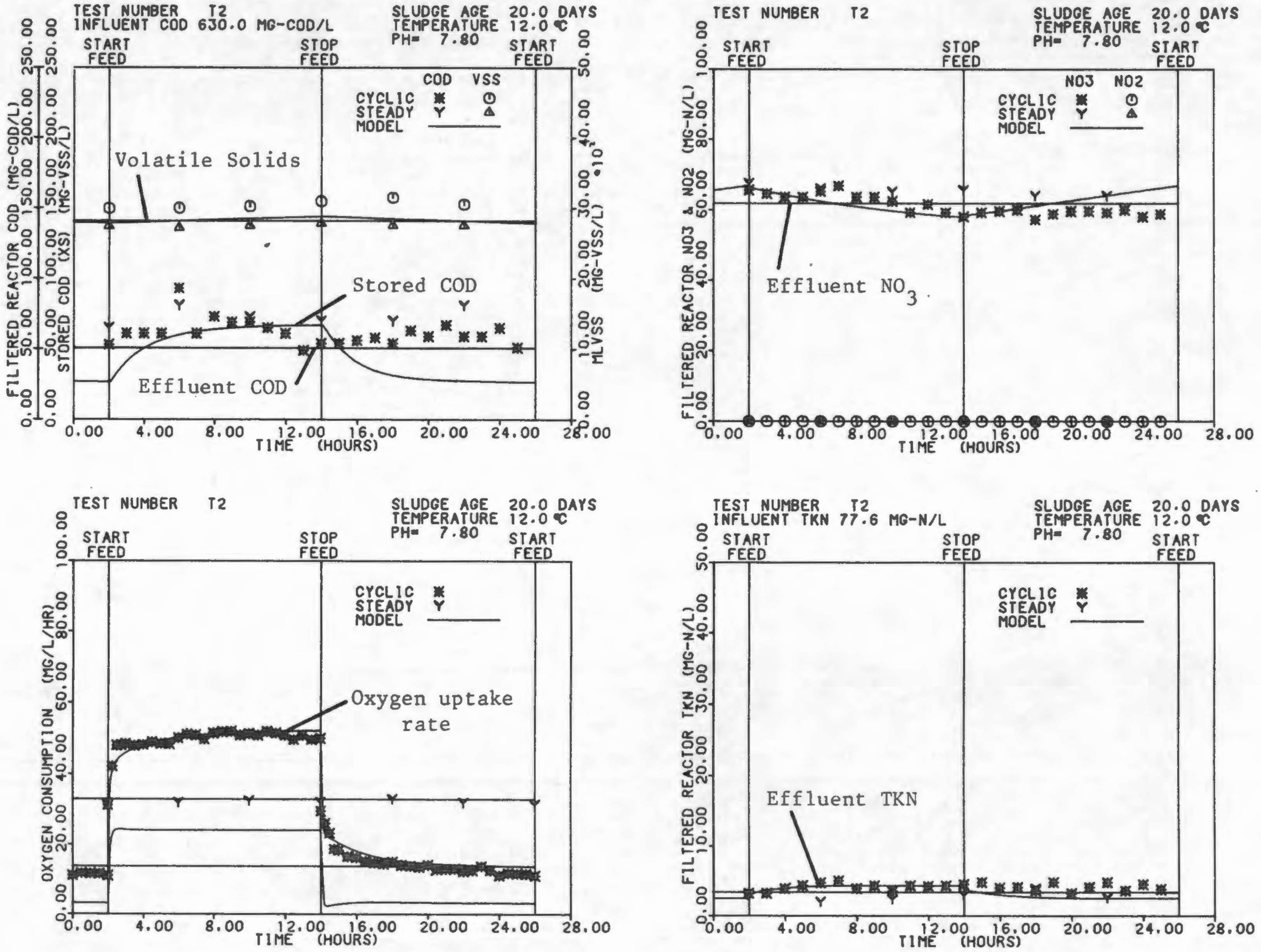


Figure 4.38: Comparison of the experimental response waves with those predicted by the mathematical model for daily square wave loading conditions at a 20 day sludge age and 12°C using the *modified* kinetic constants.

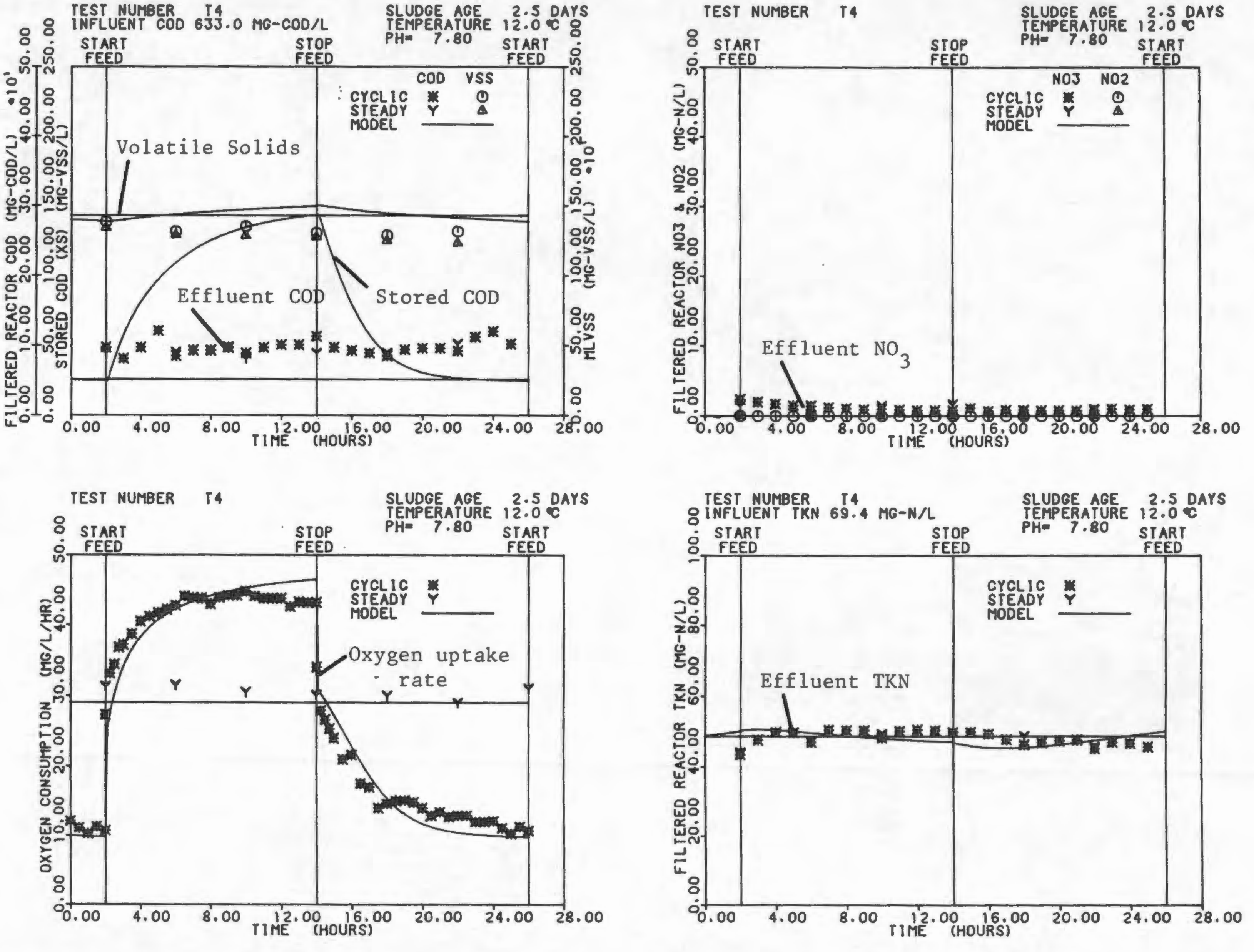


Figure 4.39: Comparison of the experimental response waves with those predicted by the mathematical model for daily square wave loading conditions at a 2,5 day sludge age and 12°C using the *modified* kinetic constants.

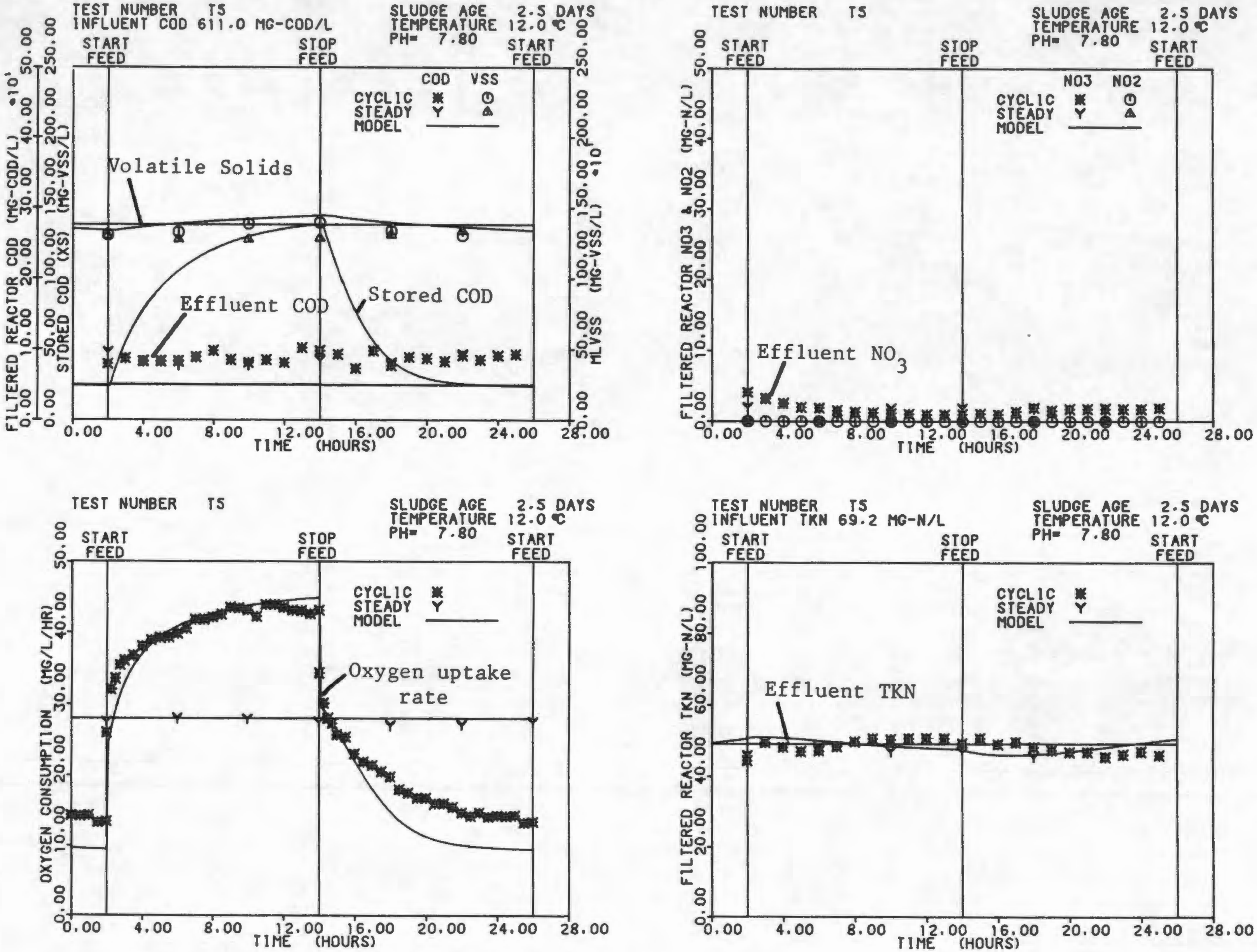


Figure 4.40: Comparison of the experimental response waves with those predicted by the mathematical model for daily square wave loading conditions at a 2,5 day sludge age and 12°C using the *modified* kinetic constants.

gradable particulate fraction, f_{bp}, and (2) an easily biodegradable soluble fraction, f_{bs}, and allocated specific kinetic properties to these two fractions. The results from this investigation indicate that the f_{bp} fraction can in fact have different kinetic properties from those 'standard' in the Dold *et al.* (1980) analysis. The distinguishing feature of the Mitchell's Plain sewage is that it may have an inordinately high concentration of fats and oils (see Chapter 2, Figures 2.1 and 2.2) and this could be the principal cause for the changes in the kinetic constants observed. If a more precise analysis of the process response is to be made one should divide each of the two biodegradable fractions into two or more subfractions but, from a design point of view, such a division is unlikely to be of any practical use if sludge ages longer than about 6 days are employed - at longer sludge ages the minor variations (even to twice an order of magnitude) in the substrate utilization rates have virtually no effect on the simulated response as the stored COD concentration on the active organism mass is generally low and the substrate is being utilized virtually at the rate at which it enters the reactor. At very short sludge ages however a sub-division may have merit. Nonetheless, the overall conclusion that can be drawn from the above simulation is: provided the measured data (on the oxygen consumption rate in particular) has been performed experimentally correct, then good COD recoveries should be achieved and the results can be simulated satisfactorily by means of the general mathematical model describing the dynamic behaviour of the aerobic activated sludge process as presented by Dold *et al.* (1980).

Finally, Dold *et al.* (1980) in their experiments on cyclic flow and load conditions for units with 2,5 day sludge ages at 12°C, found that the observed oxygen consumption rates were substantially lower than those predicted by the model. They hypothesized that this was due to an inordinately high COD/VSS ratio at short sludge ages and low temperatures. This hypothesis is, however, not supported by the experimental work conducted in this investigation where a consistent finding is that the COD/VSS ratio is not significantly increased (for practical design purposes) under these conditions. Most likely the cause for the differences they observed was the incorrect measurement of the oxygen consumption rates - it was shown in this investigation that at short sludge ages and low temperatures significant errors in the oxygen consumption rate measurement can arise if the liquid surface is not protected from contact with the air during this test. This error in the testing procedure may always give an apparently lower measured oxygen consumption rate than predicted, as reported by Dold *et al.* (1980).

CHAPTER FIVE

CONCLUSIONS

This investigation basically was orientated towards two aspects of the aerobic activated sludge process:

(1) the causes for changes in the COD/VSS ratio of activated sludge treating a raw domestic sewage, and

(2) the causes for the differences between the experimentally observed response and that predicted by the general model for the aerobic activated sludge process under dynamic loading conditions at 12°C.

5.1 THE COD/VSS RATIO OF ACTIVATED SLUDGE

Conclusions on the COD/VSS ratio are:

(1) For normal municipal sewages at the longer sludge ages (8 and 20 days) neither the operating sludge age nor the operating temperature of the activated sludge unit appeared to have any observable effect on the COD/VSS ratio. When the sludge age is shortened from 8 and 20 days to 3 days, there is a positive indication that, at 12°C, the COD/VSS ratio increases but, at 20°C, no such increase is evident.

(2) The changes in the COD/VSS ratio appear to be due to a solidified fats accumulation on the organism; at the lower temperature (12°C) more fats appear to accumulate, relative to the VSS, than at higher temperatures (20°C). This effect is particularly evident at short sludge ages (3 days and less) and at the lower temperatures. The higher COD/VSS ratios arise because the COD/VSS ratio of fats is about 2,6 compared to that of 'normal' activated sludge being about 1,40 to 1,50.

(3) To show up a positive increase in the COD/VSS ratio at 20°C as well, the fat concentration in the influent must be very high. In this investigation an addition of up to 33 percent of influent COD by mass of oleic acid was necessary to demonstrate a higher COD/VSS ratio for a 3 day sludge age at both 12°C *and* 20°C. With 'normal'

municipal effluents, the COD/VSS ratio is not expected to change significantly between 20°C and 12°C for 3 day sludge ages and longer.

(4) The experimental determination of the COD/VSS ratio is very imprecise giving rise to relatively large standard deviations for a particular set of data, of approximately 0,03 to 0,05 *i.e.* a 95 percent confidence interval of about 0,06 to 0,10. Consequently, even the mean value is subject to wide variation if the set of data from which the mean is determined contains less than about 20 values. In the experimental estimation of the COD/VSS ratio, insufficient data very likely is the reason for the wide dispersion of values reported in the literature.

(5) The value for the ratio proposed by Ekama and Marais (1978) *i.e.* COD/VSS = 1,48 $\mathrm{mgCOD.mgVSS}^{-1}$, for processes treating municipal effluents appears to be reasonably representative, for practical design purposes, for sludge ages of 3 days and longer, and temperatures ranging from 12°C to 20°C.

5.2 THE DYNAMIC BEHAVIOUR OF THE AEROBIC ACTIVATED SLUDGE PROCESS AT 12°C

(1) Dold *et al.* (1980), in their experiments on the dynamic behaviour of the aerobic activated sludge process with sludge ages of 2,5 days at 12°C found that the experimentally measured oxygen consumption rates were substantially lower than those predicted by the mathematical model. They hypothesized that a possible cause for these differences could arise if the COD/VSS ratio was higher than that normally used (COD/VSS = 1,48). This investigation has shown that the COD/VSS ratio is not significantly increased (for practical design purposes) under these conditions. Most likely the cause for differences in the observed and predicted oxygen consumption rates in the experiments after Dold *et al.* (1980) was due to the incorrect measurement of the oxygen consumption rate - especially at the short sludge ages and low temperatures, significant errors in the oxygen consumption rate measurement can arise due to oxygen transfer from the atmosphere into the liquid mass. To prevent this oxygen transfer (induced by turbulence at the liquid-air interface), the liquid

surface must be completely covered during an oxygen consumption rate test.

(2) Results from the simulation investigation indicate that the slowly biodegradable particulate COD fraction (adsorbed and stored on the active organism prior to extracellular breakdown and utilization) can in fact have different kinetic properties from those 'standard' in the Dold *et al.* (1980) analysis. A more precise analysis of the process response should include a division of each of the biodegradable substrate fractions (*i.e.* the soluble and particulate fractions) into two or more sub-fractions. However, such a division is not recommended for practical use if sludge ages longer than about 6 days are employed - at the longer sludge ages variations, even to twice an order of magnitude, in the substrate utilization rates have virtually no effect on the simulated response by reason that the stored COD concentration on the active organism is low and the substrate is utilized almost immediately on entering the reactor. At the very short sludge ages however such a sub-division may have merit.

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Table A. 1: Daily experimental data for the 3 day sludge age unit at 20°C treating domestic sewage

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
30.07	522	44,0	1386	39,5	52	11,0	28,75	1,51	7,15	406
1.08	500	40,6	1299	38,2	42	11,0	16,75	1,45	7,60	378
3.08	508	40,8	1271	31,9	114	20,7	7,25	1,43	8,10	426
5.08	506	42,1	1563	38,4	60	11,7	16,50	1,45	7,70	442
7.08	487	44,6	1483	40,7	83	10,0	25,00	1,48	7,50	441
9.08	503	45,5	1483	40,5	86	12,7	19,50	1,47	8,00	453
11.08	507	46,4	1585	40,5	72	10,5	22,75	1,52	7,50	467
13.08	513	46,1	1584	42,0	76	3,7	24,50	1,55	7,55	462
15.08	505	46,4	1535	41,5	74	5,0	24,00	1,43	8,00	425
17.08	500	44,8	1600	40,0	53	7,3	19,50	1,46	7,20	465
19.08	501	44,8	1563	42,5	68	2,8	26,00	1,49	8,10	431
21.08	511	38,4	1483	41,0	83	2,6	22,00	1,38	8,10	416
23.08	506	38,8	1595	38,0	55	6,8	14,50	1,43	7,20	440
25.08	526	38,7	1518	39,8	81	4,6	18,00	1,42	7,65	445
1.09	521	42,6	1307	41,5	85	14,2	13,75	1,55	8,00	417
3.09	514	44,1	1345	43,1	83	11,1	19,25	1,49	8,00	401
4.09	497	41,9	1684	40,5	61	4,3	22,00	1,49	8,10	401
9.09	500	46,3	1273	43,5	82	11,5	20,50	1,47	7,35	356
11.09	491	51,8	1152	45,7	77	14,4	23,50	1,42	7,10	366
13.09	501	48,9	1155	45,5	87	12,3	23,00	1,47	7,85	332
15.09	493	49,0	1049	46,5	86	15,3	22,75	1,48	8,25	333
17.09	497	48,7	1289	44,5	78	12,8	22,50	1,55	8,20	407

Table A. 1: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.09	508	49,8	1324	48,8	63	9,9	26,25	1,48	7,15	403
21.09	494	49,4	1325	39,0	65	22,0	13,75	1,51	8,20	401
23.09	487	49,1	1264	47,0	60	11,3	24,00	1,45	8,30	374
25.09	500	51,2	1292	47,5	77	12,9	24,25	1,45	8,15	378
27.09	509	53,3	1270	38,0	95	24,6	14,50	1,38	8,40	352

Table A. 2: Daily experimental data for the 3 day sludge age unit at 12°C treating domestic sewage

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell.\text{hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	NO_{3E} $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
30.07	522	44,0	1588	19,4	95	33,3	4,50	1,52	7,30	476
1.08	500	40,6	1346	21,1	79	18,7	2,00	1,58	7,60	361
3.08	508	40,8	1043	20,9	98	24,7	2,38	1,59	7,90	312
5.08	506	42,1	815	17,0	89	32,8	0,88	1,63	8,00	303
7.08	487	44,6	1054	20,8	94	29,2	1,00	1,64	7,65	382
9.08	503	45,5	1094	23,3	90	29,7	1,13	1,58	7,80	384
11.08	507	46,4	1116	24,9	95	29,2	0,50	1,59	7,70	380
13.08	513	46,1	1156	23,0	115	29,6	0,50	1,61	7,70	340
15.08	505	46,4	1032	18,8	150	31,9	0,38	1,57	8,15	343
17.08	500	44,8	1087	21,4	110	29,2	0,25	1,63	7,50	370
19.08	501	44,8	1098	24,6	97	31,1	0,25	1,60	8,20	358
21.08	511	38,4	891	24,9	93	29,0	0,25	1,56	8,20	383
23.08	506	38,8	1154	23,0	89	26,3	0,00	1,51	7,40	346
25.08	526	38,7	1053	23,1	112	27,4	0,00	1,51	7,80	370
1.09	521	42,6	978	19,8	116	30,0	1,00	1,65	8,20	345
3.09	514	44,1	1039	18,7	104	32,7	0,50	1,57	8,00	394
4.09	497	41,9	1055	19,3	96	29,6	0,50	1,57	8,10	394
9.09	500	46,3	1108	18,8	98	33,0	1,25	1,55	7,70	319
11.09	491	51,8	1071	19,0	97	39,8	0,75	1,46	7,55	307
13.09	501	48,9	1042	18,2	102	37,9	0,75	1,49	8,00	295
15.09	493	49,0	974	19,6	95	38,2	0,50	1,54	8,50	296
17.09	497	48,7	905	19,1	108	38,3	0,75	1,57	8,40	317

Table A. 2: continued

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	NO_{3E} $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
19.09	508	59,8	992	18,8	112	38,3	0,75	1,60	7,90	321
21.09	494	49,4	896	19,0	116	39,1	0,75	1,55	8,30	272
23.09	487	49,1	899	19,5	109	39,4	0,75	1,46	8,45	249
25.09	500	51,2	1126	19,4	95	38,6	0,75	1,58	8,40	285
27.09	509	53,3	899	21,2	109	41,8	0,75	1,51	8,35	271

Table A. 3: Daily experimental data for the 8 day sludge age unit at 20°C treating domestic sewage

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
30.07	522	44,0	1335	25,2	61	6,7	45,50	1,48	7,15	398
1.08	500	40,6	1330	27,5	65	2,7	26,50	1,54	7,40	388
3.08	508	40,8	1274	28,5	67	4,1	25,50	1,55	7,60	383
5.08	506	42,1	1225	27,8	74	3,8	24,75	1,47	7,60	352
7.08	487	44,6	1149	28,0	79	5,8	29,00	1,55	7,30	357
9.08	503	45,5	1202	29,2	79	3,6	29,00	1,44	7,60	351
11.08	507	46,4	1140	29,0	74	4,4	27,25	1,56	7,50	359
13.08	513	46,1	1116	29,0	109	6,7	29,50	1,49	7,55	330
15.08	505	46,4	1241	27,0	109	6,8	28,25	1,56	7,90	354
17.08	500	44,8	1230	26,9	106	7,8	28,00	1,54	6,90	374
19.08	501	44,8	1240	29,1	88	5,2	30,25	1,46	8,00	362
21.08	511	38,4	1270	28,8	72	2,6	28,00	1,44	8,05	409
23.08	506	38,8	1335	28,4	53	3,1	24,50	1,46	6,75	411
25.08	526	38,7	1349	30,0	57	3,0	24,25	1,50	7,50	423
1.09	521	42,6	1248	30,5	65	4,4	28,00	1,54	7,85	394
3.09	514	44,1	1290	30,2	59	6,3	28,00	1,52	7,85	364
4.09	497	41,9	1227	29,0	61	2,8	29,00	1,52	7,90	346
9.09	500	46,3	1253	28,1	78	9,5	27,25	1,51	7,40	364
11.09	491	51,8	1273	29,4	74	9,0	32,50	1,49	7,20	362
13.09	501	48,9	1218	30,5	76	6,3	32,00	1,50	7,80	342
15.09	493	49,0	1152	30,1	59	9,0	30,00	1,50	8,15	358
17.09	497	48,7	1162	30,1	60	9,1	30,00	1,50	8,20	394

Table A. 3: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.09	508	49,8	1331	31,3	63	8,3	31,75	1,45	7,60	360
21.09	494	49,4	1332	30,4	57	6,5	32,00	1,51	8,10	390
23.09	487	49,1	1305	29,9	53	8,3	30,75	1,46	8,20	368
25.09	500	51,2	1260	30,0	69	9,3	31,75	1,46	8,20	362
27.09	509	53,3	1475	30,1	61	10,5	31,00	1,41	8,15	409

Table A. 4: Daily experimental data for the 8 day sludge age unit at 12°C treating domestic sewage

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell.\text{hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	NO_{3E} $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
30.07	522	44,0	1798	22,5	50	11,9	34,00	1,50	7,00	554
1.08	500	40,6	1863	21,2	42	3,7	24,50	1,47	7,40	551
3.08	508	40,8	1841	22,6	37	3,3	24,50	1,49	7,60	560
5.08	506	42,1	1833	20,5	52	2,9	22,25	1,48	7,70	558
7.08	487	44,6	1843	24,9	39	2,2	27,25	1,50	7,30	551
9.08	503	45,5	1877	26,1	47	3,4	31,25	1,50	7,60	571
11.08	507	46,4	1904	26,8	38	2,7	28,75	1,51	7,40	569
13.08	513	46,1	1860	26,0	56	2,6	28,75	1,53	7,30	554
15.08	505	46,4	1844	26,1	68	3,1	29,75	1,50	7,80	547
17.08	500	44,8	1883	26,3	49	4,1	28,25	1,49	6,90	555
19.08	501	44,8	1856	27,0	40	2,5	28,50	1,47	7,90	543
21.08	511	38,4	1850	23,5	49	2,4	21,50	1,46	8,00	542
23.08	506	38,8	1891	23,5	49	2,9	21,75	1,49	6,80	578
25.08	526	38,7	1956	24,3	48	2,1	21,50	1,48	7,40	567
1.09	521	42,6	1828	26,0	53	1,4	27,75	1,50	7,70	567
3.09	514	44,1	1851	25,5	59	3,4	27,00	1,58	7,80	548
4.09	497	41,9	2058	23,0	53	1,1	27,00	1,58	7,75	548
9.09	500	46,3	1731	24,0	86	6,3	27,25	1,48	7,30	497
11.09	491	51,8	1626	26,9	94	6,3	33,75	1,51	7,15	493
13.09	501	48,9	1599	27,5	90	5,7	33,00	1,52	7,70	494
15.09	493	49,0	1596	25,8	74	6,0	30,50	1,51	8,15	472
17.09	497	48,7	1571	26,1	74	4,9	31,75	1,51	8,15	501

Table A. 4: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	$NO_{3}E$ $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.09	508	49,8	1573	26,5	87	5,3	31,75	1,53	7,50	509
21.09	494	49,4	1670	25,5	73	6,0	30,50	1,55	7,95	542
23.09	487	49,1	1726	25,2	66	6,5	29,75	1,44	8,15	530
25.09	500	51,2	1631	25,5	83	7,6	30,75	1,52	8,20	455
27.09	509	53,3	1545	25,3	87	11,5	29,00	1,48	8,10	401

Table A. 5: Daily experimental data for the 20 day sludge age unit at 20°C treating domestic sewage

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	NO_{3E} $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
30.07	522	44,0	1459	20,2	79	4,4	50,00	1,52	7,20	443
1.08	500	40,6	1527	20,5	65	4,6	30,75	1,52	7,40	449
3.08	508	40,8	1531	22,5	61	5,8	27,50	1,47	7,70	452
5.08	506	42,1	1520	22,0	82	3,4	27,25	1,52	7,70	454
7.08	487	44,6	1456	21,4	90	5,3	33,00	1,54	7,40	461
9.08	503	45,5	1512	22,5	98	7,0	34,25	1,51	7,70	459
11.08	507	46,4	1493	21,5	95	7,7	32,50	1,51	7,60	449
13.08	513	46,1	1481	21,6	107	8,6	31,75	1,50	7,45	458
15.08	505	46,4	1576	19,2	170	8,6	31,75	1,50	8,00	445
17.08	500	44,8	1584	23,2	104	8,6	31,50	1,45	7,20	455
19.08	501	44,8	1698	24,0	86	8,4	30,75	1,48	7,95	475
21.08	511	38,4	1642	23,0	87	4,1	27,00	1,44	8,05	456
23.08	506	38,8	1707	23,6	63	4,5	26,75	1,42	7,10	521
25.08	526	38,7	1820	24,0	71	4,0	26,00	1,42	7,45	534
1.09	521	42,6	1799	24,0	77	5,0	29,75	1,48	7,90	551
3.09	514	44,1	1885	23,9	65	7,0	29,75	1,52	7,90	574
4.09	497	41,9	2110	23,2	60	4,6	30,50	1,52	7,95	575
9.09	500	46,3	1911	24,3	63	4,4	32,75	1,48	7,55	536
11.09	491	51,8	1808	25,2	72	5,3	39,00	1,49	7,35	513
13.09	501	48,9	1648	25,9	86	4,9	39,25	1,50	7,80	475
15.09	493	49,0	1671	24,9	69	4,3	36,75	1,49	8,25	484
17.09	497	48,7	1631	24,3	74	8,6	32,25	1,50	8,25	501

Table A. 5: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_3E $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.09	508	49,8	1693	25,0	71	6,6	35,50	1,49	7,70	501
21.09	494	49,4	1715	25,2	67	5,9	35,25	1,46	8,20	525
23.09	487	49,1	1780	24,6	64	6,9	34,50	1,47	5,15	526
25.09	500	51,2	1851	26,0	51	6,4	36,00	1,45	8,25	514
27.09	509	53,3	1960	26,6	46	8,9	36,50	1,34	8,15	510

Table A. 6: Daily experimental data for the 20 day sludge age unit at 12°C treating domestic sewage

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
30.07	522	44,0	2446	19,1	34	3,3	48,00	1,50	7,10	751
1.08	500	40,6	2548	18,7	34	1,6	26,00	1,46	7,40	754
3.08	508	40,8	2584	20,2	33	2,6	28,75	1,48	7,55	764
5.08	506	42,1	2541	17,8	42	3,0	26,75	1,49	7,60	768
7.08	487	44,6	2642	20,2	33	0,9	31,25	1,48	7,30	775
9.08	503	45,5	2686	21,5	41	1,4	32,50	1,50	7,60	824
11.08	507	46,4	2745	21,5	40	2,9	31,50	1,47	7,40	815
13.08	513	46,1	2779	21,6	44	2,6	29,75	1,49	7,30	829
15.08	505	46,4	2770	21,5	48	2,0	31,75	1,50	7,80	839
17.08	500	44,8	2835	21,7	41	0,8	31,50	1,53	6,95	882
19.08	501	44,8	2844	21,8	40	1,2	31,50	1,49	7,85	900
21.08	511	38,4	2882	20,8	45	0,8	27,25	1,52	7,90	872
23.08	506	38,8	2919	20,8	41	1,1	27,00	1,47	6,90	864
25.08	526	38,7	2918	22,0	49	1,0	27,00	1,47	7,30	842
1.09	521	42,6	2637	23,8	51	1,6	31,50	1,55	7,70	846
3.09	514	44,1	2706	23,5	47	3,1	31,50	1,57	7,80	888
4.09	497	41,9	2983	22,1	43	3,0	28,50	1,57	7,75	888
9.09	500	46,3	2835	22,5	37	3,7	29,25	1,52	7,45	866
11.09	491	51,8	2900	22,0	43	7,1	31,25	1,54	7,30	888
13.09	501	48,9	2879	22,1	47	3,5	32,50	1,49	7,75	886
15.09	493	49,0	2931	21,9	29	4,5	31,25	1,58	8,20	928
17.09	497	48,7	2951	22,0	36	4,2	31,75	1,56	8,15	936

Table A. 6: continued

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	$NO_{3,E}$ $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
19.09	508	49,8	3011	22,4	48	4,9	32,50	1,56	7,65	924
21.09	494	49,4	2822	22,1	47	5,0	32,50	1,54	8,00	912
23.09	487	49,1	2819	22,0	49	4,8	32,75	1,49	8,10	692
25.09	500	51,2	2851	22,5	49	5,5	34,25	1,52	8,15	766
27.09	509	53,3	2862	22,9	52	5,5	35,50	1,48	8,10	672

Table A. 7: Daily experimental data for the 3 day sludge age unit at 20°C treating domestic sewage (Repeat investigation)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
13.10	616	65,5	1474	61,0	61	5,6	44,00	1,41	8,05	416
14.10	603	62,7	1612	58,0	63	5,3	39,00	1,41	8,00	455
15.10	604	63,1	1605	58,8	63	4,9	40,50	1,40	8,05	415
16.10	596	62,8	1654	59,6	59	4,7	40,75	1,37	8,00	453
17.10	592	55,2	1544	55,5	63	5,3	32,75	1,39	8,10	430
18.10	611	54,9	1551	55,1	64	6,3	32,25	1,42	8,10	440
19.10	602	55,4	1611	55,5	52	5,6	31,50	1,39	8,00	448
20.10	592	54,0	1539	55,0	57	5,5	31,00	1,40	8,05	432
21.10	606	55,3	1566	55,5	63	6,2	31,75	1,37	8,10	428
22.10	612	53,9	1574	56,0	55	5,9	30,50	1,37	8,10	430
23.10	608	53,6	1628	55,5	57	6,1	30,50	1,38	8,05	449
24.10	598	54,0	1639	53,0	65	6,2	31,00	1,37	8,05	448
25.10	608	56,0	1618	54,7	64	6,5	30,00	1,42	8,05	460
27.10	591	54,3	1532	51,8	62	6,7	29,75	1,45	8,00	445
28.10	612	54,9	1572	53,9	61	6,7	31,00	1,46	8,10	458
29.10	603	54,3	1591	53,3	61	6,7	30,00	1,46	8,05	464
30.10	594	53,9	1626	53,5	59	7,0	30,00	1,41	8,00	459
31.10	615	55,1	1608	54,0	60	6,0	31,25	1,49	8,05	480
1.11	602	55,6	1645	55,0	54	6,0	31,75	1,37	8,10	451
16.11	601	55,3	1652	53,2	64	7,1	29,75	1,40	8,05	464
17.11	609	53,8	1524	56,1	61	5,7	31,50	1,45	8,00	441
18.11	604	53,9	1608	54,5	57	5,5	30,50	1,42	8,10	457

Table A. 7: continued

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell\text{.hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	NO_{3E} $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
19.11	599	54,6	1581	53,5	61	5,3	31,25	1,50	8,05	473
20.11	605	53,9	1674	54,5	53	4,8	31,50	1,42	8,10	477
21.11	614	53,8	1654	54,0	59	4,9	31,00	1,45	8,00	479
22.11	600	53,9	1683	52,5	51	4,6	31,25	1,52	8,00	510
23.11	650	53,9	1752	57,6	57	4,0	31,50	1,44	8,00	506
24.11	616	53,9	1668	53,9	59	5,0	30,25	1,48	8,10	494
25.11	612	54,3	1693	52,9	55	8,3	28,50	1,40	7,95	473
26.11	617	53,9	1658	53,2	61	6,2	28,75	1,44	7,95	477
27.11	606	52,6	1645	52,0	60	5,4	29,00	1,43	8,00	472
28.11	596	53,8	1660	51,3	59	7,0	28,50	1,45	8,00	482
29.11	602	60,6	1702	51,8	66	9,1	31,25	1,46	8,00	498
30.11	604	59,1	1607	53,0	81	7,1	34,25	1,39	7,95	448
1.12	593	58,8	1772	51,5	71	5,5	35,00	1,38	7,95	488
2.12	603	59,5	1716	53,0	77	6,4	35,00	1,39	8,00	478
3.12	601	58,9	1711	53,2	77	5,7	35,00	1,39	8,05	476
4.12	608	59,5	1689	53,9	69	7,5	35,00	1,41	8,00	476
5.12	606	60,9	1581	54,4	78	8,5	35,00	1,44	8,00	457
6.12	597	59,4	1643	54,5	75	6,5	34,75	1,36	8,00	446

Table A. 8: Daily experimental data for the 3 day sludge age unit at 20°C treating domestic sewage (Repeat investigation)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
13.10	616	65,5	1457	56,0	51	5,6	42,25	1,43	8,10	417
14.10	603	62,7	1575	58,6	61	5,6	40,00	1,43	8,05	449
15.10	604	63,1	1457	62,1	67	4,9	41,75	1,45	8,10	423
16.10	596	62,8	1591	58,9	56	5,3	39,00	1,30	8,05	414
17.10	592	55,2	1544	55,1	61	5,9	31,75	1,38	8,10	453
18.10	611	54,9	1566	56,5	64	6,3	31,50	1,40	8,05	438
19.10	602	55,4	1555	55,0	60	6,6	30,50	1,39	8,00	432
20.10	592	54,0	1506	54,9	59	6,7	29,75	1,45	8,10	437
21.10	606	55,3	1568	54,0	57	5,9	31,00	1,41	8,10	443
22.10	612	53,9	1553	54,2	67	6,0	30,25	1,38	8,10	430
23.10	608	53,6	1614	54,5	57	6,2	29,00	1,35	8,10	437
24.10	598	54,0	1576	53,5	69	6,3	30,00	1,39	8,10	437
25.10	608	56,0	1668	54,5	54	5,7	30,25	1,41	8,10	472
26.10	588	54,5	1669	52,6	53	5,7	30,50	1,42	8,10	473
27.10	591	54,3	1641	51,7	62	5,9	27,95	1,41	8,05	462
28.10	612	54,9	1668	54,6	61	5,3	31,25	1,38	8,10	462
29.10	603	54,3	1677	54,5	57	6,7	30,50	1,43	8,05	481
30.10	594	53,9	1663	53,6	54	5,7	30,75	1,43	8,00	476
31.10	615	55,2	1690	54,1	56	5,3	31,25	1,44	8,10	488
1.11	602	55,6	1751	53,5	56	5,5	31,00	1,33	8,10	467
16.11	601	55,3	1566	53,4	64	6,6	30,25	1,39	8,05	434
17.11	609	53,8	1513	54,9	69	5,7	31,00	1,51	8,00	457

Table A. 8: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
18.11	604	53,9	1553	55,0	53	6,2	30,50	1,43	8,10	445
19.11	599	54,6	1518	54,0	63	7,1	29,75	1,47	8,05	445
20.11	605	53,9	1566	53,5	61	6,2	30,25	1,50	8,05	469
21.11	614	53,8	1531	53,7	75	5,6	31,50	1,49	8,00	457
22.11	600	53,9	1520	53,0	67	5,7	30,50	1,49	8,00	453
23.11	650	53,9	1595	56,9	78	6,7	30,25	1,47	8,00	469
24.11	616	53,9	1641	52,4	66	7,3	28,50	1,43	8,00	469
25.11	612	54,3	1642	52,2	63	7,4	27,75	1,43	7,95	469
26.11	617	53,9	1635	51,0	65	6,9	27,75	1,45	7,95	473
27.11	606	52,6	1597	52,5	60	7,4	27,50	1,42	8,00	452
28.11	596	53,8	1600	52,0	61	7,1	27,75	1,43	8,05	458
29.11	602	60,6	1607	52,7	73	9,9	31,00	1,42	8,00	456
30.11	604	59,1	1568	54,5	77	7,8	34,00	1,37	7,95	431
1.12	593	58,8	1604	52,3	85	7,3	34,25	1,43	7,95	460
2.12	603	59,5	1614	53,9	77	7,7	34,25	1,35	8,00	437
3.12	601	58,9	1569	54,2	89	6,1	35,00	1,36	8,00	427
4.12	608	59,5	1573	55,0	81	6,8	34,75	1,40	8,00	439
5.12	606	60,9	1524	56,5	80	7,8	35,00	1,42	7,95	432
6.12	597	59,4	1655	54,3	71	6,6	35,00	1,39	8,00	460

Table A. 9: Daily experimental data for the 3 day sludge age unit at 12°C treating domestic sewage (Repeat investigation)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
13.10	616	65,5	1567	31,5	115	41,3	10,00	1,48	8,25	464
14.10	603	62,7	1570	29,4	134	44,6	1,50	1,48	8,20	466
15.10	604	63,1	1576	30,0	123	44,9	1,40	1,49	8,25	470
16.10	596	62,8	1634	30,0	89	44,8	0,80	1,58	8,20	518
17.10	592	55,2	1587	29,6	100	36,1	0,70	1,40	8,20	443
18.10	611	54,9	1598	30,8	107	36,4	0,80	1,42	8,10	454
19.10	602	55,4	1611	31,9	91	37,5	0,80	1,42	8,10	458
20.10	592	54,0	1627	29,5	94	35,5	0,60	1,49	8,15	486
21.10	606	55,3	1716	30,0	82	35,7	0,69	1,43	8,15	490
22.10	612	53,9	1763	33,4	74	35,0	0,72	1,43	8,15	504
23.10	608	53,6	1750	31,0	78	34,1	0,86	1,48	8,15	518
24.10	598	54,0	1727	30,9	73	34,5	0,81	1,47	8,10	508
25.10	608	56,0	1736	31,9	74	36,1	1,03	1,44	8,15	501
26.10	588	54,5	1776	31,2	61	34,2	1,03	1,46	8,10	519
27.10	591	54,3	1720	29,9	77	34,1	1,07	1,51	8,10	520
28.10	612	54,9	1743	29,8	92	34,1	1,29	1,44	8,20	501
29.10	603	54,3	1715	31,0	81	34,7	1,27	1,48	8,10	508
30.10	594	53,9	1682	30,5	83	34,0	1,42	1,45	8,10	488
31.10	615	55,2	1609	30,2	95	35,5	1,48	1,53	8,20	492
1.11	602	55,6	1671	30,1	84	34,7	1,49	1,39	8,20	465
16.11	601	55,3	1718	31,0	68	36,4	0,68	1,42	8,10	489
17.11	609	53,8	1477	34,1	82	37,0	0,41	1,53	8,10	453

Table A. 9: continued

DATE	S_{TI} $\frac{\text{mgCOD}}{\ell}$	N_{TI} $\frac{\text{mgN}}{\ell}$	X_v $\frac{\text{mgVSS}}{\ell}$	OUR $\frac{\text{mgO}}{\ell.\text{hr}}$	S_{TE} $\frac{\text{mgCOD}}{\ell}$	N_{TE} $\frac{\text{mgN}}{\ell}$	NO_{3E} $\frac{\text{mgN}}{\ell}$	P $\frac{\text{mgCOD}}{\text{mgVSS}}$	pH	S_S $\frac{\text{mgCOD}}{\ell}$
18.11	609	53,8	1477	34,1	82	37,0	0,41	1,53	8,10	453
19.11	599	54,6	1525	32,8	90	36,6	0,41	1,49	8,10	453
20.11	605	53,9	1509	31,8	106	37,0	0,37	1,46	8,15	441
21.11	614	53,8	1492	32,9	92	36,6	0,41	1,52	8,10	455
22.11	600	53,9	1440	34,1	86	37,2	0,41	1,51	8,10	435
23.11	650	53,9	1411	39,8	90	37,0	0,42	1,52	8,10	428
24.11	616	53,9	1553	36,5	73	35,7	0,42	1,51	8,05	469
25.11	612	54,3	1518	36,2	82	35,1	0,48	1,47	8,00	445
26.11	617	53,9	1531	35,5	78	37,0	0,51	1,47	8,05	449
27.11	606	52,6	1549	36,9	69	35,6	0,64	1,46	8,00	452
28.11	596	53,8	1494	36,1	73	36,1	0,71	1,46	8,10	435
29.11	602	60,6	1544	35,1	75	42,5	0,71	1,48	8,10	456
30.11	604	59,1	1618	35,2	69	40,0	0,81	1,45	8,05	468
1.12	593	58,8	1761	30,5	77	38,9	1,36	1,42	8,05	500
2.12	603	59,5	1768	31,2	71	38,4	1,13	1,36	8,10	482
3.12	601	58,9	1692	31,8	69	39,8	1,29	1,49	8,10	504
4.12	608	59,5	1675	32,0	89	40,0	1,25	1,44	8,10	484
5.12	606	60,9	1581	33,9	78	40,9	1,08	1,43	8,05	451
6.12	597	59,4	1660	32,5	79	40,6	1,33	1,37	8,05	454

APPENDIX A

TABULATION OF EXPERIMENTAL DATA

ABBREVIATIONS

S_{TI} : total influent COD concentration $(\mathrm{mgCOD}.\ell^{-1})$

S_{TE} : total effluent COD concentration $(\mathrm{mgCOD}.\ell^{-1})$

S_S : total solids COD concentration $(\mathrm{mgCOD}.\ell^{-1})$

N_{TI} : total influent TKN concentration $(\mathrm{mgN}.\ell^{-1})$

N_{TE} : total effluent TKN concentration $(\mathrm{mgN}.\ell^{-1})$

N_{NE} : total effluent nitrate concentration $(\mathrm{mgN}.\ell^{-1})$

OUR : total oxygen consumption rate $(\mathrm{mgO}.\ell^{-1}.\mathrm{hr}^{-1})$

X_v : total volatile solids concentration $(\mathrm{mgVSS}.\ell^{-1})$

P : COD equivalence of volatile solids $(\mathrm{mgCOD}.\mathrm{mgVSS}^{-1})$

pH : mixed liquor pH

Table A.12: Daily experimental data for the 3 day sludge age unit at 20°C treating domestic sewage spiked with oleic acid (22% by mass)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
13.02	581	40,9	1399	46,6	69	7,1	17,75	1,43	8,00	401
14.02	598	41,4	1513	48,8	59	5,0	18,50	1,40	7,95	423
15.02	591	41,2	1487	48,0	59	5,1	20,25	1,41	7,95	419
16.02	591	41,4	1449	48,5	60	4,9	20,50	1,45	8,00	420
17.02	587	42,5	1336	49,9	56	5,5	21,00	1,47	8,00	392
18.02	602	41,6	1324	50,0	63	6,2	19,75	1,48	8,00	393
19.02	598	41,6	1385	48,9	61	5,6	20,25	1,42	8,00	393
20.02	613	44,8	1293	51,5	85	7,3	22,00	1,42	7,90	368
21.02	588	46,8	1298	51,0	79	6,0	25,00	1,45	7,95	376
22.02	597	46,5	1514	50,6	66	6,3	23,50	1,49	8,05	452
23.02	599	46,7	1473	51,0	80	5,9	23,50	1,41	7,95	416
24.02	592	46,9	1505	47,9	70	6,2	23,75	1,43	8,00	430
25.02	606	47,4	1501	49,0	80	6,2	24,25	1,44	8,00	433
26.02	584	46,8	1537	48,6	51	6,6	22,50	1,42	8,00	436
27.02	593	46,1	1533	46,0	74	6,5	21,75	1,36	7,90	418
28.02	601	46,2	1463	48,1	84	6,3	23,25	1,40	8,10	410
1.03	601	47,5	1439	49,0	81	6,9	23,50	1,40	8,00	402
2.03	595	47,2	1454	50,0	73	8,3	21,75	1,43	8,00	415
3.03	604	47,2	1522	49,7	68	5,0	24,25	1,42	8,30	432
4.03	586	45,7	1513	48,0	73	4,5	25,00	1,37	8,15	414
5.03	497	39,4	1443	42,2	41	3,9	20,50	1,36	8,15	392
6.03	599	47,0	1435	50,9	47	11,9	18,75	1,41	8,10	404

Table A.12: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
7.03	601	47,6	1492	50,2	61	12,2	19,00	1,37	8,00	408
8.03	610	48,4	1405	54,0	67	13,2	18,75	1,38	8,00	388
9.03	616	49,0	1542	52,0	89	9,2	22,50	1,38	7,90	425
10.03	613	48,3	1384	53,4	61	10,3	22,50	1,42	-	394
11.03	599	46,3	1382	52,1	61	9,1	21,25	1,44	8,10	398
12.03	589	46,6	1389	50,1	53	9,3	21,75	1,45	8,00	404
14.03	605	48,2	1403	48,2	75	10,7	21,00	1,43	8,10	400
15.03	617	47,4	1495	51,4	85	8,2	22,25	1,42	8,00	425
16.03	611	46,2	1428	51,1	58	8,6	21,75	1,39	7,90	398
17.03	586	46,1	1516	50,2	67	7,3	22,25	1,38	7,95	419

Table A.13: Daily experimental data for the 3 day sludge age unit at 12°C treating domestic sewage only

DATE	S_{TI} mgCOD/ℓ	N_{TI} mgN/ℓ	X_v mgVSS/ℓ	OUR mgO/ℓ.hr	S_{TE} mgCOD/ℓ	N_{TE} mgN/ℓ	NO_3E mgN/ℓ	P mgCOD/mgVSS	pH	S_S mgCOD/ℓ
13.02	582	53,8	1525	32,0	85	34,4	0,46	1,42	8,00	433
14.02	598	53,5	1536	34,1	91	34,6	0,51	1,37	8,15	421
15.02	594	52,5	1432	33,6	93	35,6	0,58	1,41	8,15	403
16.02	595	52,0	1383	34,5	96	37,0	0,61	1,40	8,15	386
17.02	597	52,8	1313	32,2	118	39,2	0,61	1,46	8,10	384
18.02	601	52,8	1148	29,3	170	39,7	0,61	1,50	8,15	344
19.02	603	52,6	1023	24,2	180	39,6	0,45	1,47	8,10	300
20.02	610	58,4	1120	30,5	170	44,9	0,32	1,46	8,10	326
21.02	611	58,7	1206	30,0	169	44,2	0,42	1,48	8,10	356
22.02	610	59,0	1292	32,2	151	44,1	0,41	1,42	8,20	355
23.02	604	58,4	1432	28,5	148	41,7	0,50	1,44	8,20	412
24.02	597	58,0	1454	30,0	126	41,5	0,51	1,42	8,20	414
25.02	610	57,4	1471	30,0	121	40,3	0,57	1,39	8,10	409
26.02	576	58,0	1399	34,5	72	41,0	0,61	1,45	8,10	406
27.02	592	58,5	1419	33,5	88	41,4	0,61	1,46	8,20	414
28.02	600	59,4	1386	34,0	92	44,2	0,66	1,40	8,20	389
1.03	596	60,3	1442	36,8	67	41,4	0,77	1,45	8,20	417
2.03	610	60,6	1462	36,5	83	42,9	0,71	1,45	8,15	423
3.03	595	58,8	1518	33,1	78	41,4	0,82	1,45	8,40	440
3.03	583	57,8	1526	32,6	73	38,1	1,12	1,44	8,25	438
5.03	479	48,2	1368	25,7	55	33,6	1,40	1,40	8,20	382
6.03	588	59,7	1460	34,2	69	41,5	1,54	1,41	8,25	412

Table A.13: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
7.03	609	59,4	1565	34,6	81	40,9	1,55	1,36	8,10	425
8.03	619	60,8	1503	36,2	91	41,6	1,62	1,39	8,15	417
9.03	621	61,2	1589	35,6	83	41,6	1,83	1,44	8,20	459
10.03	606	60,0	1512	35,6	75	40,9	2,05	1,45	-	439
11.03	601	60,2	1493	35,3	83	40,5	2,10	1,47	-	439
12.03	595	59,6	1519	34,6	73	39,5	2,18	1,41	8,20	427
14.03	618	59,9	1405	37,5	73	41,8	2,30	1,50	8,25	421
15.03	616	60,2	1353	37,0	96	41,5	2,44	1,46	8,20	394
16.03	613	59,5	1364	37,1	103	41,2	2,48	1,44	8,20	393
17.03	601	58,4	1636	36,5	74	37,8	2,51	1,38	8,10	450

Table A.14: Daily experimental data for the 3 day sludge age unit at 12°C treating domestic sewage spiked with oleic acid (22% by mass)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
13.02	584	40,3	1491	28,0	97	22,7	1,08	1,49	7,95	445
14.02	596	41,4	1478	27,5	124	23,7	1,09	1,49	8,00	432
15.02	589	42,0	1380	26,5	132	25,0	1,07	1,49	8,00	411
16.02	585	41,6	1213	26,3	157	27,1	0,95	1,57	8,00	380
17.02	588	43,3	1080	24,5	197	30,8	0,74	1,61	8,00	347
18.02	592	43,1	1013	25,5	206	31,9	0,49	1,54	7,95	312
19.02	601	42,0	1000	26,7	201	29,8	0,34	1,56	8,00	312
20.02	613	43,8	1142	27,0	189	30,0	0,20	1,53	7,85	350
21.02	597	47,5	1185	27,9	151	34,1	0,15	1,59	8,00	376
22.02	602	46,1	1240	30,0	138	30,8	0,62	1,51	7,95	374
23.02	598	46,6	1340	30,6	122	30,1	0,29	1,55	8,00	416
24.02	595	46,8	1389	30,1	120	30,9	0,29	1,49	8,10	414
25.02	604	47,0	1442	30,1	111	30,6	0,31	1,50	8,00	322
26.02	581	46,3	1439	33,8	76	29,4	0,34	1,49	8,00	428
27.02	581	46,3	1387	32,0	86	31,1	0,36	1,51	8,20	418
28.02	596	46,5	1398	33,9	82	30,2	0,37	1,55	8,10	432
1.03	590	47,0	1462	34,0	83	31,1	0,34	1,45	8,00	423
2.03	594	47,6	1420	34,0	91	32,2	0,33	1,56	7,95	443
3.03	592	47,1	1449	30,3	100	31,9	0,37	1,46	8,25	424
4.03	581	46,3	1247	33,9	103	31,3	0,39	1,43	8,15	356
5.03	499	39,7	1349	30,0	65	26,6	0,34	1,42	8,00	384
6.03	590	46,3	1392	30,0	117	30,0	0,38	1,51	8,15	420

Table A.14: continued

DATE	S_{TI} mgCOD/ℓ	N_{TI} mgN/ℓ	X_v mgVSS/ℓ	OUR mgO/ℓ.hr	S_{TE} mgCOD/ℓ	N_{TE} mgN/ℓ	$NO_{3,E}$ mgN/ℓ	P mgCOD/mgVSS	pH	S_S mgCOD/ℓ
7.03	593	47,0	1424	33,1	95	30,8	0,34	1,48	8,00	421
8.03	609	48,2	1466	30,6	115	31,0	0,29	1,45	8,05	425
9.03	619	48,7	1470	31,2	107	31,0	0,30	1,48	8,05	435
10.03	606	48,2	1360	33,3	111	32,6	0,27	1,50	–	408
11.03	586	46,6	1306	32,1	104	31,4	0,30	1,49	–	390
12.03	587	46,3	1304	32,0	106	31,0	0,34	1,50	8,05	390
14.03	612	48,2	1279	33,1	128	32,7	0,41	1,52	8,15	388
15.03	608	47,7	1338	33,9	100	32,4	0,41	1,57	8,05	421
16.03	613	46,6	1303	33,6	127	32,4	0,44	1,45	8,05	379
17.03	592	45,8	1491	32,0	88	29,1	0,45	1,37	8,05	409

Table A.15: Daily experimental data for the 3 day sludge age unit at 20°C treating domestic sewage only

DATE	S_{TI} $\frac{mgCOD}{ℓ}$	N_{TI} $\frac{mgN}{ℓ}$	X_v $\frac{mgVSS}{ℓ}$	OUR $\frac{mgO}{ℓ.hr}$	S_{TE} $\frac{mgCOD}{ℓ}$	N_{TE} $\frac{mgN}{ℓ}$	NO_{3E} $\frac{mgN}{ℓ}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{ℓ}$
19.03	591	59,4	1499	58,8	53	3,9	37,25	1,36	7,95	409
20.03	600	60,2	1584	62,0	51	4,2	38,00	1,34	8,05	423
21.03	586	60,6	1481	58,4	53	5,9	38,50	1,35	8,00	399
22.03	604	60,8	1521	56,5	71	6,3	37,25	1,38	7,90	420
23.03	607	60,8	1326	56,5	55	8,4	35,25	1,37	7,95	362
24.03	610	62,2	1519	58,1	63	9,1	35,75	1,41	7,95	427
25.03	595	61,2	1536	58,2	67	6,3	39,25	1,37	8,00	421
27.03	617	62,5	1506	58,4	65	8,8	37,50	1,42	8,25	429
28.03	606	62,4	1575	58,2	65	8,7	38,75	1,37	8,05	430
29.03	588	62,2	1636	57,0	75	7,0	38,50	1,34	8,10	438
30.03	614	42,0	1588	57,2	81	7,7	38,50	1,37	8,05	436
4.04	595	58,8	1445	57,0	81	4,1	38,75	1,38	7,95	400
5.04	596	58,5	1466	58,5	77	4,0	38,00	1,41	8,05	412
6.04	612	58,5	1469	57,5	85	3,1	38,25	1,44	8,00	424
7.04	614	58,5	1577	58,9	81	1,4	40,00	1,36	-	430
8.04	600	58,4	1507	58,7	69	1,7	40,75	1,44	8,10	434
9.04	613	59,6	1561	58,9	69	1,9	40,75	1,40	8,05	326
10.04	584	56,8	1552	56,0	67	1,7	39,50	1,39	8,00	430
11.04	597	58,4	1386	61,0	65	6,0	36,25	1,40	8,00	387
12.04	603	57,7	1440	60,5	78	3,1	39,50	1,42	8,00	408
16.04	618	58,7	1684	57,5	73	3,0	36,75	1,44	6,90	485
17.04	614	58,0	1537	58,0	95	3,2	39,50	1,43	8,20	441

Table A.15: continued

DATE	S_{TI} mgCOD/ℓ	N_{TI} mgN/ℓ	X_v mgVSS/ℓ	OUR mgO/ℓ.hr	S_{TE} mgCOD/ℓ	N_{TE} mgN/ℓ	$NO_{3\,E}$ mgN/ℓ	P mgCOD/mgVSS	pH	S_S mgCOD/ℓ
18.04	628	59,6	1538	58,8	67	6,7	34,75	1,42	8,00	438
19.04	619	58,9	1644	56,8	69	4,5	36,75	1,44	7,95	472
20.04	618	58,7	1706	55,0	73	4,1	35,75	1,47	7,95	501
21.04	615	59,6	1623	54,2	89	5,9	34,25	1,46	7,90	474
22.04	591	58,5	1585	52,5	96	5,1	35,25	1,41	7,95	448
23.04	608	56,6	1518	52,9	84	8,8	30,25	1,47	8,00	446
25.04	611	58,6	1428	52,5	134	7,5	34,50	1,48	8,10	423
26.04	619	58,6	1519	54,9	76	7,3	32,75	1,44	7,95	436
27.04	595	58,4	1508	53,2	65	9,5	31,25	1,49	7,95	449
28.04	593	58,6	1500	52,6	63	8,9	32,00	1,52	8,00	455
29.04	608	59,0	1271	54,0	97	10,1	32,50	1,46	8,00	372
30.04	591	54,6	1359	53,0	74	8,5	30,00	1,46	7,95	398
1.05	621	54,5	1500	55,8	79	7,6	29,25	1,42	8,00	425
2.05	618	54,2	1538	56,0	76	6,7	29,75	1,46	7,90	450
3.05	605	53,7	1453	56,6	73	6,7	30,50	1,43	7,90	415
4.05	624	53,7	1517	55,2	84	7,1	27,75	1,49	7,90	453
5.05	615	54,5	1477	55,0	77	11,1	25,75	1,42	8,00	419
6.05	611	54,2	1469	53,0	81	16,7	23,75	1,41	8,05	415
7.05	594	54,2	1320	52,2	114	10,2	29,25	1,36	8,00	358
8.05	605	54,6	1470	52,0	87	7,6	30,00	1,43	8,05	419
9.05	592	54,4	1310	52,0	83	7,4	30,75	1,52	8,05	399
10.05	613	54,5	1315	51,5	117	9,0	30,50	1,51	8,05	397

Table A.16: Daily experimental data for the 3 day sludge age unit at 20°C treating domestic sewage spiked with oleic acid (33% by mass)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.03	597	40,9	1421	49,3	59	5,0	19,75	1,35	7,90	384
20.03	589	40,5	1352	48,1	61	6,0	18,75	1,41	8,10	382
21.03	586	40,9	1307	48,1	71	6,3	18,75	1,38	8,00	360
22.03	589	41,6	1343	48,6	73	7,4	19,25	1,42	7,95	381
23.03	599	41,7	1340	48,0	81	6,8	19,75	1,40	7,95	374
24.03	599	42,7	1344	49,0	65	6,9	19,75	1,44	7,90	386
25.03	570	43,4	1313	49,0	86	6,7	22,25	1,43	8,00	376
27.03	575	44,1	1197	48,5	88	7,0	22,50	1,39	8,00	333
28.03	602	43,6	1195	49,2	101	7,3	22,50	1,46	8,00	349
29.03	600	43,5	1233	50,4	87	7,7	21,25	1,38	8,00	341
30.03	617	43,0	1256	48,9	89	11,0	18,25	1,44	8,05	361
4.04	599	39,0	1369	49,0	89	7,0	18,00	1,46	8,00	400
5.04	598	38,9	1249	49,8	81	7,7	18,50	1,49	8,00	371
6.04	633	38,9	1161	52,0	99	7,8	19,00	1,53	7,80	355
7.04	634	41,2	1252	49,9	114	9,7	19,00	1,53	-	383
8.04	636	42,0	1184	47,5	110	11,7	16,50	1,62	7,95	383
9.04	639	41,2	1085	48,9	105	13,7	14,75	1,63	8,00	353
10.04	608	40,7	1279	48,2	86	11,6	15,00	1,52	7,95	389
11.04	607	40,7	1395	48,5	81	9,7	15,50	1,50	7,95	419
12.04	631	41,2	1454	50,1	78	5,9	18,25	1,54	7,95	447
16.04	597	39,8	1579	46,3	83	4,3	18,50	1,49	7,10	472
17.04	611	38,1	1527	46,0	78	5,7	16,00	1,50	8,15	457

Table A.16: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
18.04	611	39,2	1507	47,0	75	6,3	16,00	1,52	8,00	458
19.04	601	39,1	1468	46,0	71	6,7	16,75	1,46	8,05	428
20.04	602	38,6	1510	35,5	88	6,3	17,00	1,48	8,05	448
21.04	603	38,8	1458	45,5	69	7,3	16,00	1,42	8,05	413
22.04	587	38,8	1424	46,7	70	7,1	17,00	1,48	8,05	422
23.04	598	39,0	1405	45,0	68	8,3	15,00	1,52	8,05	426
25.04	593	38,5	1397	40,0	152	6,5	16,50	1,55	8,15	433
26.04	598	39,1	1415	45,9	60	8,9	13,25	1,53	7,95	432
27.04	585	38,8	1405	46,4	57	7,8	15,00	1,51	7,95	425
28.04	584	39,5	1403	45,7	53	8,0	15,25	1,50	7,95	421
29.04	597	38,6	1265	47,0	57	8,0	15,50	1,46	8,00	372
30.04	592	38,4	1352	46,7	54	8,9	15,00	1,51	7,95	408
1.05	619	37,7	1481	47,0	55	6,1	14,75	1,51	8,00	447
2.05	611	37,0	1508	48,0	66	5,6	16,00	1,49	7,95	450
3.05	591	37,6	1493	48,3	60	5,6	17,00	1,47	7,90	439
4.05	598	37,9	1499	46,5	64	5,4	15,50	1,47	7,95	440
5.05	600	37,7	1444	48,4	65	5,7	15,25	1,49	8,00	431
6.05	600	37,6	1441	47,2	65	5,8	15,25	1,49	8,10	429
7.05	587	37,4	1462	46,0	62	5,6	15,25	1,52	8,05	443
8.05	605	37,1	1470	46,1	77	6,6	14,50	1,54	8,10	452
9.05	599	37,5	1559	45,9	73	6,6	14,25	1,48	8,15	462
10.05	623	37,4	1492	46,4	73	6,9	14,50	1,49	8,15	446

Table A.17: Daily experimental data for the 3 day sludge age unit at 12°C treating domestic sewage only

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.03	591	59,4	1514	36,5	74	39,8	2,75	1,44	8,10	437
20.03	600	60,2	1472	36,2	76	40,3	2,50	1,42	8,10	417
21.03	586	60,6	1367	36,2	67	42,8	1,78	1,43	8,15	392
22.03	604	60,8	1316	37,4	83	43,7	1,78	1,41	8,10	371
23.03	607	60,8	1308	37,5	86	42,8	1,70	1,44	8,15	378
24.03	610	62,2	1326	37,6	88	43,7	2,05	1,40	8,15	370
25.03	595	61,2	1319	36,5	94	43,2	1,78	1,50	8,20	397
27.03	617	62,5	1331	37,0	90	44,0	1,47	1,49	8,25	397
28.03	606	62,4	1336	36,1	97	44,1	1,62	1,45	8,15	387
29.03	588	62,2	1284	36,2	95	44,8	1,70	1,44	8,15	371
30.03	614	62,0	1299	36,5	105	44,7	1,57	1,45	8,15	377
4.04	595	58,8	1425	36,8	73	38,6	1,60	1,53	8,10	436
5.04	596	58,5	1417	34,1	81	39,5	2,17	1,43	8,15	406
6.04	612	58,4	1435	36,2	99	40,6	2,50	1,51	8,10	434
7.04	614	58,5	1229	35,0	97	41,4	2,50	1,44	-	355
8.04	600	58,4	1461	36,0	97	41,2	2,35	1,43	8,15	418
9.04	613	59,6	1482	36,0	110	43,7	1,75	1,43	8,15	424
10.04	584	56,8	1443	34,2	100	40,6	1,48	1,48	8,15	426
11.04	597	58,4	1432	33,8	88	40,0	1,55	1,45	8,20	415
12.04	603	57,7	1374	34,4	107	40,1	1,70	1,42	8,10	390
16.04	618	58,7	1633	32,0	77	38,9	1,70	1,50	7,65	489
17.04	614	58,0	1776	33,0	74	36,4	2,02	1,49	8,20	530

Table A.17: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
18.04	628	59,6	1707	34,2	100	37,8	2,38	1,50	8,15	511
19.04	619	58,9	1772	35,2	69	36,3	2,94	1,46	8,15	519
20.04	618	58,7	1776	33,1	73	36,0	3,54	1,48	8,10	525
21.04	615	59,6	1789	34,9	69	36,3	3,84	1,40	8,10	502
22.04	591	58,5	1687	34,5	74	34,6	3,09	1,46	8,10	491
23.04	608	56,6	1691	36,0	58	34,4	3,18	1,44	8,15	487
25.04	611	58,6	1620	34,6	69	34,9	3,51	1,51	8,10	490
26.04	619	58,6	1628	34,5	70	34,3	3,76	1,48	8,05	483
27.04	595	58,4	1615	34,5	61	34,6	4,04	1,48	8,05	478
28.04	593	58,6	1596	34,6	77	34,2	3,97	1,43	8,05	457
29.04	608	59,0	1402	36,3	85	34,0	3,65	1,52	8,15	425
30.04	591	54,6	1395	35,1	76	34,6	3,05	1,48	8,15	412
1.05	621	54,5	1440	35,4	85	34,5	2,30	1,52	8,15	439
2.05	618	54,2	1510	36,0	78	35,8	2,10	1,48	8,15	448
3.05	605	53,7	1479	36,1	79	34,2	2,00	1,44	8,15	427
4.05	624	53,7	1515	36,0	80	35,8	2,00	1,47	8,15	445
5.05	615	54,5	1381	35,8	87	36,5	2,15	1,49	8,15	412
6.05	611	54,2	1415	35,4	89	37,2	2,15	1,50	8,20	466
7.05	594	54,2	1484	35,2	88	36,6	2,10	1,46	8,20	434
8.05	605	54,6	1354	35,5	80	36,0	2,21	1,50	8,20	405
9.05	592	54,4	1375	35,2	89	36,4	2,50	1,49	8,25	409
10.05	613	54,5	1311	36,1	99	36,1	2,42	1,47	8,25	385

Table A.18: Daily experimental data for the 3 day sludge age unit at 12°C treating domestic sewage spiked with oleic acid (33% by mass)

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
19.03	590	40,5	1406	30,3	114	24,5	0,53	1,48	7,90	417
20.03	601	40,6	1367	30,6	126	25,2	0,52	1,51	7,95	413
21.03	586	40,9	1346	30,0	117	24,1	0,42	1,51	7,95	407
22.03	597	40,9	1334	32,2	105	26,3	0,46	1,47	7,85	391
23.03	604	41,6	1384	33,1	103	25,8	0,42	1,45	7,90	401
24.03	602	42,5	1390	34,0	106	25,6	0,36	1,51	7,90	419
25.03	597	41,7	1307	32,5	106	25,8	0,36	1,49	7,95	390
27.03	583	43,7	1269	34,0	98	27,3	0,76	1,51	8,00	384
28.03	598	43,5	1335	35,5	75	26,5	0,47	1,52	7,90	406
29.03	588	43,1	1487	35,3	69	26,0	0,52	1,49	7,90	444
30.03	584	43,0	1391	36,7	67	25,8	0,56	1,57	7,85	438
4.04	609	39,5	1428	36,2	69	23,0	0,69	1,45	8,05	414
5.04	625	39,3	1390	35,5	89	22,7	0,73	1,58	7,90	438
6.04	629	39,3	1428	36,5	79	23,2	0,83	1,58	7,85	452
7.04	634	40,7	1402	36,1	128	24,1	0,58	1,52	-	426
8.04	625	41,6	1467	34,2	91	25,5	0,46	1,46	7,95	426
9.04	655	41,6	1393	36,9	99	26,3	0,34	1,52	7,90	424
10.04	605	41,4	1414	36,1	88	25,0	0,41	1,53	7,90	434
11.04	599	40,6	1389	36,1	81	24,1	0,44	1,54	7,90	428
12.04	616	40,7	1349	35,8	89	25,0	0,49	1,52	7,90	410
16.04	613	40,3	1764	33,0	79	20,4	0,56	1,49	7,40	527
17.04	612	38,3	1731	32,9	70	19,3	0,52	1,47	8,00	543

Table A.18: continued

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	X_v $\frac{mgVSS}{\ell}$	OUR $\frac{mgO}{\ell.hr}$	S_{TE} $\frac{mgCOD}{\ell}$	N_{TE} $\frac{mgN}{\ell}$	NO_{3E} $\frac{mgN}{\ell}$	P $\frac{mgCOD}{mgVSS}$	pH	S_S $\frac{mgCOD}{\ell}$
18.04	600	38,9	1596	33,6	69	21,6	0,52	1,54	8,00	543
19.04	603	39,1	1631	32,5	61	20,2	0,69	1,45	7,95	491
20.04	604	38,5	1614	33,0	63	20,4	0,75	1,50	7,95	468
21.04	595	38,9	1596	36,8	61	20,4	0,93	1,44	7,95	483
22.04	587	38,8	1509	35,8	58	20,7	1,01	1,48	7,95	461
23.04	581	39,2	1490	34,7	56	20,6	1,14	1,54	7,95	448
25.04	589	38,5	1578	34,0	67	20,2	1,08	1,54	8,00	460
26.04	608	38,7	1613	34,5	54	18,3	1,29	1,53	8,05	486
27.04	595	39,2	1582	35,2	57	19,9	1,38	1,49	7,95	493
28.04	585	38,9	1481	32,2	61	20,7	1,34	1,59	7,95	472
29.04	608	38,6	1298	35,1	85	21,0	1,64	1,52	7,95	470
30.04	596	38,5	1269	35,3	88	21,8	1,93	1,58	8,00	395
1.05	611	38,0	1308	35,2	86	21,0	2,02	1,62	8,00	402
2.05	620	37,8	1347	35,2	86	19,6	1,78	1,59	8,00	425
3.05	601	37,6	1396	35,0	75	19,6	1,30	1,57	8,00	428
4.05	599	37,5	1428	35,2	76	20,2	1,27	1,57	8,00	439
5.05	446	7,7	1537	20,4	60	4,7	0,00	1,43	8,00	449
6.05	599	7,7	1551	19,5	58	2,9	0,00	1,76	7,50	439
7.05	542	8,1	1504	17,4	92	2,5	0,00	1,89	8,10	498
8.05	601	7,7	1131	23,0	151	9,9	0,00	1,89	7,85	568
9.05	637	8,8	1153	18,4	94	4,3	0,00	2,11	8,25	427
10.05	622	8,0	1174	17,8	109	4,1	0,00	2,12	8,10	488

Table A.19: Daily experimental data for 20 day sludge age units at 12°C - 24-hour test preparation period

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	O.U.R $\frac{mgO}{\ell.hr}$	S_{TE} ($mgCOD.\ell^{-1}$)		N_{TE} ($mgN.\ell^{-1}$)		N_{NE} ($mgN.\ell^{-1}$)		X_V ($mgVSS.\ell^{-1}$)	
				Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
27.04	595	58,4	27,2	60	79	3,1	2,9	44,00	46,00	2912	2805
28.04	593	58,6	26,6	58	68	2,9	3,7	42,75	43,50	2913	2714
29.04	608	59,0	27,2	67	52	3,2	3,5	42,00	41,50	2904	2721
30.04	591	54,6	27,2	59	40	3,3	2,3	40,25	40,25	2923	2738
1.05	621	54,5	28,1	51	37	3,1	1,9	39,75	40,75	2949	2786
2.05	618	54,2	27,9	55	40	2,7	1,9	39,75	40,00	2939	2790
3.05	605	53,7	28,0	61	65	2,5	2,1	40,25	40,00	2999	2800
4.05	624	53,7	27,3	51	49	2,3	2,1	40,50	40,25	3051	2913
5.05	615	54,5	27,1	45	60	2,1	1,7	40,00	40,75	3005	2862
6.05	611	54,2	28,0	47	34	2,2	2,3	40,50	40,75	2992	2831
7.05	594	54,2	27,1	54	60	2,1	1,8	40,75	40,25	3003	2913
8.05	605	54,6	27,0	51	60	2,0	1,9	40,25	40,50	2987	2874
9.05	592	54,4	27,1	65	60	2,1	2,0	40,00	40,75	2868	2965
10.05	613	54,5	27,2	66	57	2,3	2,1	39,75	40,50	2993	2875

Table A.20: Daily experimental data for 2,5 day sludge age units at 12°C - 24-hour test preparation period

DATE	S_{TI} $\frac{mgCOD}{\ell}$	N_{TI} $\frac{mgN}{\ell}$	O.U.R. $\frac{mgO}{\ell.hr}$	S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
				Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
4.06	595	58,8	28,5	90	80	36,8	38,5	0,93	0,80	1150	1297
5.06	597	59,1	28,2	85	79	38,2	38,5	0,95	0,79	1197	1251
6.06	601	59,0	27,8	83	85	38,1	38,7	0,87	0,82	1234	1301
7.06	598	58,9	27,9	87	91	38,5	38,8	0,99	0,78	1209	1221
8.06	611	58,9	28,3	81	78	38,6	38,7	0,81	0,60	1276	1253
9.06	615	59,2	28,1	77	85	38,7	38,7	0,75	0,91	1299	1201
10.06	608	59,5	27,7	91	83	38,5	38,6	1,03	0,85	1289	1298
11.06	610	59,1	28,3	80	82	38,4	38,6	0,97	1,10	1301	1284
12.06	601	58,8	28,2	87	77	38,5	38,5	1,21	0,95	1354	1267
13.06	597	59,3	28,2	83	88	38,6	38,7	1,01	0,79	1331	1275

Table A.21: Experimental Data recorded during 24-hour test T1

SLUDGE AGE: 20 days TEMPERATURE: 12°C DATE: 17.05.82

INFLUENT COD: 627 mgCOD.ℓ^{-1} INFLUENT TKN: 74,6 mgN.ℓ^{-1} pH: 7,85

TIME	O.U.R.(mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
06.00	13,50									
06.30	13,50									
07.00	12,90									
07.30	13,00									
08.00	12,20	32,50	44,0	55,0	3,0	3,7	55,6	62,8	3064,0	2902,0
08.05	32,20									
08.15	41,00									
08.30	46,00									
08.45	44,50									
09.00	44,60		44,0		4,1		56,4			
09.30	47,00									
10.00	48,10		32,0		4,0		59,2			
10.30	47,80									
11.00	47,20		36,0		4,3		56,8			
11.30	49,20									
12.00	50,00	33,70	40,0	36,0	5,0	2,7	56,4	62,0	3078,0	2882,0
12.30	49,60									
13.00	50,10		40,0		3,9		58,4			
13.30	48,70									
14.00	48,50		48,0		4,3		56,4			

Table A.21: continued

TIME	O.U.R. ($mgO.\ell^{-1}.hr^{-1}$)		S_{TE} ($mgCOD.\ell^{-1}$)		N_{TE} ($mgN.\ell^{-1}$)		N_{NE} ($mgN.\ell^{-1}$)		X_V ($mgVSS.\ell^{-1}$)	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
14.30	47,80									
15.00	47,00		48,0		3,1		56,4			
15.30	49,00									
16.00	47,60	33,30	44,0	44,0	4,0	2,5	57,6	60,4	3106,0	2868,0
16.30	50,30									
17.00	51,10		53,0		3,9		56,8			
17.30	51,40									
18.00	51,50		44,0		3,7		54,4			
18.30	50,00									
19.00	50,50		53,0		4,2		56,8			
19.30	50,10									
20.00	49,80	33,20	48,0	48,0	4,6	3,9	56,4	58,4	3136,0	2876,0
20.05	35,50									
20.15	28,30									
20.30	25,20									
20.45	24,30									
21.00	21,50		48,0		4,8		55,2			
21.30	18,30									
22.00	17,50		40,0		4,0		55,6			
22.30	16,80									
23.00	17,00		42,0		3,9		56,4			
23.30	16,00									

Table A.21: continued

TIME	O.U.R. (mgO.ℓ^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
24.00	16,30	33,10	42,0	51,0	3,6	2,3	55,2	59,6	3176,0	2918,0
00.30	15,60									
01.00	15,10		51,0		3,6		55,2			
01.30	15,00									
02.00	14,80		40,0		2,7		55,2			
02.30	14,80									
03.00	14,00		42,0		3,8		55,6			
03.30	14,60									
04.00	14,00	33,50	38,0	44,0	3,6	3,4	55,6	59,6	3146,0	2908,0
04.30	13,50									
05.00	13,80		42,0		2,5		55,2			
05.30	13,00									
06.00	13,50		42,0		3,4		54,4			
06.30	13,50									
07.00	12,90		34,0		3,3		54,0			
07.30	13,00									
08.00	12,20	31,50								

Table A.22 : Experimental data recorded during 24-hour test T2

SLUDGE AGE: 20 days TEMPERATURE: 12°C DATE: 20.05.82
INFLUENT COD: 630 mgCOD.ℓ^{-1} INFLUENT TKN: 77,6 mgN.ℓ^{-1} pH: 7,80

TIME	O.U.R (mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mg VSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
06.00	11,1									
06.30	11,7									
07.00	11,6									
07.30	11,5									
08.00	11,0	31,1	53,0	65,0	3,2	2,9	65,6	67,6	2994,0	2740,0
08.05	31,2									
08.15	42,2									
08.30	48,1									
08.45	48,2									
09.00	48,5		61,0		3,2		64,6			
09.30	48,0									
10.00	48,3		61,0		3,9		63,6			
10.30	49,0									
11.00	48,6		61,0		4,3		63,6			
11.30	48,5									
12.00	50,2	32,0	93,0	81,0	4,7	2,0	65,2	66,0	3000,0	2720,0
12.30	51,2									
13.00	51,0		61,0		5,0		66.8			
13.30	49,9									
14.00	51,6		73,0		3,9		63,6			

Table A.22: continued

TIME	O.U.R. (mgO.ℓ^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
14.30	51,9									
15.00	52,0		69,0		4,3		63,6			
15.30	51,0									
16.00	51,4	32,5	69,0	73,0	3,5	2,4	62,4	65,2	3024,0	2748,0
16.30	51,0									
17.00	52,0		65,0		4,3		59,2			
17.30	51,6									
18.00	51,0		61,0		4,2		61,6			
18.30	49,8									
19.00	51,0		49,0		4,3		59,2			
19.30	49,8									
20.00	50,1	32,1	54,0	70,0	4,5	3,0	58,0	65,6	3096,0	2782,0
20,05	29,5									
20.15	26,0									
20.30	23,2									
20.45	18,7									
21.00	18,3		54,0		4,8		59,2			
21.30	16,5									
22.00	16,2		56,0		4,0		59,6			
22.30	15,2									
23.00	14,7		58,0		4,1		60,0			
23.30	14,4									

Table A.22: continued

TIME	O.U.R. (mgO.ℓ^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
24.00	15,0	33,0	54,0	70,0	3,6	3,9	57,2	64,0	3148,0	2752,0
00.30	14,0									
01.00	13,8		63,0		4,8		58,8			
01.30	13,5									
02.00	14,1		59,0		3,2		59,6			
02.30	12,8									
03.00	12,9		67,0		4,1		59,6			
03.30	13,0									
04.00	12,2	32,0	59,0	81,0	4,8	2,6	59,2	64,0	3052,0	2750,0
04.30	12,5									
05.00	13,7		59,0		3,6		60,0			
05.30	12,5									
06.00	11,1		65,0		4,5		58,0			
06.30	11,7									
07.00	11,6		51,0		3,8		58,8			
07.30	11,5									
08.00	11,0	31,5								

Table A.23: Experimental data recorded during 24-hour test T4.

SLUDGE AGE: 2,5 days TEMPERATURE: 12°C DATE: 15.06.82

INFLUENT COD: 633 mgCOD.ℓ^{-1} INFLUENT TKN: 69,4 mgN.ℓ^{-1} pH: 7,85

TIME	O.U.R. (mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
06.00	12,1									
06.30	11,1									
07.00	10,3									
07.30	11,3									
08.00	10,7	31,3	97,0	89,0	43,4	44,0	2,37	1,47	1384,0	1340,0
08.05	27,3									
08.15	33,1									
08.30	34,4									
08.45	36,8									
09.00	37,2		81,0		47,6		2,00			
09.30	38,7									
10.00	40,5		97,0		49,8		1,76			
10.30	41,2									
11.00	41,7		121,0		49,7		1,52			
11.30	42,2									
12.00	42,8	31,5	85,0	90,0	47,0	47,2	1,41	1,50	1316,0	1288,0
12.30	44,1									
13.00	43,9		93,0		50,4		1,22			
13.30	43,8									
14.00	43,0		93,0		50,3		1,10			

Table A.23: continued

TIME	O.U.R. (mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
14.30	43,9									
15.00	44,2		97,0		50,3		0,93			
15.30	44,2									
16.00	44,8	30,50	89,0	81,0	48,2	49,3	0,99	1,47	1352,0	1284,0
16.30	44,1									
17.00	43,8		97,0		50,1		0,87			
17.30	43,8									
18.00	43,8		101,0		50,5		0,79			
18.30	42,6									
19.00	43,3		101,0		50,3		0,80			
19.30	43,2									
20.00	43,2	30,1	113,0	89,0	49,8	48,7	0,82	1,67	1304,0	1276,0
20.05	34,0									
20.15	27,9									
20.30	26,6									
20.45	25,3									
21.00	24,0		97,0		49,8		1,11			
21.30	21,0									
22.00	21,6		93,0		49,3		0,68			
22.30	17,6									
23,00	17,0		89,0		47,7		0,85			
23.30	14,0									

Table A.23: continued

TIME	O.U.R. (mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mgCOD.ℓ^{-1})		N_{TE} (mgN.ℓ^{-1})		N_{NE} (mgN.ℓ^{-1})		X_V (mgVSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
24.00	14,6	30,0	85,0	89,0	46,2	48,7	0,85	0,85	1288,0	1248,0
00.30	15,0									
01.00	15,1		94,0		46,8		0,75			
01.30	14,8									
02.00	14,0		96,0		47,3		0,75			
02.30	12,9									
03.00	13,4		96,0		47,6		0,75			
03.30	12,7									
04.00	12,9	29,0	92,0	102,0	45,1	45,6	0,80	1,00	1316,0	1232,0
04.30	12,9									
05.00	12,0		112,0		46,9		1,00			
05.30	12,0									
06.00	12,1		120,0		46,6		0,90			
06.30	11,1									
07.00	10,3		102,0		45,6		0,95			
07.30	11,3									
08.00	10,7	31,0								

Table A.24: Experimental data recorded during 24-hour test T5

SLUDGE AGE: 2,5 days TEMPERATURE: 12°C DATE: 22.06.82
INFLUENT COD: 611 mgCOD.ℓ^{-1} INFLUENT TKN: 69,2 mgN.ℓ^{-1} pH: 7,80

TIME	O.U.R. (mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mg COD.ℓ^{-1})		N_{TE} (mg N.ℓ^{-1})		N_{NE} (mg N.ℓ^{-1})		X_V (mg VSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
06.00	14,3									
06.30	14,2									
07.00	14,3									
07.30	13,3									
08.00	13,4	27,5	79,0	96,0	44,4	45,9	4,10	1,95	1308,0	1300,0
08.05	26,0									
08.15	32,0									
08.30	33,5									
08.45	35,4									
09.00	36,0		87,0		49,6		3,25			
09.30	36,7									
10.00	38,0		83,0		48,2		2,55			
10.30	38,9									
11.00	39,2		83,0		47,0		2,00			
11.30	39,3									
12.00	39,8	28,0	83,0	77,0	47,2	48,2	1,90	1,90	1328,0	1276,0
12.30	40,5									
13.00	41,8		89,0		48,4		1,55			
13.30	41,8									
14.00	42,1		98,0		49,8		1,35			

Table A.24: continued

TIME	O.U.R. (mgO.ℓ^{-1}.hr^{-1})		S_{TE} (mg COD.ℓ^{-1})		N_{TE} (mg N.ℓ^{-1})		N_{NE} (mg N.ℓ^{-1})		X_V (mg VSS.ℓ^{-1})	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
14.30	42,5									
15.00	43,5		85,0		50,7		1,25			
15.30	43,4									
16.00	43,1	27,9	81,0	77,0	50,4	47,0	1,15	1,85	1388,0	1276,0
16.30	42,2									
17.00	43,9		85,0		50,7		1,05			
17.30	43,9									
18.00	43,5		81,0		50,8		0,95			
18.30	43,1									
19.00	43,0		102,0		50,7		0,95			
19.30	42,6									
20.00	43,1	27,5	98,0	85,0	49,3	47,0	1,00	1,85	1396,0	1284,0
20.05	34,3									
20.15	30,1									
20.30	28,0									
20.45	27,3									
21.00	25,7		93,0		50,7		1,10			
21.30	25,4									
22.00	23,0		73,0		49,0		1,00			
22.30	21,9									
23.00	21,4		98,0		49,6		1,40			

Table A.24: continued

TIME	O.U.R. $(mgO.\ell^{-1}.hr^{-1})$		S_{TE} $(mgCOD.\ell^{-1})$		N_{TE} $(mgN.\ell^{-1})$		N_{NE} $(mgN.\ell^{-1})$		X_V $(mgVSS.\ell^{-1})$	
	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady	Dynamic	Steady
23.30	20,5									
24.00	19,8	27,0	77,0	81,0	48,2	45,4	1,95	1,80	1336,0	1308,0
00.30	18,0									
01.00	17,5		89,0		47,3		1,55			
01.30	16,8									
02.00	16,8		87,0		46,8		1,75			
02.30	16,0									
03.00	16,0		83,0		46,8		1,75			
03.30	15,5									
04.00	14,7	27,1	91,0	93,0	45,4	45,4	1,75	1,90	1304,0	1336,0
04.30	14,2									
05.00	14,7		85,0		46,1		1,75			
05.30	14,1									
06.00	14,3		91,0		46,9		1,75			
06.30	14,2									
07.00	14,3		93,0		45,9		1,90			
07.30	13,3									
08.00	13,4	27,5								

APPENDIX B

ENERGY MASS BALANCES

B.1 ENERGY MASS BALANCES - THEORY

The only viable method to determine the reliability of experimentally measured data is to perform energy mass balances around the system using such data. Two energy mass balances of significance in the single-reactor aerobic activated sludge process are:

(1) the carbonaceous energy mass balance in terms of the Chemical Qxygen Demand (COD), and

(2) the nitrogen mass balance in terms of Nitrogen (N).

B.1.1 Carbonaceous energy mass balance

This energy mass balance around the system is done in terms of COD. The total carbonaceous energy entering the system is accounted for in three fractions either incorporated within or

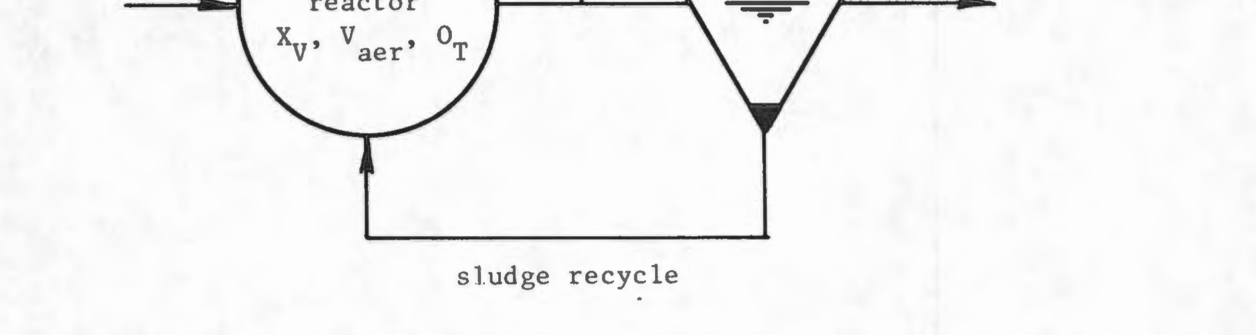

Figure B.1: Completely mixed aerobic activated sludge process under constant flow and load conditions.

leaving the process:

(1) a fraction, composed of organic particulate and soluble COD, leaves the system via the effluent flow

(2) a fraction is incorporated into the sludge mass through physical enmeshment and adsorption for metabolic purposes and leaves the system via the sludge waste flow, and

(3) a fraction disappears by oxidation and is accounted for by the oxygen utilized.

Consequently the carbonaceous energy mass balance for the single-reactor aerobic activated sludge process is given by:

$$MCOD_{INF} = MCOD_{EFF} + MCOD_{WASTE} + MCOD_{OXI} \qquad B.1$$

where $MCOD_{INF}$ = mass of COD in the influent ($mgCOD.d^{-1}$)

$MCOD_{EFF}$ = mass of COD in the effluent ($mgCOD.d^{-1}$)

$MCOD_{WASTE}$ = mass of COD in the waste flow ($mgCOD.d^{-1}$)

$MCOD_{OXI}$ = mass of COD oxidized ($mgCOD.d^{-1}$).

Referring to Figure B.1 and noting that the mass parameters are the product of concentration and flow (or volume), Equation B.1 may be written as:

$$Q.S_{TI} = \{(Q-q)S_{TE} + q.S_{TE}\} + q.P.X_v + O_C.V_{aer}$$

$$= Q.S_{TE} + q.P.X_v + O_C.V_{aer} \qquad B.2$$

where Q = average influent flow rate ($\ell.d^{-1}$)

q = average sludge waste flow rate ($\ell.d^{-1}$)

S_{TI} = influent COD concentration ($mgCOD.\ell^{-1}$)

S_{TE} = effluent COD concentration ($mgCOD.\ell^{-1}$)

P = COD/VSS ratio of mixed liquor ($mgCOD.mgVSS^{-1}$)

X_v = mixed liquor volatile suspended solids concentration in the aerobic reactor ($mgVSS.\ell^{-1}$)

O_C = carbonaceous energy oxygen consumption rate ($mgO.\ell^{-1}.hr^{-1}$)

V_{aer} = volume of aerobic reactor (ℓ).

If nitrification occurs in an aerobic activated sludge process, the oxygen consumption rate, as measured experimentally, includes the oxygen demand due to nitrification:

$$O_T = O_C + O_N \qquad B.3$$

where O_T = total oxygen consumption rate ($mgO.\ell^{-1}.hr^{-1}$)

O_C = carbonaceous energy oxygen demand ($mgO.\ell^{-1}.hr^{-1}$)

O_N = nitrification oxygen demand ($mgO.\ell^{-1}.hr^{-1}$)

The oxygen demand for nitrification is accounted for by the oxidation of ammonia and organic nitrogen to nitrate. Stoichiometrically it can be shown that 1 mg of free or saline ammonia oxidized to nitrate requires 4,57 mgO, thus:

$$O_N = 4{,}57\ N_{NE} \qquad B.4$$

where N_{NE} = nitrate concentration in the aerobic reactor

= nitrate concentration in the effluent if no denitrification occurs ($mgN.\ell^{-1}$).

Then in a single reactor aerobic activated sludge process with nitrification and under constant flow and load conditions the carbonaceous energy mass balance is given by:

$$Q.S_{TI} = Q.S_{TE} + P.q.X_v + (O_T.V_{aer} - 4{,}57\ N_{NE}.Q) \qquad B.5$$

dividing Equation B.5 by Q

$$S_{TI} = S_{TE} + P.X_V.R_h/R_s + (O_T.R_h - 4{,}57.N_{NE}) \qquad B.6$$

where $R_h = V_{aer}/Q$ = hydraulic retention time (days)

$R_s = V/q$ = sludge age (days).

B.1.2 Nitrogen mass balance

This energy mass balance around the system is done in terms of nitrogen. The available nitrogen in the influent is mainly in the form of ammonia and organic nitrogen and is measured as Total Kjeldahl Nitrogen (TKN); it is accounted for in three fractions either incorporated or leaving the process as follows:

(1) a fraction leaves the system via the effluent flow as nitrogen ($mgN.\ell^{-1}$)

(2) a fraction is incorporated into the active mass by synthesis and enmeshment into the sludge floc and leaves the system via the sludge waste flow, and

(3) a fraction is oxidized to nitrate (if the sludge age is long enough for nitrification to occur) and leaves the system via the effluent flow ($mgN.\ell^{-1}$).

The nitrogen mass balance for the single-reactor aerobic activated sludge process is given by:

$$MTKN_{INF} = MTKN_{EFF} + MTKN_{WASTE} + MTKN_{OXI} \qquad B.7$$

where $MTKN_{INF}$ = mass of TKN in the influent ($mgN.d^{-1}$)

$MTKN_{EFF}$ = mass of TKN in the effluent ($mgN.d^{-1}$)

$MTKN_{WASTE}$ = mass of TKN in the waste flow ($mgN.d^{-1}$)

$MTKN_{OXI}$ = mass of TKN oxidized to nitrate ($mgN.d^{-1}$)

Referring to Figure B.1 and noting that the mass parameters are the product of concentration and flow (or volume), Equation B.7 may be written as:

$$Q.N_{TI} = \{(Q-q)N_{TE} + q.N_{TE}\} + f_n.X_v.q + \{(Q-q)N_{NE} + q.N_{NE}\}$$

$$= Q.N_{TE} + f_n.X_v.q + Q.N_{NE} \qquad B.8$$

where

Q = average influent flow rate ($\ell.d^{-1}$)

q = average sludge waste flow rate ($\ell.d^{-1}$)

N_{TI} = influent TKN concentration ($mgN.\ell^{-1}$)

N_{TE} = effluent TKN concentration ($mgN.\ell^{-1}$)

f_n = fraction of nitrogen incorporated into the active organism mass ($mgN.mgVSS^{-1}$)

X_v = mixed liquor volatile suspended solids concentration in the aerobic reactor ($mgVSS.\ell^{-1}$)

N_{NE} = effluent nitrate concentration ($mgN.\ell^{-1}$)

dividing Equation B.8 by Q

$$N_{TI} = N_{TE} + f_n.X_v.R_h/R_s + N_{NE} \qquad B.9$$

where

R_h = V_{aer}/Q = hydraulic retention time (days)

R_s = V/q = sludge age (days).

Then, making use of Equations B.6 and B.9, the COD and N recoveries may be calculated in percent by using the daily measured data.

B.2 COMPUTER PROGRAM

A listing of the computer program performing all the COD and N mass balances on the experimentally measured data for all the aerobic units under constant flow and load conditions is given below. Note that a full explanation of all input and output parameters is given at the start of the program listing.

```
WOLF(1).BALANCE
      C*****************************************************************
      C
      C       MASS BALANCE PROGRAM : AEROBIC SINGLE REACTOR
      C
      C*****************************************************************
      C
      C       FUNCITON:
      C
      C       THIS PROGRAM PERFORMS COD AND N MASS BALANCES
      C       FOR A SINGLE-REACTOR AEROBIC ACTIVATED SLUDGE
      C       UNIT USING EXPERIMENTALLY MEASURED DATA
      C
      C       INPUT:
      C
      C       (A) PROCESS OPERATING PARAMETERS
      C
      C            RS = SLUDGE AGE
      C            V = VOLUME
      C            W = INFLUENT FLOW
      C            T = TEMPERATURE
      C
      C       (B) EXPECTED SEWAGE CHARACTERISTICS
      C
      C            STIEXP = INFLUENT COD CONCENTRATION
      C            NTIEXP = INFLUENT TKN CONCENTRATION
      C            FUS = UNBIODEGRADEBLE SOLUBLE FRACITON
      C            FUP = UNBIODEGRADEBLE PARTICULATE FRACITON
      C            FNA = INFLUENT AMMONIA FRACTION
      C
      C       (C) CARBONACEOUS CONSTANTS
      C
      C            YH = YIELD OF ORGANISMS FROM COD UTILIZED
      C            BH20 = ENDOGENOUS RESPIRATION RATE
      C            F = ENDOGENOUS RESIDUE FRACTION
      C            KV20 = MAXIMUM RATE OF COD TRANSFER FROM SEWAGE
      C                   INTO STORAGE
      C            P = COD TO VSS RATIO
      C
      C       (D) NITROGEN CONSTANTS
      C
      C            YN = YIELD OF NITRIFIER ACTIVE MASS FROM AMMONIA
      C            BN20 = ENDOGENOUS RESPIRATION RATE FOR NITRIFIERS
      C            UNM20 = MAXIMUM GROWTH RATE FOR NITRIFIERS
      C            KN20 = HALF SATURATION COEFFICIENT FOR
      C                   UTILIZAITON OF AMMONIA
      C            KR20 = ORGANIC NITROGEN CONVERSION RATE
      C            FN = ENDOGENOUS RESIDUE FRACITON FOR
      C                 NITIFIERS
      C
      C      (E) EXPERIMENTAL DATA
      C
      C           DATE
      C           STI = INFLUENT COD CONCENTRATION
      C           NTI = INFLUENT TKN CONCENTRATION
      C           XV = VOLATILE SOLIDS CONCENTRATION
      C           OUR = OXYGEN UPTAKE RATE
      C           STE = EFFLUENT COD CONCENTRATION
      C           NTE = EFFLUENT TKN CONCENTRATION
      C           NNE = EFFLUENT NITRATE CONCENTRATION
      C
      C      OUTPUT:
```

```
C
C       (A) EXPECTED RESULTS
C
C            STI,NTI,XV,OUR,STE,NTE,NNE AS FOR INPUT
C
C       (B) EXPERIMENTAL MASS BALANCE RESULTS
C
C            STI,STE,P AS FOR INPUT
C            O2 = OXYGEN UTILIZED
C            WASTE = COD EQUIVALENT OF WASTE FLOW
C            OUT = TOTAL COD OUTPUT
C            RATIO OF COD INPUT TO OUTPUT IN %
C            NTI,NTE,NNE AS FOR INPUT
C            WAST = N EQUIVALENT OF WASTE FLOW
C            OUT = TOTAL N OUTPUT
C            RATIO OF N INPUT TO OUTPUT IN %
C
C       NOTE:
C
C            COD CONCENTRATIONS MEASURED BY COD-TEST
C            IN MG-COD/L
C            NITROGEN CONCENTRATIONS MEASURED BY TKN-TEST
C            IN MG-N/L
C            VOLATILE SUSPENDED SOLIDS CONCENTRATION
C            MEASURED BY VSS-TEST IN MG-VSS/L
C            OXYGEN CONSUMPTION RATE IN MG-O/L/HOUR
C            UNIT OF MASS IS MG
C            UNIT OF TIME IS DAY
C            SYMBOL S REFFERS TO COD
C            SYMBOL X REFFERS TO VSS
C            SYMBOL N REFFERS TO NITROGEN
C            SYMBOL O REFFERS TO OXYGEN
C
C***********************************************************************
C
        REAL KV20,KVT,KR20,KRT,KN20,KNT,MSR,MXA,MAF,MXT,MAV
        REAL NTI,NTIEXP,NI,NTE,NN,NNE,MAT,NOT,NS,NOI
C
C       READ PROCESS OPERATING PARAMETERS
C
        READ(8,10) RS,V,Q,T
 10     FORMAT()
C
C       READ EXPECTED SEWAGE CHARACTERISTICS
C
        READ(8,10) STIEXP,NTIEXP,FUS,FUP,FNA
C
C       READ CARBONACEOUS CONSTANTS
C
        READ(8,10) YH,BH20,F,KV20,P
C
C       READ NITROGEN CONSTANTS
C
        READ(8,10) YN,BN20,UNM20,KN20,KR20,FN
C
C       CALC TEMP DEPENDENT CONSTANTS
C
        BHT=BH20*(1.029)**(T-20.0)
        KVT=KV20*(1.029)**(T-20.0)
        UNMT=UNM20*(1.123)**(T-20.0)
        BNT=BN20*(1.029)**(T-20.0)
        KNT=KN20*(1.123)**(T-20.0)
```

```
      KRT=KR20*(1.029)**(T-20.0)
C
C     CALC EXPECTED RESULTS
C
      SBI=STIEXP*(1.0-FUS-P*FUP)
      SB=(BHT+1./RS)/(YH*KVT)
      SU=FUS*STIEXP
      SEFF=SB+SU
      MSB=Q*(SBI-SB)
      MXA=YH*RS*MSB/(1.+BHT*RS)
      MXF=F*BHT*RS*MXA
      MXI=FUP*Q*STIEXP*RS
      MXV=MXA+MXF+MXI
      XVEXP=MXV/V
      MOC=(1.-P*YH)*MSB+P*(1.-F)*BHT*MXA
      OC=MOC/(V*24.0)
      NS=FN*MXV/(RS*Q)
      NAT=FNA*NTIEXP
      NOI=(1.-FNA)*NTIEXP-FN*FUP*STIEXP
      Z=BNT+1./RS
      NA=KNT*Z/(UNMT-Z)
      RH=V/Q
      NO=NOI/(1.+RH*KRT*MXA/V)
      NT=NA+NO
      NN=NTIEXP-NS-NT
      ON=4.57*NN/(RH*24.0)
      OTEXP=OC+ON
C
C     PRINT EXPECTED RESULTS
C
      WRITE(5,11) RS,T,V,Q
 11   FORMAT(1H1,'******************************'/
     1'   EXPECTED PROCESS RESPONSE'/
     2' ******************************'//
     3'  PROCESS PARAMETERS:'/
     4'      SLUDGE AGE     = ',F4.1,' DAYS'/
     5'      TEMPERATURE    = ',F4.1,' DEG C'/
     6'      VOLUME         = ',F4.1,' LITRES'/
     7'      INF. FLOW      = ',F4.1,' L/D'//)
      WRITE(5,12) STIEXP,NTIEXP,XVEXP,OTEXP,SEFF,NT,NN
 12   FORMAT('  EXPECTED RESULTS:'/
     1'      INF. COD = ',F5.1,' MG COD/L'/
     2'      INF. TKN = ',F4.1,' MG N/L'/
     3'      XV       = ',F6.1,' MG VSS/L'/
     4'      OUR      = ',F4.1,' MG/L/HR'/
     5'      STE      = ',F4.1,' MG COD/L'/
     6'      NTE      = ',F4.1,' MG N/L'/
     7'      NNE      = ',F4.1,' MG N/L')
C
C     READ EXPERIMENTAL RESULTS
C
      WRITE(5,13)
 13   FORMAT(1H1,'    ************************'/
     1'        MASS BALANCE RESULTS'/
     2'       ************************'//
     3' * INDICATES VALUES WHERE ACTUAL P IS USED'///
     *32X,'COD BALANCE',44X,'NITROGEN BALANCE'//
     *10X,63('-'),7X,32('-')//
     4' DATE',5X,'STI',4X,'P*',5X,'O2',4X,'WASTE',1X,'WASTE*',2X,
     5'STE',3X,'OUT',3X,'OUT*',2X,'%COD',2X,'%COD*',7X,
     6'NTI',4X,'NTE',2X,'NNE',2X,'WAST',2X,'OUT',3X,'% N'///)
 90   READ(8,10) DATE,STI,NTI,XV,OT,STE,NTE,NNE,PACT
```

```
         IF(DATE.GT.32.) GO TO 98
         N3=FN*XV*RH/RS
         SUMN=NTE+NNE+N3
         PCN=(SUMN/NTT)*100.0
         OC=OT*24.0-4.57*NNE/RH
         S1=OC*RH
         S2=P*XV*RH/RS
         S2ACT=PACT*XV*RH/RS
         SUMS=S1+S2+STE
         SUMACT=S1+S2ACT+STE
         PCC=(SUMS/STT)*100.0
         PCCACT=(SUMACT/STT)*100.0
         WRITE(5,14) DATE,STI,PACT,S1,S2,S2ACT,STE,SUMS,SUMACT,
        1PCC,PCCACT,NTI,NTE,NNE,N3,SUMN,PCN
   14    FORMAT(1X,F5.2,3X,F5.1,2X,F4.2,3X,F5.1,2X,F5.1,1X,F5.1,1X,
        1F5.1,2X,F5.1,1X,F5.1,2X,F5.1,1X,F5.1,7X,F4.1,3X,
        2F4.1,1X,F4.1,1X,F4.1,2X,F4.1,2X,F5.1)
         GO TO 99
   98    WRITE(5,15)
   15    FORMAT(1H1,'* END OF RESULTS *')
         END

.P RMTENG
```

```
89012345678901234567890123456789012345678901234567890123456789012345678901
```

APPENDIX C

STUDENT-T TEST

To determine whether there is a significant difference between the measured COD/VSS ratio for the various single-reactor aerobic activated sludge units under differing operating conditions the 'Student-t' test was used. To be able to use the 'Student-t' test the following parameters must be known:

(1) the measured means, $\bar{x}_1$ and $\bar{x}_2$

(2) the standard deviations, σ_1 and σ_2

(3) the number of data points n_1 and n_2 used.

Note that the 'Student-t' test only applies when $n \leq 100$.

A summary of the basic procedure for this test is given below:

(1) Set up a null hypothesis stating that there is no significant difference between the measured mean COD/VSS ratios of two units:

$$H_o : \mu_2 - \mu_1 = 0$$

(2) Set up an alternative hypothesis stating that there is a significant difference between the measured mean COD/VSS ratios of two units:

$$H_1 : \mu_2 - \mu_1 \neq 0$$

(3) Choose a level of confidence; for all the data analysis as presented in this project a 95 percent confidence level was accepted.

(4) Determine the 'degrees of freedom' for the 'Student-t' test from:

$$\text{degrees of freedom} = (n_1 + n_2) - 2.$$

Find the confidence interval boundary value of 't' from tables (for the chosen confidence interval and the 'degrees of freedom').

(5) Find the combined standard deviation (of the two measured

means) from the two standard deviations of the two measured means:

$$S_{\text{combined}} = \sqrt{\frac{(n_1-1)\sigma_1^{\,2} + (n_2-1)\sigma_2^{\,2}}{(n_1+n_2)-2}}$$

(6) Calculate the actual 't*' value from

$$t^* = \frac{(\bar{x}_2-\bar{x}_1) - (\mu_2-\mu_1)}{S.\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

$$(\text{where } \mu_2 - \mu_1 = 0)$$

(7) If 't*' lies outside the confidence interval, in other words if 't*' *is greater than* 't' then the null hypothesis is *rejected.*

An example of the above procedure to test whether there is a significant difference in the measured mean COD/VSS ratios for the 8 day sludge age unit at 12°C and 20°C (under constant flow and load conditions, treating a raw domestic sewage) is given below: from Table 4.6

$\bar{x}_{12} = 1{,}494$ $\sigma_{12} = 0{,}025$ $n_1 = 25$

$\bar{x}_{20} = 1{,}504$ $\sigma_{20} = 0{,}045$ $n_{20} = 25$

(1) $H_o : \mu_2-\mu_1 = 0$

(2) $H_1 : \mu_2-\mu_1 \neq 0$

(3) Use a 95 percent confidence interval

(4) degrees of freedom = 48

then from tables $t_{48}^{0{,}025} = 2{,}012$

(5) $S_{\text{combined}} = 0{,}036$

(6) $t^* = 0{,}971$

(7) $t^* < t$, therefore *accept* the null hypothesis, in other words there is *no* significant difference between the measured COD/VSS

ratios for the 8 day sludge age units at 12°C and 20°C (at a 95 percent confidence level).