THE CONTACT STABILIZATION ACTIVATED SLUDGE PROCESS

by

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DECLARATION BY CANDIDATE

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

Signed by candidate

April, 1979.

SYNOPSIS

In 1978 Ekama and Marais put forward a general model for the activated sludge process based on an energy requirement for adsorption of the nutrient onto the organisms. They briefly outlined an alternative bi-substrate hypothesis in which the energy requirement for adsorption fell away. No evidence in support of this alternative hypothesis was presented. The objective of this thesis was to investigate which of the two hypotheses gave the better description of the activated sludge process kinetics. When the adsorption hypothesis was replaced by the bi-substrate hypothesis in the general model and applied to the completely mixed activated sludge process and their predictions compared with experimental data, it was not possible to establish conclusively which hypothesis is to be preferred. As a consequence it was decided to test the two models under extreme conditions. The contact stabilization process was selected as the one presenting a most severe test of the predictive power of any hypothesis on activated sludge kinetics, and most likely therefore to establish the superiority of one hypothesis over the other.

In order to obtain experimental data against which the hypotheses could be evaluated a series of laboratory scale tests on the contact stabilization process were conducted under time invariant and cyclic flow and load conditions at two temperatures, 12°C and 20°C.

From a comparison of the experimentally observed and theoretically predicted data it was concluded that an additional factor had to be taken into account before a valid comparison could be made - whereas the general activated sludge theory accepted a rapid and complete enmeshment of influent particulate COD, in the contact reactor the experimental data indicated incomplete enmeshment in the short contact time available. When allowance was made for partial enmeshment in the predicted response of the system it was concluded that the bi-substrate hypothesis was superior to the adsorption one.

Theoretical analyses of plant behaviour indicated that the nitrification response is particularly sensitive to slight changes in the nitrification rate constants. This was borne out by the experimental results where it was found that virtually every sewage batch showed different nitrification response characteristics. It was concluded that consistency in nitrification response would only be obtained if artificial substrates were utilised.

The kinetic constants defining the bi-substrate hypothesis initially were taken to be the same as those determined from the experimental data of Ekama and Marais. Under the extreme conditions in the contact stabilization process it was found that only one of these constants, the maximum specific growth rate utilizing soluble substrate, K_{ms}, had to be modified in order to obtain good correspondence between the experimental data and theoretical predictions. The use of this modified constant in the general activated sludge theory had inconsequential effects on the predictions, and can therefore be taken to constitute an improved evaluation as it allows for the general theory to be extended over a greater range of processes.

The model appears to be sufficiently reliable to be used as a tool for analysing a design under any proposed cyclic conditions.

Due to the partial enmeshment in the contact reactor there is a relatively high COD concentration in the effluent. As nitrification is also partial in the contact reactor, the TKN concentration in the effluent tends to be high. These two behaviour characteristics make the process unsuitable for application as a final treatment method in South Africa. It may however find application as an intermediate treatment facility to reduce high COD concentrations before discharge to a sewer system.

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LIST OF SYMBOLS

1. SYMBOLS USED BY OTHER RESEARCHERS WHICH APPEAR IN CHAPTER TWO AND WHICH DIFFER FROM THOSE USED IN THIS INVESTIGATION.

Ohron and Jenkins (1972)

Symbol	Description	Units
F	Influent flow. (Corresponds to Q_i)	ℓ/d
k_d	Net organism decay rate. Additional subscripts c and s refer to the contact and stabilization reactors respectively (corresponds to b)	/d
q	Overall process substrate removal rate. Mass of COD removed per mass of volatile solids. Subscripts c and s refer to the contact and stabilization reactors respectively.	mg COD/mg VSS/d
R	Recycle flow. (Corresponds to Q_r)	ℓ/d
S	General parameter for substrate concentration. Subscript c, s, o, and 1 refer to the contact reactor, stabilization reactor, influent and effluent flows respectively. (Subscripts correspond to subscripts c, s, i and e respectively)	mg COD/ℓ
t	Nominal retention times in the reactors. Subscripts c and s refer to contact and stabilization reactors respectively. (Corresponds to R_h)	hr.
X	General parameter for volatile sludge concentration. Subscripts c, s, r and 1 refer to the contact reactor, stabilization reactor, recycle or effluent flows respectively. (Corresponds to X)	mg/ℓ
Y_c	Growth yield efficiency. (Corresponds to Yield coefficient Y_h)	mg VSS/mg COD
μ_n	Overall process sludge growth rate. Additional subscripts c and s refer to the contact and stabilization reactors respectively. (Corresponds to $1/R_s$)	

Gujer and Jenkins (1975)

Additional symbols to those above:

Symbol	Description	Units
i	Conversion factor for wasted sludge. Subscripts w, gc and ds refer to the wasted sludge, and that in the contact and stabilization reactors respectively. (Corresponds to P)	mg COD/ng VSS
q_{COD}	Overall process COD removal rate. Subscripts c and s refer to the contact stabilization reactors respectively. (Corresponds to q above)	mg COD/mg VSS/d
r_h	Heterotrophic respiration rates. Subscripts c and s refer to the contact and stabilization rates respectively. (Corresponds to 0)	mgO/mgVSS/day

Adams and Eckenfelder (1970)

a'	Oxygen use rate coefficient for synthesis.	mgO_2/mgBOD
b'	Endogenous oxygen use rate coefficient	mgO_2/mg VSS
K_1	overall substrate removal rate coefficient relative to total volatile solids.	ℓ/mg VSS/d
K_r	specific oxygen uptake rate	mgO_2/d/mg MLVSS
q	Average substrate removal rate per unit of volatile solids. (Corresponds to q above)	mg COD/mg VSS
S_o	Influent substrate concentration (Corresponds to s_i)	mg/ℓ
S_e	Effluent soluble substrate concentration (Corresponds to $S_{ue} + S_{bse}$)	mg/ℓ
t	Reactor retention time. (Corresponds to R_h)	

2. SYMBOLS USED DURING THIS INVESTIGATION.

Symbol	Description	Units
* b	Specific endogenous respiration rate. Subscripts h or n refer to heterotrophic or nitrifiers respectively.	/d
BOD	Biochemical Oxygen Demand. Subscripts 5, t or u refer to the value at 5 or t days, or the ultimate value (20 days) respectively.	BOD/ℓ
COD	Chemical Oxygen Demand	mg COD/ℓ
F/M(X)	Food to micro-organism ratio.	mg/mg
f	Unbiodegradable fraction of the active organisms.	mg VSS/mg VSS
f_{bs}	Soluble fraction of biodegradable COD in the influent.	mg COD/mg COD
f_{ca}	Fraction of the biodegradable COD required for adsorption.	mg COD/mg COD
f_{ma}	Maximum fraction of stored solids with respect to active mass.	mg VSS/mg VSS
f_{n}	Nitrogen content of the sludge.	mg N/mg VSS
f_{na}	Fraction of influent TKN in the ammonia form.	mg N/mg N
f_{nu}	Soluble unbiodegradable organic nitrogen fraction.	mg N/mg N
f_{oe}	Fraction of nitrogen released through endogenous respiration in the organic nitrogen form.	mg N/mg N
f_{os}	Fraction of nitrogen required for cell synthesis in the organic nitrogen form.	mg N/mg N
f_{ssb}	Fraction on unadsorped particulate COD which remains unenmeshed in the contact reactor.	mg COD/mg COD
f_{us}	Fraction of soluble unbiodegradable COD in the influent.	mg COD/mg COD
f_{up}	Fraction of particulate unbiodegradable COD in the influent	mg VSS/mg COD

Symbol	Description	Units
* K_a	Substrate adsorption rate coefficient.	ℓ/mg VSS/d
* K_{mp}	Maximum specific growth rate coefficient for heterotrophic organisms utilizing stored particulate substrate.	mg VSS/mg COD/d
* K_{ms}	Maximum specific growth rate coefficient for utilizing soluble substrate.	mg VSS/mg COD/d
* K_n	Saturation coefficient for *nitrosomanas*.	mg N/ℓ
* K_r	Organic nitrogen to ammonia conversion rate coefficient.	ℓ/mg VSS/d
* K_{sp}	Saturation coefficient for heterotrophic cell synthesis from stored particulate substrate.	mg COD/ℓ
* K_{ss}	Saturation coefficient for heterotrophic cell synthesis from soluble substrate.	mg COD/ℓ
M	Superscript M indicates mass values, not concentrations.	
N	General parameter for nitrogen concentration. First subscript u, o, a, n or t refers respectively to soluble unbiodegradable organic, biodegradable organic, ammonia, nitrate or total Kjeldhal nitrogen concentrations. Second subscript i, p, r, w, e, c or s refers respectively to influent, process, recycle, waste, effluent, contact reactor or stabliziation reactor. A further subjscript t refers to the value at time t.	mg N/ℓ
N'_{ai}	Influent ammonia concentration adjusted for heterotrophic cell synthesis.	mg N/ℓ
N_{pi}	Influent inert particulate organic nitrogen.	mg N/ℓ
N_s	Nitrogen required for heterotrophic synthesis.	

Symbol	Description	Units
O	General parameter for oxygen consumption rate. First subscript a, e, s, c, n or t refers respectively to adsorption, endogenous respiration, synthesis, carbonaceous, nitrification or total oxygen consumption rate. A second subscript c, s, or p refers to values in the contact reactor, stabilization reactor or overall process respectively. A further subscript t refers to the value at time t.	mg O/ℓ/d
P	COD equivalent of volatile solids	mg COD/mg VSS
p	Mixed liquor pH value	
Q	General parameter for the influent flow. First subscript e, r, w refers respectively to effluent flow, the recycle flow and the waste flow. A further subscript refers to the value at time t.	ℓ/d
Q_i	Daily influent flow vector for process value. Subscript t refers to the flow value at time t.	ℓ/d
q	Steady state waste flow rate.	ℓ/d
R_h	General parameter for hydraulic retention time. Subscripts a or n refer to actual or nominal values respectively. Additional subscripts c or s refer to contact or stabilization reactors respectively.	d
R_s	Sludge age. Additional subscript m refers to the minimum value required for nitrification.	d
r	Recycle ratio.	
SLR	Sludge loading rate.	mg/mg/d
SUR	Substrate utilization rate. Subscripts a, v or t refer to the value in terms of active, volatile or total settleable solids respectively.	mg/mg/d

Symbol	Description	Units
S	General parameter for substrate concentrations. The first subscript b, u or t refers respectively to the biodegradable, unbiodegradable soluble and total concentrations. Second subscript s and p added onto b refer to biodegradable soluble and particulate substrate respectively. Additional subscripts i, c, s, p, r or e refer to the influent, contact reactor, stabilization reactor, process, recycle flow or effluent flow.	mg COD/ℓ
S_{pi}	Influent inert particulate COD concentration.	mg COD/ℓ
T	Temperature	°C
t	General parameter for time.	d
VSS	Volatile Settleable Solids	
V	General parameter for volume. Subscripts c, s or p refer respectively to contact, stabilization or process overall.	ℓ
w	Waste flow ratio.	
X	General parameter for sludge concentration. First subscript a, s, e, i, n, v or t refers respectively to active, stored, endogenous, inert, *nitrosomonas*, volatile or total solids. A second subscript i, r, w, e, c, s or p refers respectively to influent, recycle, waste, effluent, contact reactor, stabilization reactor or overall process values. A further subscript t refers to the value at time t.	mg VSS/ℓ
X_a X_s X_e	Active, stored and endogenous residue solids concentrations. Additional subscripts ℓ or g refer respectively to concentrations lost or gained through biological reaction.	mg VSS/ℓ
Y_h	Yield coefficient for heterotrophic organisms utilizing stored substrate.	mg VSS/mg COD
Y_n	Yield coefficient for *nitrosomonas*.	mg VSS/mg N

Symbol	Description	Units
α	Fractional distribution of sludge between contact reactor and overall process.	
β	Fractional distribution of sludge between stabilization reactor and overall process.	
Δ	Prefix denoting the change in the parameter.	
Δt	Integration step length	d
η_C	COD removal efficiency. Subscripts c or s refer to contact or stabilization reactors respectively.	
η_n	Nitrification efficiency. Subscripts t or e refer to theoretical or experimental values respectively.	
ϕ	General parameter for pH dependency coefficients. Subscripts h or n refer to heterotrophic organisms or *nitrosomonas* respectively. Additional subscripts a, s or e refer to adsorption, synthesis or endogenous respiration rates respectively.	
μ_h	Specific growth rate of heterotrophic organisms. Subscript m refers to the maximum value	/d
# μ_n	Specific growth rate of *nitrosomonas*.	/d

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* Additional subscripts T or 20 refer to the values at T°C or 20°C respectively

\# Additional subscripts p or 7,2 refer to the values at pH = p or 7,2 respectively.

Values of Kinetic Constants

Values of Kinetic and Other Constants Utilized in the Theoretical Model for the Contact Stabilization Process are given in Table 4.13 on page 4.52.

CHAPTER ONE

INTRODUCTION

Since 1968 one of the main research aspects undertaken by the Public Health Section of the Department of Civil Engineering at the University of Cape Town has been the investigation of the activated sludge process in waste water treatment. This research has culminated in the development of a generalised activated sludge model which describes the behaviour of the process over a wide spectrum of cyclic load and flow conditions and process configurations (Ekama and Marais, 1978).

The model of Ekama and Marais was originally based on what, for convenience, can be called the Adsorption Hypothesis. This hypothesis states that the COD substrate found in domestic sewage is of an essentially particulate nature, that prior to assimilation adsorption of this material onto the organisms is necessary, and that energy is required for this adsorption process. Application of the model has generally given response predictions in conformity with observed data.

Ekama and Marais in their report mentioned that the observed response possibly could be explained equally well by hypothesising that the influent sewage consists of two different substrates, one soluble and/or readily assimilable and the other particulate and more slowly assimilable, and that whereas adsorption of the particulate substrate is still required, adsorption itself is not an energy requiring process.

This hypothesis, called the Bi-substrate Hypothesis, has been developed fully and incorporated into an amended version of the original model. With due calibration, the bi-substrate theory has given marginally better predictions compared to the adsorption theory. However, these improvements were not marked enough to establish in a conclusive manner whether the bi-substrate hypothesis is preferable to the adsorption hypothesis.

A decisive assessment of the two hypotheses should be possible if the two versions of the model can be compared where the activated sludge process is operating under "extreme" conditions. For example, in the Contact Stabilization Process (CSP), because of its configuration and hydraulic flow pattern, a small percentage of the sludge removes the organic matter from the influent during a very short contact period. Correct prediction of the behaviour of the contact reactor response under cyclic flow conditions can be considered to be an extremely severe test of any general activated sludge process model.

Ekama and Marais (1978) applied the adsorption hypothesis to the CSP and compared model predictions with the CSP experimental results published by Gujer and Jenkins (1972). These results were obtained on plants operating under steady flow and load conditions. While very good correlation was obtained for the nitrification process, the model predictions for the removal of carbonaceous material showed an unsatisfactory correlation with the published data. However, the comparison could not be made in a rigorous manner as the data reported by Gujer and Jenkins were in an incomplete form.

In order to check the theoretical model rigorously, it was decided to generate experimental data on a laboratory scale CSP unit under steady and cyclic loading conditions. The response data would provide a basis upon which the predictions of the two hypotheses could be compared in order to assess which provided the more accurate prediction of the response of the CSP. This thesis deals with the theoretical and experimental investigation undertaken to assess the merits of the adsorption and bi-substrate hypotheses in predicting the response of the contact stabilization process.

Chapter Two consists of a review of the literature on activated sludge with particular reference to the CSP.

Chapter Three develops the bi-substrate hypothesis and applies it to the CSP model.

Chapter Four gives a description of the experimental investigation; the data is presented and analysed.

Chapter Five illustrates the design applications of the model.

In Chapter Six the conclusions drawn from the investigation are presented.

CHAPTER TWO

A REVIEW OF THE LITERATURE

2.1 CARBONACEOUS DEGRADATION

According to Stanbridge (1977), the first breakthrough in the evolution of modern sewage treatment was made by Pasteur in 1862 when he distinguished between aerobic and anaerobic bacteria. However, in 1882 it was still thought that oxidation of organic matter in sewage was a chemical process, with oxygen being derived from the air during the passage of the sewage over, or through the soil. In 1882, Dr. A. Smith was the first of several investigators who attempted to achieve a similar result by blowing air through sewage, but they all found oxidation was a very slow process, requiring weeks to obtain a satisfactory effluent.

The next advance was the development of the biological filter. It was observed that when sewage was filtered through a coarse filter material, initially little purification was achieved until a gelationous film formed on the surfaces of the filter media, whereupon a satisfactory effluent was produced within the comparatively short period the sewage trickled through the filter. The improvement in the rate of purification apparently was associated with the growth of this film, consequently investigators enquired into the feasibility of developing such a film without the need of supporting media. The floc thus produced could then be mixed with the sewage and held in contact with it under aerobic conditions to achieve the oxidation of the carbonaceous matter. This was achieved early in the 20th Century by Ardern and Lockett.

Ardern and Lockett (1914) noted that a floc developed if a batch of sewage was aerated for a long period. When this floc was separated from the effluent and added to a further sample of sewage, the floc rapidly increased with a concomitant increase in the clarification rate of the sewage added. The floc or sludge thus generated was called "active" to distinguish it from sludges obtained directly from settlement of raw sewage and which did not possess the clarification property.

In this way the designation "activated sludge" came into use. In 1915 Ardern and Lockett applied their discovery to the development of continuous laboratory scale and pilot scale processes to establish the "activated sludge process". They designed the first full scale activated sludge plant for Worcester, England, in 1915.

A schematic diagram of a "conventional" activated sludge plant is shown in Fig. 2.1.

The technique of sludge reaeration was first incorporated in Manchester's Davyhulme Works, built in 1921. Sludge reaeration requires that the sludge return flow from the settling tank is aerated for a selected period of time before it is mixed with the incoming sewage at the head of the main reactor. This reaeration technique repeatedly reappears in the history of the activated sludge process, and a schematic layout of the process is shown in Fig. 2.2.

Haseltine (1961) reports that in America the first full scale activated sludge plant was commissioned in 1917 at Houston, Texas, and that use was made of sludge reaeration. The advantages attributed to its use were: "the use of sludge reaeration would probably effect a saving of 20% in tank volume, permit a shorter mixed liquor aeration period and effect a slight saving in air consumption", (U.S. Public Health Bulletin No.123). This reduction in volume results from the fact that the densified sludge from the settler is reaerated in its concentrated form in the reaeration zone. However, by about 1940, reaeration of sludge in full scale plants, which up to that time had been limited to about 10% of the total aeration volume, was falling out of favour in the United States. Although its use was still common practice in Britain, very little evidence was produced to evaluate its effectiveness.

In America, from about 1940, Gould, Hatfield, Kraus and others experimentally investigated the use of reaeration, but with large percentages of the aeration volume being set aside for the reaeration. Hatfield developed a process in 1942 which utilized 33% of the total volume for

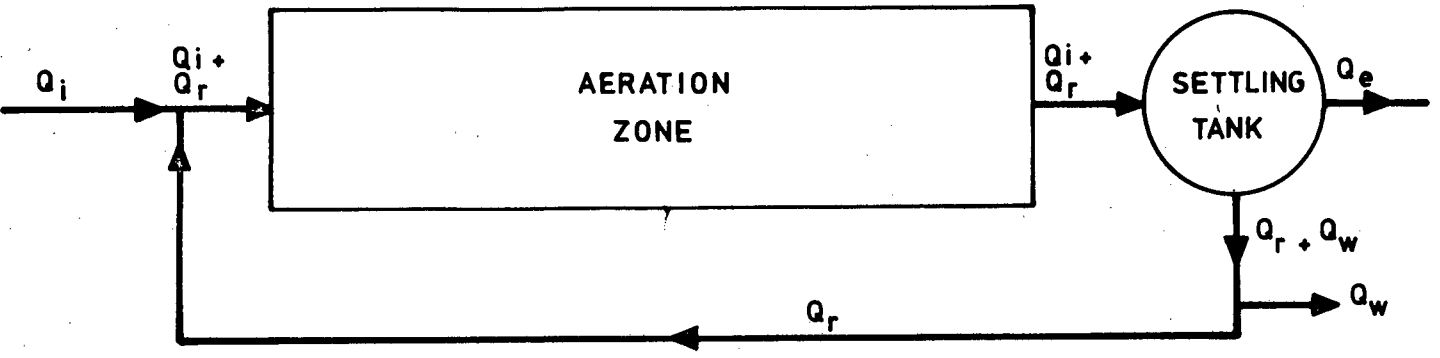


Fig. 2.1 *Diagrammatical layout of a conventional activated sludge process.*

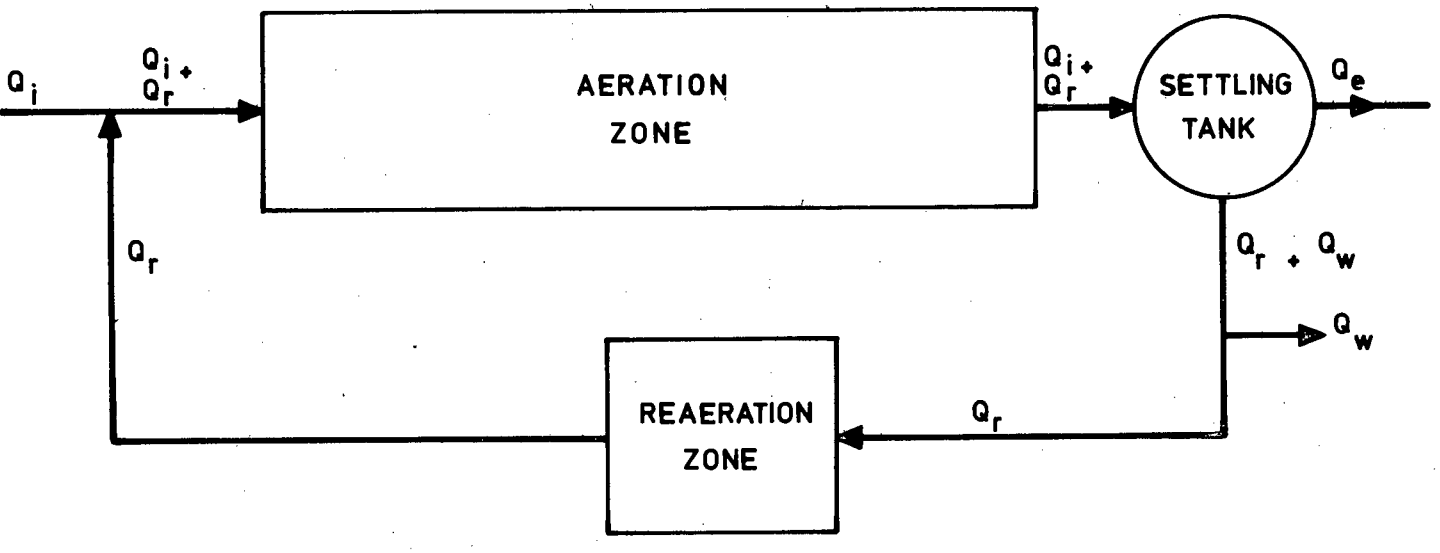


Fig. 2.2 *Diagrammatical layout of a conventional activated sludge process utilizing reaeration.*

reaeration. Later, Haseltine (1961) reported that the system would be more efficient if up to 50% of the total volume was set aside for reaeration. Kraus (1955) developed a variation in which only a portion of the return activated sludge was reaerated. Gould (1942) patented a step aeration process which allowed for the variation of the reaeration from between 25% and 75% of the total. Ulrich and Smith (1951 and 1957) developed what they called the "Biosorption process" to overcome the bulking and overloading problems occurring at the Austin Plant in Texas. This is simply a reaeration plant with approximately 70% of the volume set aside for reaeration. When operating as a conventional works, the plant was unable to handle an average flow of 22,5 Mℓ/day without severe bulking problems. However, after conversion to the Biosorption process it could treat satisfactorily 52 to 60 Mℓ/day with no additional aeration tank capacity. Bulking problems disappeared and the effluent quality improved. A contact time of only 15 to 30 minutes removed between 85 and 99% of the organic matter from the influent. This was explained by theorising that "the activated sludge adsorbs and absorbs a very high percentage of both the suspended solids and dissolved pollutional material". The sludge, with the adsorbed material, is then densified in the clarifier and "aerobically digested" in the reaeration zone in preparation for recycling back into the contact zone.

Zablatsky, Cornish and Adams (1959) coined the name "contact stabilization" for the process where the bulk of the aeration volume is set aside for reaeration. They undertook an investigation, as a result of which the Bergen County sewage treatment facilities were modified from a conventional activated sludge process to the contact stabilization process. Oxygen requirements, stabilization time, mixed liquor contact time and load factors were all developed experimentally, both by laboratory scale batch experiments and full scale modifications until the most satisfactory results were obtained. The process was highly efficient and was far less sensitive to shock loads. Frothing and bulking problems were greatly reduced and the existing aeration tank capacities were found to be adequate for treatment of at least twice the design loading for the conventional process.

Grich (1961) conducted an investigation into the operation of four "reaeration" plants. He found that these were far less sensitive to severe cyclic loadings and that the aeration volume capacity requirement was greatly reduced. He assumed that the system operated by adsorption of the organic matter by the sludge in the contact zone and assimilation of that matter in the reaeration zone. He found that a paper pulp waste, while requiring a similar contact period to an ordinary sanitary waste, required a far longer reaeration period. To explain this, he hypothesized that whereas the more complex organic material is adsorbed by the sludge as rapidly as for the sanitary waste, a longer detention period is required for the breaking down and assimilation of the more complex matter.

Up to the early 1960's, the approach to the development of the contact stabilization process was on an *ad hoc* basis. When the need arose, work was done in optimizing the process to solve a specific problem, mainly by trial and error, often within the framework of an existing plant. No attempt was made to rationalise the kinetics of the process, although it was generally believed that the organic waste is adsorbed by the sludge floc during the brief contact period and is assimilated subsequently during the longer reaeration or stabilization period.

Early attempts to establish some theoretical rationale for the contact stabilization process is principally due to Ohron and Jenkins (1972) and Gujer and Jenkins (1975). We shall now deal with these two theoretical models in sequence.

Ohron and Jenkins

One of the first attempts to rationalize the contact stabilization process kinetics was made by Ohron and Jenkins (1972). They based their model on the hypothesis that the two phases of biological activity, namely growth and decay, are essentially split between the two reactors; that only cell growth is significant in the contact basin, whereas nicro-organism decay predominates in the stabilization basin.

The kinetics of their model is defined by the following equations

Contact Substrate Removal Rate:

$$q_c = \frac{(S_o - S_c)}{t_c X_c} \tag{2.1}$$

where

S_o = influent substrate concentration

S_c = contact tank substrate concentration

t_c = nominal retention time in contact tank

X_c = sludge concentration in contact tank.

Net Sludge Growth Rate in the Contact Tank:

$$\mu_{nc} = \frac{(1 + R/F)X_c - R/F\ X_s}{t_c X_c} \tag{2.2}$$

where

R = recycle flow

F = influent flow

X_s = sludge concentration in stabilization tank.

Net Organism Decay Rate in the Stabilization Tank:

$$k_{ds} = \frac{X_r - X_s}{t_s X_s} \tag{2.3}$$

where

X_r = sludge concentration in the recycle flow

t_s = nominal retention time in the stabilization tank.

Overall Process Substrate Removal Rate:

$$q = \frac{F(S_o - S_1)}{V_c X_c + V_s X_s} \qquad (2.4)$$

where

S_1 = effluent substrate concentration

V_c, V_s = contact and stabilization tank volumes respectively.

Overall Process Sludge Growth Rate:

$$\mu_n = \frac{(F - w)X_1 + wX_c}{V_c X_c + V_s X_s} \qquad (2.5)$$

where

w = waste flow rate from the contact tank

X_1 = sludge concentration escaping in the effluent.

Ohron and Jenkins furthermore defined α and β as the fractions of the total sludge in the contact and stabilization tanks respectively, i.e.

$$\alpha = \frac{V_c X_c}{V_c X_c + V_s X_s} \qquad (2.6)$$

and

$$\beta = \frac{V_s X_s}{V_c X_c + V_s X_s} \qquad (2.7)$$

thus

$$\mu_n = \alpha \mu_{nc} - \beta k_{ds} \qquad (2.8)$$

In the course of their investigations, Ohron and Jenkins found that when the contact stabilization process was operated with a low value of α, i.e. the loading rate in the contact reactor was very high, the rate of sludge production was lower than for a conventional activated sludge plant. Furthermore, they found that the nett sludge growth can

be described to vary linearly with the contact substrate removal rate, q_c, (Eq. 2.1), according to the equation:

$$\mu_{nc} = Y_c q_c - k_{dc} \qquad (2.9)$$

where

Y_c = growth yield coefficient (mg VSS/mg COD utilized)

k_{dc} = organism decay rate in contact reactor.

In terms of their theory a yield coefficient value of Y_c = 0,74 mg VSS produced/mg COD utilized was necessary to fit their data. This is more than double the yield coefficient previously reported for conventional activated sludge plants. Ohron and Jenkins justified this high value by referring to work done by Menar and Jenkins (1967) who reported yield factors of up to 0,73 mg VSS/mg COD for very high substrate removal rates in the conventional activated sludge process. It is interesting to note, however, that if it is hypothesized that only storage and enmeshment of COD takes place in the contact reactor without any assimilation (an hypothesis directly opposite to that proposed by Ohron and Jenkins), the net sludge growth rate would be given by

$$\mu_{nc} = (\frac{1}{P})q_c - k_{dc} \qquad (2.9a)$$

where

P = the COD equivalent of volatile solids.

Now P is reported in the literature to be equal to 1,42 so that

$$\frac{1}{P} = 0,70$$

whereas

Y_c = 0,73 in Eq. (2.9).

The analysis above demonstrates that two directly contradictory hypotheses of behaviour produce values of sludge yield coefficients within 5% of each other. This raises the point that another factor, apart from

the substrate removal rate and the sludge growth rate, must be monitored to establish the relative occurrence of growth and death in the two reactors. Gujer and Jenkins (1975) attempted to achieve this by introducing the concept of process mass balances.

Gujer and Jenkins

Gujer and Jenkins chose the oxygen equivalence of a substance as their mass balance parameter and developed the following mass balance equations:

For the overall process:

$$q_{COD} = \mu_n i_w + r_h \qquad (2.10)$$

For the contact reactor:

$$q_{COD_c} = \mu_{nc} i_{gc} + r_{hc} \qquad (2.11)$$

For the stabilization reactor:

$$q_{COD_s} = k_{ds} i_{ds} + r_{hs} \qquad (2.12)$$

where i = conversion factor for the wasted sludge kg COD/k VSS. Subscripts w, gc and ds refer to the waste sludge, contact reactor and stabilization reactor respectively.

r_h = heterotrophic respiration rates.

In their experimental study, Gujer and Jenkins accepted four basic independent variables, namely, process loading, temperature, recycle ratio and the fractional distribution of the sludge mass between the two reactors. Of the four, they found that only temperature and process loading had a significant effect on sludge production; the recycle ratio and fractional distribution of sludge between the two reactors had very little effect on the mass of sludge produced. With this observation they refuted the finding of Ohren and Jenkins (1972) that the contact stabilization process produced less sludge than a conventional process at high process loading. The observed values of the dependent variables, namely respiration rate, r_h, and net sludge growth rate, μ_n, were plotted against a range of values of the overall process COD removal rate, q_{COD}. The experiments were done at 11 and 21°C and least square linear regression analysis was done on each of the plots

to produce the values of a and b in Eqs. (2.13 to 2.16).

$$r_h = a \cdot q_{COD} + b \tag{2.13}$$

$$r_{hc} = a_c \cdot q_{COD} + b_c \tag{2.14}$$

$$r_{hs} = a_s \cdot q_{COD} + b_s \tag{2.15}$$

$$\mu_n = a' \cdot q_{COD} + b' \tag{2.16}$$

This linear form of equation to describe the kinetics of the activated sludge process has been widely adopted by researchers. For example, Adams and Eckenfelder (1970) undertook a study to compare the response of completely mixed activated sludge plants under steady and transient loading conditions. They used a modification of the Garrett and Sawyer (1952) model defined by two equations:

$$q = \frac{S_o - S_e}{X_v t} = K_1 S_e \tag{2.17}$$

and

$$K_r = a'q + b' \tag{2.18}$$

where

q = average substrate removal rate per unit of volatile solids

K_1 = overall substrate removal rate coefficient

S_o = influent substrate concentration

S_e = effluent soluble substrate concentration

X_v = average biological solids concentration

t = reactor retention time (days)

K_r = specific oxygen uptake rate (mg O_2/day/mg MLVSS)

a' = oxygen use rate coefficient for synthesis (mg O_2/mg BOD)

b' = endogenous oxygen use rate coefficient (per day).

The values of a' and b' are obtained from plotting experimentally observed values of K_r against q and fitting a straight line to the data. This approach is identical to that employed by Gujer and Jenkins for the contact stabilization process as outlined previously.

However, Adams and Eckenfelder found that their model had to be calibrated for various loading conditions. This requires a laboratory study to be run which closely simulates expected full scale conditions for each design application of the model in order to establish the relevant values of K_r, a' and b'. They found in general that under transient loading conditions the average substrate removal rate, K_1, and the endogenous rate of specific oxygen uptake, b', tend to increase compared with the values for steady state conditions, but there appeared to be no predictable pattern to this increase, and, the values obtained were very different from those found by Gujer and Jenkins (1972).

It would seem that the linearized approach of the above two models does not entirely define the kinetics of the activated sludge process. Gujer and Jenkins (1972) and Eckenfelder (1970) acknowledge this in their papers and both suggest that the discrepancies found in their investigations may be due to adsorption of the substrate by the organisms. This would not be evident in a purely steady state study, but becomes important in a spatially varied process such as contact stabilization, or under dynamic loading conditions.

In order to obviate the need for laboratory calibration of models for each design application obviously it would be desirable to have one general model of the activated sludge process which would have fixed constants applicable to all aspects of the process. For this to become a reality a method has to be found to theoretically predict the sludge growth, decay, and respiration rates which are independent of the loading conditions imposed on the process. The first step in this development was taken by McKinney (1962) when he established the

theoretical importance of the sludge age or solids retention time and stated that the volatile sludge was made up of active, endogenous residue and inert fractions. The active fraction contains the live biological organisms, the endogenous residue is the unbiodegradeble fraction of the organism remaining after death, and the inert fraction is the particulate unbiodegradeble volatile material in the influent which accumulates in the reactor. The three fractions of the sludge vary with the sludge age. Since the specific substrate removal rate has in the past been expressed relative to the total sludge concentration, the equation relating sludge growth rate to substrate removal rate cannot produce a straight line. (Marais and Ekama, 1976).

Marais and Ekama utilized McKinney's ideas on the constitution of the sludge. They defined two different substrate utilization rates as follows:

$$SUR_v = \frac{(S_{bi} - S_b)\, Q}{X_v\, V_p} \qquad (2.19)$$

and

$$SUR_a = \frac{(S_{bi} - S_b)\, Q}{X_a\, V_p} \qquad (2.20)$$

where

SUR_v, SUR_a = substrate utilization rate, relative to the total and active sludge concentrations respectively

S_{bi} = biodegradable COD concentration in influent (mg COD/ℓ)

S_b = biodegradable COD concentration in effluent (mg COD/ℓ)

X_v = $X_a + X_e + X_i$ = total volatile sludge concentration (mg VSS/ℓ)

X_a = active sludge concentration (mg A VSS/ℓ)

X_e = concentration of unbiodegradable endogenous residue (mg VSS/ℓ)

X_i = concentration of unbiodegradable volatile particulate matter introduced with the influent (mg VSS/ℓ)

V = total volume of the process (ℓ)

Q = influent flow (ℓ/d)

The true Food to Micro-organism Ratio (F/M) of McKinney is given by SUR_a, but due to the difficulty of establishing the value of the active fractions of the sludge, most previous models have attempted to approximate F/M with SUR_v. Marais and Ekama set out to develop a model which would overcome these difficulties.

In developing their theory for the steady state solution of single reactor completely mixed systems, they based it on the following conceptual model of the biological growth kinetics involved in the activated sludge process:

When an organism is brought into contact with a biodegradable energy source

(i) "The energy is utilised by the organism to synthesis organism mass: a fraction of the energy is incorporated as organism mass, the rest is lost as heat. The fraction lost as heat is directly proportional to the oxygen utilised.

(ii) Concomitantly with (i) above, but distinct from it, there is a loss of live mass to provide energy for cell maintenance, called endogenous respiration. Not all the live mass that disappears <u>per se</u> is lost as energy, approximately 20 per cent remains as unbiodegradable organic residue, called endogenous residue. A mass of oxygen must be supplied proportionately to the <u>volatile mass</u> that disappears from the <u>system</u>".

In a single completely mixed reactor under steady state loading conditions only the net responses can be measured. Hence, because the original model was only derived for steady state loadings, storage of energy by the organisms was not incorporated. For the quantitization of the model the following problems had to be resolved:

(i) At what rate is the energy incorporated into the cell?

(ii) What fraction of the input energy is incorporated as cell mass?

(iii) What is the rate of endogenous mass loss?

The sythesis of new cell material from the energy removed from the influent is described by the Monod equation:

$$\frac{dX_a}{dt} = \frac{\mu_m S_b}{K_s + S_b} X_a \qquad (2.21)$$

where

μ_m = maximum specific growth rate of the organisms (mg VSS/mg VSS/d)

S_b = concentration of biodegradable COD surrounding the organisms (mg (COD/ℓ))

K_s = substrate concentration at which the specific growth rate of the organisms is equal to half the maximum specific growth rate (mg COD/ℓ)

Eq. (2.21) can be modified to the form

$$\frac{dX_a}{dt} = \frac{Y K_m S_b}{K_s + S_b} X_a \qquad (2.22)$$

where

Y = growth yield coefficient, being the mass of organisms synthesized per unit of mass COD utilised (mg VASS/mg COD utilised)

$$K_m = \frac{\mu_m}{Y}$$

In the activated sludge process the object is to maintain the substrate concentration S as low as possible, so $K_s >> S$ and Eq. (2.22) can be written

$$\frac{dX_a}{dt} = Y K S_b X_a \qquad (2.23)$$

where

$$K = \frac{K_m}{K_s}$$

The energy lost or the oxygen equivalent lost during synthesis expressed as COD is equal to the oxygen required, and is given by the difference between the energy input and the energy actually synthesized into VSS

$$dO = (1 - PY) dS_b \qquad (2.24)$$

where

dO = oxygen required (mg O_2)

P = COD equivalent of volatile solids (mg COD/mg VSS)

dS_b = energy input (mg COD)

The kinetics of the endogenous respiration is described by

$$\frac{dX_e}{dt} = - b X_a \qquad (2.25)$$

where

b = specific endogenous respiration rate (mg VASS/mg VASS/d)

and the production of the endogenous residue is described by

$$\frac{dX_e}{dt} = f\, b\, X_a \qquad (2.26)$$

where

f = fraction remaining as endogenous residue

The nett energy released as COD during endogenous mass loss is given by the oxygen equivalent of the mass that disappears from the system

$$\frac{dO}{dt} = P\,(1 - f)\,bX_a \qquad (2.27)$$

In order that the concentration of inert material, X_i, be quantified the influent sewage is divided into three fractions as follows

$$S_{ti} = S_{bi} + S_{ui} + S_{pi} \qquad (2.28)$$

where

S_{ti} = total influent COD (mg COD/ℓ)

S_{bi} = biodegradable influent COD (mg COD/ℓ)

S_{ui} = soluble unbiodegradable influent COD (mg COD/ℓ)

S_{pi} = particulate unbiodegradable influent COD (mg COD/ℓ)

No differentiation is made between soluble and particulate biodegradable COD, as they both seemed to be equally amenable to biodegradation.

The accumulation of inert material is described by

$$\frac{dX_i}{dt} = \frac{S_{pi}}{P}\,\frac{Q}{V_p} \qquad (2.29)$$

Now, by doing a process mass balance on X_a, X_e, X_i and S_b, the following equations are described

$$X_a = \frac{Y(S_{bi} - S_b) \cdot R_s}{(1 + bR_s) \cdot R} \quad (2.30)$$

$$X_e = f \cdot b \cdot X_a \cdot R_s \quad (2.31)$$

$$X_i = \frac{S_{pi}}{P} \quad \frac{R_s}{R} \quad (2.32)$$

$$S_b = \frac{S_{bi}}{1 + KRX_a} = \frac{1 + bR_s}{YKR_s} \quad (2.33)$$

where

R_s = sludge age (days)

$$= \frac{\text{the mass of sludge wasted every day}}{\text{total mass of sludge in the system}}$$

R = hydraulic retention time (days)

$= V_p/Q$

and the oxygen demand per litre of process volume per day can be written as

$$dO/day = \frac{(1 - PY)(S_{bi} - S_b)}{R} + P(1 - f)bX_a \quad (2.34)$$

Marais and Ekama undertook an extensive experimental investigation to establish the values of Y, b, K and P. The values of Y and b were found to be extremely difficult to establish simultaneously from a set of data as a compensatory effect of one on the other made it possible always to select a value of Y and b such that the experimental data was consistently reproduced. Finally, b was established independently by conducting aerobic digestion tests, and from this the corresponding value of Y was established. The values arrived at are given below:

$Y = 0,43$ mg VASS/mg COD

$b = 0,24$ mg VASS/mg VASS/day

$K = 0,07$ ℓ/mg VSS/day

$P = 1,48$ mg/COD/mg VSS

Eqs. (2.30 and 2.31) contain the parameter R. However, this is a process parameter, not a kinetic parameter. To keep the model completely general, Marais and Ekama introduced the concept of mass parameters, which were defined as follows:

$$M(\Delta S) = Q(S_{bi} - S_b) \tag{2.35}$$

$$M(X_a) = V.X_a = \frac{Y.R_s}{1 + R_s} . M(\Delta S) \tag{2.36}$$

$$M(X_e) = V.X_e = f.b.R_s.m(X_a) \tag{2.37}$$

$$M(X_i) = V.X_i = \frac{S_{pi}}{P} . R_s.Q \tag{2.38}$$

$$\frac{M(O_s)}{day} = dO.V = (1 - PY)\, M(\Delta S) + (1 - f)P.b.M(X_a) \tag{2.39}$$

Figure 2.3 shows how the various mass parameters vary with sludge age. From this figure it can be seen very clearly how the fractional composition of the sludge changes with sludge age, and hence, the extent of the error introduced by approximating the F/M ratio by SUR_v.

In terms of this model SUR_a and SUR_v can be defined as follows for <u>settled</u> sewage (i.e. $S_{pi} = 0$):

$$SUR_a = - \frac{M(\Delta S)}{M(X_a)} = - \frac{1/R_s + b}{Y} \tag{2.40}$$

which can be written

$$1/R_s = Y.SUR_a - b \tag{2.41}$$

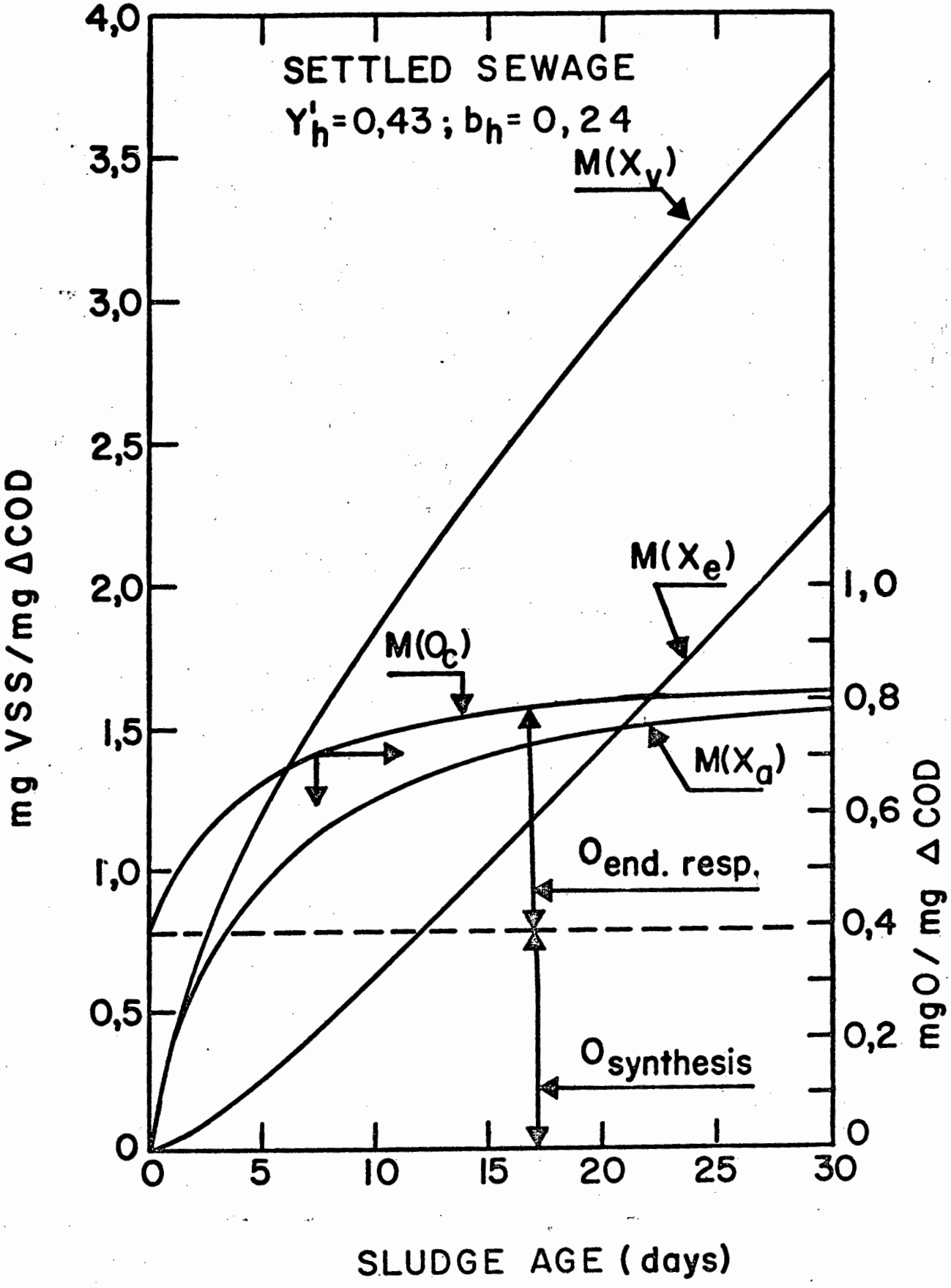


Fig. 2.3 *Relationship between the masses of sludge fractions and daily oxygen demand with sludge age in the reactor for unit mg COD utilized per day.* [*After Ekama and Marais (1978)*]

and

$$SUR_v = \frac{M(\Delta S)}{M(X_v)} = \frac{1/R_s + b}{Y} \cdot \frac{1/R_s}{1/R_s + f.b} \qquad (2.42)$$

where $MX_v = MX_a + MX_e$ for settled sludge.

Eq. (2.42) can be written

$$1/R_s = \frac{1/R_s + f.b}{1/R_s} \cdot Y \cdot SUR_v - b \qquad (2.43)$$

where $1/R_s$ is equivalent to the sludge production rate μ in previous models.

Similarly the oxygen utilization rates, which previously were written in the form

$$\frac{M(O)}{M(X_v)} = a' SUR_v + b' \qquad (2.44)$$

can in terms of the Marais-Ekama model, be presented as

$$\frac{M(O)}{M(X_a)} = (1 - PY) SUR_a + (1 - f) P b \qquad (2.45)$$

and

$$\frac{M(O)}{M(X_v)} = (1 - PY) SUR_v + \frac{(1 - f) . P . b}{1 + f . b . R_s} \qquad (2.46)$$

If Y and b are constant then Eqs. (2.43 and 2.46) when plotted against $1/R_s$ and MO/MX_v plotted against SUR_v are curved lines passing through the origen not straight lines as indicated by Eqs. (2.41 and 2.45) respectively, the constants obtained are not directly related to Y and b, therefore, the approximation on which the previous models are based, can only be of use for deriving ad hoc parameters for a specified waste over a specified range of R_s. Thus the previous models are not suitable for development of a general activated sludge process model.

In 1978 Ekama and Marais applied their model to space and time dependent dynamic loading conditions. They undertook an extensive experimental project to test their model's predictions of kinetic parameter behavioural patterns under transient loading conditions. Because of the complexity of the calculations involved in modelling dynamic conditions, digital computer programs were written to facilitate the evaluation of the kinetic behaviour.

During the experimental investigation they found that the model as concieved for steady state loading patterns could not satisfactorily explain certain observations when applied to dynamic loading conditions. The deficiencies in the model are clearly illustrated in Fig. 2.4 reproduced from Ekama and Marais (1978). The figure shows the model predictions compared to the experimental observations in a single reactor, square wave loading pattern test at 20°C and a sludge age of 2,5 days. There are two main factors the model does not predict satisfactorily: (1) The oxygen demand, is overpredicted during the non-feed period and (2) the COD concentration is predicted as following the cyclic loading pattern, whereas it is observed experimentally to stay virtually constant over the entire feed cycle. The observed response of the experimental unit would seem to suggest that the rate of substrate removal from the liquid phase is faster than the rate of synthesis. Consequently, while the substrate is being added to the system, storage takes place. Once the supply ceases, synthesis with its high energy requirement continues until the supply of stored substrate is depleted.

To obtain an improved agreement between the model and the experimental observations it was found necessary to incorporate two additional steps:

(i) The provision of a mechanism whereby the substrate is stored on the active fraction of the sludge mass at a rate which is dependent on the concentration of substrate in the surrounding liquid

(ii) The utilization of the stored substrate for synthesis at a rate which is dependent upon the concentration of the stored substrate.

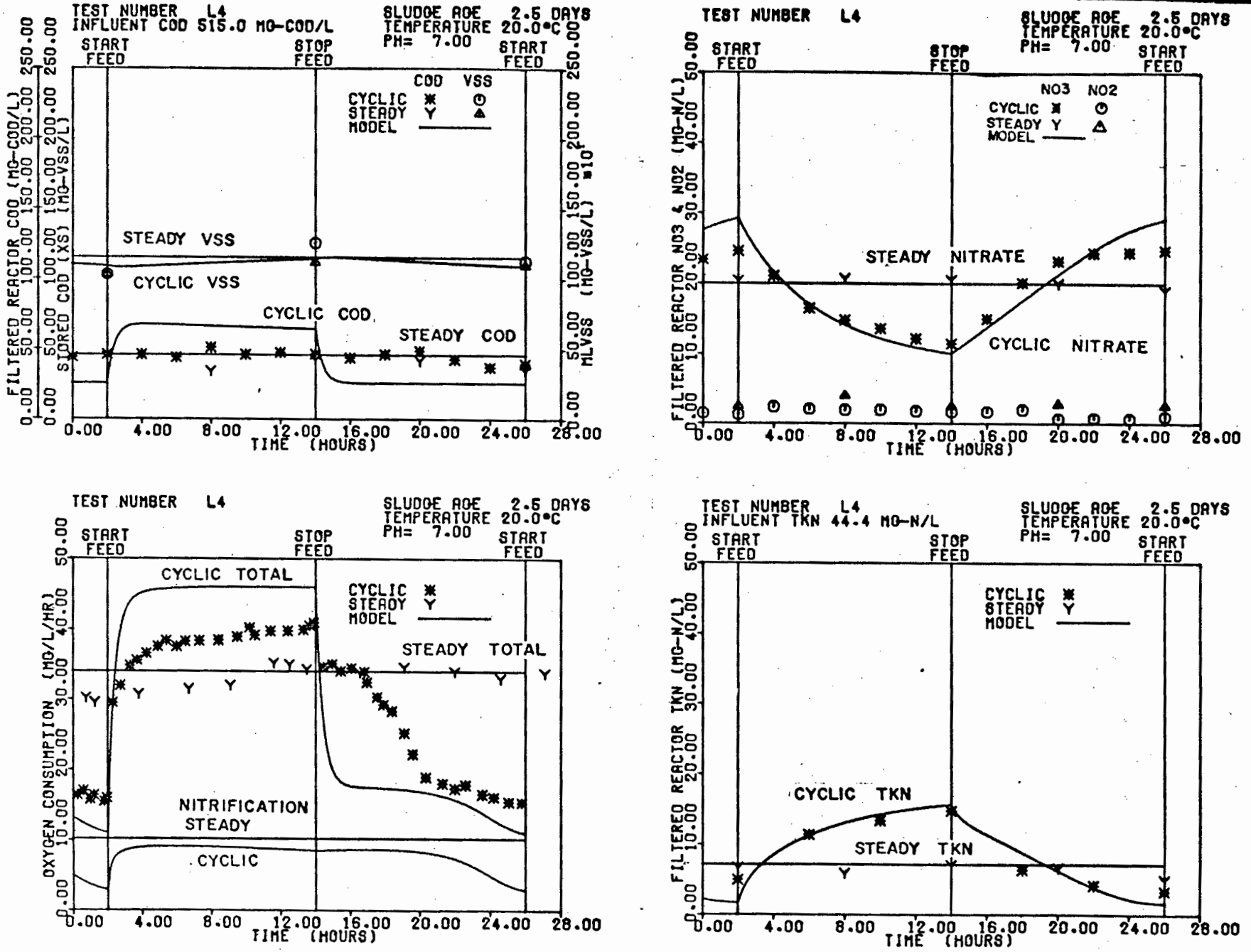


Fig. 2.4 *Comparison of the theoretical response waves predicted by the Marais model with those observed experimentally for daily cyclic square wave loading conditions at 2,5 days sludge age, 20°C and pH = 7,0.* [*After Ekama and Marais (1978)*].

Although the two kinetic modifications gave a better agreement between observed and theoretically predicted value, these did not explain the precipitous drop in the oxygen demand immediately subsequent to the feed termination (see Fig. 2.4).

The behaviour of the oxygen demand rate seemed to indicate that there is a high rate energy absorbing mechanism involved in the biological kinetics which commences immediately the substrate comes into contact with the organisms and ceases as soon as the influent flow is interrupted. Ekama and Marais first attempted, unsuccessfully, to link this sudden drop in oxygen demand to the nitrification kinetics of the process. They finally hypothesized that the adsorption of the substrate by the active mass is an energy absorbing process. Accepting this hypotheses an intensive experimental study of the extent of the drop in oxygen demand was conducted, and from these results, together with the work done by Stern and Marais (1974) and Wilson and Marais (1976) on observations in the primary anoxic zone of a denitrification plant, Ekama and Marais concluded that 7,8% of the influent COD is utilized in the adsorption of the substrate by the active mass.

They found that their experimental observations of the adsorption mechanism were best described by a modification of the equation proposed by Blackwell (1971). Blackwell proposed that the rate at which the substrate is removed from the liquid is given by

$$\frac{dS_b}{dt} = - R_k X_v \left(f_{mv} - \frac{X_s}{X_v}\right) \qquad (2.47)$$

where

R_k = substrate transfer rate constant (mg COD/mg VSS/d)

F_{mv} = maximum fraction of substrate that can be incorporated in the sludge mass sotred (mg VSS/mg VSS)

X_s = stored substrate concentration (mg VSS/ℓ)

Ekama and Marais introduced two modifications in proposing Eq. (2.48) by making it into (1) a first order equation with respect to the substrate concentration (S_b) and (2) dependent on the active organism concentration (X_a)

$$\frac{dS_b}{dt} = - K_a.S_b.X_a \left(f_{ma} - \frac{X_s}{X_a}\right) \qquad (2.48)$$

where

K_a = substrate adsorption rate coefficient

f_{ma} = maximum fraction of stored solids with respect to active mass

The rate at which substrate is stored on the organism is given by

$$dS_s = (1 - f_{ca}) \frac{dS_s}{dt} \qquad (2.49)$$

where

S_s = stored substrate in terms of COD

f_{ca} = fraction of COD removed from the liquid phase utilized for adsorption i.e. 0,078

Now S_s can be expressed in terms of VSS as follows

$$S_s = P.X_s \qquad (2.50)$$

where

X_s = stored COD in terms of VSS

Therefore $$\frac{P.dX_{sg}}{dt} = (1 - f_{ca}) \cdot \frac{dS_b}{dt} \qquad (2.51)$$

In terms of the adsorption energy hypothesis the energy required to adsorb the concentration of substrate, X_{sg}, is given by the oxygen consumed during the adsorption phase:

i.e. $$O_a = f_{ca} \cdot \frac{dS_b}{dt}$$

$$= f_{ca}.K_a.X_a.S_b \left(f_{ma} - \frac{X_s}{X_a}\right) \qquad (2.52)$$

where

O_a = oxygen consumption rate for the adsorption of substrate ($mgO_2/\ell/d$)

Ekama and Marais still utilized a Monod-type relationship to define the synthesis of cells from the substrate, but instead of relating it to the surrounding substrate in the liquid, they now relate it to the stored substrate concentration in terms of COD as follows:

$$\frac{dX_a}{dt} = Y. \frac{K_m(X_sP)}{K_s + (X_sP)} X_a \qquad (2.53)$$

where

X_sP = the COD equivalent of the stored substrate

The oxygen demand for synthesis is taken as the difference between the total COD released from storage, and that fraction which is synthesised to new cell material.

i.e.

$$O_s = (1 - PY) \frac{K_m(X_sP)}{K_s + (X_sP)} X_a \qquad (2.54)$$

where

O_s = oxygen demand for synthesis (mg O_2/ℓ/day)

As a portion of the influent COD is required to provide energy adsorption, the value of Y has to be adjusted from 0,43 to 0,48 but this constant is the only one that needs to be changed.

The predictions of this 'adsorption model' can be compared with the experimentally observed responses in Fig. 2.5. It can be seen that the cyclic oxygen demand behaviour is now accurately predicted.

In their model, Ekama and Marais proposed two alternative theories for the endogenous respiration. In the first approach the net results only are modelled, and the internal mechanisms which produce those results are disregarded. In essence, this approach assumed that a large cell is formed, which with time feeds on itself to provide energy for cell maintenance, resulting in its progressive decrease in size until is dies, leaving only the unbiodegradable endogenous residue. As this internal energy can only be of use to the cell through the use of a terminal electron acceptor, the process has an oxygen demand which can be equated to the COD equivalent of the cell mass which disappears. This was the approach

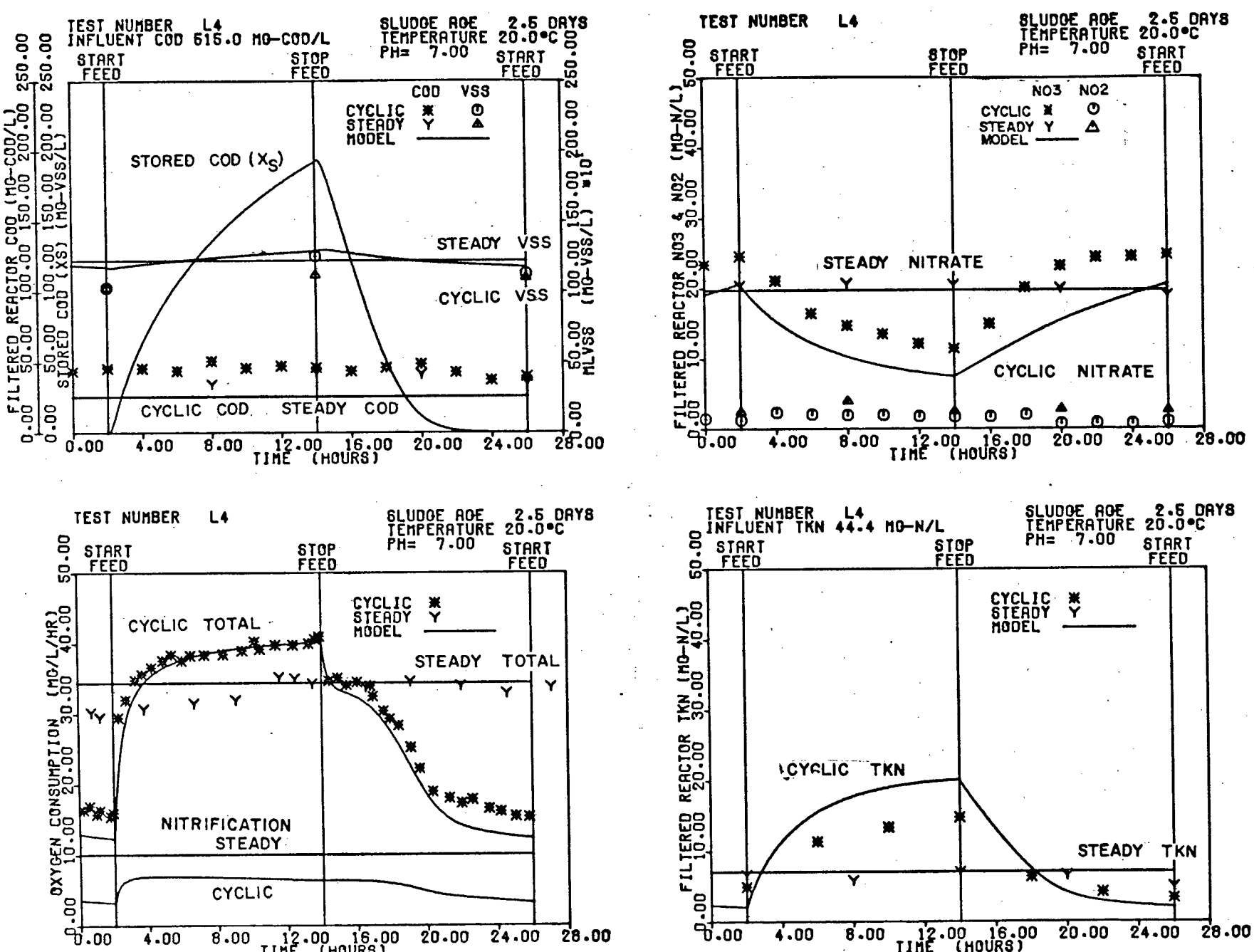


Fig. 2.5 *Comparison of the response waves calculated by the theorectical model incorporating adsorption, and storage of COD and the Monod kinetics for nitrification with those observed experimentally for daily cyclic square wave loading conditions at 2,5 days sludge age, 20°C and pH = 7,0.* [*After Ekama and Marais (1978)*].

utilized in Ekama and Marais' model for steady state conditions and the equations defining the process have been discussed earlier.

In the second approach, attempt is made to take account of the mechanisms involved in the growth/death process. It is hypothesised that when the 'death' of a cell occurs, the biodegradable fraction of the cell is lysed back into the liquid where it becomes part of the biodegradable substrate. It subsequently passes through the same phases of adsorption, storage and synthesis as the influent substrate, with the same oxygen demands. The unbiodegradable fraction accumulates in the form of endogenous residue. In this approach, then, it is assumed that endogenous respiration in the form of cell maintenance does not occur at all, that the only processes requiring oxygen in the life cycle of the organisms are the adsorption of the substrate and the synthesis of new cells.

Ekama and Marais (1978) modelled both hypotheses and compared the results with experimental observations. They found that both produced very similar results, which accurately predicted the observed response, and so they decided to incorporate the simpler first approach into their model.

In the conclusions to their report, Ekama and Marais propose an alternative to the adsorption hypothesis to explain the behaviour of the process oxygen demand under cyclic loading conditions. They hypothesized that (1) the influent substrate consists of two fractions; (a) a soluble, easily assimilable fraction which does not require adsorption and storage prior to assimilization and (b) an essentially particulate fraction which requires adsorption prior to assimilization. (2) the adsorption of the particulate material does not require energy.

According to the alternative hypothesis the utilization of the easily assimilable fraction of the influent substrate is in accordance with Monod's equation, but with a very high utilization rate constant and a low half saturation constant, similar to the utilization of free and saline ammonia by the nitrosomonas in the nitrification. In terms of this hypothesis the sharp reduction in the oxygen consumption rate observed at the abrupt termination of feed is due to the cessation of the oxygen demand for the synthesis reaction utilizing the easily biodegradable soluble COD.

During the course of this investigation the model has been adapted to include this alternative hypothesis, with very satisfactory results. The observed cyclic variation in oxygen demand is accurately predicted. Furthermore, whereas with the energy adsorption theory the lowest sludge age at which the modelled process remained stable at 14°C is 3,4 days. In the bi-substrate hypothesis the minimum stable sludge age is lower, i.e. 1,5 days at 14°C. The stable operation of 1,5 days is near the limit observed in practice, hence the bi-substrate hypothesis appears to have distinct advantages over the adsorption hypothesis.

2.2 NITRIFICATION

The oxidation of ammonia to nitrate is known as nitrification. In 1877 Schloesing and Muntz demonstrated that nitrification is a biological mediated reaction. Initially the removal of ammonia from waste waters was not considered necessary, as dilution in natural waterways reduced the concentration to below toxic levels. In fact it was considered undesirable in the activated sludge process as denitrification (which is the biological reduction of nitrates to gaseous nitrogen) in the settler gave rise to problems with floating sludge during the settling process. However, as the volumes of waste water increased the toxic effects of ammonia on higher forms of aquatic life began to manifest themselves. Added to this was the fact that nitrification has a high oxygen demand, and if it takes place in a natural waterway it can lead to serious deoxygenation.

A further problem in the discharge of effluents into natural waterways is that of eutrophication. The high concentrations of nitrogen and phosphorus in effluents results in massive algae growth in the water ways, lakes and dams which receive them, and the natural ecology suffers.

Control of eutrophication can be effectively achieved by limiting the amount of nitrogen in the effluent. This is accomplished by designing activated sludge plants that denitrify, which in turn requires that full nitrification of the influent must also be provided for in the plant.

Biological nitrification takes place in two sequential steps, each step involving a different autotrophic bacteria species, namely *nitrosomonas* and *nitrobacters* respectively:

(1) *Nitrosomonas* convert free and saline ammonia to nitrite as follows:

$$NH_4^+ + \tfrac{3}{2}\ O_2 + \textit{nitrosomonas} \rightarrow 2H^+ + H_2O + NO_2 \qquad (2.55)$$

(2) *Nitrobacter* convert nitrite to nitrate as follows:

$$NO_2^- + \tfrac{1}{2}\ O_2 + \textit{nitrobacter} \rightarrow NO_3^- \qquad (2.56)$$

From a survey of the literature, it is evident that the first step is the limiting one. Not only is the specific growth rate of *nitrosomonas* very much slower than that of *nitrobacter*, it is also very much more sensitive to temperature and pH changes as well as the presence of toxins in the influent. The limiting effect of the first step in the process is evidenced by the extremely low concentrations of nitrite normally found in nitrified effluents. As a result of this most nitrification models have concentrated on the growth characteristics of the *nitrosomonas*.

Kinetic studies of nitrification in the activated sludge process have only been undertaken relatively recently. One of the first was done by Downing, Painter and Knowles (1964). They based their model on the Monod formulation, and by doing so set the pattern for most other investigators. They were the first to introduce the concept of a minimum sludge age for nitrification which is defined as the sludge age at which the nitrosomonas grow at a rate just greater than the rate at which they are removed from the reactor in the wasted sludge. Other models based on the Monod formulation were proposed by Lijklema (1973), Poduska and Andrews (1974) and Gujer (1977).

A feature of the nitrification process as opposed to the biodegradation of carbonaceous matter, is that the nitrifiers are specific organism types which utilize a specific soluble substrate in a readily assimilable form. These conditions are in fact essentially those

under which Monod derived his relationship, and would explain why the Monod approach gives such a satisfactory description of the process. In the literature however, there is a very wide range of values proposed for the Monod constants. This dispersion of values is probably due to the exclusivity of action of the nitrifying organisms. In the carbonaceous biodegradation process there are a great number of different organisms which perform a similar function. If the prevailing conditions do not suit a specific organism, it is simply replaced by one which can thrive under the particular set of conditions. Hence carbonaceous degradation kinetics is relatively insensitive to moderate physical and chemical variations in the influent and process. However, as only *nitrosomonas* and *nitrobacter* can perform the nitrifying process, the sensitivity of the whole process is dependent on the sensitivity of these two types of bacteria.

Because of the uncertainty evident in the establishing of the Monod constants for nitrification, Ekama and Marais (1978) proposed their own modification of the theory, and experimentally established values for the constants. As with their investigation into the carbonaceous biodegradation, they started off by dividing the influent sewage up into its constituent fractions. They found that the influent nitrogenous matter (N_{ti}) was composed as follows:

$$N_{ti} = N_{ai} + N_{oi} + N_{ui} + N_{pi} \qquad (2.57)$$

where

N_{ai} = concentration of free and saline ammonia in the influent (mg N/ℓ)

$$= f_{na}.N_{ti} \qquad (2.58)$$

N_{ui} = concentration of soluble unbiodegradable organic nitrogen in the influent (mg N/ℓ)

$$= f_{nu}.N_{ti} \qquad (2.59)$$

N_{pi} = concentration of particulate unbiodegradable organic nitrogen in the influent (mg N/ℓ)

$$= f_{n}.S_{pi}/P \qquad (2.60)$$

where

f_n = nitrogen fraction of the influent unbiodegradable particulate material

N_{oi} = concentration of biodegradable organic nitrogen in the influent (mg N/ℓ)

$$= (1 - f_{na}).N_{ti} - N_{ui} - N_{pi} \qquad (2.61)$$

As in earlier models, the kinetics of the *nitrosomonas* were considered to be the limiting factor, and in fact it was assumed that the nitrification of ammonia to nitrate was a one step process, dependent on the Monod formulation of *nitrosomonas* specific growth rate.

$$\mu_n = \frac{\mu_{nm} N_a}{(K_n + N_a)} \qquad (2.62)$$

where

μ_n = specific growth rate of *nitrosomonas* (per day)

μ_{nm} = maximum specific growth rate of *nitrosomonas* (per day)

K_n = saturation coefficient (mg N/ℓ)

N_a = ammonia concentration (mg N/ℓ)

It would appear from experimental observation that adsorption and storage of substrate by the *nitrosomonas* do not take place. Ekama and Marais (1978) put this down to the fact that the substrate, ammonia, is in a soluble and easily assimible form. Hence, they defined the specific net growth rate of *nitrosomonas* as

$$\frac{dX_n}{dt} = \frac{\mu_{nm} N_a}{K_n + N_a} \cdot X_n - b_n X_n \qquad (2.63)$$

where

X_n = concentration of active *nitrosomonas* (mg VSS/ℓ)

b_n = endogenous respiration rate of *nitrosomonas* (per day)

The rate of utilization of ammonia was related to the synthesis of *nitrosomonas*

$$\frac{dN_a}{dt} = \frac{-(\mu_{nm}/Y_n)N_a}{(K_n + N_a)} \cdot X_n \qquad (2.64)$$

where

Y_n = yield coefficient of *nitrosomonas* from ammonia utilized

hence the rate of production of nitrates becomes

$$\frac{dN_n}{dt} = \frac{+(\mu_{nm}/Y_n)N_a}{(K_n + N_a)} \cdot X_n \qquad (2.65)$$

where

N_n = nitrate concentration (mg N/ℓ)

In their model Ekama and Marais took the nitrification process reaction to be stoichiometric. The errors introduced by this simplification were shown by Haug and McCarty (1971) to be extremely small, hence, the oxygen demand for nitrification is given by

$$O_n = 4{,}57\ dN_a/dt \qquad (2.66)$$

where

O_n = oxygen demand for nitrification (mg O/ℓ/day)

They also found that the concentration of *nitrosomonas* produced by a municipal sewage was so small relative to the total sludge production (less than 4%), that it could be ignored. Consequently, the accumulation of endogenous residue of the nitrifier mass was also ignored.

During their investigation it became clear that to model adequately the nitrification process, cognisance must be taken of the heterotrophic nitrogen demand as well as the re-introduction of organic nitrogen to the available concentration from release of organic nitrogen due to endogenous respiration (or lysis) of the heterotrophs.

This is clearly illustrated in Fig. 2.6 (after Ekama and Marais 1978) which shows the variation in TKN, ammonia and organic nitrogen concentrations between reactors in a serial four reactor process. The behaviour of the organic nitrogen curve was explained as follows:

In the first two reactors, before full nitrification has taken place, the heterotrophs utilize ammonia as their source of nutrient nitrogen and the build up of organic nitrogen can be attributed to the lysis of dead cells. However, once the level of ammonia concentration becomes limiting in reactors three and four, the heterotrophs turn to the organic nitrogen for their nutrient supply, hence the drop in organic nitrogen concentrations.

Observations of high ammonia concentrations in an aerobic digestor fed on an ammonia free influent led Ekama and Marais to conclude that the heterotrophs are capable of transforming organic nitrogen into ammonia. In endeavouring to establish the nature of both the nitrogen released by lysis of cells and the nitrogen required for heterotrophic synthesis they made the following assumptions:

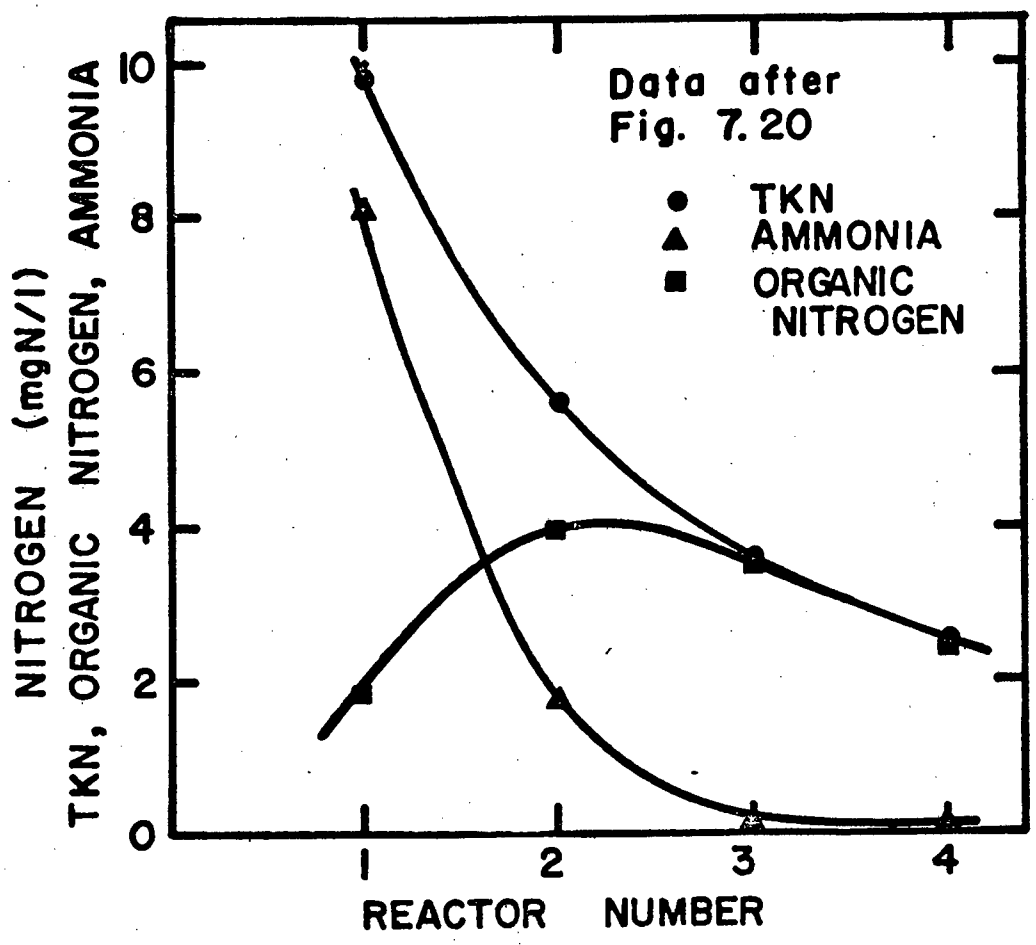


Fig. 2.6 *Free and saline ammonia and TKN concentrations observed in a series reactor pilot plant illustrating the changes in organic nitrogen through the process.* [*After Ekama and Marais (1978)*].

(i) nitrogen released by the lysis of dead cell material is split into two fractions: a fraction, f_{oe}, being organic nitrogen, the remaining fraction $(1 - f_{oe})$, being ammonia

(ii) nitrogen required for synthesis is also split into two fractions, an organic nitrogen fraction, f_{os}, and an ammonia fraction $(1 - f_{os})$

(iii) the active heterotrophic cell mass is capable of converting organic nitrogen to free and saline ammonia, at a rate fixed by the first order equation,

$$\frac{dN_o}{dt} = K_r N_o X_a \qquad (2.67)$$

where

K_r = specific conversion rate constant for organic nitrogen to ammonia (ℓ/mg VSS/day)

In checking these assumptions experimentally they found that the values of f_{oe}, f_{os} and K_r were compensating, i.e. if a value for one is adjusted to give a best fit with experimental data for chosen values of the other two, there is little difference in the general results for a variety of chosen values. For ease of modelling it was eventually decided to assume that nitrogen released after lysis of cell material is all in an organic form, and that heterotrophs can only utilize nitrogen in the form of ammonia, i.e. $f_{oe} = 1$ and $f_{os} = 0$.

They found that the maximum specific growth rate μ_{nm} and the saturation coefficient K_n were both effected by temperature and pH variations according to the following simplified forms of the Arrhenius equation

$$\mu_{nmT} = \mu_{nm20}(1{,}123)^{(T-20)} \qquad (2.68)$$

where

T = temperature in °C

μ_{nmT} = maximum specific growth rate at T°C (/d)

μ_{nm20} = maximum specific growth rate at base temperature 20°C (/d)

$$K_{nT} = K_{n20}(1,123)^{(T-20)} \qquad (2.69)$$

where

K_{nT} = saturation coefficient at T°C

K_{n20} = saturation coefficient at base temperature 20°C

In the pH range $5 < p < 7,2$

$$\mu_{nmp} = \mu_{nm7,2}(2,35)^{(p-7,2)} \qquad (2.70)$$

where

p = pH of mixed liquor

μ_{nmp} = maximum specific growth rate at a pH of p (/d)

$\mu_{nm7,2}$ = maximum specific growth rate at a base pH of 7,2 (/d)

and

$$K_{np} = K_{n20}(2,35)^{(p-7,2)} \qquad (2.71)$$

where

K_{np} = saturation coefficient at a pH of p

K_{n20} = saturation coefficient at a base pH of 7,2

Both the maximum specific growth rate and the saturation coefficient were found to remain approximately constant over the pH range $7,2 < p < 8,5$

Therefore, eq. (2.62) can be written in the form

$$\mu_{nTp} = \frac{\mu_{nm20}(2,35)^{(p-7,2)}(1,123)^{(T-20)}}{(K_{n20}(2,35)^{(7,2-p)}(1,123)^{(T-20)} + N_a)} \cdot N_a \qquad (2.72)$$

The yield coefficient, Y_n, and the endogenous respiration rate b_n of *nitrosomonas* were assumed to vary in the same way as those for heterotrophs, i.e.

$$b_{nT} = b_{n20}(1,029)^{T-20} \qquad (2.73)$$

where

b_{nT} = the endogenous respiration rate at temperature T°C (/day)

b_{n20} = the endogenous respiration rate at a base temperature 20°C (/day)

and Y_n is assumed to be insensitive to temperature changes.

In a paper on nitrification in the contact stabilization process, Gujer and Jenkins (1975) introduced the concept of the nitrification efficiency of the process. They defined it as

$$N_{nc}/N_{ns} = \eta_{ne} \qquad (2.74)$$

where

N_{nc}, N_{ns} = nitrate concentrations in the contact and stabilization reactors respectively (mg N/ℓ)

η_{ne} = experimental nitrification efficiency

Assuming that full nitrification takes place in the stabilization reactor, Eq. (2.74) gives a measure of the process nitrification when compared with full nitrification. Because the substrate is soluble and not adsorbed by the organisms the nitrification efficiency desired for the process is greatly effected by the design of the process; from Gujer and Jenkins (1975) it can be shown that η_{ne} is effected by the sludge age, R_s recycle ratio, r, fractional distribution

steady state response is not the best approach to use in testing a model. A full experimental investigation into the CSP would be extremely valuable in checking the general model of Ekama and Marais and any modifications to their model, in particular the bi-substrate modification discussed earlier.

The bi-substrate hypothesis has not been fully developed by Ekama and Marais. Consequently this hypothesis needs to be incorporated in the general and the CSP model. The data generated by Ekama and Marais can be used to calibrate the model and the data from the CSP can then be used to compare the predictive powers of the adsorption and bi-substrate hypotheses.

CHAPTER THREE

APPLICATION OF THE MODIFIED MARAIS-EKAMA MODEL TO THE CONTACT-STABILIZATION PROCESS

3.1 INTRODUCTION

As with all activated sludge processes, the kinetic equations that define the contact stabilization process (CSP) are functions of the daily COD load on the process, MS, the sludge age of the process, R_s, and the temperature, T, at which the process operates. However, due to the configuration of the process (shown in Fig. 1), two further parameters, namely the recycle ratio, r, and the fractional distribution of the total mass of volatile solids MX_{vp} between the contact and the stabilization reactor, α, have to be taken into account.

In order to develop process equations some estimate of MX_{vp} is required as a starting point. Gujer and Jenkins (1972) reported that the total mass of volatile solids produced by the CSP was very closely approximated by the mass produced by the completely mixed activated sludge process. During the course of this investigation it was confirmed that, for the same daily COD mass loading, MX_v calculated for a completely mixed process produced an approximation of MX_{vp} for the CSP which was sufficiently accurate to serve as a design starting point.

Once MX_{vp} is established, the overall process volume, V_p, can be found for a specified average process MLVSS concentration, X_{vp}, as follows:

$$V_p = \frac{MX_{vp}}{X_{vp}}$$

In the CSP, MX_{vp} is made up of the fractional masses in the contact

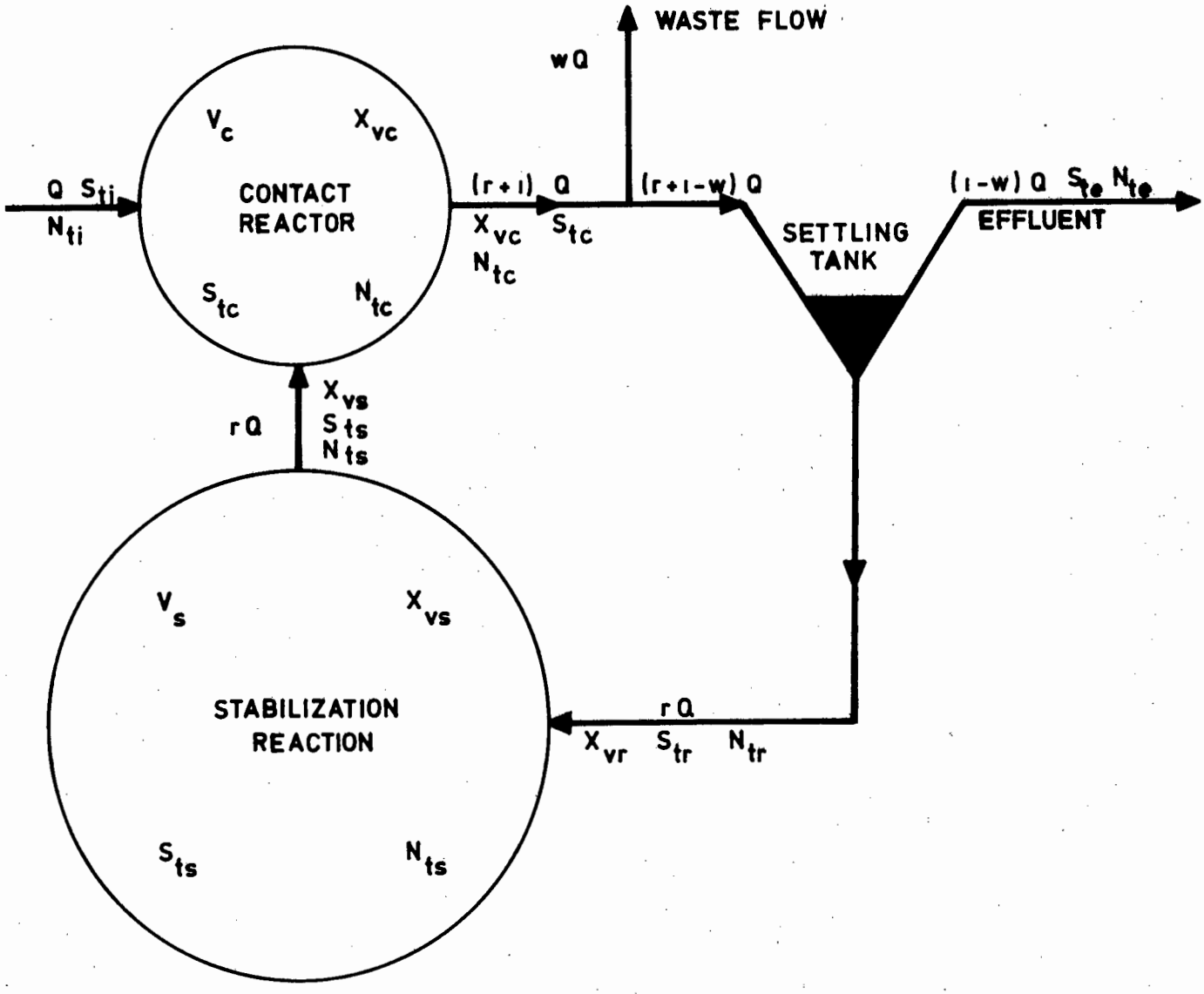


Fig. 3.1 *Diagrammatical layout of the contact stabilization process*

Q = Average Daily Flow (ℓ/d)

V = Volume

X_v = Volatile Sludge Concentration (mgVSS/ℓ)

w = Sludge waste flow ratio

r = Sludge Recycle Ratio

S_t = Total COD concentration (mg/ℓ)

N_t = Total TKN concentration (mg/ℓ)

The subscripts i, e, c, s, p and r refer to the influent and effluent flows, the contact and stabilization reactors, the overall process and the recycle flow respectively.

and stabilization reactors respectively, i.e.

$$X_{vp}V_p = X_{vc}V_c + X_{vs}V_s \tag{3.1}$$

and

$$V_p = V_c + V_s \tag{3.2}$$

where

V_c = volume of contact reactor (ℓ)

V_s = volume of stabilization reactor (ℓ)

X_{vc} = volatile solids concentration in contact reactor (mg VSS/ℓ)

X_{vs} = volatile solids concentration in stabilization reactor (mg VSS/ℓ)

Now a set of process equations can be established which will give V_c, V_s, X_{vc} and X_{vs} in terms of the specified parameters R_s, α, r and X_{vp} and the approximated process volume V_p. This will then define the process framework within which biological kinetic equations can be applied. As will be shown later in this chapter, to theoretically predict the response of a spatially varied process such as the CSP, a numerical step by step method has to be used to simultaneously integrate the biological differential equations in each reactor. The completely mixed activated sludge (CMAS) steady state and the CSP process equations provide a very useful set of variable values at which to start this integration.

3.2 DEVELOPMENT OF THE PROCESS EQUATIONS

With reference to Fig. 1, doing a mass balance around the settling tank on the total volatile solid concentration:

Mass of volatile solids flowing in = $(r + 1 - w)QX_{vc}$

Mass of volatile solids flowing out = rQX_{vr}

$\therefore \quad rQX_{vs} = (r + 1 - w)QX_{vc}$

$$\therefore \quad X_{vs} = \frac{(r + 1 - w)}{r} X_{vc} \tag{3.3}$$

The fractional mass distribution of sludge, α, is defined as

$$\alpha = \frac{X_{vc} V_c}{X_{vp} V_p} \tag{3.4}$$

The sludge age, R_s, is defined as

$$R_s = \frac{\text{mass of sludge in process}}{\text{mass of sludge wasted}}$$

$$= X_{vp} V_p / wQX_{vc} \tag{3.5}$$

Substituting Eq. (3.1) into Eq. (3.4)

$$\alpha = \frac{X_{vc} V_c}{X_{vc} V_c + X_{vs} V_s} \tag{3.6}$$

Substituting Eq. (3.3) into Eq. (3.6)

$$\alpha = \frac{X_{vc} V_c}{X_{vc} V_c + V_s X_{vc} (1 + r - w)/r}$$

$$= rV_c / [rV_c + V_s(1 + r - w)] \tag{3.7}$$

From Eq. (3.2)

$$V_c = V_p - V_s \tag{3.8}$$

Substituting Eq. (3.8) into Eq. (3.7)

$$\alpha = \frac{r(V_p - V_s)}{r(V_p - V_s) + V_s(1 + r - w)}$$

$$= \frac{r(V_p - V_s)}{rV_p + V_s(1 + r - w - r)}$$

$$= \frac{r(V_p - V_s)}{rV_p + V_s(1 - w)}$$

Solving for V_s

$$V_s = \frac{V_p r(1 - \alpha)}{\alpha + r - \alpha w} \tag{3.9}$$

Substituting Eq. (3.9) into Eq. (3.2)

$$V_c = V_p - \frac{V_p r(1 - \alpha)}{\alpha + r - \alpha w}$$

$$= \frac{V_p(\alpha + r - \alpha w) - V_p r(1 - \alpha)}{\alpha + r - \alpha w}$$

$$= V_p \alpha \frac{(1 + r - w)}{(\alpha + r - \alpha w)} \tag{3.10}$$

Substituting Eqs. (3.9 and 3.10) into Eq. (3.1)

$$X_{vp} V_p = X_{vc} V_p \frac{\alpha(1 + r - w)}{\alpha + r - \alpha w} + \frac{X_{vs} V_p r(1 - \alpha)}{\alpha + r - \alpha w}$$

$$\therefore \quad X_{vp} = \frac{X_{vc}\alpha(1 + r - w) + X_{vs} r(1 - \alpha)}{\alpha + r - \alpha w} \tag{3.11}$$

Substituting Eq. (3.3) into Eq. (3.11) and rearranging

$$X_{vc} = \frac{X_{vp}(\alpha + r - \alpha w)}{1 + r - w} \tag{3.12}$$

Substituing Eq. (3.12) into Eq. (3.3)

$$X_{vs} = \frac{X_{vp}(\alpha + r - \alpha w)}{r} \tag{3.13}$$

In the CMAS, the sludge wastage ratio w is a direct function of the sludge age, the process volume and the daily influent flow.

i.e. $R_s = \frac{V_p X_{vp}}{wQX_{vp}}$

so $w = \frac{V_p}{R_s Q}$

However, in the CSP, where the sludge is wasted from the contact reactor, the wasted sludge concentration X_{vc} differs from the process sludge concentration, and as a result w becomes a function of r and α in addition to R_s, V_p and Q. The expression for w in the CSP can be derived as follows

Substituting Eq. (3.1) into Eq. (3.5)

$$R_s = \frac{X_{vc}V_c + X_{vs}V_s}{wQX_{vc}} \tag{3.14}$$

Substituting Eq. (3.3) into Eq. (3.14)

$$R_s = \frac{X_{vc}V_c + X_{vc}V_s(1 + r - w)/r}{wQX_{vc}}$$

$$\therefore \quad w = \frac{V_c + V_s(1 + r - w)/r}{R_sQ} \tag{3.15}$$

Substituting Eqs. (3.9) and 3.10) into Eq. (3.15) and rearranging

$$w = \frac{V_p(1 + r - w)}{(\alpha + r - \alpha w)R_sQ} \tag{3.16}$$

Under operating conditions αw is normally small and can be ignored.

Therefore, solving for w in Eq. (3.16)

$$w = \frac{V_p(1 + r)}{R_sQ(\alpha + r) + V_p} \tag{3.17}$$

From the development above a process configuration is completely defined by the following set of equations:

$$V_p = V_c + V_s \tag{3.2}$$

$$w = (1 + r)/[1 + QR_s(\alpha + r)/V_p] \tag{3.17}$$

$$V_c = V_p\alpha(1 + r - w)/(\alpha + r - \alpha w) \tag{3.10}$$

$$V_s = V_p r(1 - \alpha)/(\alpha + r - \alpha w) \quad (3.9)$$

$$X_{vc} = X_{vp}(\alpha + r - \alpha w)/(1 + r - w) \quad (3.12)$$

$$X_{vs} = X_{vp}(\alpha + r - \alpha w)/r \quad (3.13)$$

The biological kinetic equations proposed by Ekama and Marais (1978) will now be modified to incorporate the bi-substrate hypothesis and then be applied to the CSP configuration in order to evaluate the biologically dependent variables.

3.3 DEVELOPMENT OF THE BIOLOGICAL KINETIC EQUATIONS

3.3.1 Kinetics of the Bi-substrate Hypothesis for Carbonaceous Degradation

3.3.1.1 Influent COD Fractions

With the introduction of the hypothesis that there is a soluble, readily assimilable fraction of COD in the influent, the fractional division of the influent proposed by Ekama and Marais (1978) has to be modified to incorporate this additional fraction. Hence the influent is assumed to be made up as follows:

$$S_{ti} = S_{bsi} + S_{bpi} + S_{ui} + S_{pi} \quad (3.18)$$

where

S_{ti} = total influent COD concentration (mg COD/ℓ)

S_{bsi} = soluble biodegradable influent COD concentration (mg COD/ℓ)

S_{bpi} = particulate biodegradable influent COD concentration (mg COD/ℓ)

S_{ui} = soluble unbiodegradable influent COD concentration (mg COD/ℓ)

S_{pi} = particulate unbiodegradable influent COD concentration (mg COD/ℓ)

and

$$S_{bi} = S_{bsi} + S_{bpi}$$

$$= S_{ti} - S_{ui} - S_{pi} \qquad (3.19)$$

where

S_{bi} = total biodegradable influent COD concentration (mg COD/ℓ)

For modelling purposes it is convenient to express S_{bsi} in terms of S_{bi} and S_{ui} and S_{pi} in terms of S_{ti}.

For unsettled sewage

$S_{bsi} = f_{bs} \cdot S_{bi}$ where $0,20 < f_{bs} < 0,25$

$S_{ui} = f_{us} \cdot S_{ti}$ where $0,05 < f_{us} < 0,12$

$S_{pi} = f_{up} \cdot P \cdot S_{ti}$ where $0,09 < f_{up} < 0,13$

For settled sewage

$S_{bsi} = f_{bs} \cdot S_{bi}$ where $0,20 < f_{bs} < 0,25$

$S_{ui} = f_{us} \cdot S_{ti}$ where $0,05 < f_{us} < 0,12$

$S_{pi} = f_{up} \cdot P \cdot S_{ti}$ where $0,00 < f_{up} < 0,05$

The particulate unbiodegradable COD of the influent may be expressed in terms of mg VSS/ℓ

$$X_{ii} = S_{pi}/P = f_{up} \cdot S_{ti} \quad (\text{mg VSS}/\ell) \qquad (3.20)$$

As pointed out by Ekama and Marais (1978) sewages vary greatly in nature, depending amongst other things on the proportion of industrial wastes present. The sewage from the Strandfontein sewer which was used in this investigation is an unsettled sewage and was found

to have the following characteristics:

$f_{bs} = 0,234$

$f_{us} = 0,10$

$f_{up} = 0,09$

3.3.1.2 Adsorption of Particulate Biodegradable COD

Although the adsorption of the particulate biodegradable COD is not considered to be an energy requiring process, it is still taken to be a biological process, and the Blackwell equation as modified by Ekama and Marais is accepted as suitable to describe the rate of adsorption, so

$$\frac{dS_{bp}}{dt} = - K_a X_a S_{bp} (f_{ma} - X_s/X_a) \qquad (3.21)$$

and the rate of increase of stored COD is given by

$$\frac{dX_{sg}}{dt} = K_a X_a S_{bp} (f_{ma} - X_s/X_a)/P \qquad (3.22)$$

Ekama and Marais found that K_a varies with temperature according to the following relationship:

$$K_{aT} = K_{a20}(1,03)^{(T-20)} \qquad (3.23)$$

where

K_{aT} = adsorption rate constant at T° C (ℓ/mg VSS/d)

K_{a20} = adsorption rate constant at 20°C.

3.3.1.3 Synthesis of Cell Mass

In terms of the bisubstrate theory, the synthesis reaction is made up of the sum of the two separate synthesis reactions. The first is the rapid, direct assimilation of the soluble COD by the active mass,

while the second is the slower process of assimilation of the stored particulate COD. No distinction is made in the model between types of organisms which utilize the two forms of substrate as it is assumed that the entire active mass can utilize both the particulate and soluble substrate and that the type of new cell mass synthesized does not depend on the form of substrate utilized. [This is justified from the findings of Blackwell (1971) and Jacquart, Lefort and Rovel (1973), who incorporated different transfer mechanisms into their models for the assimilation of soluble and particulate substrate by the same organisms].

For the soluble substrate that is directly utilized to generate active mass, the Monod type equation describes the growth rate:

$$\frac{dX_a}{dt} = \frac{Y_h K_{ms} S_{bs}}{K_{ss} + S_{bs}} \cdot X_a \qquad (3.24)$$

where

K_{ms} = maximum specific growth rate constant utilizing soluble substrate (mg VSS/mg COD/d)

and

K_{ss} = soluble substrate concentration at which the specific growth rate of the organisms is equal to half the maximum specific growth rate (mg COD/ℓ)

and the rate at which the soluble substrate is utilized is given by

$$\frac{dS_{bs}}{dt} = - \frac{K_{ms} S_{bs}}{K_{ss} + S_{bs}} \cdot X_a \qquad (3.25)$$

The oxygen consumption rate for synthesis of soluble substrate is given by

$$O_{ss} = (1 - PY_h) \frac{K_{ms} S_{bs}}{K_{ss} + S_{bs}} \cdot X_a \qquad (3.26)$$

For the synthesis of active mass utilizing the stored substrate, the

equation proposed by Ekama and Marais (1978) is used, i.e.

$$\frac{dX_a}{dt} = Y_h \cdot \frac{K_{mp} X_s P}{K_{sp} + X_s P} \cdot X_a \qquad (3.27)$$

where

K_{mp} = maximum specific growth rate constant utilizing particulate stored substrate mg VSS/mg COD/day

K_{sp} = particulate stored substrate concentration at which the specific growth rate of the organisms is equal to half the maximum specific growth rate (mg COD/ℓ)

and the rate at which the stored substrate is utilized is given by

$$\frac{dX_{s\ell}}{dt} = - \frac{K_{mp} X_s P}{K_{sp} + X_s P} X_a \qquad (3.28)$$

The oxygen consumption rate for the synthesis of stored particulate substrate is given by

$$O_{sp} = (1 - PY_h) \frac{K_{mp} X_s P}{(K_{sp} + X_s P)} \cdot X_a \qquad (3.29)$$

From Eqs. (3.24 and 3.27) the overall rate of synthesis of new cell material can be written as

$$\frac{dX_a}{dt} = Y_h \cdot \left(\frac{K_{ms} S_{bs}}{K_{ss} + S_{bs}} + \frac{K_{mp} X_s P}{K_{ms} + X_s P}\right) \cdot X_a \qquad (3.30)$$

and the associated total oxygen consumption rate for sy nthesis is given from Eqs. (3.26 and 3.29)

$$O_s = (1 - PY_h)\left(\frac{K_{ms} S_{bs}}{K_{ss} + S_{bs}} + \frac{K_{mp} X_s P}{K_{sp} + X_s P}\right) X_a \qquad (3.31)$$

The values of K_{ms} and K_{mp} vary with temperature according to the following equations (Marais and Ekama, 1976):

$$K_{msT} = K_{ms20}\ (1{,}200)^{T-20} \qquad (3.32)$$

where

K_{msT} = maximum specific growth rate constant utilizing soluble substrate at T°C

K_{ms20} = maximum specific growth rate constant utilizing particulate substrate at 20°C.

$$K_{mpT} = K_{mp20}(1{,}100)^{T-20} \qquad (3.33)$$

where

K_{mpT} = maximum specific growth rate constant utilizing particulate substrate at T°C

K_{mp20} = maximum specific growth rate constant utilizing soluble particulate at 20°C.

The yield factor Y_h and the saturation coefficients K_{ss} and K_{sp} appear to be virtually insensitive to temperature changes.

3.3.1.4 Endogenous Respiration

A large measure of uncertainty exists as to the exact mechanism of endogenous respiration. Ekama and Marais offer the two different approaches set out in Chapter 2. Because of the uncertainty as to the exact mechanism involved, the lead of Ekama and Marais has been followed here in employing the simpler of the two theories. This is the "black box approach" in which only the nett results are modelled and any intermediate steps are ignored. It is assumed that the biodegradable fraction of the sludge mass that disappears from the system is utilized for maintenance energy by the organism itself and therefore is directly equated to the oxygen consumption for endogenous respiration. The unbiodegradable fraction remains and accumulates in the process as endogenous residue.

If b_h is assumed to be the nett endogenous respiration rate constant per day for heterotrophic organisms, then

$$\frac{dX_{a\ell}}{dt} = - b_h X_a \quad (\text{mg VSS}/\ell/\text{d}) \tag{3.34}$$

where

$X_{a\ell}$ = active organisms lost due to endogenous respiration

and the unbiodegradable endogenous residue which accumulates is given by

$$\frac{dX_e}{dt} = f\, b_h X_a \quad (\text{mg VSS}/\ell/\text{d}) \tag{3.35}$$

where

f = the unbiodegradable fraction of the live mass which disappears during endogenous respiration.

The COD equivalent of the nett volatile mass that disappears from the system per day (mg VSS/ℓ/d) is equated to oxygen consumption for endogenous respiration, i.e.

$$O_e = P(1 - f) b_h X_a \quad (\text{mg O}/\ell/\text{d}) \tag{3.36}$$

The heterotrophic endogenous respiration rate varies with temperature according to the following equation (Marais and Ekama, 1976):

$$b_{hT} = b_{h20}\, (1{,}029)^{T-20} \tag{3.37}$$

where

b_{hT} = heterotrophic endogenous respiration rate at T°C (/d)

b_{h20} = the rate at 20°C (/d)

Equations (3.18) to (3.37) completely define the kinetics of the removal of the carbonaceous material in the activated sludge process.

3.3.2 Nitrification

In this investigation the nitrification model proposed by Ekama and Marais (1978) is accepted without modification. The kinetics of the process have been fully described in Chapter 2, hence only a summary of the pertinent equations will be given here.

The specific nett growth rate of *nitrosomonas* is given by:

$$\frac{dX_n}{dt} = \frac{\mu_{nm} N_a}{K_n + N_a} \cdot X_n - b_n X_n \qquad (3.38)$$

where

X_n = concentration of active *nitrosomonas* (mg VSS/ℓ)

μ_{nm} = maximum specific growth rate of *nitrosomonas* (/day)

N_a = concentration of ammonia (mg N/ℓ)

K_n = ammonia saturation coefficient (mg N/ℓ)

b_n = endogenous respiration rate of *nitrosomonas* (/day)

The rate of utilization of ammonia is related to the synthesis of *nitrosomonas*,

$$\frac{dN_a}{dt} = - \frac{(\mu_{nm}/Y_n) N_a}{K_n + N_a} \cdot X_n \qquad (3.39)$$

where Y_n = yield coefficient of *nitrosomonas* from ammonia utilized,

hence the rate of production of nitrates is given by:

$$\frac{dN_n}{dt} = + \frac{(\mu_{nm}/Y_n)N_a}{K_n + N_a} \cdot X_n \qquad (3.40)$$

where

N_n = nitrate concentration (mg N/ℓ)

The oxygen demand for nitrification is given as the stoichiometric equivalent of the oxidation of ammonia to nitrates, i.e.

$$O_n = 4,57 \frac{(\mu_{nm}/Y_n)N_a X_n}{K_n + N_a} \qquad (3.41)$$

where

O_n = oxygen demand for nitrification (mg O/ℓ/d)

Ekama and Marais define the rate at which the heterotrophic organisms convert organic nitrogen to ammonia as

$$\frac{dN_o}{dt} = - K_r N_o X_a \qquad (3.42)$$

where

K_r = the conversion rate of organic nitrogen to ammonia (ℓ/mg VSS/day)

The values of K_n, K_r and μ_{nm} vary with temperature and pH according to the following equations

$$K_{nTp} = K_n (2,35)^{7,2-p} (1,123)^{(T-20)} \qquad (3.43)$$

where

K_{nTp} = saturation coefficient at T°C and pH = p

K_n = saturation coefficient at 20°C and pH = 7,2

p = pH of mixed liquor if $5 < p < 7,2$

= 7,2 if $7,2 < p < 8,5$

$$K_{rT} = K_{r20}\ (1,029)^{T-20} \qquad (3.44)$$

where

K_{rT} = conversion rate of organic nitrogen to ammonia at T°C

K_{r20} = conversion rate at 20°C.

$$\mu_{nmTp} = \mu_{nm}\ (1,123)^{T-20}\ (2,350)^{p-7,2} \qquad (3.45)$$

where

μ_{nmTp} = specific growth rate at temperature T and pH = p

μ_{nm} = maximum specific growth rate at temperature 20° and pH = 7,2

p = pH of mixed liquor, if $5 < p < 7,2$

= 7,2 if $7,2 < p < 8,5$.

The endogenous respiration rate of the *nitrosomonas* varies with temperature as follows

$$b_{nT} = b_{n20}\ (1,029)^{T-20} \qquad (3.46)$$

where

b_{nT} = endogenous respiration rate at temperature T°C (/day)

b_{n20} = endogenous respiration rate at a base temperature 20°C (/day)

The endogenous respiration rate does not appear to be pH dependent.

The yield coefficient for *nitrosomonas* Y_n is assumed to be insensitive to changes in both temperature and pH.

3.3.3 Steady State Formulae of Biological Functions

Since the CSP is a space dependent dynamic process, the process kinetic equations have to be applied within each reactor in the process framework, and solved by means of step by step time incremental methods. To reduce the computation time involved in solving these equations the initially assumed values of the process variables must be as close to the final values as possible. It was found during the course of this investigation that the process variable response values of the CSP under time invariant input conditions can be approximated fairly accurately by accepting the steady state solutions provided by a completely mixed single reactor with a volume equal to V_p. From these process response values the initial approximations of the variable values in the two reactors and the recycle can be established [Eqs. (3.9), (3.10), (3.12) and (3.13)]. The initial values can be established from the steady state equations for the CMAS listed below (Marais and Ekama, 1976).

3.3.3.1 Steady State Biodegradation of Carbonaceous Material

The concentrations of soluble and particulate substrates in the process are given by the following equations: (The second subscript, p, indicates process)

$$S_{bsp} = \frac{1 + b_h R_s}{Y_h (K_{ms}/K_{ss}) R_s} \qquad (3.47)$$

and

$$S_{bpp} = \frac{1 + b_h R_s}{Y_h (K_{mp}/K_{sp}) R_s} \qquad (3.48)$$

and

$$S_{up} = S_{ui} \qquad (3.49)$$

The various components of the process volatile sludge concentration X_{vp} are given by

$$X_{ap} = \frac{Y_h (S_{bi} - S_{bp}) R_s Q}{(1 + b_h R_s) V_p} \qquad (3.50)$$

$$X_{ep} = 0{,}2\ b_h X_{ap} R_s \tag{3.51}$$

and

$$X_{ip} = \frac{S_{pi}}{P} \cdot \frac{R_s . Q}{V_p} \tag{3.52}$$

3.3.3.2 Steady State Nitrification

The process ammonia concentration is given by

$$N_{ap} = \frac{K_n(b_n + 1/R_s)}{\mu_{nm} - (b_h + 1/R_s)} \tag{3.53}$$

The organic nitrogen concentration is given by

$$N_{op} = \frac{N_{oi}}{(1 + K_r X_{ap} V_p/Q)} \tag{3.54}$$

The unbiodegradable TKN fraction is given by

$$N_{up} = N_{ui} \tag{3.55}$$

The concentration of nitrogen incorporated in the sludge mass is given by

$$N_{sp} = f_n \cdot \frac{X_{vp}}{R_s} \cdot \frac{V_p}{Q} \tag{3.56}$$

The process nitrate concentration is given by

$$N_{np} = N_{ti} - N_{ap} - N_{op} - N_{up} - N_{sp}$$

and finally, the concentration of *nitrosomonas* in the process is given by

$$X_{np} = \frac{Y_n . N_{np} . R_s \cdot Q}{(1 + b_n R_s) V_p} \tag{3.57}$$

3.4 APPLICATION OF THE BIOLOGICAL KINETICS TO THE CONTACT STABILIZATION PROCESS

The two reactors in the CSP are considered to be completely mixed. This implies that the influent is instantaneously and thoroughly mixed with the reactor contents, and the effluent flow has the same constitution as the reactor contents.

By considering mass balances of the different process variables around each of the reactors, including the settling tank, the differential equations for each variable in that reactor can be derived. The general mass balance equation applied to each reactor is

Rate of change of process variable =

\+ rate of mass input
\- rate of mass output
± rate of mass change due to process reaction (3.58)

The following symbols are used:

Q = influent flow vector (ℓ/d). The first subscripts c, s, r, e or w refer respectively to the contact or stabilization reactors, the recycle flow, the effluent flow or the waste flow. A further subscript t refers to the value at time t.

S = substrate concentration vector (mg COD/ℓ). The first subscript s, p, u or t refers to the soluble and particulate biodegradable, the unbiodegradable soluble, or total concentrations. The second subscripts i, c, s, r or w refer respectively to the influent, contact or stabilization reactors, recycle or waste concentrations. A further subscript t refers to the value at time t.

X = sludge concentration vector (mg VSS/ℓ). The first subscript a, s, e, i, n or v refers respectively to active, stored, endogenous, inert, *nitrosomonas* or total volatile concentration. The second subscript c, s, r or w refers respectively to the influent, contact or stabilization reactor or waste concentrations. A further subscript t refers to the values at time t.

N = nitrogen concentration vector (mg N/ℓ). The first subscript u, o, a, n or t refers respectively to soluble unbiodegradable, biodegradable organic, ammonia, nitrate or total Kjeldhal nitrogen concentrations. A second subscript c, s, r or w refers to the contact or stabilization reactor, recycle or waste values. A further subscript t refers to the value at time t.

V = volume vector (ℓ). Subscripts c, s or p refer respectively to the contact or stabilization reactor or the total process values.

3.4.1 The Contact Reactor

Utilizing Eq. (3.57), each process variable is traced through the reactor configuration as shown in Fig. 2.

1. Soluble biodegradable COD, S_s, in the reactor:

   Rate of change of soluble biodegradable COD =

   + rate of gain via influent flow
   + rate of gain via recycle flow
   - rate of loss via effluent flow
   - rate of loss due to synthesis of cell mass

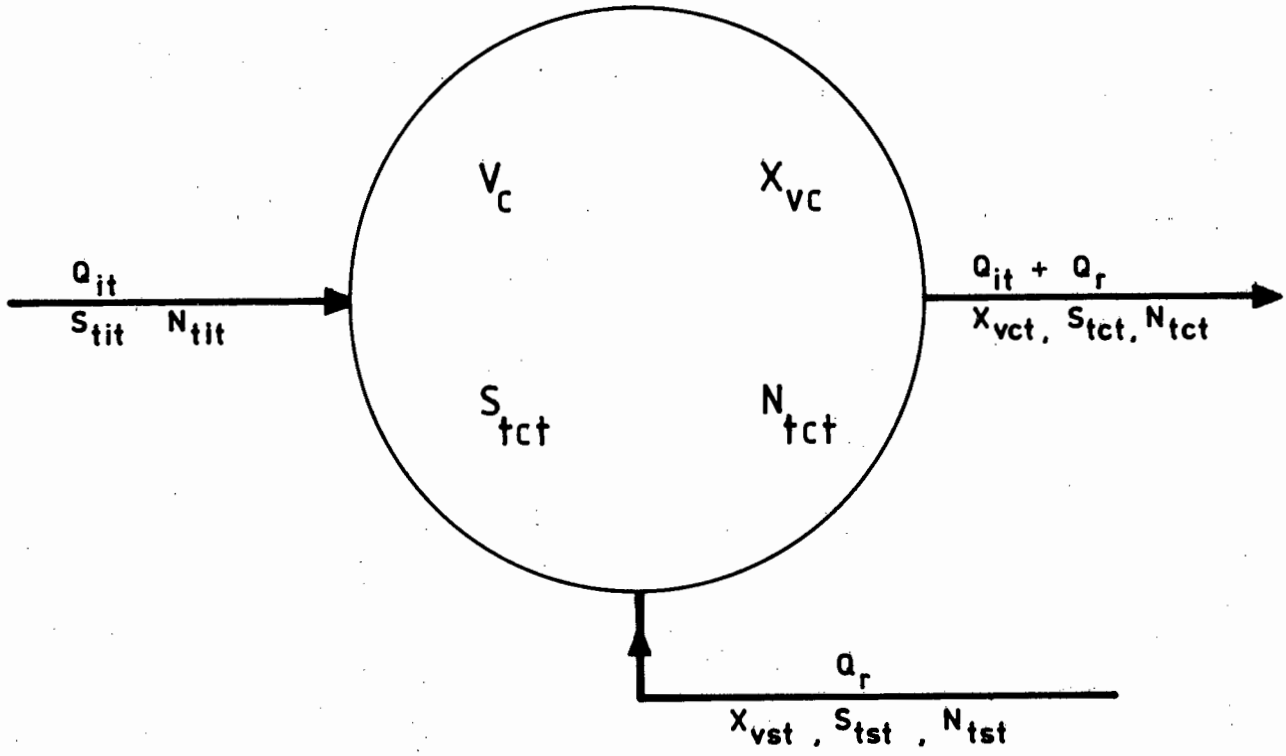


Fig. 3.2 *Process kinetics for the contact reactor*

$$dS_{sct}/dt = Q_{it}(S_{sit})/V_c + Q_r(S_{sst})/V_c - (Q_r + Q_{it})(S_{sct})/V_c - \frac{K_{ms}}{K_{ss}} \frac{S_{sct}}{S_{sct}} \cdot X_{act} \qquad (3.59)$$

2. Particulate biodegradable COD, S_p, in the reactor:

Rate of change of particulate biodegradable COD =

+ rate of gain via influent flow
+ rate of gain via recycle flow
- rate of loss via effluent flow
- rate of loss COD adsorption

$$dS_{pct}/dt = Q_{it}(S_{pit})/V_c + Q_r(S_{pst})/V_c - (Q_r + Q_{it})(S_{pct})/V_c - K_a X_{act} S_{pct}(f_{ma} - X_{sct}/X_{act}) \quad (3.60)$$

3. Soluble unbiodegradable COD, S_u, in the reactor:

Rate of change of unbiodegradable COD =

+ rate of gain via the influent flow
+ rate of gain via the recycle flow
- rate of loss via the effluent flow

$$dS_{uct}/dt = Q_{it}(S_{uit})/V_c + Q_r(S_{ust})/V_c - (Q_{it} + Q_r)S_{uct}/V_c \quad (3.61)$$

4. Active mass concentration, X_a, in the reactor:

Rate of change of active mass =

+ rate of gain via the recycle flow
+ rate of gain due to synthesis of soluble substrate
+ rate of gain due to synthesis of stored particulate substrate
- rate of loss due to endogenous respiration
- rate of loss due to effluent flow

$$\frac{dX_{act}}{dt} = \frac{Q_r}{V_c} X_{ast} + Y_h \cdot \frac{K_{ms} S_{sct}}{(K_{ss} + S_{sct})} \cdot X_{act} + Y_h \frac{K_{mp} X_{sct} P}{(K_{sp} + X_{sct} P)} \cdot X_{act} - b_h X_{act} - \frac{Q_{it} + Q_r}{V_c} X_{act} \quad (3.62)$$

5. Stored COD (as VSS) accumulated in the sludge X_{sct}:

Rate of change of stored COD =

+ rate of gain due to COD adsorption
- rate of loss due to synthesis of cell mass from stored COD
+ rate of gain via the recycle flow
- rate of loss via the effluent flow

$$\frac{dX_{sct}}{dt} = + K_a X_{act} S_{pct} (f_{ma} - X_{sct}/X_{act})/P$$

$$- \frac{K_{mp} X_{sct}}{(K_{sp} - X_{sct} P)} \cdot X_{act} + \frac{X_{sst} Q_r}{V_c} - \frac{Q_{it} + Q_r}{V_c} \cdot X_{sct} \qquad (3.63)$$

6. Endogenous residue, X_e, accumulating in the reactor as particulate inert material:

   Rate of change of endogenous residue =

   + rate of gain due to cell death
   + rate of gain via recycle flow
   - rate of loss via the effluent flow

$$\frac{dX_{ect}}{dt} = f\, b_h X_{act} + \frac{Q_r}{V_c} X_{est} - \frac{(Q_{it} + Q_r)}{V_c} X_{ect} \qquad (3.64)$$

7. Inert material, X_i, accumulating in the reactor through the inert solids in the influent:

   Rate of change of inert material =

   + rate of gain via the influent flow
   + rate of gain via the recycle flow
   - rate of loss viat the effluent flow

$$\frac{dX_{ict}}{dt} = \frac{Q_{it}}{V_c} X_{iit} + \frac{Q_r}{V_c} X_{ist} - \frac{Q_{it} + Q_r}{V_c} X_{ict} \qquad (3.65)$$

8. Total volatile solids, X_v, (MLVSS) in the reactor;

   Rate of change of total volatile solids =

   + rate of change of stored solids
   + rate of change of active soids
   + rate of change of endogenous residue
   + rate of change of inert solids

$$\frac{dX_{vct}}{dt} = \frac{dX_{act}}{dt} + \frac{dX_{sct}}{dt} + \frac{dX_{ect}}{dt} + \frac{dX_{ict}}{dt} \qquad (3.66)$$

9. Unbiodegradable organic nitrogen, N_u, in the reactor:

Rate of change of unbiodegradable nitrogen =

+ rate of gain via the influent flow
- rate of loss via the effluent flow
+ rate of gain via the recycle flow

$$\frac{dN_{uct}}{dt} = \frac{Q_{it}N_{uit}}{V_c} - \frac{(Q_{it} + Q_r)N_{uct}}{V_c} + \frac{Q_r N_{ust}}{V_c} \qquad (3.67)$$

10. Organic nitrogen concentration, N_o, in the reactor:

Rate of change of biodegradable organic nitrogen =

+ rate of gain via the influent flow
- rate of loss via the effluent flow
+ rate of gain from endogenous respiration
- rate of loss due to cell synthesis
+ rate of gain via the recycle flow
- rate of conversion to ammonia by heterotrophs
- rate of loss due to adsorption
+ rate of loss due to release from storage

$$\frac{dN_{oct}}{dt} = \frac{Q_{it}N_{oit}}{V_c} - \frac{(Q_{it} + Q_r)}{V_c} N_{oct} + f_{oe}f_n(1 - f)b_h X_{act}$$

$$- f_{os}f_n Y_h \left[\frac{K_{ms}S_{sct}}{(K_{ss} + S_{sct})} + \frac{K_{mp}X_{sct}P}{(K_{sp} + X_{sct}P)} \right] X_{act}$$

$$+ \frac{Q_r}{V_c} N_{ost} - K_r N_{oct} X_{act} - f_{ns}K_a X_{act} S_{bct} \left(f_{ma} - \frac{X_{sct}}{X_{act}} \right) \frac{1}{P}$$

$$+ f_{ns}Y_h \frac{K_{mp}X_{sct}P}{(K_{sp} + X_{sct}P)} X_{act} \qquad (3.68)$$

11. Ammonia concentration, N_a, in the reactor:

Rate of change of ammonia =

+ rate of gain via the influent flow

+ rate of gain from the conversion of biodegradable organic nitrogen

+ rate of gain from endogenous respiration

- rate of loss due to organism synthesis

- rate of loss via the effluent flow

+ rate of gain via the recycle flow

- rate of loss due to nitrification

$$\frac{dN_{act}}{dt} = \frac{Q_{it}N_{ait}}{V_c} + K_r N_{oct}X_{act} + (1 - f_{oe})f_n(1 - f)b_h X_{act}$$

$$- (1 - f_{os})f_n Y_h\left(\frac{K_{ms} S_{sct}}{K_{ms} + S_{sct}} + \frac{K_{mp} .X_{sct}.P}{K_{mp} + X_{sct}.P}\right)X_{act}$$

$$- \frac{(Q_{it} + Q_r)}{V_c} N_{act} + \frac{Q_r N_{ast}}{V_c} - \frac{(\mu_{nm} /Y_h)N_{act}}{K_n + N_{act}} . X_{nct} \qquad (3.69)$$

12. Active *nitrosomonas* concentration, X_n, in the reactor:

Rate of change of *nitrosomonas* concentration =

+ rate of gain via the recycle flow

- rate of loss via the effluent flow

+ rate of gain due to cell synthesis

- rate of loss due to endogenous respiration

$$\frac{dX_{nct}}{dt} = \frac{Q_r X_{nst}}{V_c} - \frac{Q_{it} + Q_r}{V_c} . X_{nct} + \frac{(\mu_{nm})N_{act}}{K_n + N_{act}} . X_{nct}$$

$$- b_{nT} X_{nct} \qquad (3.70)$$

13. Concentration of nitrate, N_n, in the reactor:

Rate of change of nitrate concentration =

+ rate of gain via the influent flow
+ rate of gain via the recycle flow
- rate of loss via the effluent flow
+ rate of gain due to nitrification

$$\frac{dN_{nct}}{dt} = \frac{Q_{it}N_{nit}}{V_c} + \frac{Q_r N_{nst}}{V_c} - \frac{Q_{it} + Q_r}{V_c} N_{nct} + \frac{(\mu_{nm} / Y_n)N_{act}}{K_n + N_{act}} \cdot X_{nct} \qquad (3.71)$$

14. Total unoxidised nitrogen in the reactor, which corresponds to the experimentally measured TKN concentration, is the arithmetic sum of changes in soluble unbiodegradable nitrogen, N_{uit}, organic nitrogen, N_{oct}, and ammonia, N_{act}, concentrations

$$\frac{dN_{tct}}{dt} = \frac{dN_{uct}}{dt} + \frac{dN_{oct}}{dt} + \frac{dN_{act}}{dt} \qquad (3.72)$$

15. The total unoxidised COD in the reactor, S_{tct}, is given by the sum of the soluble unbiodegradable COD, S_{uct}, and the remaining unutilized soluble and particulate biodegradable COD, S_{sct} and S_{pct}. However, the soluble and particulate variables are treated separately in the process as the former is able to leave the system in the effluent flow, whereas the latter is maintained in the process through entrapment in the floc, densification in the settler and recirculation with the return sludge.

16. The total oxygen demand, O_{tct}, in the reactor:

The total oxygen demand =

+ the energy lost during synthesis utilizing soluble substrate
+ the energy lost during synthesis utilizing particulate substrate
+ the energy lost during endogenous respiration
+ the energy loss during nitrification

$$O_{tct} = (1 - PY_h) \cdot \frac{K_{ms} S_{sct}}{K_{ss} + S_{sct}} \cdot X_{act} + (1 - PY_h) \frac{K_{mp} X_{sct} P}{K_{sp} + X_{sct} P} \cdot X_{act}$$

$$+ P(1 - f) b_h X_{act} + 4{,}57 \frac{(\mu_{nm}/Y_h) N_{act} \cdot X_{nct}}{K_n + N_{act}} \qquad (3.73)$$

3.4.2 The Settling Tank

In modelling the settling tank, the same simplifications made by Ekama and Marais are used. It is assumed that the settling tank acts purely as a separator of the sludge and the liquid. It is assumed to be 100% efficient with no sludge escaping over the weirs and also with no build-up of sludge in the settling tank. Further, it is assumed that there is no biological activity in the tank, so that the soluble biological parameters in the effluent flow and in the recycle flow to the stabilization reactor have the same value as that in the contact reactor. For these assumptions to approximate to reality, the retention time of the sludge in the settling tank must be kept to a minimum. This is achieved by having a high recycle value, which is acceptable in South Africa as the settlers tend to be used purely as solid/liquid separators, and not as sludge thickeners.

Furthermore, in South Africa a short retention time in the settler of a full scale plant is desirable for another reason. If this sludge is allowed to become anoxic, denitrification occurs. The

nitrogen bubbles thus formed cause partial flotation of the sludge in the settler. This effect will be particularly evident in the hot summer conditions under which plants have to operate in South Africa.

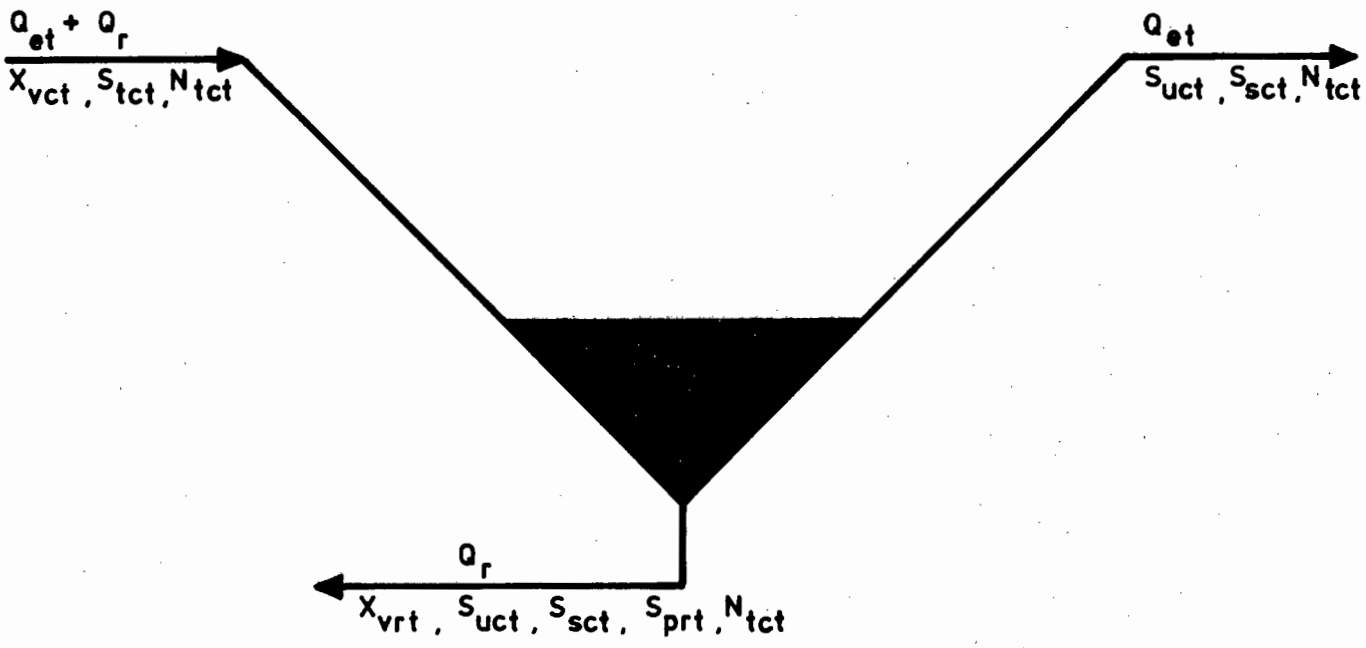


Fig. 3.3 *Process kinetics for the settling tank of a contact stabilization process.*

Referring to Fig. 3, doing mass balances on the solid fraction of the mixed liquor, for example the active mass, X_a, or the particulate biodegradable COD, S_p, yield:

$$X_{art} = \frac{(Q_{et} + Q_r)}{Q_r} \cdot X_{act} \tag{3.74}$$

$$S_{prt} = \frac{(Q_{et} + Q_r)}{Q_r} \cdot S_{pct} \tag{3.75}$$

Similarly a mass balance on the soluble fraction of the mixed liquor, for example the soluble biodegradable COD, S_s, and the ammonia, N_a, yields:

$$S_{srt} = \frac{(Q_{et} + Q_r)}{(Q_{et} + Q_r)} \cdot S_{sct} = S_{sct} \tag{3.76}$$

$$N_{art} = \frac{(Q_{et} + Q_r)}{(Q_{er} + Q_r)} \cdot N_{act} = N_{act} \tag{3.77}$$

i.e. there is no change in the concentration of soluble fractions in the settling tank

3.4.3 The Stabilization Reactor

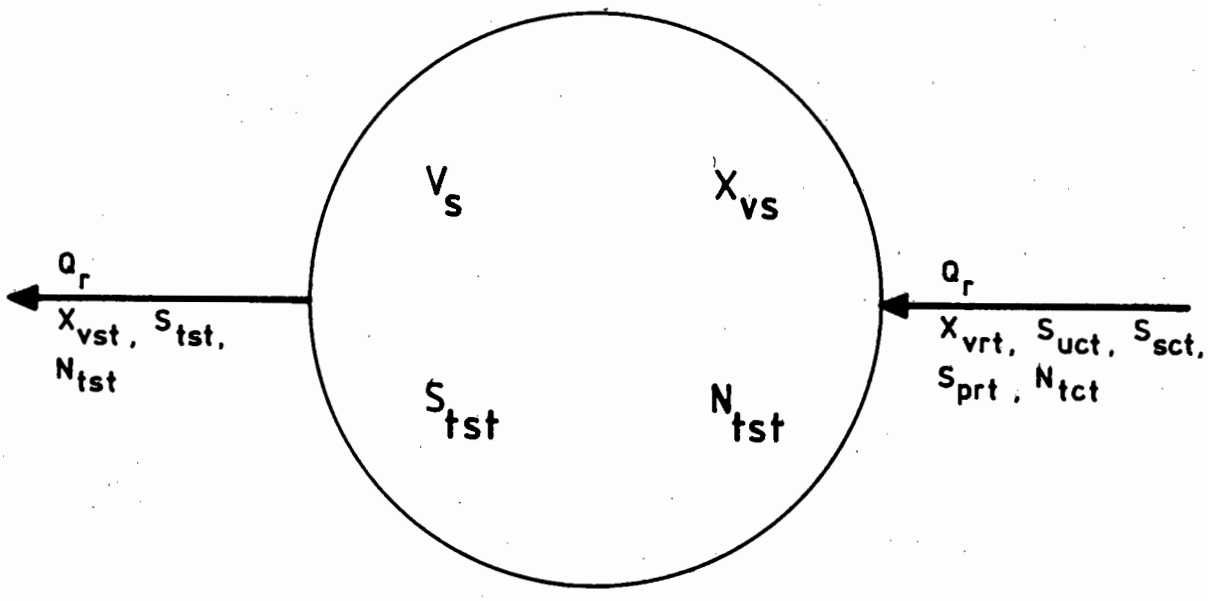


Fig. 3.4 *Process kinetics for the stabilization reactor.*

The set of process kinetic equations for the stabilization reactor can be drawn up in the same way as for the contact reactor using the mass balance Eq. (3.58), e.g. the differential equations for the soluble biodegradable COD, S_s, and the endogenous residue, X_e, in

the stabilization reactor are drawn up as follows:

Rate of change of soluble biodegradable COD in reactor =

+ rate of gain via influent flow
- rate of loss via effluent flow
- rate of cell synthesis utilizing soluble COD

$$\frac{dS_{sst}}{dt} = Q_r(S_{sct})/V_s - Q_r(S_{sst})/V_s - \frac{K_{ms}\ S_{sst}}{K_{ss} + S_{sst}} \cdot X_{ast} \qquad (3.78)$$

Rate of change of endogenous residue in reactor =

+ rate of gain via influent flow
- rate of loss via effluent flow
+ rate of gain due to cell death

$$\frac{dX_{est}}{dt} = \frac{Q_r}{V_s} X_{ert} - \frac{Q_r}{V_s} X_{est} + f\ b_h\ X_{ast} \qquad (3.79)$$

3.4.5 The Mathematical Model

The equations derived above constitute a set of twelve ordinary simultaneous differential equations with twelve unknowns for each reactor, i.e. S_s, S_p, S_u, X_a, X_e, X_i, X_s, X_n, N_u, N_a, N_o and N_n. The other variables, X_v, N_t, O_c, O_s, O_e, O_n and O_t are linear combinations of the above twelve dependent variables. The differential equations are first order and non-linear.

The nature of the CSP is such that a means of separating the sludge from the effluent must be incorporated into the model, so the settling tank kinetics, as developed above, must be taken into account.

The solution set of the CSP consists of a complementary function and a particular integral for each reactor in the system. The complementary function (cyclic response) about the particular integral (steady

state response) which develops in the contact reactor of the process serves as the influent forcing function into the settling tank and in turn determines the influent forcing function which is recycled into the stabilization reactor. The complementary function which develops in the stabilization reactor then defines the influent forcing function of the recycle back into the contact tank.

3.5 THE SOLUTION OF THE MATHEMATICAL MODEL

3.5.1 Method of Solution

The set of equations, derived above describing the CSP is solved numerically by a discrete finite difference step-by-step method.

Systems such as the CSP which consist of more than one reactor, operate under space varying as well as time varying conditions. These systems show a dynamic response even if the time forcing functions are constant because the process variables are subject to spatial variations. Although steady state conditions can exist in each reactor taken individually, due to the non-linearity of the equations defining the CSP in each tank, no explicit solutions are possible for the process as a whole. This applies even to time invariant inputs and solutions have to be obtained by numerical integration of the differential equations.

The cyclic time varying forcing functions result from daily cyclic loading conditions and discontinuous daily sludge wasting procedures. These conditions lead to a cyclic response and the solution of the equations is composed of both the particular integral (steady state) and the complementary function (variations about the steady state).

A finite time interval, Δt is selected and the equations written in discrete form with the following approximation

$$\frac{dS_{sct}}{dt} = \frac{S_{sc(t+1)} - S_{sct}}{\Delta t} \qquad (3.80)$$

This equation links the beginning and end of each interval. Solving for the end value

$$S_{sc(t+1)} = S_{sct} + \Delta t \, (dS_{sct}/dt) \qquad (3.81)$$

The values of each of the other process variables at time (t+1) are found in a similar fashion by using their respective discrete approximations of the differential equations

The full solution procedure is as follows:

1. The total daily COD and TKN mass loads are calculated by integrating the influent cyclic variation curves. The CMAS steady state equations (3.50) to 3.52) are then used to calculate MX_v. An average overall sludge concentration X_{vp} is then chosen and V_p is calculated. Using equations (3.9), (3.10), (3.11) and (3.12), the parameters V_c, V_s, X_{vc} and X_{vs} are calculated and these values are then assessed as to their practical suitability. If these are unsuitable, a new value of X_{vp} is chosen and the process is repeated until suitable values are arrived at.

2. Once V_c, V_s, X_{vc} and X_{vs} have been fixed, the steady state equations (3.47) to (3.49) and (3.53) to (3.57) can be used to establish the starting values of variables in the two reactors. The initial conditions for the recycle concentrations are calculated from the densification characteristics of the settling tank, using the steady state values as input.

3. From these assumed values of V_c and V_s and the initial variable values established, together with the cyclic influent inputs, the values of the process variables in the contact reactor are calculated at time (t+1) utilizing their discrete approximations of the differential equations, e.g. Eq. (3.81).

4. The values of process variables at (t+1) in turn serve as starting conditions to calculate the values at (t+2).

5. The solution of the set of equations (one for each unknown) is advanced step by step in this fashion over the whole day for the contact reactor.

6. Steps 3 to 5 are repeated, first for the settling tank and then for the stabilization reactor, noting that the cyclic responses in the contact reactor serve as the cyclic input for the settling tank and so on.

7. Steps 3 to 6 are repeated for a second day using the last value of the first day as initial conditions for the second day.

8. The value of certain process variables calculated at each time interval in each reactor for the first day are compared with the corresponding values calculated for the second day.

9. If the difference between any pair of values is greater than a certain pre-selected amount, the calculation procedure must continue for another day using the last values of the previous day as initial conditions.

10. Again a comparison is made between the latest values of the process variables and those calculated for the previous day.

11. This procedure, steps 8 to 10, is repeated until the selected process variables calculated for two consecutive days differ by less than the pre-selected amount. The system is then to be in a dynamic steady state.

It was found necessary to use different integration step lengths for the soluble and particulate carbonaceous material degradation kinetics and the nitrification kinetics. A value of six minutes for the integration of the particulate carbonaceous degradation kinetic equations yielded a stable response, whereas a step interval of two minutes was necessary for the integration of the soluble carbonaceous degradation kinetic equations and the nitrification kinetic

of soluble substrate and nitrification kinetic equations.

3. A simplistic model of the settling tank is included for solid-liquid separation.

4. The value of the convergence criterion is pre-selective. A large value will allow fewer iterations to convergence but the solution will be less accurate. A value of 0,1% is recommended as this value produces a fairly rapid but accurate solution. The number of iterations increases approximately exponentially as the convergence criteria are reduced. The UNIVAC 1106 takes approximately 0,5 secs. calculation time per reactor, per iteration.

5. For the time variant inputs, daily averages of the process variables are calculated for each of the reactors for direct comparison with the steady state process variable profiles through the system. The averages of these process variable profiles are also calculated for comparison with the equivalent steady state single reactor process.

6. The computer model for the time variant inputs can be used to calculate the process response for three different cases of input forcing waves:

   (a) A sinusoidal variation of input flow, COD concentration and TKN concentration given the average daily values and amplitudes of each.

   (b) An influent flow, COD and TKN concentration variation pattern observed at a particular site or plant, for which all the hourly values of the flow, COD and TKN concentrations have to be supplied. The values of the inputs required at each step interval are linearly interpolated from these hourly values. This input variation option allows for the solution of a particular design or existing plant. It

should be noted that the "dynamic steady state" solution is calculated, which assumes that the input loading patterns are repeated identically every day until the calculation converges.

(c) A square wave pattern for influent flow, with the COD and TKN concentrations kept constant. The square wave pattern may consist of a constant base flow with a constant peak flow of given length.

The plotting programme, utilizing the CALCOMP plotting package reads directly the theoretical response waves of the process variable calculated by the variant time programme and plots these response waves graphically. A similar plotting programme which also utilizes the CALCOMP plotting package, reads in the experimental response waves. The theoretically calculated and experimentally observed response waves are then plotted at the same scales so that a direct comparison may be made between theoretical and experimental behaviour.

Listings of the computer models and plotting routines are given in Appendix B.

CHAPTER FOUR

THE EXPERIMENTAL INVESTIGATION

4.1 INTRODUCTION

The main objectives of this laboratory scale experimental investigation was to (1) observe the biological response of the Contact Stabilization Process (CSP) to various input conditions and (2) compare the adsorption and substrate models with the experimental response to establish which of the two best described the behaviour of the CSP.

As established earlier, there are five major parameters which influence the response of the CSP, namely the daily COD load on the process, (MS), the sludge age of the process, (R_s), the temperature (T) at which the process operates, the sludge recycle rate, (r), and the fractional distribution of the sludge between the two reactors, (α). For this investigation it was decided that the recycle rate and the fractional distribution of the sludge would be kept constant, while the sludge age, the daily COD load pattern and the process temperature would be varied. The reason for maintaining r and α at constant values was that Gujer and Jenkins (1975) found that these two parameters had far less effect on the efficiency of process removal of carbonaceous material than the other three. Theoretically this observation is also consistent in terms of the substrate theory : Although r and α have a marked effect on the contact reactor hydraulic retention time, the particulate carbonaceous substrate, which forms the bulk of the influent COD, is either adsorbed by the organisms or enmeshed in the floc and in this form removed from the effluent in the settling tank. As these two processes are extremely rapid they are virtually independent of the hydraulic retention time in the contact reactor. With regard to the soluble COD fraction, the theoretical efficiency of its removal is affected by the length of the contact time because the assimilation of this substrate takes place at a fixed

rate. Even though the rate is relatively fast, it is not fast enough to remove all the soluble substrate in the contact time available, so the shorter the contact time the smaller the amount of soluble substrate concentration in the contact effluent. However as only about a quarter of the biodegradable COD is soluble, this does not have a very marked effect on the overall COD removal efficiency of the process.

In contrast, with regard to nitrification efficiency, the substrate is predominantly soluble and so very little TKN is removed by adsorption or enmeshment. Hence the nitrification efficiency in the CSP configuration is extremely sensitive to the α and r values chosen.

In this investigation it was decided that a vlue of $\alpha = 0{,}1$ should be used. With this value of α only one tenth of the sludge is responsible for the initial removal of the carbonaceous material from the influent. It represents, therefore, an extreme situation and constitutes a severe test of the predictive capacity of the model.

A very high recycle rate in the CSP process approximates a completely mixed system, which would tend to defeat the objective of this investigation. However, a low recycle rate results in a low process nitrification efficiency as a small fraction of the soluble TKN substrate is recycled into the stabilization reactor where the bulk of the nitrifying organisms are retained. With these two considerations in mind, a recycle rate of $r = 2$ was selected.

The investigation consisted of two parts :

(1) Time invariant flow and load conditions
(2) Cyclic flow and load conditions

(1) Time Invariant Flow and Load Conditions

Two laboratory scale units were run under time invariant load and flow conditions. The first unit was run at 20°C sequentially at sludge ages of 6 and 10 days. The second one was run at 12°C, at a sludge age

of 6 days, and tested for two conditions (a) with nitrification being allowed to take place and (b) with the nitrification being inhibited.

Time invariant conditions were tested first as this mode of operation does not include as many variables as the cyclic mode and the process is easier to monitor. The results would allow an initial assessment of whether the general activated sludge model can predict the CSP response without recalibration before the investigation was expanded to cover the more complex cyclic load and flow conditions. The time invariant mode would also provide data to check the models predictions of temperature effects.

(2) Cyclic Flow and Load Conditions

In the second part of this investigation a unit was run under daily cyclic sine and square wave time variant load and flow conditions at 20°C and a sludge age of 6 days. Cyclic flow conditions impose a most severe test on the model's predictive powers.

In order to obtain adequate results for predicting cyclic response, monitoring of the process is neccessary over continuous periods of about 36 hours, at hourly intervals. An appreciable number of response variables have to be measured during each cyclic test period. As this involves a considerable effort it was felt that if the model accurately predicted the response of the CSP at various sludge ages and temperature under steady flow and load conditions, and was found also to provide accurate predictions of the response under cyclic load and flow conditions at one sludge age, this would be sufficient proof of the generality of the model. To ensure that the tests undertaken provided a satisfactory and reliable set of data, three tests were undertaken at the selected sludge age of 6 days.

4.2 THE EXPERIMENTAL LABORATORY UNIT

Figure 4.1 shows the diagrammatical layout of the laboratory scale units used throughout the investigation. The influent was pumped from the daily feed container into the contact reactor by means of a peristaltic pump. The influent dropped into the reactor from above the liquid level, as shown, so that any leak in the feed tube of the pump would not result in the reactor being emptied of its contents

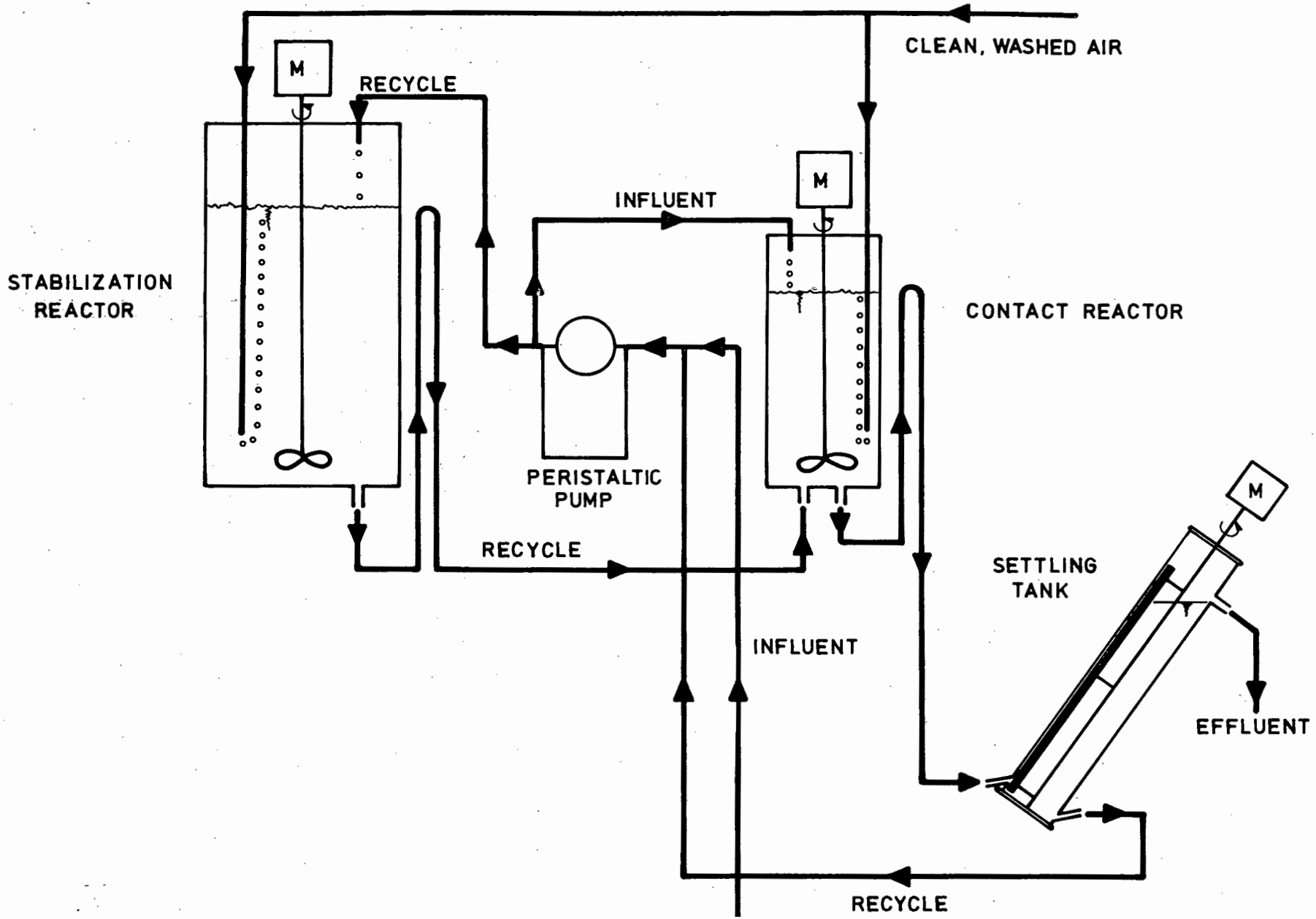


Fig. 4.1 *Diagrammatical layout of the contact stabilization process equipment used during the experimental investigation.*

by syphoning action. The outflow from the contact reactor was over an adjustable overflow weir and gravitated to the bottom of the settling tank. The overflow from the settling tank was collected in a bucket. The underflow from the settling tank was recycled by means of a peristaltic pump back to the stabilization reactor where it drip discharged into the top of the reactor. The overflow weir of the stabilization reactor was also of the adjustable kind, the flow gravitating to the bottom of the contact reactor.

The only deviation from this layout was the use of two settlers in parallel to cope with the increased flow during the cyclic loading tests. A brief description of each of the plant components is given below.

4.2.1. The Contact and Stabilization Reactors

The contact and stabilization reactors consisted of cylindrical perspex containers, 125 mm and 215 mm in diameter respectively. The liquour in the reactors was kept thoroughly mixed by a paddle set at the end of a shaft driven by an electric motor. The motor was mounted on a platform which covered approximately $^{2}/_{3}$ of the top of the reactors. The speed of the motor and the size of the paddle were adjusted by trial and error until complete mixing of the liquour was achieved, independent of the bubble aeration mixing effects, yet not causing too much turbulence at the surface. This aspect is extremely important, as during oxygen demand rate tests the paddle must keep the liquour thoroughly mixed with a minimum of surface turbulence to prevent a significant amount of oxygen entering the body of the liquid through the surface.

The mixed liquour in the reactors was kept aerated by the bubbling of clean, washed air, through a 3 mm diameter vertical perspex tube with a diffuser on the end. The supply of air was controlled by manually regulating a valve on the air supply to keep the dissolved oxygen level between 1,5 mg/ℓ and 3,5 mg/ℓ.

The overflow mechanism for the reactors was of the adjustable type shown

in Figure 4.2. This allowed for the accurate maintainance of the correct reactor volumes. As long as the connecting tubes were kept clear they gave very little trouble.

To prevent rotation of the liquour and to promote mixing, full length vertical baffles were glued to the inside of the reactors.

4.2.2. The Settling Tank

This consisted of an inclined perspex tube, 7,5 mm in diameter with a central electically driven shaft with a windscreen wiper attached to wipe the inside of the tube clean. The rate of rotation was 1 rev/1/2 minute, which is too fast for good settling. Consequently the electric motor driving this shaft was timed to run intermittentently for one revolution every 2 or 3 minutes. This prevented any accummulation of organisms on the surface of the tank, yet allowed the densification of the sludge at the bottom of the tank. The inlet to the tank is inclined upwards and the outlet is inclined downwards as shown in Figure 4.1 to prevent shortcircuiting of the flow. At the recycle rate of 2 : 1 utilized in this investifation the accummulation of sludge at the bottom of the tank was negligible. and the underflow sludge always remained aerobic.

4.2.3. The Daily Feed Container

This consisted of a rubberised dustbin with lid which had a capacity of approximately 72ℓ. The feed takeoff was ± 15 mm above the bottom of the container, and the feed was kept mixed by a motor driven paddle rotating just clear of the bottom at approximately 20 r.p.m.

Provision was made for the feed to be aerated by bubbling air through it in order to compensate for loss of dissolved oxygen in the flows when doing the oxygen demand tests in the contact reactor. The oxygenation of the influent was found to be of crucial importance to the measurement of O_2 demand of the process. The reason for this and the full test procedure are fully described in Section 4.3.1.

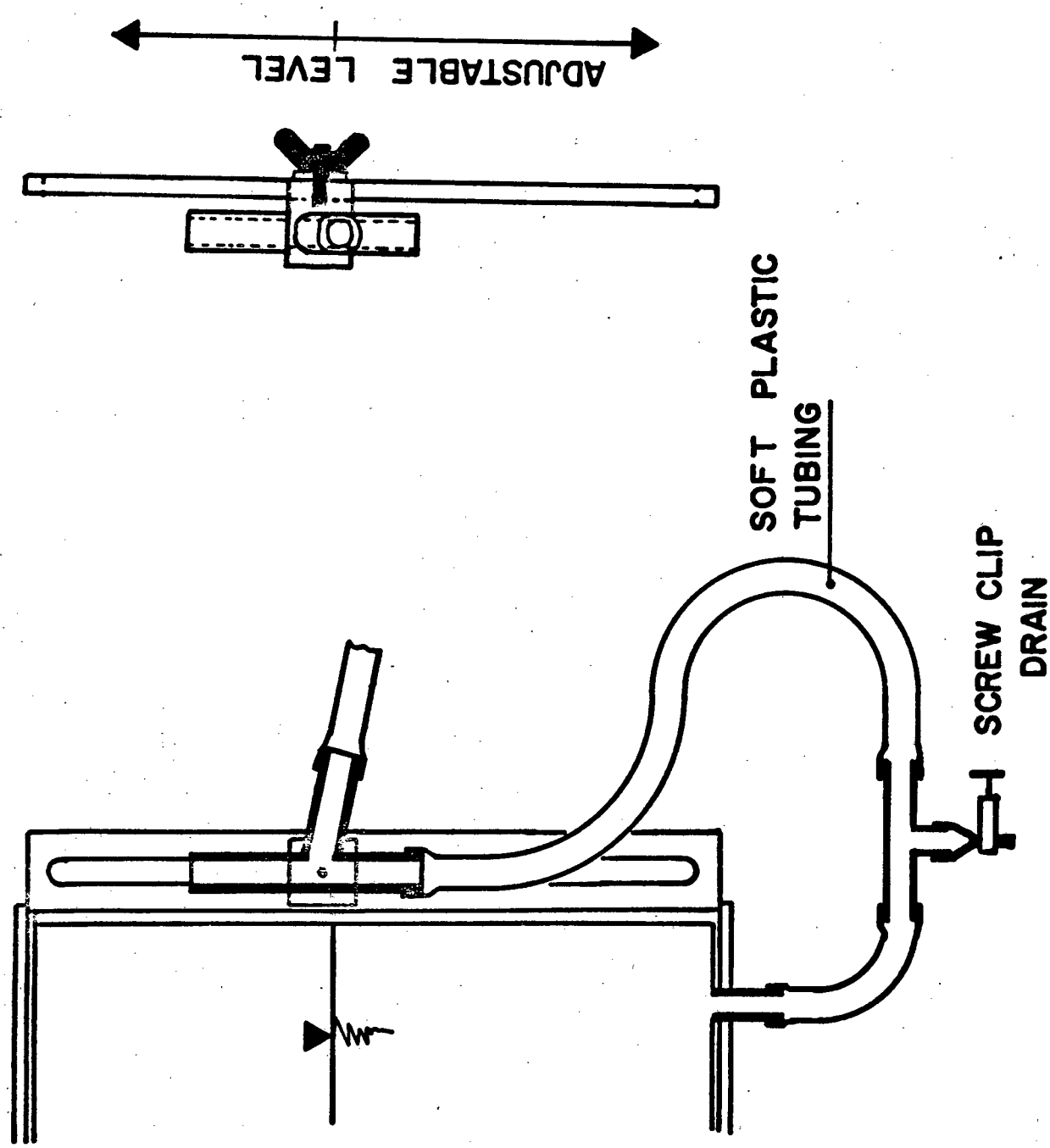


Fig. 4.2 *Detail of the overflow weirs used to control the level in the contact and stabilization reactors.*

4.2.4 Peristaltic Feed and Recycle Pump

The circular type of peristaltic pump with electronic speed control was used. The pump has rollers which can be adjusted for various types and sizes of feeding tube and room for 4 tubes. When the pump speed is adjusted to deliver through one feed tube at the rate necessary for the daily feed, a recycle rate of 2 : 1 can be achieved by using two feeding tubes (on the same pump) for the recycle flow.

4.2.5 Connecting Tubing

The connecting tubing was of soft, transparent plastic of varying diameters. The tubing has to be soft so that it can be cleared of any organism growth on the walls by simply squashing the tubing. The diameter of the tubing has an important bearing on the performance of the plant. Smaller diameter tubes were used when a high velocity was required to prevent the settling out of solids in the tube; also where blockages were unlikely to occur as in the case of the pumped feed and recycle lines. Larger diameter tubes are necessary in the gravity feed lines to the settler as blockages were likely to occur.

4.3 EXPERIMENTAL PROCEDURE

The units were mounted on vertical boards with each reactor placed on a support bolted into the board. The board was held vertical by a metal frame mounted on wheels so that the whole unit could be moved to any convenient location in the laboratory. A wide, shallow galvanised sheet metal tray was positioned under the entire unit in order to catch any spilled or leaked sludge. Should spillage occur it could be returned to the unit without causing any major disruption to the experiment.

The influent supply was collected in a 1 300ℓ tank on the back of a truck from the Strandfontein sewer at a point just before it enters the treatment ponds. The sewage was pumped from the sewer intermittently for short periods spanning about an hour. This was done to ensure that the sewage collected

was representative and not likely to contain a slug of any particular substance such as a toxin. The influent supply was then transported to the laboratory where it was pumped into three 450ℓ stainless steel storage vessels in a cold room. While pumping from the supply vehicle the tank contents were violently agitated by sparging with compressed air to keep the contents well mixed. The flow from the tank to the storage vessels was passed through a special fine macerator in order to prevent large particles in the sewage blocking the connecting tubes of the laboratory units. The cold room was kept at 4°C to inhibit any biological action which might have taken place during storage. Collecting the supply in this manner insured that a relatively constant feed of uniform sewage could be maintained for up to two weeks.

The daily feed was removed from the storage vessels by means of a tap at the bottom after the contents had been thoroughly mixed by means of a manual mixer. The measured amount of sewage was then diluted with tap water to achieve the desired COD concentration and passed through a sieve to remove any grit or fibrous material which could cause blockages in the units. The daily sewage feed was then placed in the feed container from where it was pumped into the unit. Because the influent was periodically aerated in the daily feed container, great care had to be taken that biological activity did not take place in the container. Consequently the influent was stored in an open refrigerator which maintained the temperature at approximately 9°C. Furthermore, the container and the influent feed line were scrubbed out with boiling water every two days, to prevent biological growth.

The Cape waters are very badly buffered, and consequently it was found that the nitrification caused a drop in pH which, in turn, inhibited the nitrification performance of the plant. To ensure that the pH remained above 7,2 , a stock supply of 72 gm/ℓ sodium bicarbonate buffer solution was made up and 150 mℓ added to each 36ℓ influent batch.

The sludge age was maintained hydraulically by means of a semi-continuous draw-off from the contact tank. A peristaltic pump

was connected to timing device which was set to run every half hour at high speed for a short period. This ensured that no solids settled out in the pipe, and that the concentration of the waste flow was the same as the concentration of the contact tank. The amount to be wasted daily was calculated using equation (3.17). After allowance had been made for the volumes wasted through sampling, the volume wasted each day was calculated to ensure a constant sludge age.

4.3.1 Test Methods

The tests to determine the concentrations of COD and TKN in the samples were performed in accordance with the procedures laid down in "Standard Methods for the Examination of Water and Wastewater", 13th Edition (1971), published by the American Public Health Association, AWWA and WPCF.

Nitrate and Nitrite concentrations in the samples were determined by the auto analyser automated method, in accordance with the Industrial Methods 33,68 and 35,69W testing procedures as laid out in Technicon Auto-Analyser Methodology.

The dissolved oxygen concentrations were measured by means of a Yellow Springs oxygen probe. The probe was calibrated daily as follows: The probe was immersed in a jar containing clean tap water. The contents were sparge aerated and well stirred until the dissolved oxygen concentration reached a constant level which was assumed to be the dissolved oxygen saturation concentration. After being zeroed, the meter was then calibrated to read the saturated oxygen level given in tables for the existing temperature and atmosphere pressure conditions.

With regard to the oxygen consumption rate test, initially it was done as follows: the dissolved oxygen concentration in the reactor to be tested was raised to about 8 mg/ℓ by sparging with an additional supply of clean air. Once the dissolved oxygen concentration had reached the required level all supplies of air to the reactor were cut off. While this reactor was still being fed and stirred the oxygen probe which was

connected to a Philips PM 8220 Pen Recorder, recorded the drop in the dissolved oxygen level for a period of about six minutes. The total oxygen consumption rate for the reactor was then given by the slope of the line (usually linear) of the dissolved oxygen concentration versus time plot on the recorder.

It was soon realised, however, that an imbalance in the oxygen concentration levels of the flows to and from the reactor during the test constituted a built-in"oxygen demand" for the reactor - effluent O_2 concentration was normally higher than influent concentration so that there is a net loss of O_2 mass from the reactor due to the difference in O_2 concentration between the influent and effluent flows. This caused an error in the measurement of the biological oxygen consumption rate which appeared to be particularly significant in the contact reactor. To form an estimate of the error and to devise remedial procedures it is necessary to investigate the problem theoretically - this is set out below.

The differential equation which describes the dissolved oxygen concentration in a well mixed flow reactor is:

$$V\frac{d}{dt} DO = Q(DO_{IN} - DO) - VB \qquad (4.1)$$

where

DO = the dissolved oxygen concentration (mg O_2/ℓ)

Q = total influent (and hence effluent) flow into the reactor

DO_{IN} = mean dissolved oxygen concentrations in the various influent flows (mg O_2/ℓ)

V = volume of the reactor (ℓ)

B = biological oxygen consumption rate mg/ℓ/hr.

If DO_{IN} and B are assumed to be constant during the course of the test, the solution to the above equation is:

$$DO = [DO_o - DO_{IN} + \frac{VR}{Q}]\, e^{-\frac{Qt}{V}} + DO_{IN} - \frac{VB}{Q} \qquad (4.2)$$

where

DO_o = dissolved oxygen concentration at time t=0 (mg O_2/ℓ)

Usually the hydraulic retention time of the reactor, V/Q, is long compared to the time Δt over which a test is done, so that the exponential term can be approximated with adequate accuracy by

$$e^{-\frac{Qt}{V}} = 1 - \frac{Qt}{V}$$

The error in this assumption is less than $1/2\ (\frac{Qt}{V})^2$

Combining Eqs. (4.1 and 4.2) yields:

$$DO = DO_o - (DO_o - DO_{IN} + \frac{VB}{Q})\frac{Qt}{V} \qquad (4.3)$$

The slope of the linear plot of DC versus time t is given by,

$$\text{slope} = -(D_o - DO_{IN} + \frac{VB}{Q})\frac{Q}{V} \qquad (4.4)$$

Solving for B,

$$-B = \text{slope} + \frac{Q}{V}(DO_o - DO_{IN}) \qquad (4.5)$$

If the measured slope is taken to give an estimate of the true biological O_2 demand, B, then from Eq. (4.5) the error introduced is

$$\text{Error} = \frac{Q}{V}\,(DO_o - DO_{IN}) \qquad (4.6)$$

The extent to which the biological oxygen consumption rate in the contact reactor can be over-estimated is illustrated by an example below:

Consider the situation illustrated in Fig. 4.3

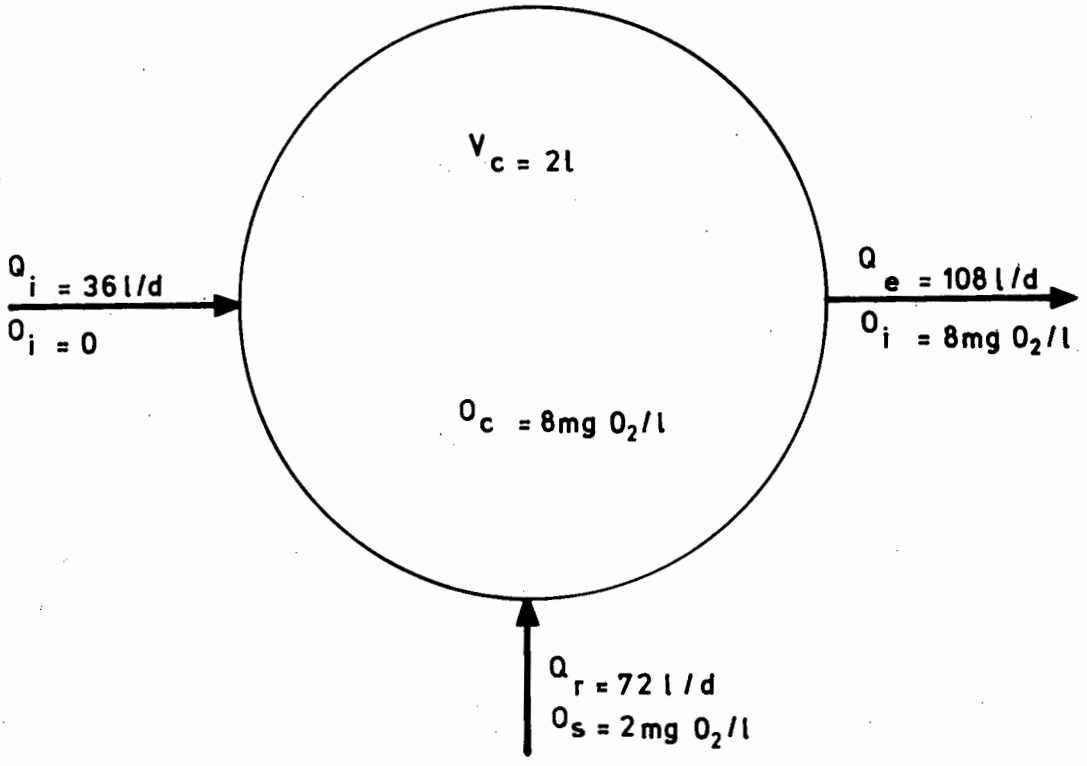


Fig. 4.3 *Oxygen mass balance in contact reactor.*

The contents of the reactor have been oxygenated so that the dissolved oxygen level in the reactor, (and hence in the effluent) is 8 mg O_2/ℓ. The influent flow has a zero dissolved oxygen level and the recycle flow has the same dissolved oxygen level as the stabilization reactor, say 2 mg O_2/ℓ. Therefore the mean dissolved oxygen concentrations in the various influent flows are given by:

$$DO_{IN} = \frac{Q_i \cdot O_i + Q_r \cdot Q_s}{Q(1 + r)}$$

$$= \frac{36 \cdot 0 + 72 \cdot 2}{108}$$

$$= 1{,}33 \text{ mg } O_2/\ell$$

The error term in the measurement is given by Eq. (4.6):

$$\text{Error} = \frac{108}{2}(8 - 1{,}33)$$

$$= 360 \text{ mg } O_2/\ell/\text{day}$$

$$= 15 \text{ mg } O_2/\ell/\text{hr}.$$

This constitutes a significant error.

Since the error term is inversely proportional to the hydraulic retention time of the reactor being measured, the example chosen constitutes an extreme case which is likely to occur only in the CSP. The stabilization reactor, which has a large V/R value typical of normal activated sludge reactors, is far less sensitive to this error, and under testing conditions similar to those described above it only would have been approximately 1,5 mg $O_2/\ell/$hr. which can be ignored.

Experimentally the following procedure was adopted to minimise this problem in the contact reactor. The influent and the contents of the stabilization reactor were aerated to a dissolved oxygen level equal to that in the contact reactor at the start of the test, i.e. $DO_{IN} = DO_o$, and maintained at this level for the duration of the test. Hence from Eq. (4.6) the theoretical error will be equal to zero.

4.3.2 Mass Balance in Experimental Data

The principles of conservation of energy and matter form an essential part in the analysis of activated sludge experimental data. If the data does not satisfy these two principles then the data must be considered to be unreliable and of dubious value for analysis purposes.

The two checks which are most easily carried out are

1. Nitrogen mass balance
2. COD mass balance.

4.3.2.1 Nitrogen mass balance

Nitrogen enters the system in the form of ammonia and organic compounds, and the mass entering is measured by means of the TKN test. If the system is nitrifying, most of the influent TKN is converted to nitrate and leaves the system in this form in the effluent. The nitrate mass thus leaving is measured by conducting nitrate concentration tests on the effluent. The remainder of the nitrogen is either unaffected and also leaves the system in the effluent where it's concentration is measured, or is incorporated into the sludge mass and leaves the system during the daily sludge wastage. The mass of nitrogen which is incorporated into the sludge was established by Ekama and Marais (1978) based on a large set of experiments and a survey of the literature. Consequently, the nitrogen mass balance of a set of data can be established by utilizing the principle of the conservation of mass, as follows:

$$Q\,N_{ti} = Q\,N_{te} + Q\,N_{ne} + f_n.X_{vc}.w.Q \qquad (4.7)$$

where

Q = daily influent flow (ℓ/day)

N_{ti} = Unfiltered total TKN concentration in influent (mg N/ℓ)

N_{te} = Unfiltered total TKN concentration in the effluent (mg N/ℓ)

N_{ne} = Nitrate concentration in effluent (mg N/ℓ)

f_n = Nitrogen fraction of the sludge
= 0,1 mg N/mg VSS

X_{vc} = MLVSS concentration in the wastage flow (mg VSS/ℓ)

w = Sludge wastage flow ratio.

4.3.2.2 COD mass balance

Energy enters the system in the form of the organic matter in the influent and is measured by the COD test. The soluble COD in the influent, both biodegradable and unbiodegradable, which leaves the system in it's

original form, does so in the effluent flow, where its concentration is measured by the COD test. The particulate unbiodegradable fraction in the influent is enmeshed in the sludge floc and leaves the system in the sludge wasted, together with any biodegradable particulate matter which has not been degraded.

The biodegradable COD fraction of the influent in both soluble and particulate form is the source of energy for biological metabolism. The fraction utilised as energy leaves the system in the form of heat and is measured by the mass of oxygen utilised. The balance of the biodegradable COD is incorporated in the sludge mass as active and endogenous organic mass and leaves the system in the waste sludge flow.

The COD equivalent (or energy potential) of the sludge wasted has been established by Ekama and Marais (1978) from an extensive experimental investigation. Knowing the various points and masses of COD leaving the system, as well as the oxygen consumption rate, a COD mass balance can be made by utilizing the principle of conservation of energy in the following form:

$$Q.S_{ti} = O_{cp}.V_p + P.X_{vc}.w.Q + Q.S_{te} \qquad (4.8)$$

where

S_{ti} = unfiltered total COD concentration in the influent (mg COD/ℓ)

O_{cp} = process carbonaceous oxygen consumption rate (mg O/ℓ/day)

V_p = process volume (ℓ)

P = COD equivalent of VSS
= 1,48 mg COD/mg VSS

S_{te} = unfiltered total COD concentration in the effluent (mg COD/ℓ)

In a nitrifying system, the measured oxygen consumption rate is the sum of the carbonaceous and nitrification oxygen demands. However,

the carbonaceous fraction may be calculated by deducting the nitrification component as follows:

$$O_{cp} = O_{tp} - 4{,}57 \cdot N_{ne} \cdot Q/V \qquad (4.9)$$

where

O_{tp} = total process oxygen consumption rate mg O/ℓ/day

4.3.3 Time Invariant Flow and Load Conditions

Time invariant flow and load conditions were established by feeding the unit a fixed daily quantity of influent with a fixed COD concentration at a constant rate over a whole day. The feed cycle was started at 11 am each day and sampling from the reactors and effluent for that cycle was done at approximately 9 am the following day so that the unit could adjust to the daily feed batch before samples were taken.

Daily samples of 100 mℓ were pipetted from each reactor. The sludge was densified in a centrifuge and the supernatant poured off and filtered through Watman's No. 1 filter paper. Mercuric chloride was then added to the supernatant sample to ensure that any remaining bacteria were killed so as to prevent any further biological action taking place. The densified sludge from the two samples was then used to perform VSS tests, while the filtered supernatant samples were tested for COD, TKN and nitrate concentrations. An unfiltered sample of the effluent, taken at the same time as the samples from the reactors was also tested for COD, TKN and nitrate concentrations, while an unfiltered sample of the influent, taken before the feed cycle commenced was tested to check the COD concentration and to determine the TKN concentration. The result of the COD test on the influent sample was always known before the next influent batch had to be prepared so that any necessary adjustment to the dilution proportions could be made. In this way it was possible to maintain the influent COD concentration at a relatively constant level. The difference between the COD and TKN concentrations in the contact reactor samples

and the effluent samples were a measure of the concentration of solids being lost over the weir of the settling tank. Three oxygen demand tests were performed daily in each reactor at 9 am, 12 noon and 5 pm, and the average of the values calculated for the day.

4.3.4 Cyclic Flow and Load Conditions

To achieve cyclic flow conditions the concentration of COD and TKN in the influent was maintained at constant values but the flow rate was varied cyclicly through the day, inducing a cyclic response from the unit. The only way that the responses could be delineated was to do tests at regular intervals over the whole 24 hour feed period.

The two loading patterns employed were:

(a) Sine wave flow pattern. This was achieved by using a specially designed peristaltic pump which has a rheostat driven by a built-in timer which produced an approximate sine wave flow pattern with an amplitude of approximately 0,8 times the average flow every 24 hours. Table 4.10 shows the flow measurement and testing pattern employed for this test.

(b) Square wave flow pattern. This consisted of a base flow continuous over 24 hours with a square wave superimposed of 12 hours duration and a total flow rate of three times the base flow. This flow pattern was achieved by splitting the influent feed line to two feed pumps, one of which operated continuously over the full 24 hour cyclé to provide the base flow, and the other set at the speed required to pump twice the base flow operated over a 12 hour period. Table 4.11 shows the testing pattern employed for this test.

Before the cyclic loading patterns were imposed on the unit it had been run under time invariant flow and load conditions until it displayed a constant response pattern for at least two sludge ages. The unit was then run under cyclic loading conditions for at least one sludge age (i.e. 6 days) before a 24 hour test was conducted. This procedure was followed to ensure that the unit was at a dynamic steady state at the

The process parameters were now calculated:

Assume $V_p = 14$

Because w is very small its value can be approximated by Eq. (3.17)

$$w = (1 + r)/[1 + QR_s(\alpha + r)/V_p]$$

$$= (1 + 2)/[1 + 36.6(0,1 + 2)/14]$$

$$= 0,08982$$

Let

$$V_c = 2\ \ell$$

From Eq. (3.10):

$$V_p = \frac{V_c(\alpha + r - \alpha w)}{\alpha(1 + r - w)}$$

$$= \frac{2(0,1 + 2 - 0,1 \cdot 0,08982)}{0,1(1 + 2 - 0,08982)}$$

$$= 14,3\ \ell$$

From Eq. (3.2):

$$V_s = V_p - V_c$$

$$= 14,3 - 2$$

$$= 12,3\ \ell$$

The true value of w for this experiment can be calculated now, using Eq. (3.17):

$$w = (1 + 2)/[1 + 36.6(0,1 + 2)/14,3]$$

$$= 0,09169$$

Checking the volumes using Eqs. (3.9 and 3.10):

$$V_s = V_p r(1 - \alpha)/(\alpha + r - \alpha w)$$

$$= 14{,}3 \;.\; 2(1 - 0{,}1)/(0{,}1 + 2 - 0{,}1 \;.\; 0{,}09169)$$

$$= 12{,}31 \; \ell$$

$$V_c = V_p \alpha(1 + r - w)/(\alpha + r - \alpha w)$$

$$= 14{,}3 \;.\; 0{,}1(1 + 2 - 0{,}09169)/(0{,}1 + r - 0{,}1 \;.\; 0{,}09169)$$

$$= 1{,}989$$

$$\doteq 2 \; \ell$$

The independent process design parameters for the unit are given in Table 4.1, and the process parameters defining the configuration of the unit are given in Table 4.2. A summary of the tests performed daily on the unit is given in Table 4.3.

Once the daily tests indicated that the unit had reached a dynamic steady state, it was run for a further 23 days, or approximately 4 sludge ages. Plots of the results are given in Figs. 4.4 to 4.7 inclusive and the results are tabulated in Appendix A.1. The mean values of these daily process variable tests were calculated and are given in Table 4.4.

A nitrogen and COD mass balance check was done on the experimental data in accordance with Eqs. (4.7 and 4.8). The balance accounted for 94% of the influent nitrogen and 96% of the influent COD; these percentages were considered to be well within scope of allowable experimental error. Using Eq. (3.4), the experimental value of α is 0,107 whereas the design value is 0,100.

As a result of the checks performed above, the experimental data were considered to be sufficiently accurate to be used for theoretical analysis. This is carried out in Section 4.5.2.1.

Table 4.2

Independent Process Design Parameters for the Laboratory Scale Contact-Stabilization Unit run at 20°C and 6 day sludge age.

Parameter	Value
Sewage	Unsettled
Sludge age, R_s(d)	6,0
Recycle ratio, s	2,0
Fractional distribution of sludge in process, α	0,10
Temperature °C	20
Volume of process, V_p (ℓ)	14,3
Influent flow, Q, (ℓ/d)	36,0

Table 4.2

Process Parameters giving the Configuration of the Laboratory Scale Contact-Stabilization Unit run at 20°C and 6 day sludge age.

Parameter		Value
Waste flow ratio, w		0,092
Volumes (ℓ)		
Contact Reactor		2,0
Stabilization Reactor		12,3
Hydraulic Retention Time (hrs)		
Actual:	Contact Reactor	0,42
	Stabilization Reactor	4,07
Nominal:	Contact Reactor	1,31
	Stabilization Reactor	4,07

Table 4.3

Process Variables Measured on Experimental Contact-Stabilization Unit during time invariant tests.

Variable	Influent	Contact Reactor	Effluent	Stabilization Reactor
COD	*	x	*	x
TKN	*	x	*	x
MLVSS		x		x
NO_3,NO_2		x	x	x
O_t †		x		x

† Oxygen consumption rate

* Analysis conducted on unfiltered samples

x Analysis conducted on filtered samples

Table 4.4

Mean Values of Process Variables Observed during time invariant tests at 20°C and 6 days sludge age over a Period of 4 Sludge Ages.

Variable	Influent	Contact Reactor	Effluent	Stabilization Reactor
COD (mg COD/ℓ)	512	62	90	54
TKN (mg N/ℓ)	56	11	15	2
MLVSS (mg VSS/ℓ)	-	1301	-	1772
NO_3 + NO_2	<0,1	27	26	36
O_t †		61	-	32

† Oxygen consumption rate

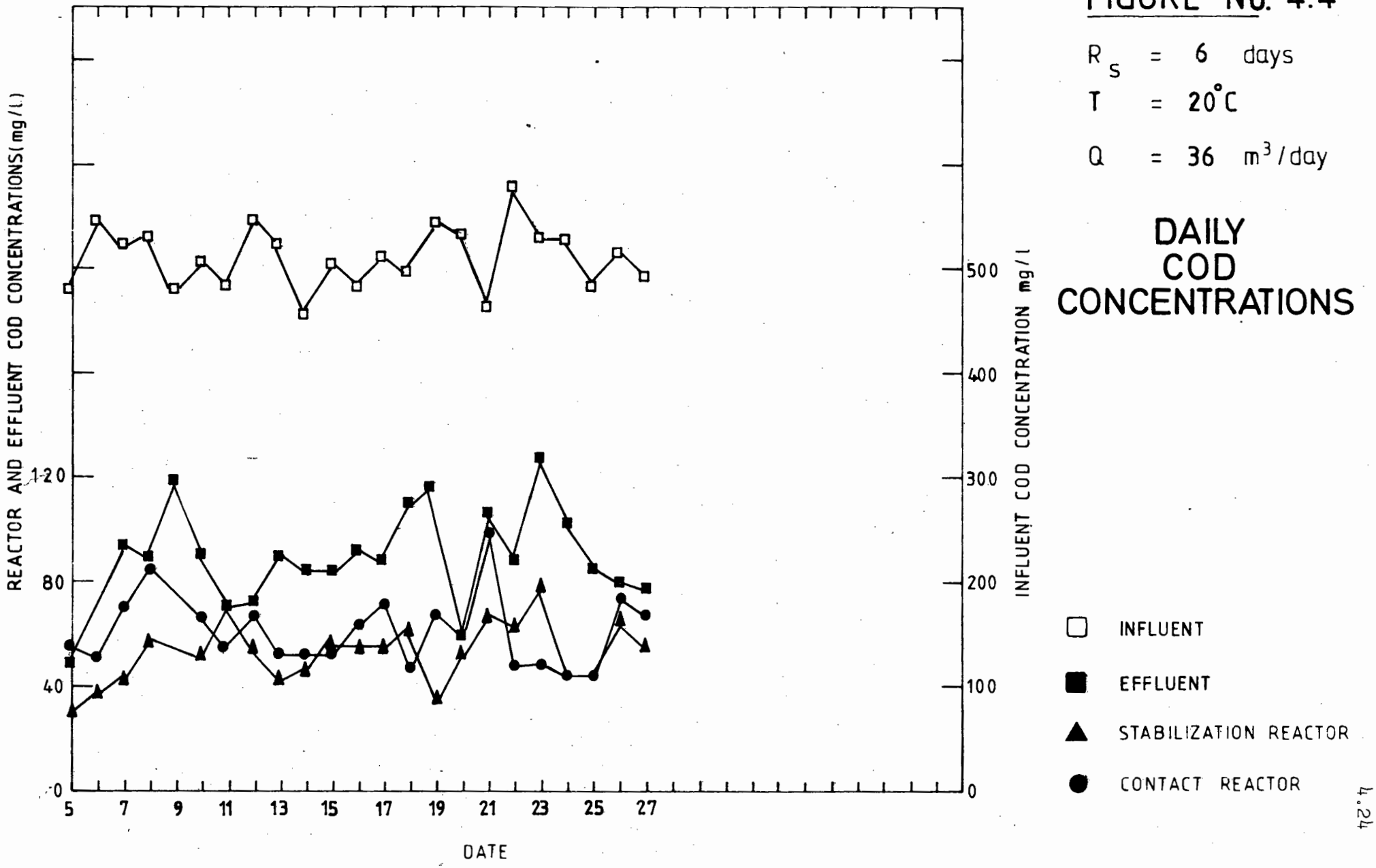
FIGURE No. 4.4

R_s = 6 days

T = 20°C

Q = 36 m^3/day

DAILY COD CONCENTRATIONS



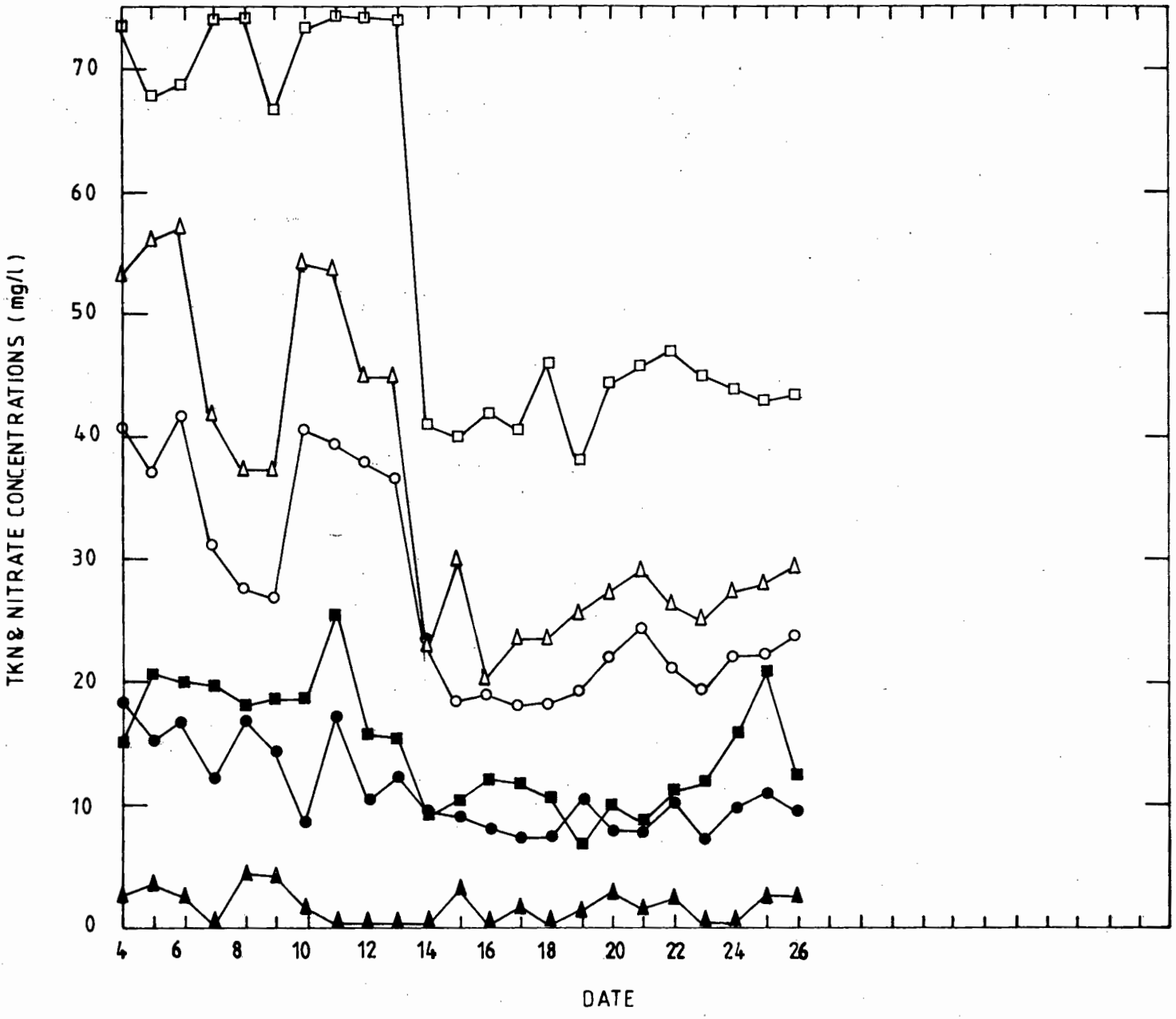


FIGURE No. 4.5

R_s = 6 days

T = 20°C

Q = 36 m^3/day

DAILY TKN & NITRATE CONCENTRATIONS

NITRATE

△ STABILIZATION REACTOR

○ CONTACT REACTOR

TKN

□ INFLUENT

■ EFFLUENT

▲ STABILIZATION REACTOR

● CONTACT REACTOR

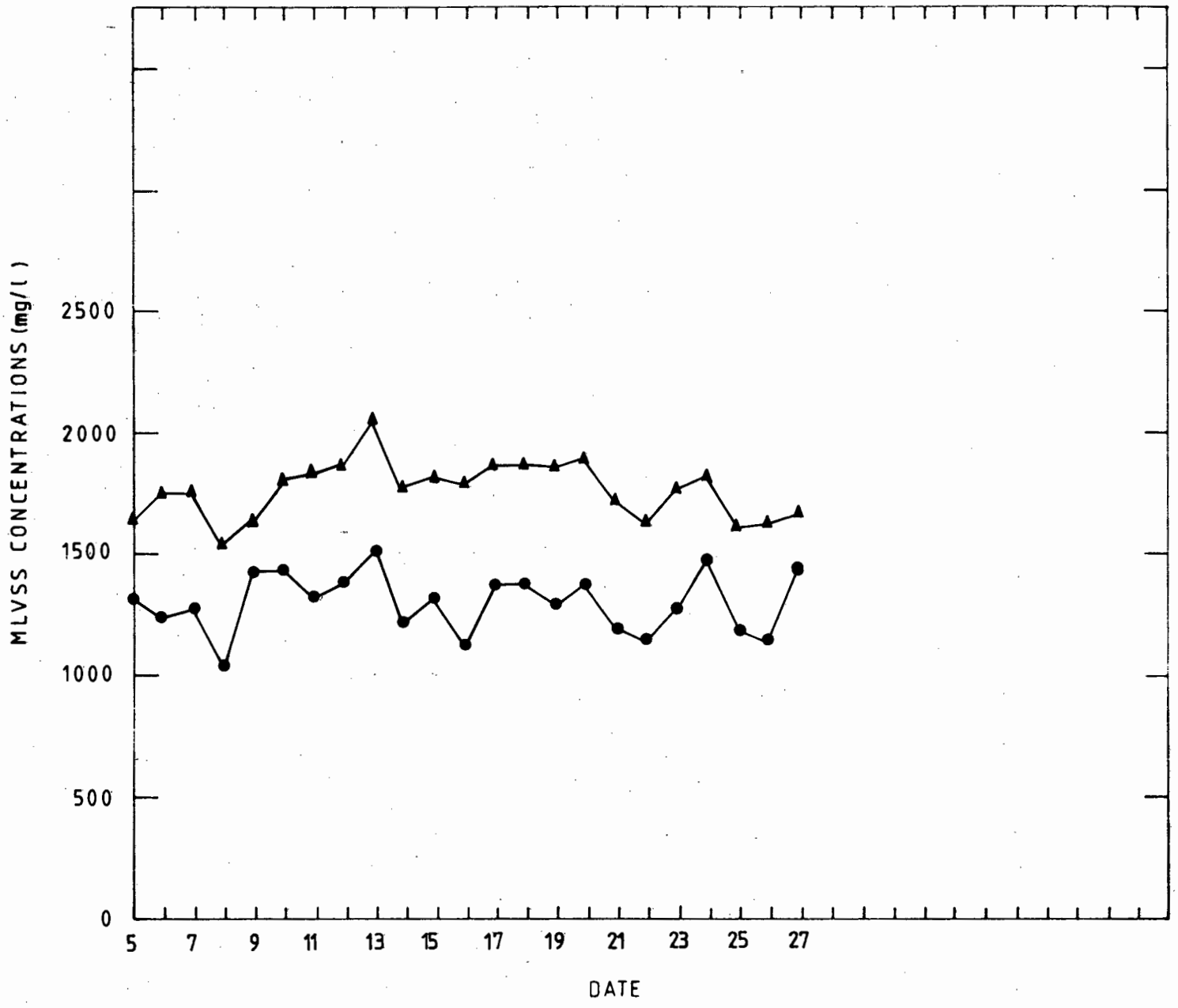
FIGURE No. 4.6

R_s = 6 days

T = 20°C

Q = 36 m^3/day

DAILY MLVSS CONCENTRATIONS



▲ STABILIZATION REACTOR

● CONTACT REACTOR

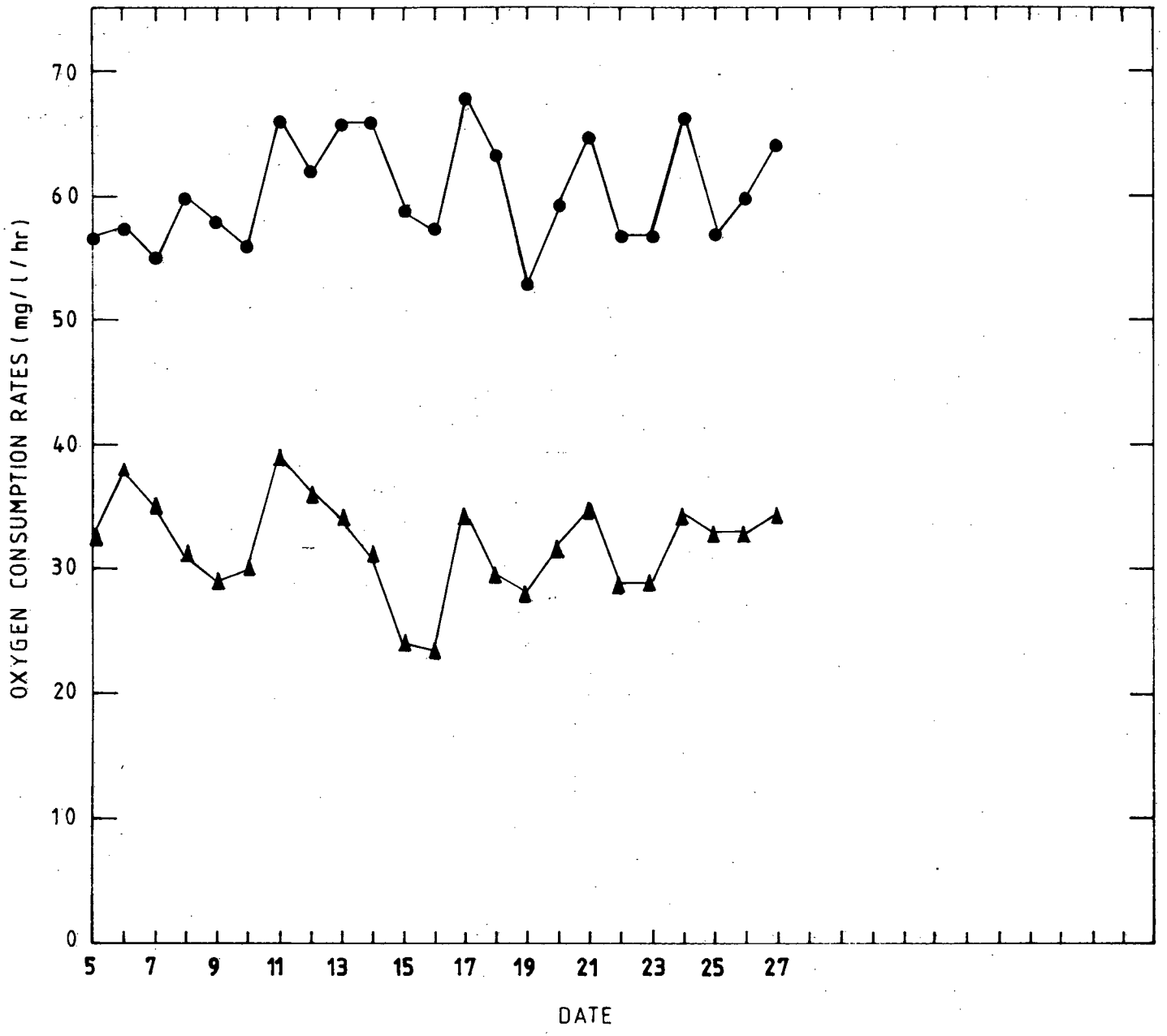


FIGURE No. 4.7

R_s = 6 days

T = 20°C

Q = 36 m^3/day

DAILY OXYGEN CONSUMPTION RATES

▲ STABILIZATION REACTOR

● CONTACT REACTOR

4.4.1.2 Unit run at 20°C and 10 days sludge age

After the completion of the 6 day sludge age test the running procedure of the unit was adapted to a 10 day sludge age. It was estimated that an influent of

$Q = 24$ ℓ/day

with a COD concentration of

$S_{ti} = 500$ mg/ℓ

would result in a similar X_{vp} to that obtained in the previous test. The independent process design parameters for this test are given in Table 4.5. These were used to calculate the process parameters for the unit as before, and the results are given in Table 4.6

Once a dynamic steady state had been achieved, the unit was monitored for 25 days or 2 1/2 sludge ages in accordance with the daily test pattern set out in Table 4.3. The daily results are shown plotted in Figs. 4.8 to 4.11 inclusive and tabulated in Appendix A.2. The mean values of these daily process variable tests were calculated and are given in Table 4.7.

As before, the nitrogen and COD mass balances were checked in accordance with Eqs. (4.7 and 4.8). The balance showed a nitrogen and COD recovery of 96% and 97% respectively, which is within the limits of reliability of the test cum process and considered highly satisfactory. The data gives a value for $\alpha = 0{,}104$ (theoretically $\alpha = 0{,}10$) which is also considered to be satisfactory for analysis purposes. This data is analysed in Section 4.5.2.2.

4.4.1.3 Unit run at 12°C and 6 days sludge age

Shortly after the establishment of the first unit, a second, identical unit was started up in a cold room, at a constant temperature of 12°C. The design parameters were the same as those given in Table 4.1, except

Table 4.5

Independent Process Design Parameters for the Laboratory Scale Contact-Stabilization Unit run at 20°C and 10 days sludge age.

Parameter	Value
Sewage	Unsettled
Sludge age, R_s(d)	10,0
Recycle ratio, s	2,0
Fractional distribution of sludge in in process, α	0,10
Temperature °C	20
Volume of process, V_p(ℓ)	14,3
Influent flow, Q, (ℓ/d)	24,0

Table 4.6

Process Parameters giving the Configuration of the Laboratory Scale Contact-Stabilization Unit run at 20°C and 10 days sludge age.

Parameter		Value
Waste flow ratio, w		0,083
Volume (ℓ)		
	Contact Reactor	2,0
	Stabilization Reactor	12,3
Hydraulic Retention Time (hrs)		
Actual:	Contact Reactor	0,66
	Stabilization Reactor	6,27
Nominal:	Contact Reactor	1,98
	Stabilization Reactor	6,27

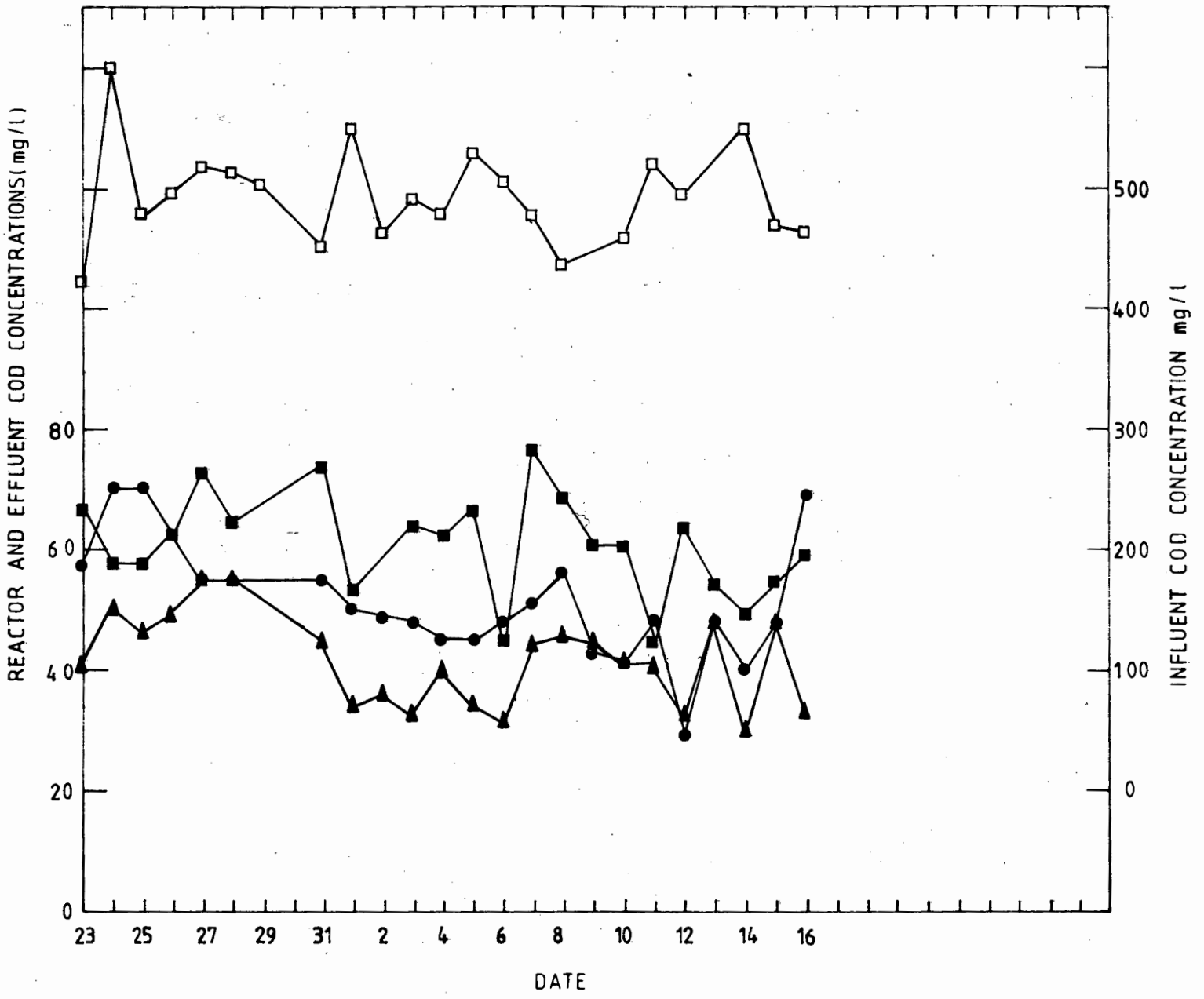
FIGURE No. 4.8

R_s = 10 days

T = 20°C

Q = 24 m^3/day

DAILY COD CONCENTRATIONS



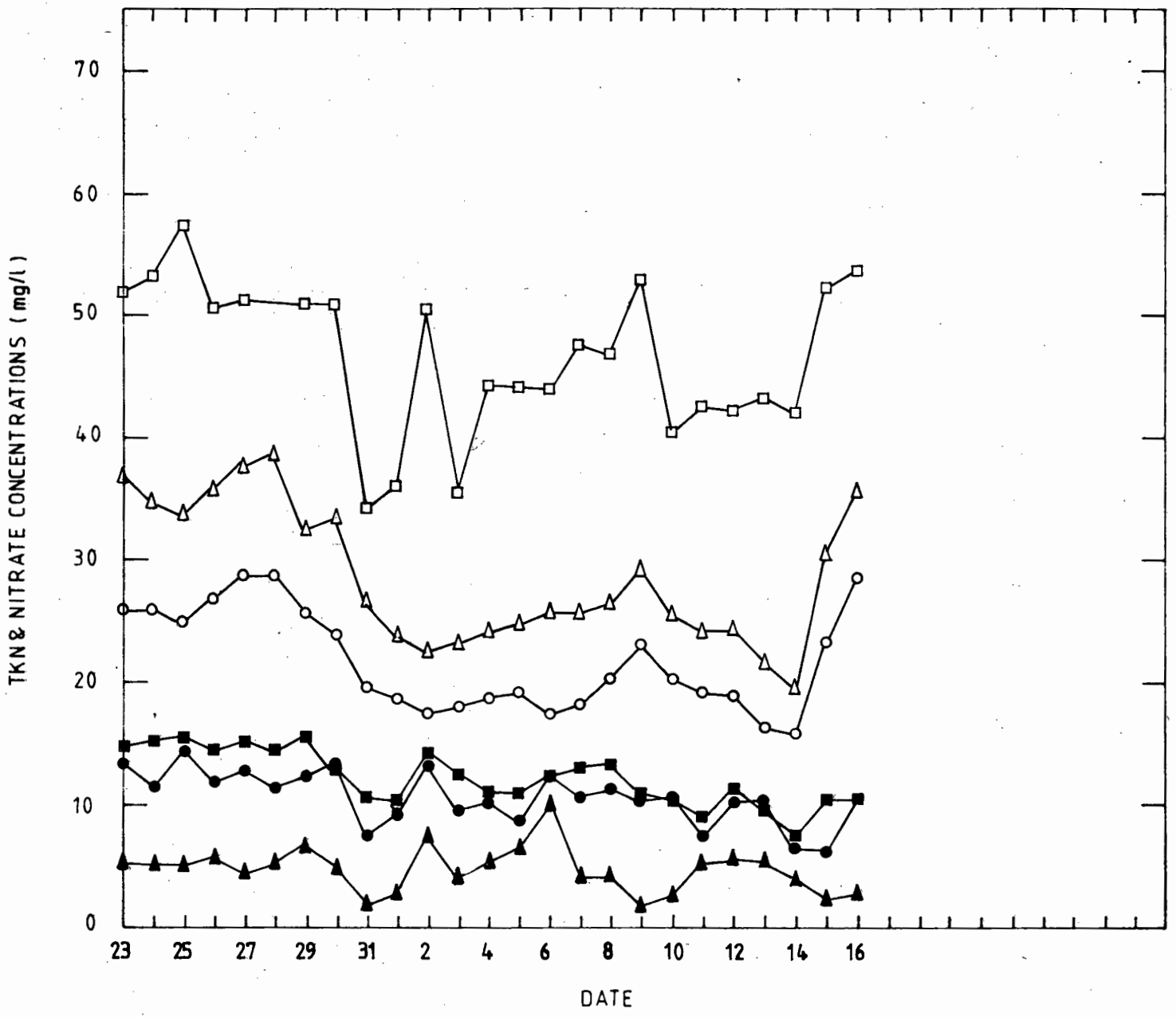


FIGURE No. 4.9

R_s = 10 days

T = 20°C

Q = 24 m^3/day

DAILY TKN & NITRATE CONCENTRATIONS

NITRATE

△ STABILIZATION REACTOR

○ CONTACT REACTOR

TKN

□ INFLUENT

■ EFFLUENT

▲ STABILIZATION REACTOR

● CONTACT REACTOR

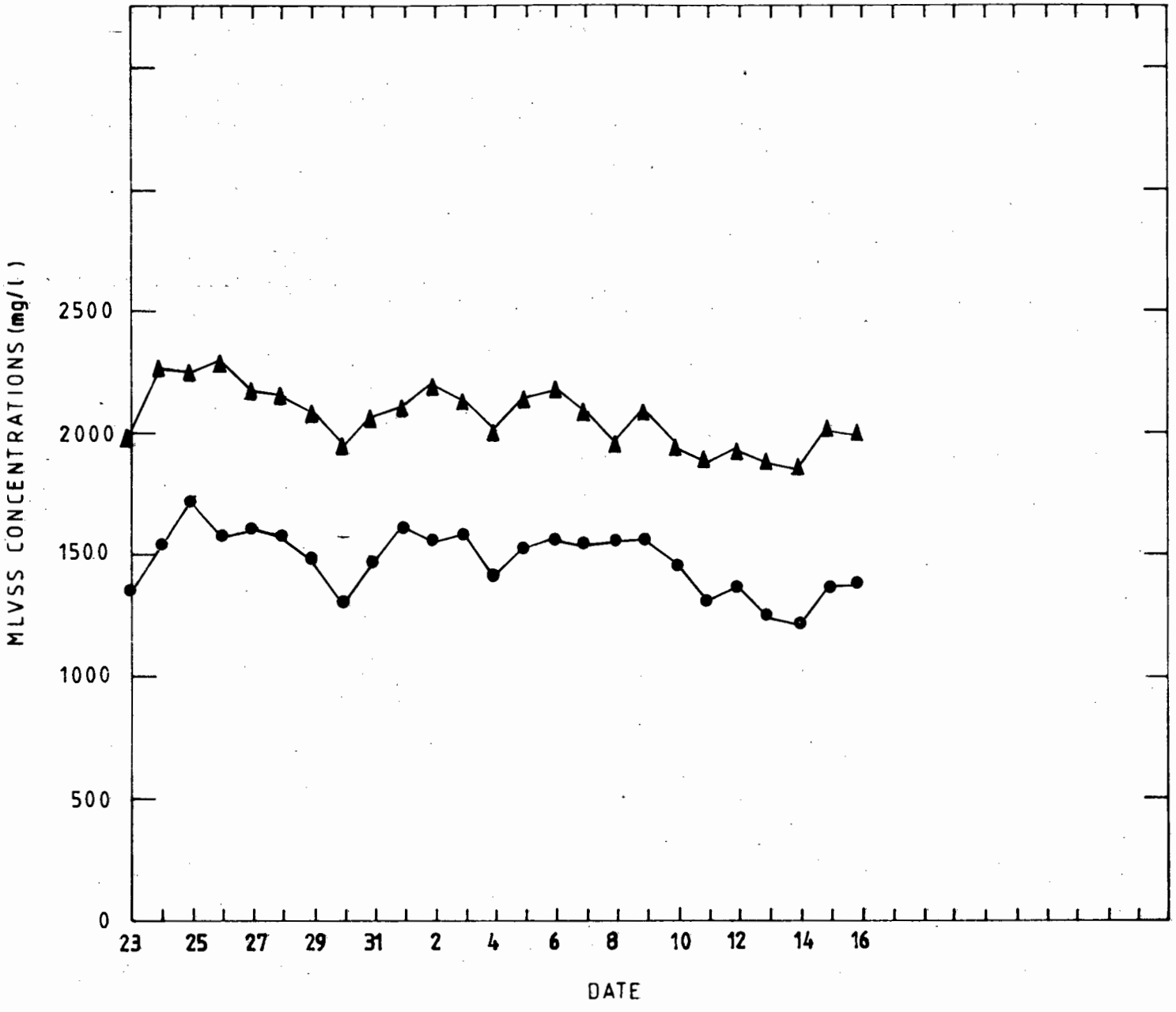
FIGURE No. 4.10

R_s = 10 days

T = 20°C

Q = 24 m^3/day

DAILY MLVSS CONCENTRATIONS



▲ STABILIZATION REACTOR

● CONTACT REACTOR

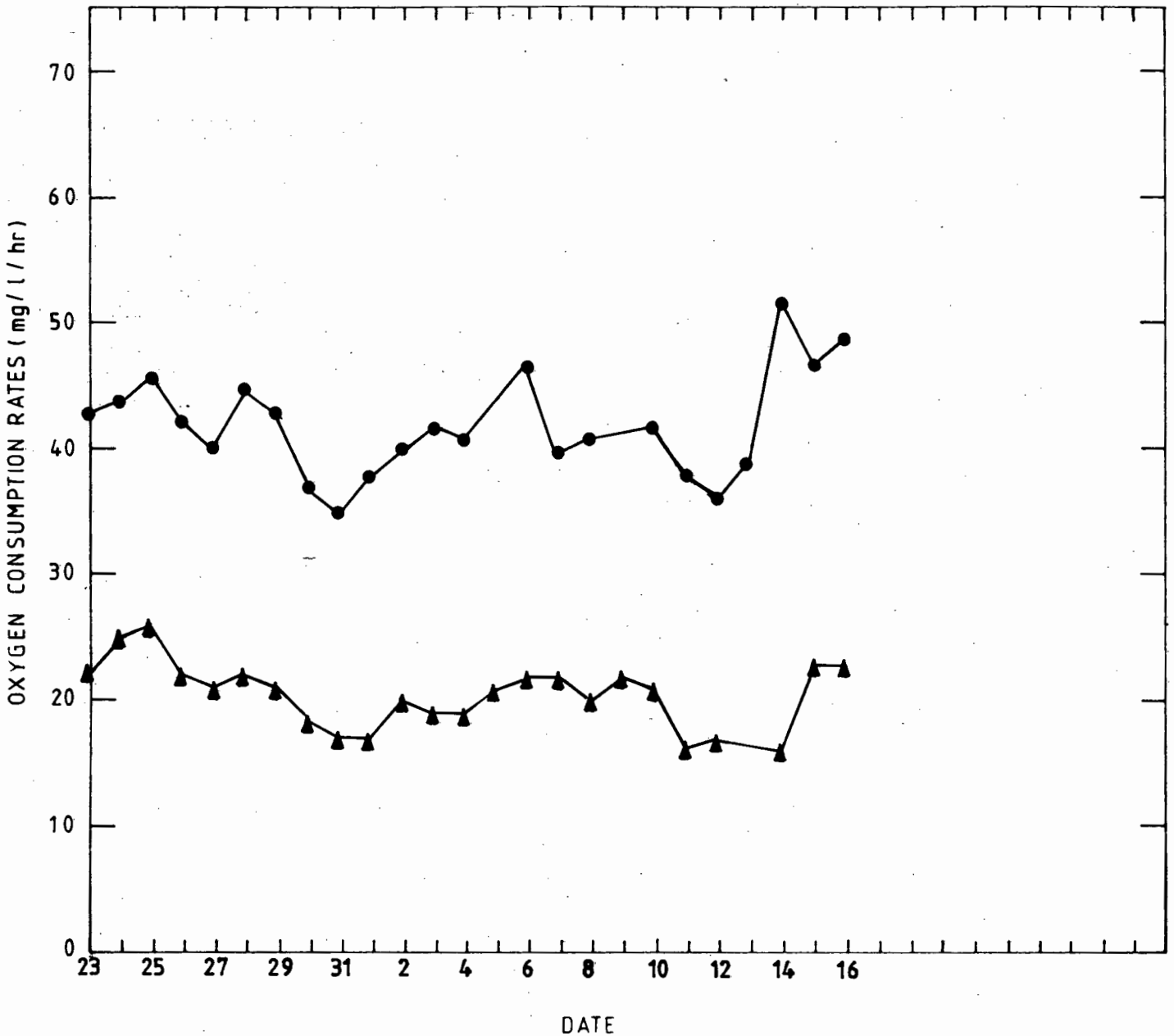


FIGURE No. 4.11

R_s = 10 days

T = 20°C

Q = 24 m^3/day

DAILY OXYGEN CONSUMPTION RATES

▲ STABILIZATION REACTOR

● CONTACT REACTOR

that the process temperature was 12°C. The process parameters and the testing pattern followed were identical to those shown in Tables 4.2 and 4.3 respectively. Two series of tests were run, with and without nitrification respectively.

(a) Unit run with nitrification

Initially no attempt was made to inhibit the growth of nitrifying organisms, and nitrification was found to occur readily. Once a dynamic steady state was established, the unit was monitored under these conditions for 34 days, or approximately 5-1/2 sludge ages. The daily results are plotted in Figs. 4.12 to 4.15 inclusive and are tabulated in Appendix A.3. The mean values of these daily process variable tests are given in Table 4.8.

The mass balance checks were performed on the data as before, utilizing Eqs. (4.7 and 4.8). Whereas the nitrogen mass balance provided an excellent recovery of 101%, the COD mass balance resulted in a highly unsatisfactory recovery of only 83%. An intensive effort was made to find the reason for this imbalance.

It was first thought that the problem lay in the measurement of the oxygen consumption rate. Different oxygen meters and recorders were used to measure the same consumption rates at 20° and 12°, but consistent results were still obtained at both temperatures. Different methods of calibrating the oxygen probe were then attempted, but all gave essentially the same results. The drive rate of the recorders which operates the time scale of the dissolved oxygen versus time plot was checked in both recorders and found to be accurate.

The possibility of the fault lying with either the COD or VSS tests was also considered. However, exactly the same sampling and testing techniques, equipment and chemicals were employed for samples coming from the units at both 20°C and 12°C. Furthermore, these samples were tested in random order, hence it is considered to be highly unlikely that an experimental error could have occurred in the testing of only the samples from the 12°C unit.

Table 4.7

Mean Values of Process Variables Observed during time invariant tests at 20°C and 10 day sludge age over a period of 3½ sludge ages.

Variable	Influent	Contact Reactor	Effluent	Stabilization Reactor
COD (mg COD/ℓ)	496	52	61	42
TKN (mg N/ℓ)	47	11	12	5
MLVSS (mg VSS/ℓ)		1478	-	2073
$NO_3 + NO_2$	<0,1	22	21	29
O_t †	-	49	-	22

† Oxygen consumption rate

Table 4.8

Mean Values of Process Variables Observed during time invariant tests at 12°C and 6 days sludge age with nitfirication over a period of 5½ sludge ages.

Variable	Influent	Contact Reactor	Effluent	Stabilization Reactor
COD (mg COD/ℓ)	510	55	69	49
TKN (mg N/ℓ)	50	14	15	6
MLVSS (mg VSS/ℓ)	-	1531	-	2206
$NO_3 + NO_2$	<0,1	22	22	29
O_t †	-	33	-	25

† Oxygen consumption rate

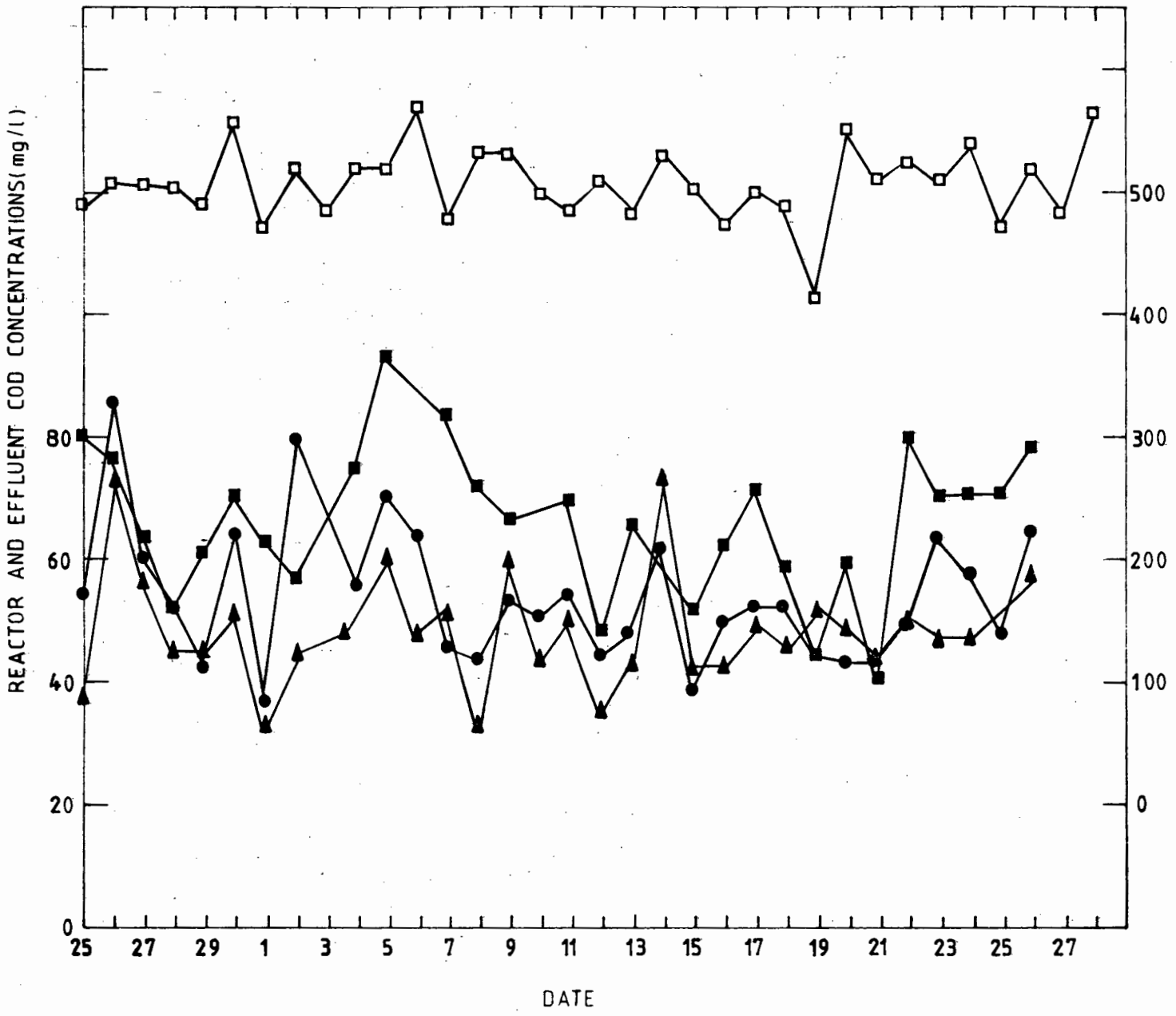
FIGURE No. 4.12

R_s = 6 days

T = 12°C With Nitrification

Q = 36 m^3/day

DAILY COD CONCENTRATIONS



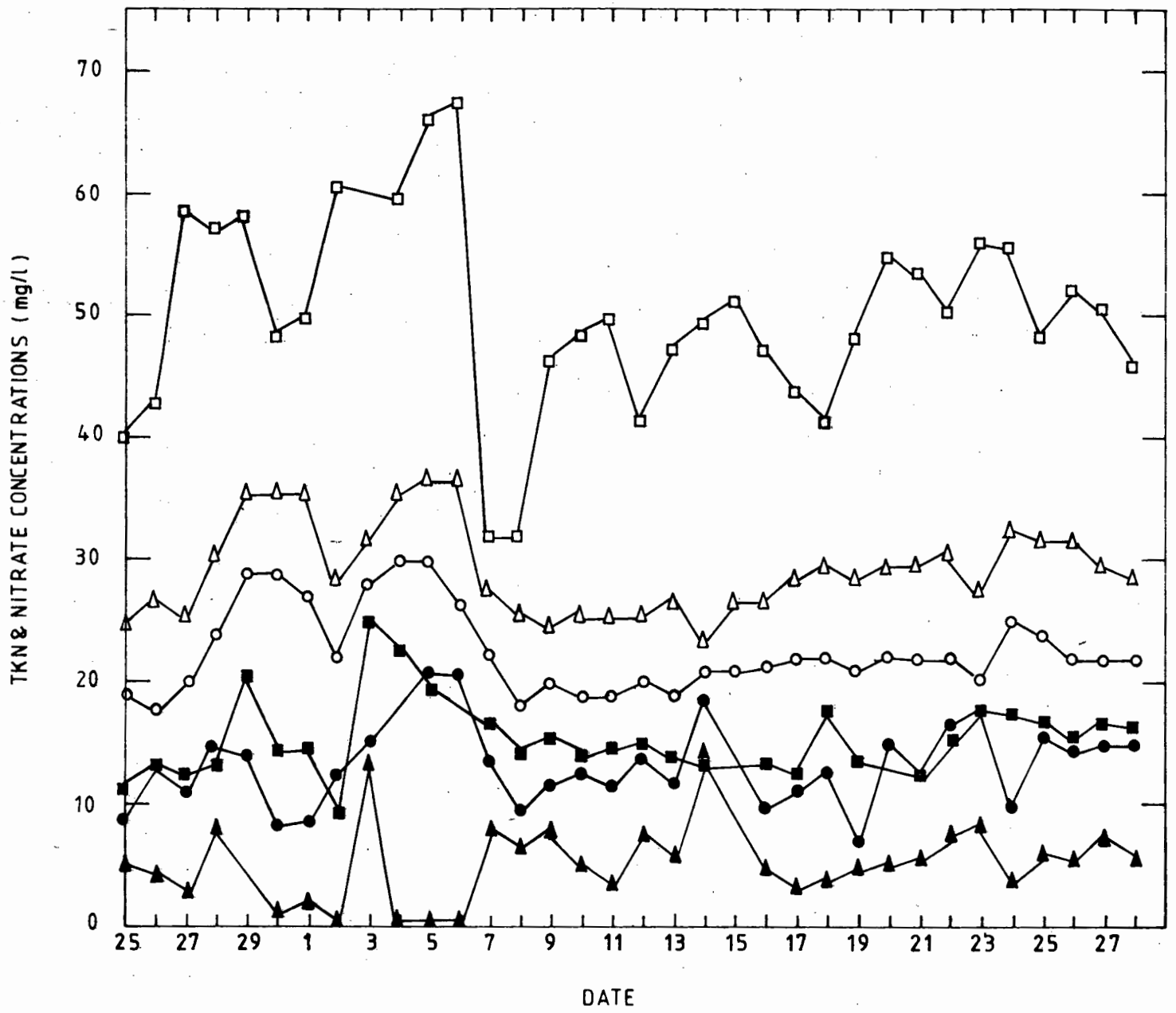


FIGURE No. 4.13

R_s = 6 days

T = 12°C With Nitrification

Q = 36 m^3/day

DAILY TKN & NITRATE CONCENTRATIONS

NITRATE

△ STABILIZATION REACTOR

○ CONTACT REACTOR

TKN

□ INFLUENT

■ EFFLUENT

▲ STABILIZATION REACTOR

● CONTACT REACTOR

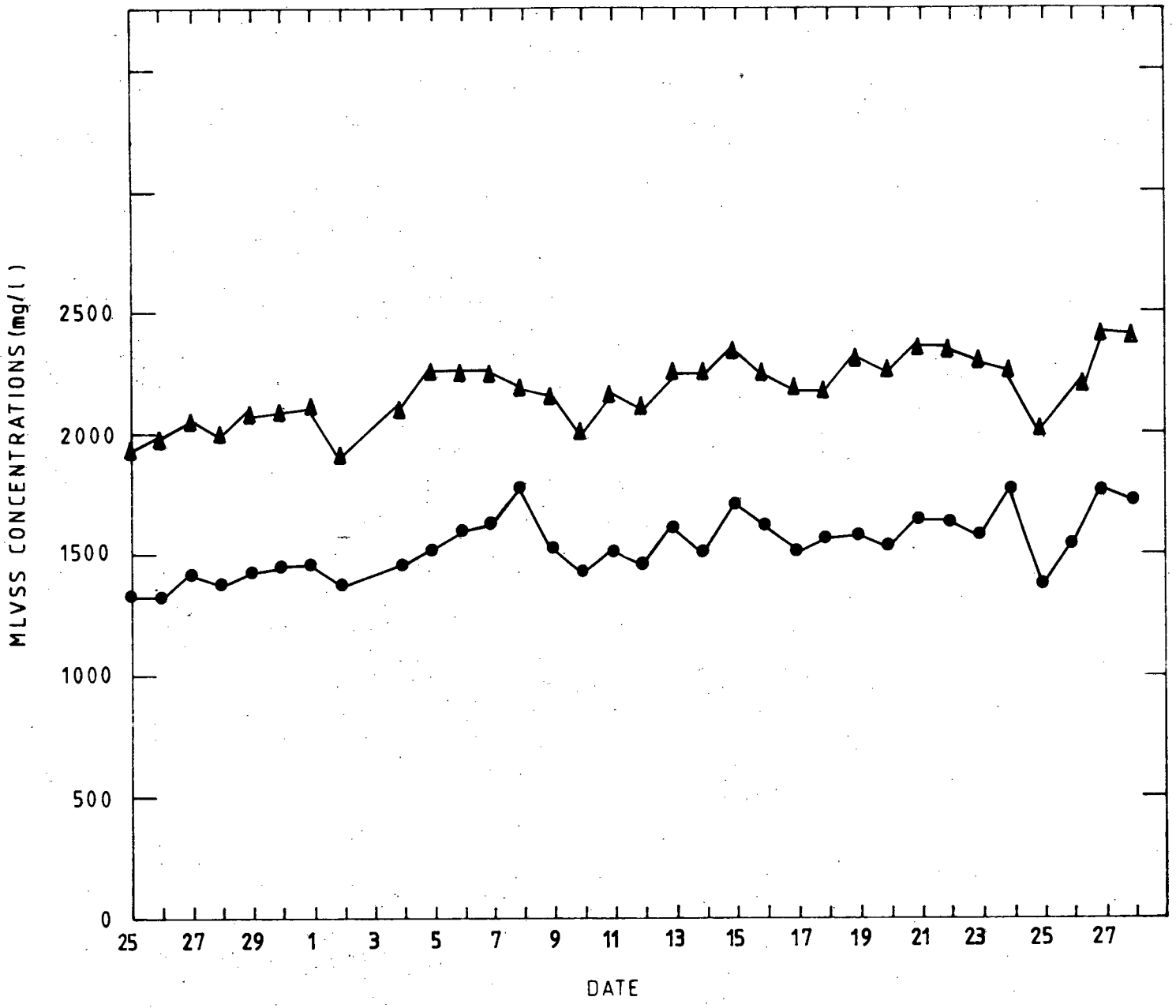
FIGURE No. 4.14

R_s = 6 days

T = 12°C With Nitrification

Q = 36 m^3/day

DAILY MLVSS CONCENTRATIONS



▲ STABILIZATION REACTOR

● CONTACT REACTOR

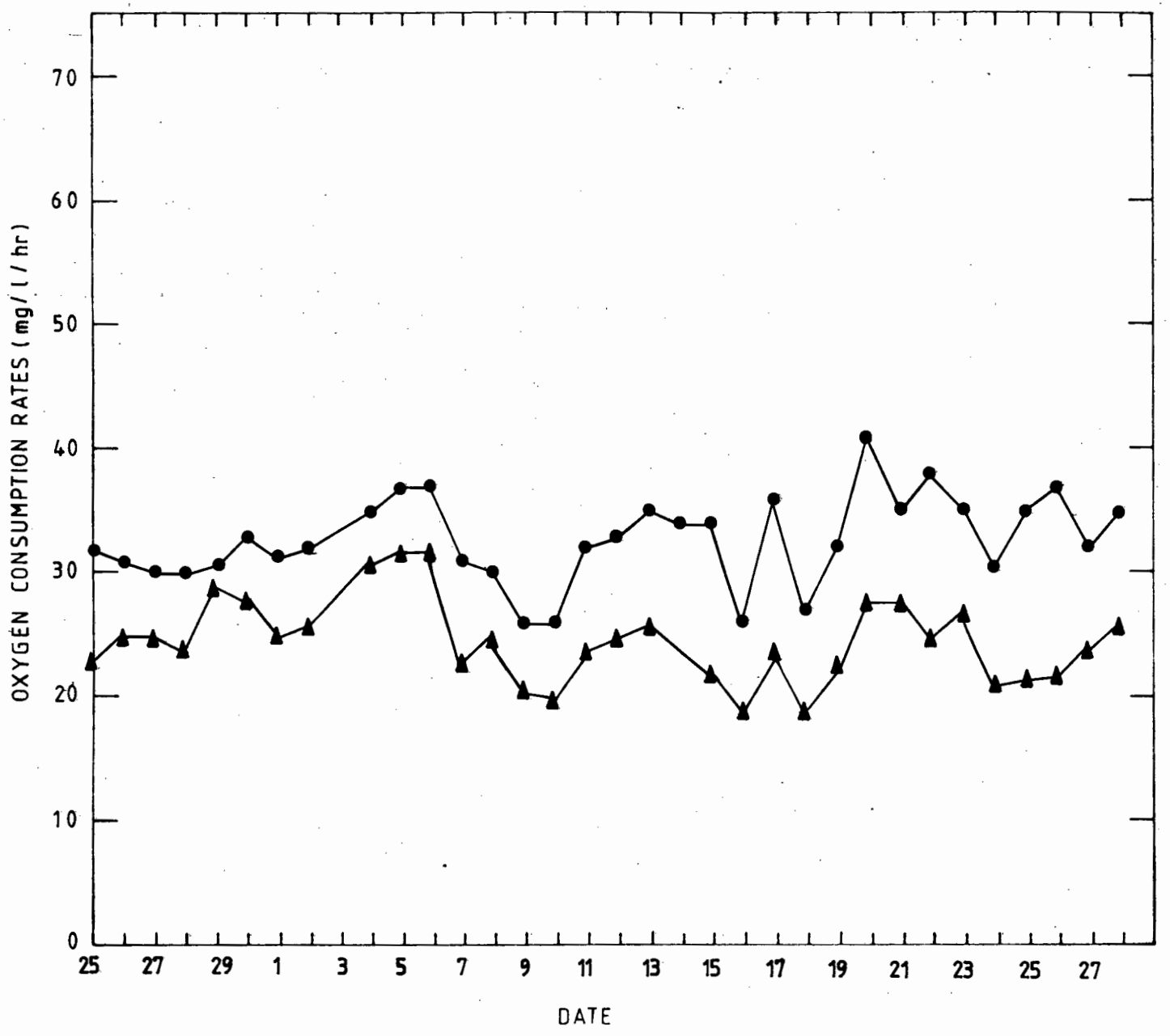
FIGURE No. 4.15

R_s = 6 days

T = 12°C With Nitrification

Q = 36 m^3/day

DAILY OXYGEN CONSUMPTION RATES



▲ STABILIZATION REACTOR

● CONTACT REACTOR

This problem of obtaining a poor COD mass balance on activated sludge plants running at 12°C has been encountered previously. An analysis of the data published by Ekama and Marais (1978) for a CMAS system run at 12°C and sludge ages of 3,3 and 30 days for cyclic and steady state tests gave COD recovery rates of 84%. Nitrogen recoveries were, however, all within acceptable limits.

Returning to the lack of an acceptable balance on the CSP COD values, in an endeavour to obtain a clearer insight into what the problem might be it was decided to inhibit nitrification in the unit so that the measured oxygen consumption rate would be equal to the carbonaceous oxygen consumption rate.

(b) Unit run without nitrification

By adding 720 mg of thiourea to each daily influent batch of 36 ℓ, the growth of *nitrosomonas* was inhibited to such an extent that nitrification in the plant ceased completely. The thiourea appeared to have very little effect on the heterotrophic organisms, although the unit had to be run for nearly 3 sludge ages before a dynamic steady state was achieved. The unit was monitored for a further 12 days, or 2 sludge ages, in accordance with the test pattern set out in Table 4.3. The results are plotted in Figs. 4.16 to 4.19 inclusive, and tabulated in Appendix A.4. The mean values of these daily process variables are given in Table 4.9.

When the mass balance checks were performed on the data, results similar to those for the nitrifying unit were achieved. The nitrogen mass gave a recovery of 106%, which, though a little high, was quite acceptable. However, the COD mass balance again gave a low recovery of 84%, which is only marginally better than the one for a nitrifying unit.

A full analysis and discussion of this set of data is carried out in Section 4.5.2.3.

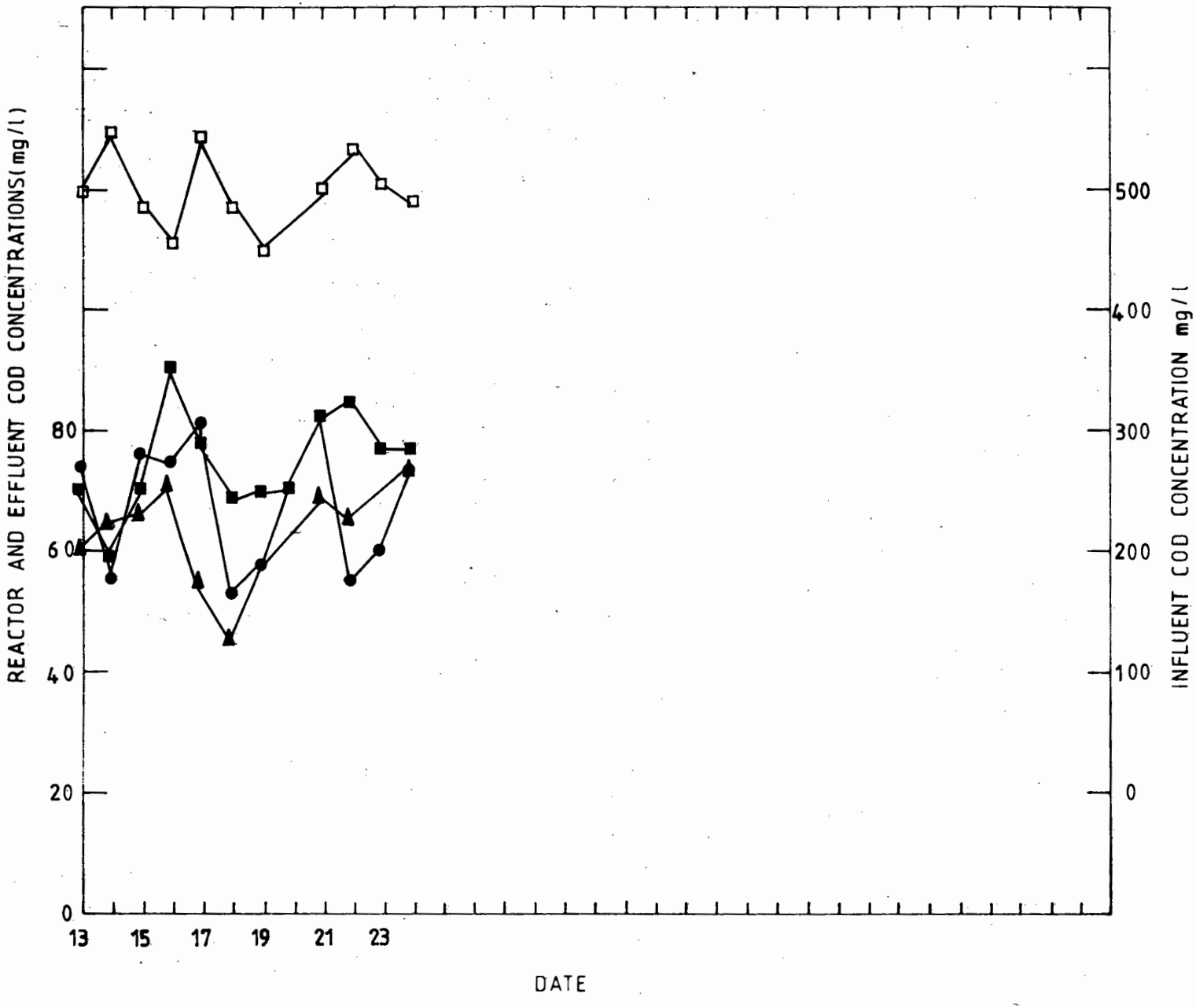


FIGURE No. 4.16

R_s = 6 days

T = 12°C Without Nitrification

Q = 36 m^3/day

DAILY COD CONCENTRATIONS

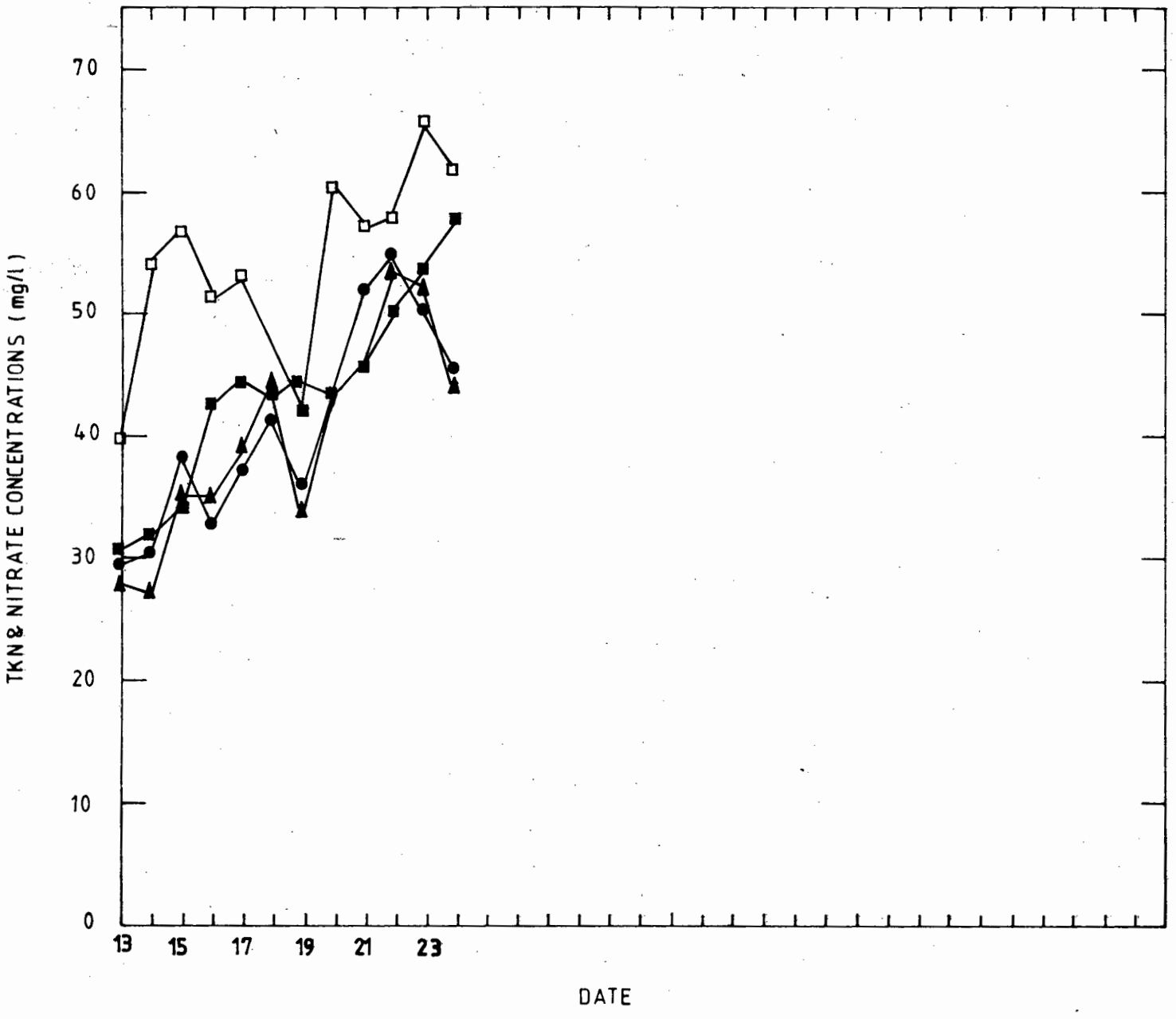
- INFLUENT
- EFFLUENT
- STABILIZATION REACTOR
- CONTACT REACTOR

FIGURE No. 4.17

R_s = 6 days

T = 12°C Without Nitrification

Q = 36 m^3/day



DAILY TKN & NITRATE CONCENTRATIONS

NITRATE

△ STABILIZATION REACTOR

○ CONTACT REACTOR

TKN

□ INFLUENT

■ EFFLUENT

▲ STABILIZATION REACTOR

● CONTACT REACTOR

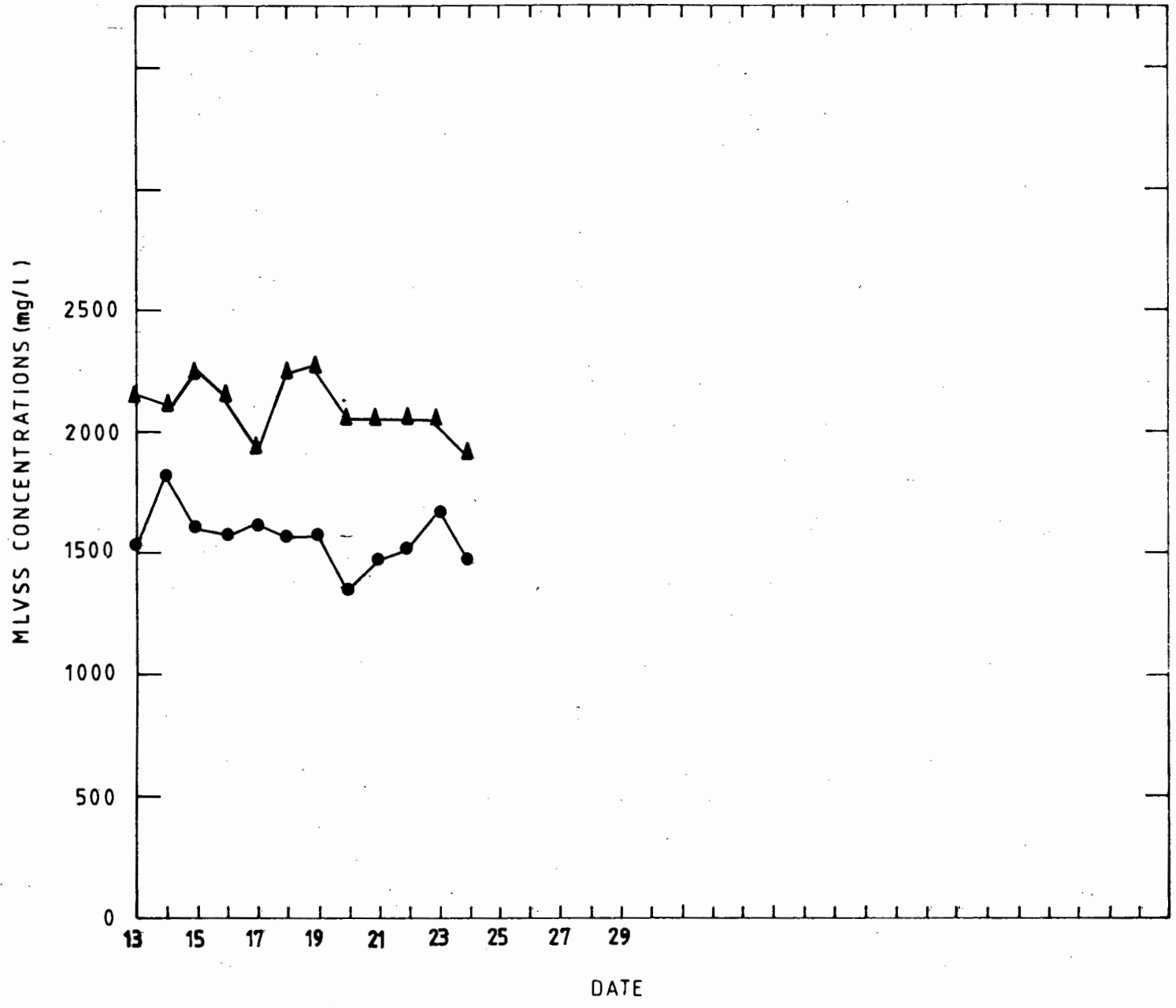
FIGURE No. 4.18

R_s = 6 days

T = 12°C Without Nitrification

Q = 36 m^3/day

DAILY MLVSS CONCENTRATIONS



▲ STABILIZATION REACTOR

● CONTACT REACTOR

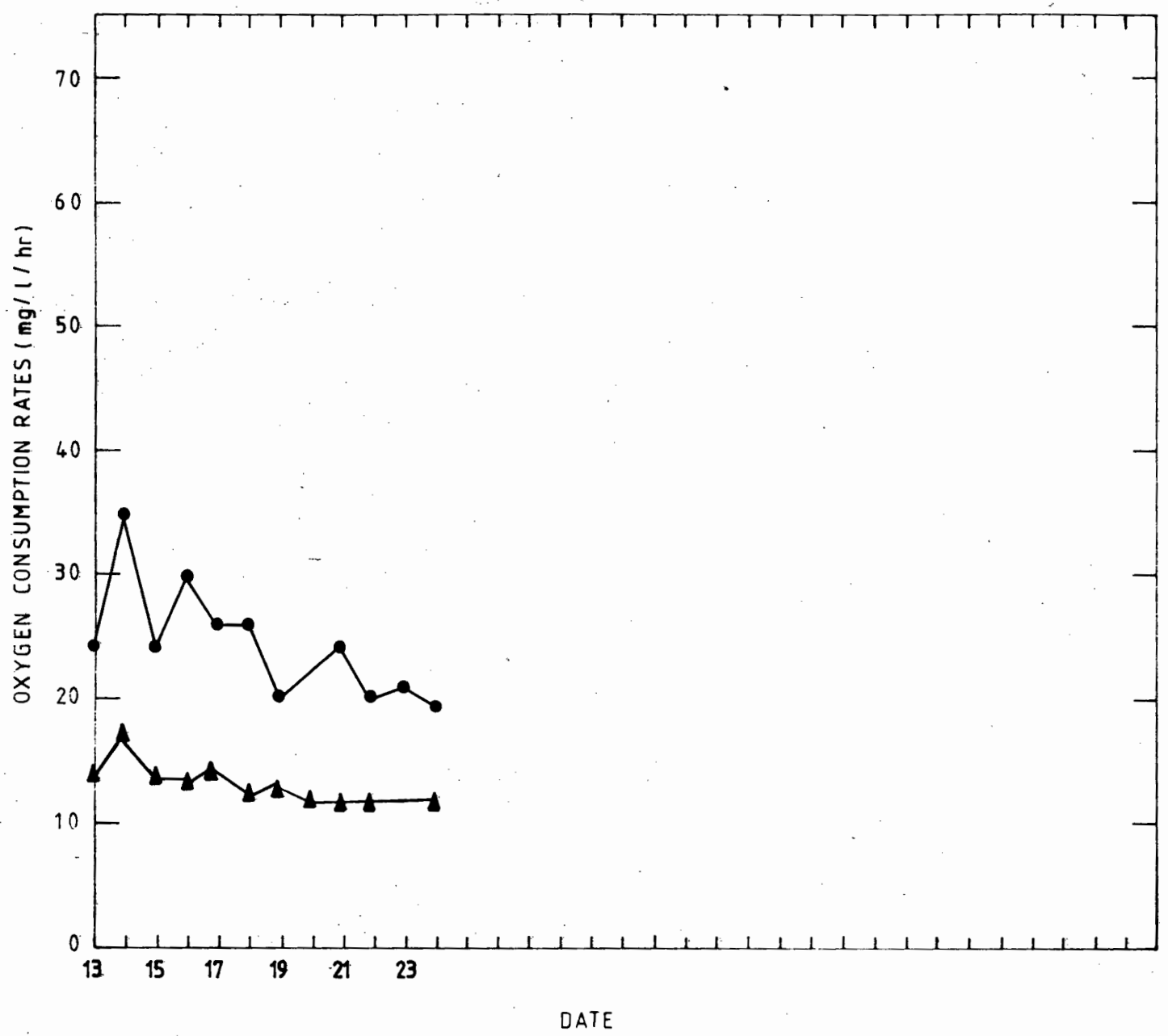
FIGURE No. 4.19

R_s = 6 days

T = 12°C Without Nitrification

Q = 36 m^3/day

DAILY OXYGEN CONSUMPTION RATES



▲ STABILIZATION REACTOR

● CONTACT REACTOR

4.44

Table 4.9

Mean Values of Process Variables Observed during time invariant tests at 12°C and 6 days sludge age without nitrification over a period of 2 sludge ages.

Variable	Influent	Contact Reactor	Effluent	Stabilization Reactor
COD (mg COD/ℓ)	503	69	75	64
TKN (mg N/ℓ)	54	41	43	41
MLVSS (mg VSS/ℓ)	-	1545	-	2124
$NO_3 + NO_2$	<0,1	<0,1	<0,1	<0,1
O_t †	-	24	-	14

† Oxygen consumption rate

4.4.2 Cyclic Flow and Load Conditions

4.4.2.1 Sine wave pattern

Once the unit had been allowed to achieve a dynamic steady state for the sine wave loading pattern as described in Section 4.3.4, two 24 hour tests were performed 4 days apart. However, only the first test is reported here as the second test produced an unacceptable mass balance.

The testing pattern for the 24 hour test is given in Table 4.10 and the results are plotted in Fig. 4.20 and tabulated in Appendix A.5. Because the cyclic feed pump was difficult to set exactly, the daily feed was 37 ℓ/d. As a result the recycle ratio, r, was 1,92, not 2, and the sludge wastage flow ratio, w, was 0,089, not 0,092.

Mass balances performed on the data gave a nitrogen recovery of 107% and a COD recovery of 96%, which was considered to be satisfactory.

The process parameters were the same as for the steady feed and load tests are given in Tables 4.1 and 4.2. These results are analysed in Section 4.5.1.1.

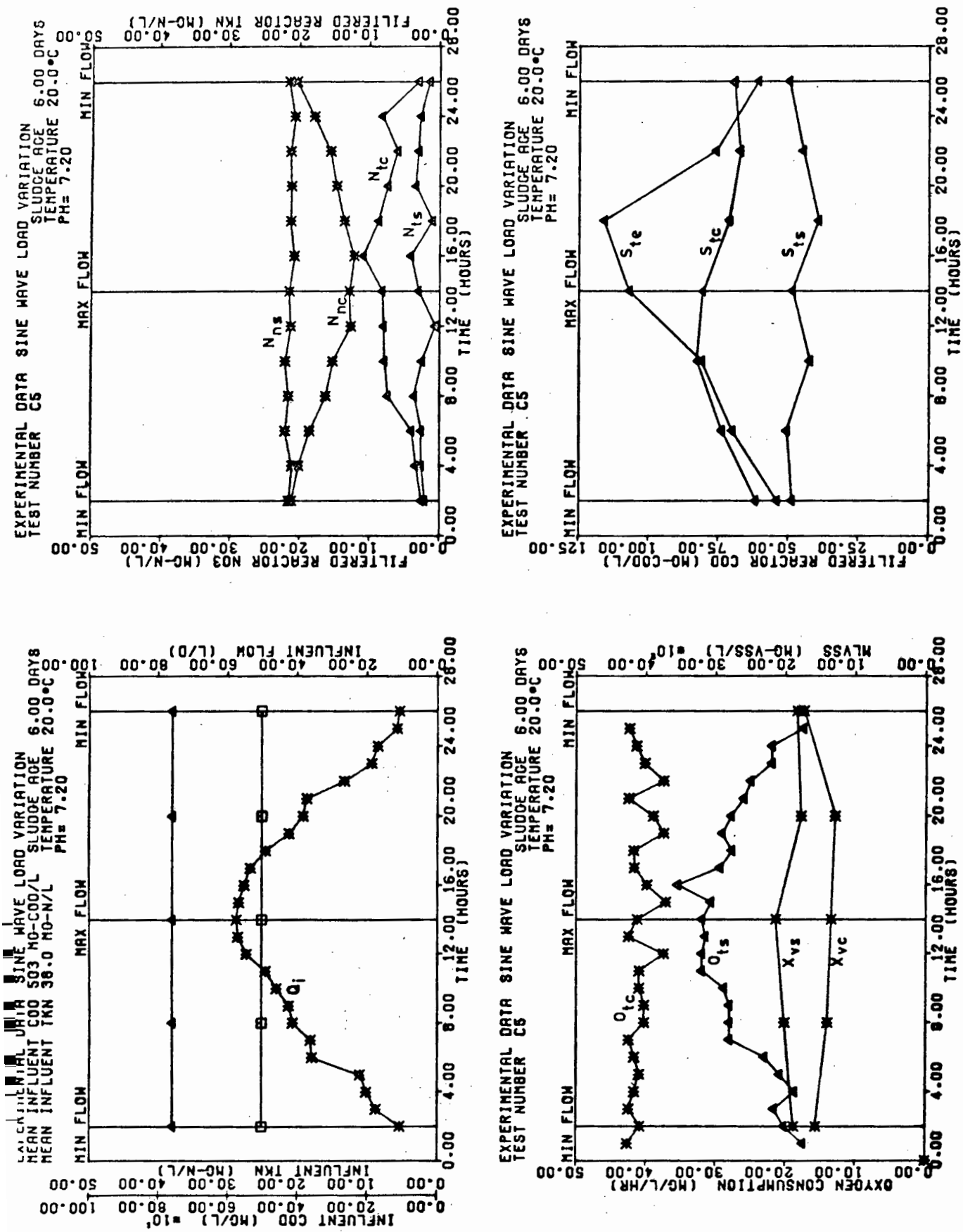


Fig. 4.20 *Experimentally observed response of the CSP unit subjected to a sine wave cyclic loading pattern.*

Table 4.10

24 Hour Testing Pattern for Sine Wave Test

Time	Pumping Rate	COD			TKN			NITRATE			VSS		O.D.	
		C	S	E	C	S	E	C	S	E	C	S	C	S
0000	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1000	x												x	x
2000	x				x	x	x	x	x	x			x	x
3000	x												x	x
4000	x	x	x	x	x	x	x	x	x	x			x	x
5000	x												x	x
6000	x				x	x	x	x	x	x	x	x	x	x
7000	x												x	x
8000	x	x	x	x	x	x	x	x	x	x			x	x
9000	x												x	x
1000	x				x	x	x	x	x	x			x	x
1100	x												x	x
1200	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1300	x												x	x
1400	x				x	x	x	x	x	x			x	x
1500	x												x	x
1600	x	x	x	x	x	x	x	x	x	x			x	x
1700	x												x	x
1800	x				x	x	x	x	x	x	x	x	x	x
1900	x												x	x
2000	x	x	x	x	x	x	x	x	x	x			x	x
2100	x												x	x
2200	x				x	x	x	x	x	x			x	x
2300	x												x	x
2400	x	x	x	x	x	x	x	x	x	x	x	x	x	x

4.4.2.2 Square wave pattern

After the completion of the sine wave tests the unit was run under time invariant flow and load conditions for a period of one sludge age before the load cycle was changed to a square wave pattern. This consisted of a base flow of 18 ℓ/day which was fed continuously and a square wave of 12 hour duration with a total flow of three times the base flow, i.e. 54 ℓ/day.

The process parameters are the same as those for the steady feed and load tests and are given in Tables 4.1 and 4.2. The testing pattern for the 24 hour test is given in Table 4.11, and the results are plotted in Fig. 4.21 and tabulated in Appendix A.6. During this test the temperature of the influent flows and the temperature and pH of the two reactors were also checked on an hourly basis and the results are tabulated in Appendix A.7. As will be evident from the testing pattern, the period immediately following the start and end of the high rate feed was tested at short intervals so that rapid changes in response could be monitored.

Mass balance checks on the data produced 100% recovery from nitrogen and 104% for COD, which was considered to be satisfactory.

This data is analysed in Section 4.5.1.2.

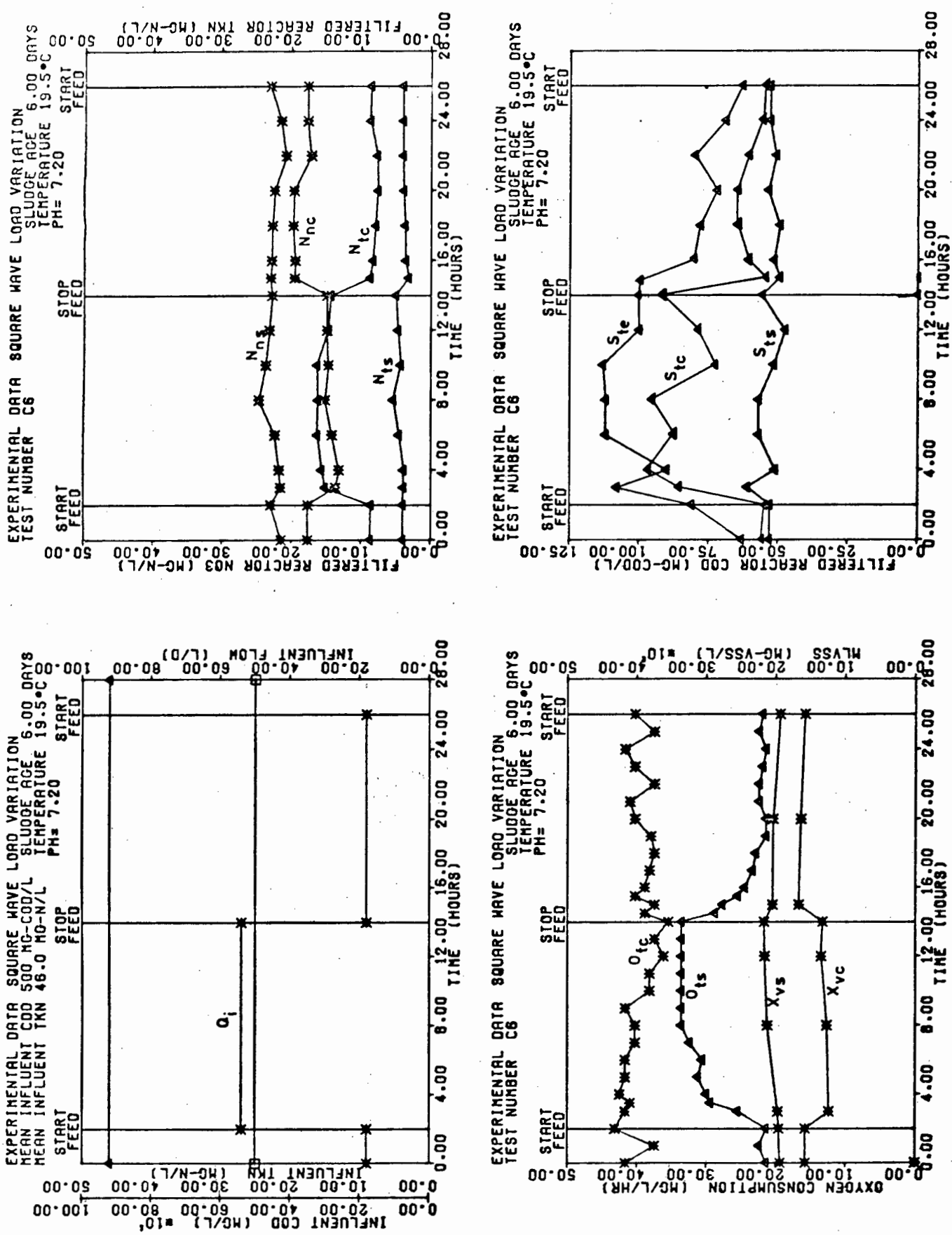


Fig. 4.21 *Experimentally observed response of the CSP unit subjected to a square wave cyclic loading pattern.*

Table 4.11

24 Hour Testing Pattern for Square Wave Test

Time	COD			TKN			NITRATE			VSS		O.D.	
	C	S	E	C	S	E	C	S	E	C	S	C	S
1000	x	x	x	x	x	x	x	x	x	x	x	x	x
1100												x	x
1200	x	x	x	x	x	x	x	x	x	x	x	x	x
1250												x	x
1300	x	x	x	x	x	x	x	x	x	x	x	x	x
1350												x	x
1400	x	x	x	x	x	x	x	x	x			x	x
1500												x	x
1600	x	x	x	x	x	x	x	x	x			x	x
1700												x	x
1800	x	x	x	x	x	x	x	x	x	x	x	x	x
1900												x	x
2000	x	x	x	x	x	x	x	x	x			x	x
2100												x	x
2200	x	x	x	x	x	x	x	x	x	x	x	x	x
2300												x	x
2400	x	x	x	x	x	x	x	x	x	x	x	x	x
0050												x	x
0100	x	x	x	x	x	x	x	x	x	x	x	x	x
0150												x	x
0200	x	x	x	x	x	x	x	x	x			x	x
0300												x	x
0400	x	x	x	x	x	x	x	x	x			x	x
0500												x	x
0600	x	x	x	x	x	x	x	x	x	x	x	x	x
0800	x	x	x	x	x	x	x	x	x			x	x
0900												x	x
1000	x	x	x	x	x	x	x	x	x	x	x	x	x

4.5 THEORETICAL ANALYSIS OF EXPERIMENTAL DATA

In the model both the adsorption and bi-substrate hypothesis assume that all particulate COD and TKN not adsorbed or assimilated by the active fraction of the sludge are enmeshed by the sludge floc and removed from the process effluent in the settling tank. Furthermore, it is assumed that the settling tank is completely efficient so that the respective COD and TKN tests, when performed on the filtered contact reactor contents and unfiltered process effluent, should theoretically give identical values. On studying the experimental data it is clear that the settler certainly did not operate with 100% efficiency. The values from the effluent were invariably greater than those from the contact reactor.

There are two possible explanations for the discrepancy noted above; (1) enmeshment of the particulate substrate by the floc is complete within the short contact time, but the settling tank is not perfectly efficient, so that solids escaping have the same constituent fractions as the mixed liquor. This would cause, in effect, a reduction of the sludge age. (2) The enmeshment by the floc of the smaller feed particles of COD and TKN is not as complete as assumed, i.e. there is only partial removal of the particulate substrate in the short contact time available. This would, in effect, cause a reduction in the biodegradable COD and TKN available for metabolism and hence a reduction in the active mass generated, but would not affect the sludge age. The consequence of the two extreme alternatives will now be analysed and discussed.

Since the effects are most clearly illustrated by the analysis of the cyclic square wave data, this data is analysed first.

Table 4.12 gives the characteristics of the Strandfontein sewage utilized in this investigation and Table 4.13 gives the full list of model constants.

4.5.1 Cyclic Flow and Load Conditions

4.5.1.1. Square Wave Pattern

(1) Full enmeshment and sludge loss via effluent

If it is assumed that the settling tank is not perfectly efficient but enmeshment is complete, then the difference between the filtered and

Table 4.12 Characteristics of the Strandfontein Raw Sewage

Symbol	Value	Units	Symbol	Value	Units
f_{bs}	0,234	mg COD/mg COD	f_{un}	0,00	mg N/mg N
f_{us}	0,10	mg COD/mg COD	f_{na}	0,75	mg N/mg N
f_{up}	0,09	mg VSS/mg COD			

Table 4.13 Values of the kinetic constants for the adsorption and bi-substrate models upon which the Theoretical Predictions are based

Symbol	Value		Units	Symbol	Value		Units
	Adsorp	Bi-sub			Adsorp	Bi-sub	
K_{a20}	0,135	0,135	ℓ/mg VSS/d	f_{oe}	1,00	1,00	mgN/mg VSS
K_{mp20}	2,50	2,50	mgCOD/mgVSS/d	f_{os}	1,00	1,00	mgN/mg VSS
K_{ms20}	-	3,00	mgCOD/mgVSS/d	f_{ma}	1,00	1,00	mgVSS/mgVSS
K_{sp20}	100	100	mg COD/ℓ	f_{ca}	0,078	-	mgCOD/mgCOD
K_{ss20}	-	20	mg COD/ℓ	K_{r20}	0,015	0,015	/mgVSS/d
b_{h20}	0,24	0,24	/d				
Y_h	0,48	0,45	mgVSS/mgCOD	μ_{nm}	0,66	0,66	/d
f	0,20	0,20	mgVSS/mgVSS	K_n	1,00	1,00	mg N/ℓ
f_n	0,10	0,10	mgN/mg VSS	b_{n20}	0,04	0,04	/d
P	1,48	1,48	mgCOD/mgVSS	Y_n	0,10	0,10	mgVASS/mgN

unfiltered COD effluent values is due to sludge particles escaping in the effluent. The loss of sludge via the effluent will affect the sludge age of the system, so it must be adjusted before a valid comparison can be made between the model and the experimental observations.

With reference to Tables 4.2 and 4.14. Total mass of sludge wasted in effluent

$$= (MS^{*}_{te} - MS_{tc})36/P$$

$$= \frac{(97 - 80)36}{1,48} \text{ mg VSS/d}$$

$$= 444 \text{ mg VSS/d}$$

Mass of sludge wasted normally

$$= X_{vc(ave)} \cdot w \cdot Q$$

$$= 1455 \cdot 0,0917 \cdot 36$$

$$= 4803 \text{ mg VSS/d}$$

$\therefore$ Total mass of sludge wasted daily

$$= 4803 + 444$$

$$= 5247 \text{ mg VSS/d}$$

$\therefore$ Equivalent volume of mixed liquor wasted

$$= \frac{5247}{1455} \quad \ell/d$$

$$= 3,61 \quad \ell/d$$

i.e. new sludge wastage ratio, w,

$$= \frac{3,61}{36}$$

$$= 0,1002$$

Now from Eq. (3.17)

$$w = (1 + r)/[1 + QR_s(\alpha + r)/V_p]$$

$$0,1002 = \frac{1 + 2}{1 + 36 \cdot R_s(0,1 + 2)/14,3}$$

$$0,1002 = \frac{3}{1 + 5,29.R_s}$$

i.e.

$$R_s = 5,5 \text{ days.}$$

Both the adsorption and the bi-substrate hypothesis models were run at sludge ages of 5,5 days, and the results can be compared with the experimental data in Figs. 4.22 and 4.23 respectively.

(2) Partial enmeshment - particulate COD escapes in the effluent, but there is no sludge loss.

A fraction of the accumulated particulate COD concentration entering the settling tank is allowed to escape in the effluent, but no sludge is lost dia the effluent, i.e. the sludge age is not effected and remains at 6 days. By trial simulation the best correlation between theoretical predictions and experimental observations was achieved if 60% of the unadsorped particulate COD entering the settling tank was assumed to remain unenmeshed. The predictions of the adsorption and bi-substrate models when adapted to allow only partial enmeshment can be compared with the experimental observations in Figs. 4.24 and 4.25 respectively.

Discussion

Table 4.14 gives a comparison between the parameter values of all four versions of the model and the experimental data when averaged over the whole cycle. The values in the table give a very good indication of the respective daily masses involved in the process and consequently provide a valuable means of judging the overall performance of the various versions of the model.

It must be noted that in the case of full enmeshment versions of the adsorption and bi-substrate models, the experimental effluent COD values to be compared with the theoretical are filtered ones, while for the partial enmeshment versions the unfiltered experimental COD effluent values are compared with the theoretical values.

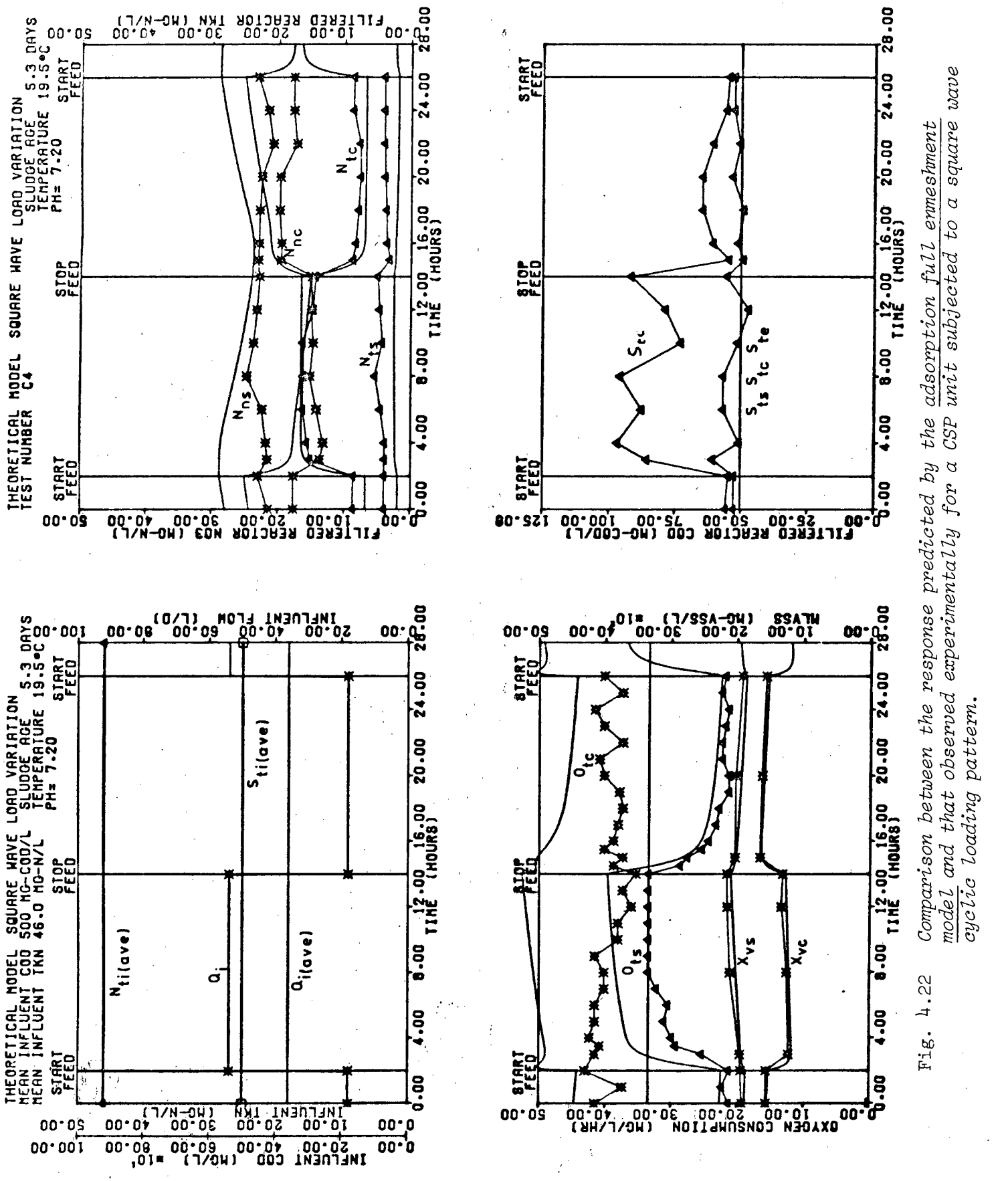


Fig. 4.22 *Comparison between the response predicted by the adsorption full emmeshment model and that observed experimentally for a CSP unit subjected to a square wave cyclic loading pattern.*

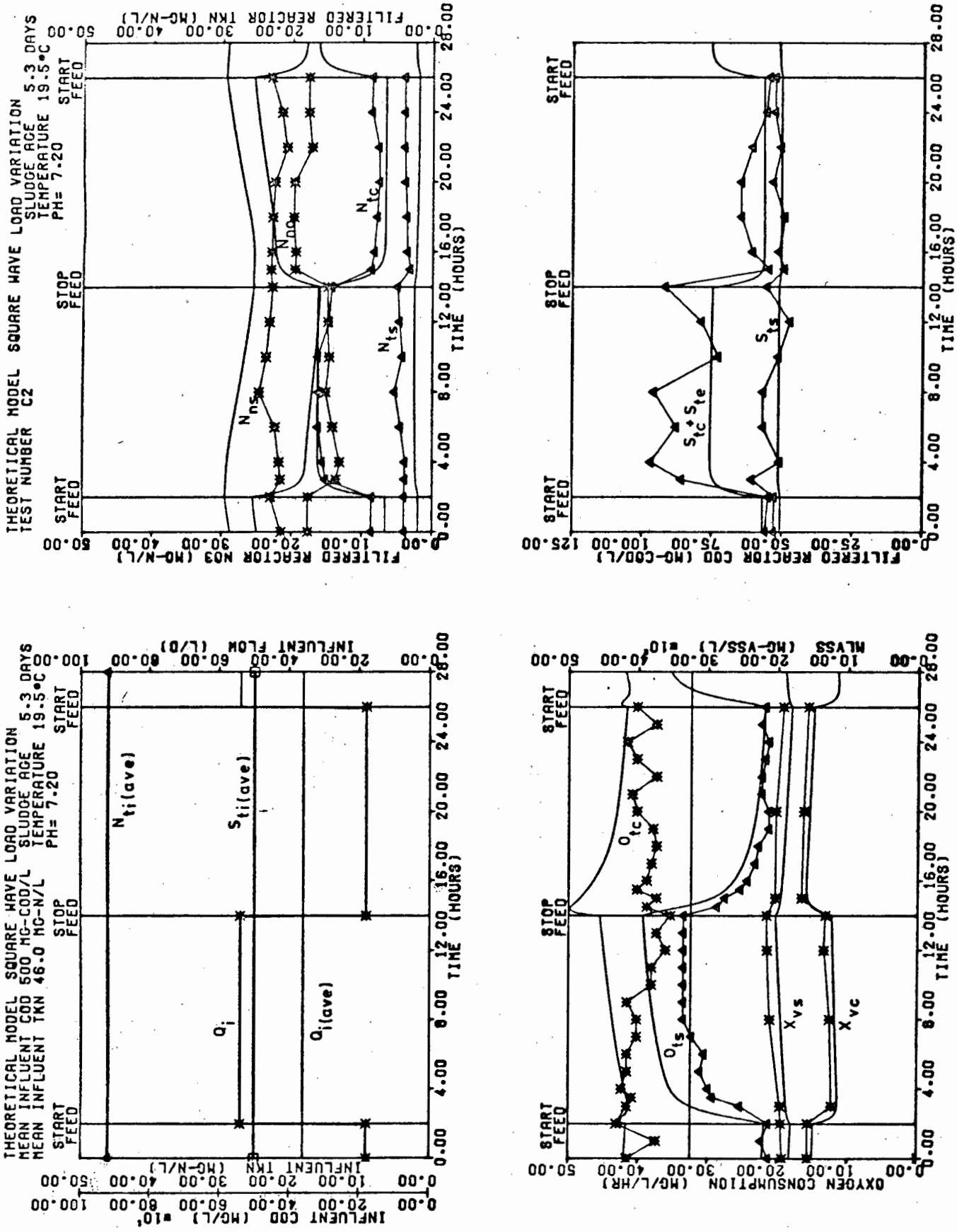


Fig. 4.23 *Comparison between the response predicted by the bi-substrate full enmeshment model and that observed experimentally for a CSP unit subjected to a square wave cyclic loading pattern.*

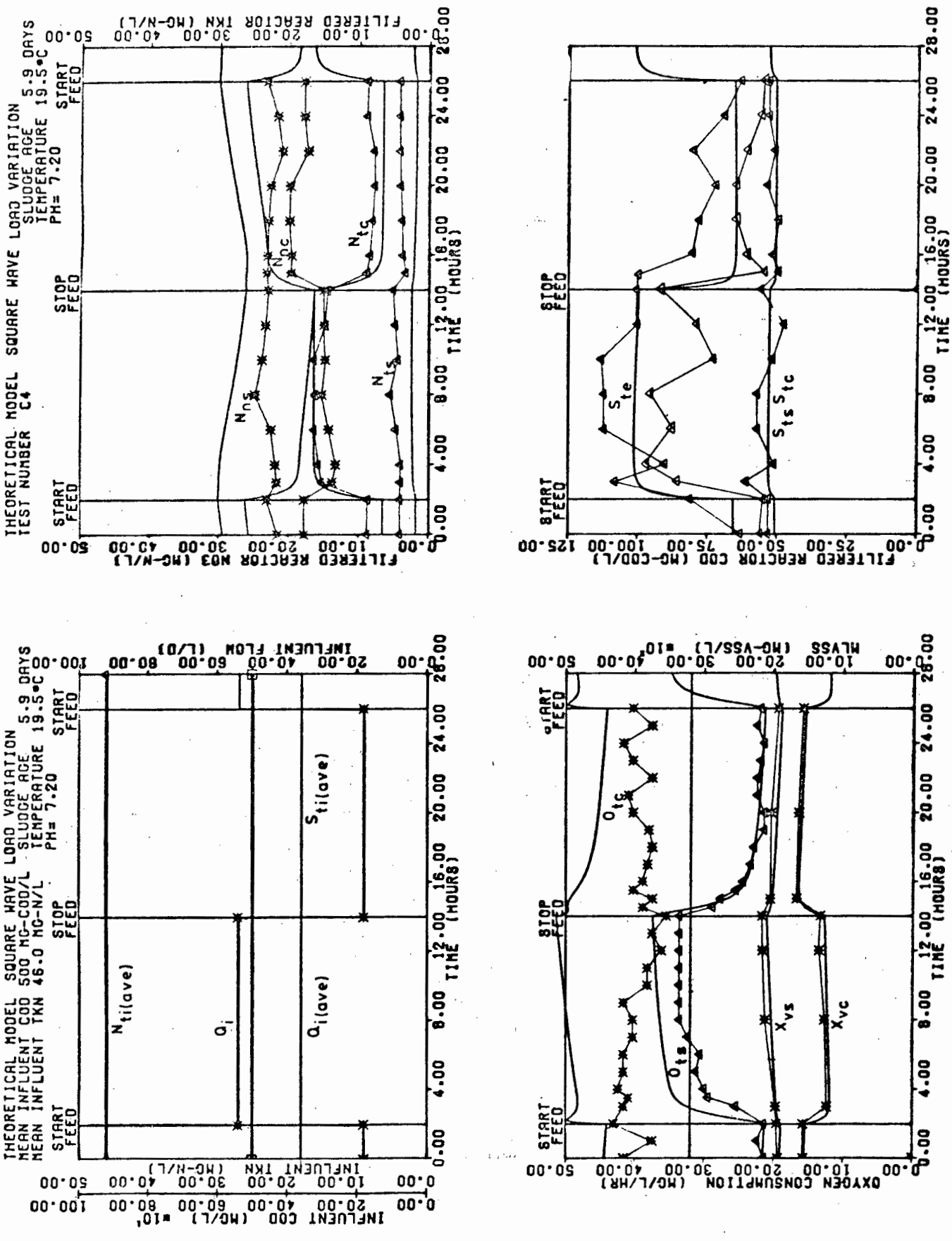


Fig. 4.24 *Comparison between the response predicted by the adsorption partial enmeshment model and that observed experimentally for a CSP unit subjected to a square wave cyclic loading pattern.*

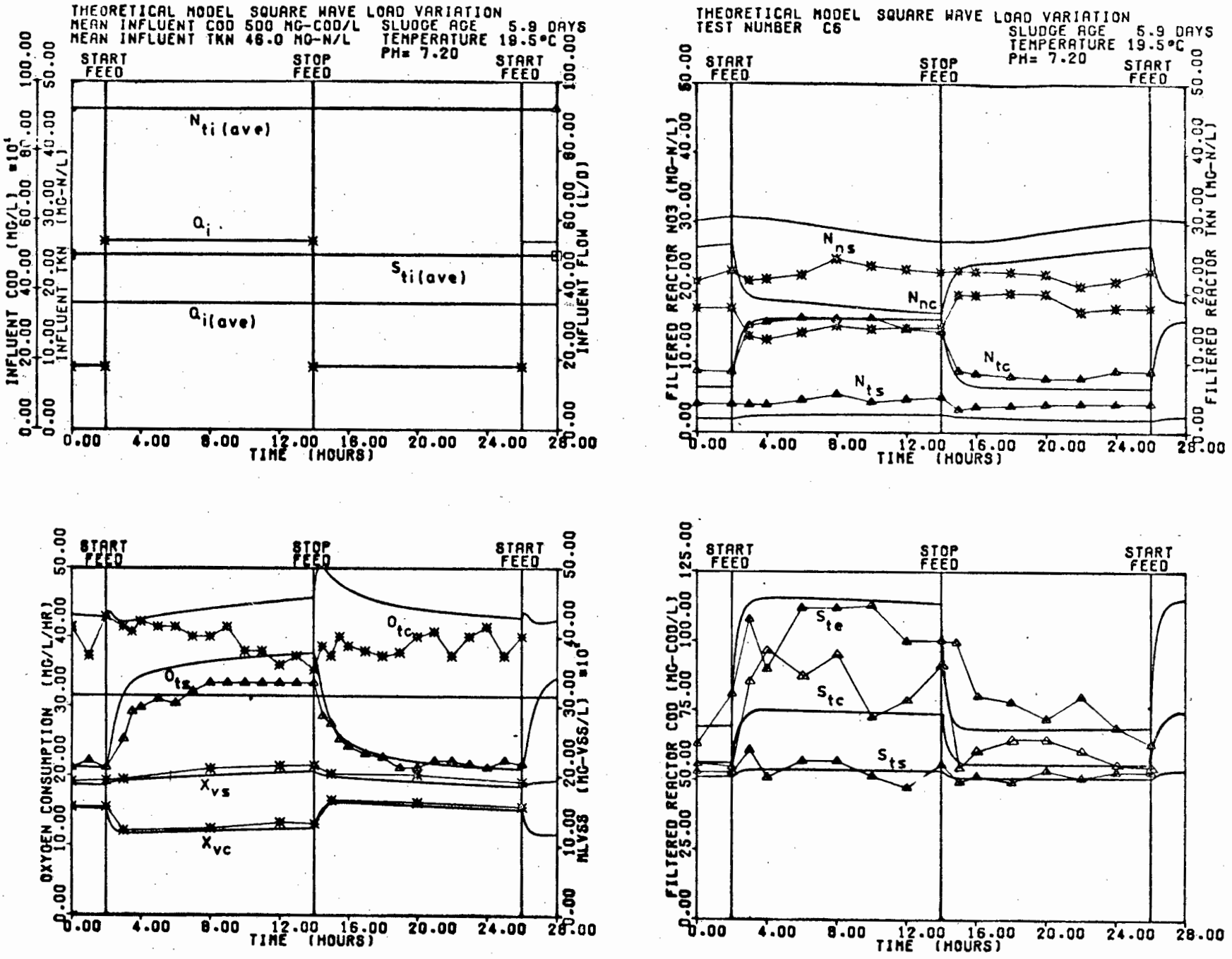


Fig. 4.25 *Comparison between the response predicted by the bi-substrate partial enmeshment model and that observed experimentally for a CSP unit subjected to a square wave cyclic loading pattern.*

Table 4.14 Comparison of parameter values averaged over the full feed cycle for the square wave test

Parameter	Experimental	Bi-substrate with full enmeshment	Adsorption with full enmeshment	Bi-substrate with partial enmeshment	Adsorption with partial enmeshment
X_{ve}	1458	1357	1401	1388	1415
X_{vs}	2051	1913	1975	1959	1996
X_{vp}	1968	1836	1895	1879	1915
$MX_{v\,w}$	4912	4958	5119	4581	4670
O_{tc}	39,5	43,8	48,5	44,5	47,9
O_{ts}	27,6	30,6	31,0	29,4	29,4
O_{np}	7,5	9,0	8,8	9,6	9,4
O_{cp}	21,6	23,4	24,6	21,9	22,6
O_{tp}	29,3	32,4	33,4	31,5	32,0
S_{tc}	74	66	50	66	50
S_{ts}	53	51	50	53	50
MS_{te}*	97	-	-	103	92
MS_{te}	80	71	50	71	50
N_{tc}	11,9	11,6	11,7	11,4	11,7
N_{ts}	4,2	2,3	2,2	2,3	2,4
MN_{te}	15,7	13,9	14,1	13,8	14,1
N_{nc}	16,7	20,4	19,7	21,7	21,1
N_{ns}	22,8	27,4	26,3	29,0	28,1
MN_{ne}	15,6	18,8	18,2	19,9	19,4

X_{vc}, X_{vs} and X_{vp} = the average sludge concentrations in the contact reactor, stabilization reactor and overall process respectively (mg/ℓ)

MX_{vw} = total mass of sludge wasted daily (mg/day)

O_{tc}, O_{ts} = the average mass of oxygen utilized in the contact and stabilization reactors respectively (mg/ℓ/hr)

O_{np}, O_{cp}, O_{tp} = the average process oxygen utilization rates for nitrification, carbonaceous degradation and the total respectively (mg/ℓ/hr)

S_{tc}, S_{ts} = the average filtered COD concentrations in the contact and stabilization reactors respectively.

MS_{te}*, MS_{te} = the respective average unfiltered and filtered masses of COD leaving the system per litre of effluent

N_{tc}, N_{ts} = average filtered TKN concentrations in the contact and stabilization reactors respectively (mg/ℓ)

MN_{te} = the average unfiltered TKN mass leaving the system per litre of effluent.

N_{nc}, N_{ns} = the average concentrations of nitrates in the contact and stabilization reactors respectively.

Considering full enmeshment in the adsorption model, because no soluble biodegradable COD fraction is hypothesized, the filtered COD values in the contact reactor, stabilization reactor and the effluent are predicted as constant, equal to the concentration of soluble unbiodegradable COD in the influent (Fig. 4.22). In contrast, the bi-substrate hypothesis, because it assumes different metabolism rates for the soluble and the particulate COD, predicts a marked cyclic behaviour of the soluble COD in the contact reactor and the effluent and a low, virtually constant value equal to the unbiodegradable soluble COD in the stabilization reactor.

With regard to the soluble COD concentrations, the experimental data shows the same behaviour as that predicted by the bi-substrate model, although the observed filtered COD values in the contact reactor and effluent are higher than predicted during the square wave loading phase (Fig. 4.23). Therefore, despite the fact that the full enmeshment bi-substrate model under predicts the observed average filtered COD concentration in the effluent by about 11% (Table 4.14), the bi-substrate hypothesis gives a very much more realistic description of the COD concentrations in the CSP than the adsorption hypothesis.

In the partial enmeshment version of the adsorption and bi-substrate models, both the filtered COD concentration in the contact reactor and the unfiltered COD concentration in the effluent can be compared. Considering the unfiltered COD concentration in the effluent both models give satisfactory correspondence between experimental and theoretical values. (Figs. 4.24 and 4.25).

The average mass of COD leaving the system per litre of effluent, MS_{te}*, is underpredicted by the adsorption model by approximately 6%, whereas the bi-substrate model overpredicts the value by the same amount. However, the filtered COD concentrations in the contact reactor again underline the superiority of the bi-substrate hypothesis in predicting the presence of soluble biodegradable COD in the contact reactor. (Table 4.14).

It would appear therefore that the bi-substrate hypothesis is superior to the adsorption hypothesis in predicing the COD concentrations in the CSP, and that the partial enmeshment version of the model is marginally better than the full enmeshment version. This assessment, however, is not clear cut enough to justify the adoption of the partial enmeshment version of the bi-substrate model without making further comparisons between other theoretical and experimental parameters. Comparisons that can be made are (1) VSS concentrations in the reactors, (2) oxygen consumption rates, (3) TKN and (4) Nitrate concentrations in the reactors.

(1) VSS concentrations

The theoretical predictions for the four versions are shown in Figs. 4.22 to 4.25. The cyclic changes are all in excellent agreement with the experimental observations.

With regard to the average concentrations of sludge in the system, (X_{vp}), shown in Table 4.14, all four versions of the model give concentrations which are within 4% of each other, and although all the predictions are lower than the experimentally observed values, they are all within 7% of it. It would appear therefore, that no additional evidence in support of the partial enmeshment bi-substrate version over the others can be derived from studying the VSS concentration predictions.

(2) Oxygen consumption rate

(a) In the contact reactor:

Before analysing the difference between the theoretical and experimental oxygen consumption rates in the contact reactor, the severity of the test being placed on the predictive powers of a general activated sludge model must be clearly understood. During the square wave flow period 9% of the

sludge in the process removes approximately 80% of the influent COD and 70% of the influent TKN in a contact time of 23 minutes. Therefore, with the relative lack of sophistication inherent in models at this stage of our knowledge, the best that can be hoped for with a parameter as sensitive as the oxygen consumption rate in the contact reactor is that the trends in its cyclic behaviour pattern are correctly predicted. Too much emphasis therefore must not be placed on the finer details of cyclic behaviour patterns or on absolute values of the oxygen consumption rate in the contact reactor.

The adsorption hypothesis predicts a markedly cyclic behaviour which closely follows the square wave feed pattern (Figs. 4.22 and 4.24), whereas the experimental values remain virtually constant throughout the whole cycle. Furthermore, Table 4.14 shows that the adsorption hypothesis overpredicts the average oxygen consumption rate in the contact reactor by 22%. In contrast, the bi-substrate hypothesis predicts a pattern which is much closer to the experimentally observed values (Figs. 4.23 and 4.25). However, the bi-substrate hypothesis does predict a tendency for the values to increase gradually during the square wave feed period, whereas the experimentally observed values remain relatively constant throughout the whole cycle. The average value given in Table 4.14 shows the bi-substrate theory overpredicts the oxygen consumption rate in the contact reactor by 12%.

The fact that the oxygen consumption rate in the contact reactor remains virtually constant throughout the cycle is an observation not at all to be expected from experience of activated sludge behaviour. Intuitively it would be expected to follow the same cyclic response pattern as the influent feed, similar to the way predicted by the adsorption hypothesis. In order to understand the reasons for this behaviour, it must be appreciated that it is due to a hydraulic phenomenon in the CSP: Earlier in this chapter the point was made that as the recycle ratio increases the CSP approaches a completely mixed condition. Now the recycle flow remains constant at a selected value of twice the average influent flow rate throughout the cycle, so that during the base influent flow period the recycle ratio is in fact equal to $(2 \times 36)/18 = 4$. Hence the process

is closer to a completely mixed situation than when it is subjected to the square wave flow, when the recycle ratio is equal to (2 x 36)/54 = 1,33. This is reflected in the behavioural pattern of the VSS concentrations in the contact and stabilization reactors where it can be seen that the difference between the concentrations increases when the recycle ratio decreases because the VSS get "washed out" of the contact reactor by the high influent flow rate.

The cyclic behavioural pattern of the sludge concentration in the contact reactor described above is the key to explaining the relative constancy of the oxygen consumption rates observed experimentally. This is clearly illustrated in Figs. 4.26 and 4.27, which show the variation of the X_{ac}, O_{ac}, O_{sc}, O_{ec}, O_{nc} and O_{tc} concentrations in the contact reactor predicted by the bi-substrate and adsorption hypotheses respectively. Dealing with the bi-substrate hypothesis predictions first: When the square wave flow period commences, the availability of substrate in the contact reactor increases, and therefore the oxygen consumption rate for synthesis, O_{sc}, increases. However, concomitant with the increase in the substrate, there is a decrease in the concentration of active mass, X_{ac}, in the contact reactor and hence a decrease in the oxygen consumption rate for endogenous respiration. Because nitrification is taking place virtually at the maximum rate in the contact reactor even under base flow conditions, as the *nitrosomonas* get "washed out" by the square wave flow, the oxygen consumption rate for nitrification decreases. Hence the increase in oxygen consumption rate of synthesis and the decrease for endogenous respiration and nitrification tend to cancel, giving rise to the constancy of the total oxygen consumption rate.

During the square wave flow period the active mass of the whole process gradually increases due to the high metabolism rate. The values of X_{ac}, O_{sc}, O_{ec} and O_{nc} increase accordingly, resulting in a gradual increase in O_{tc}. At the point in time at which the square wave flow is switched off, X_{ac} increases sharply to the value under the base flow, inducing a corresponding sharp increase in O_{ec} and O_{nc}. However, the organisms still have a large mass of particulate substrate stored and the level of soluble substrate concentration in the contact reactor is still relatively high. Hence the oxygen demand for synthesis, O_{sc}, does not decrease as rapidly as

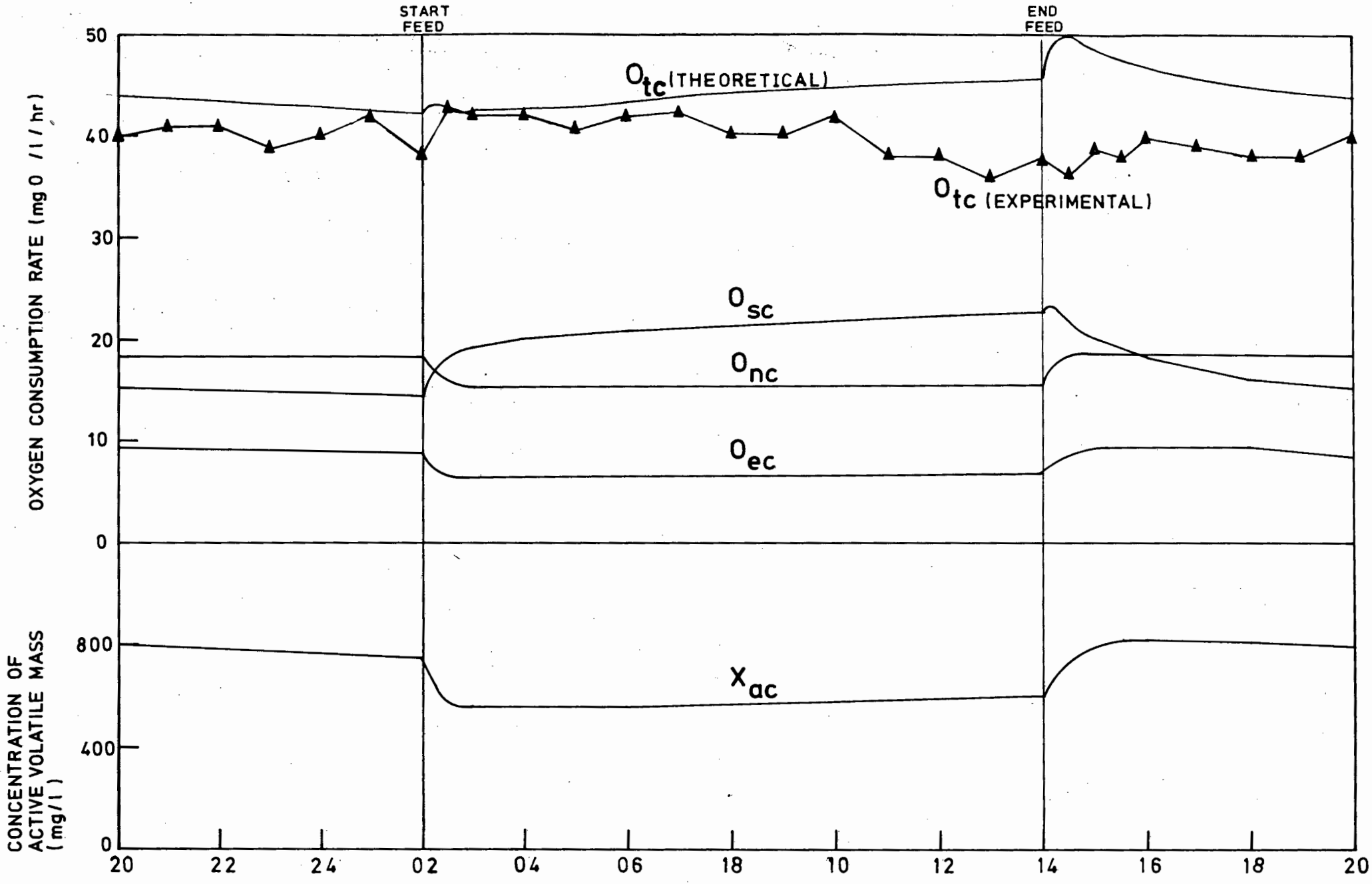


Fig. 4.26 *Comparison of how the oxygen consumption rates for synthesis, endogenous respiration and nitrification predicted by the partial enmeshment bi-substrate model vary with the predicted VASS concentration in the contact reactor.*

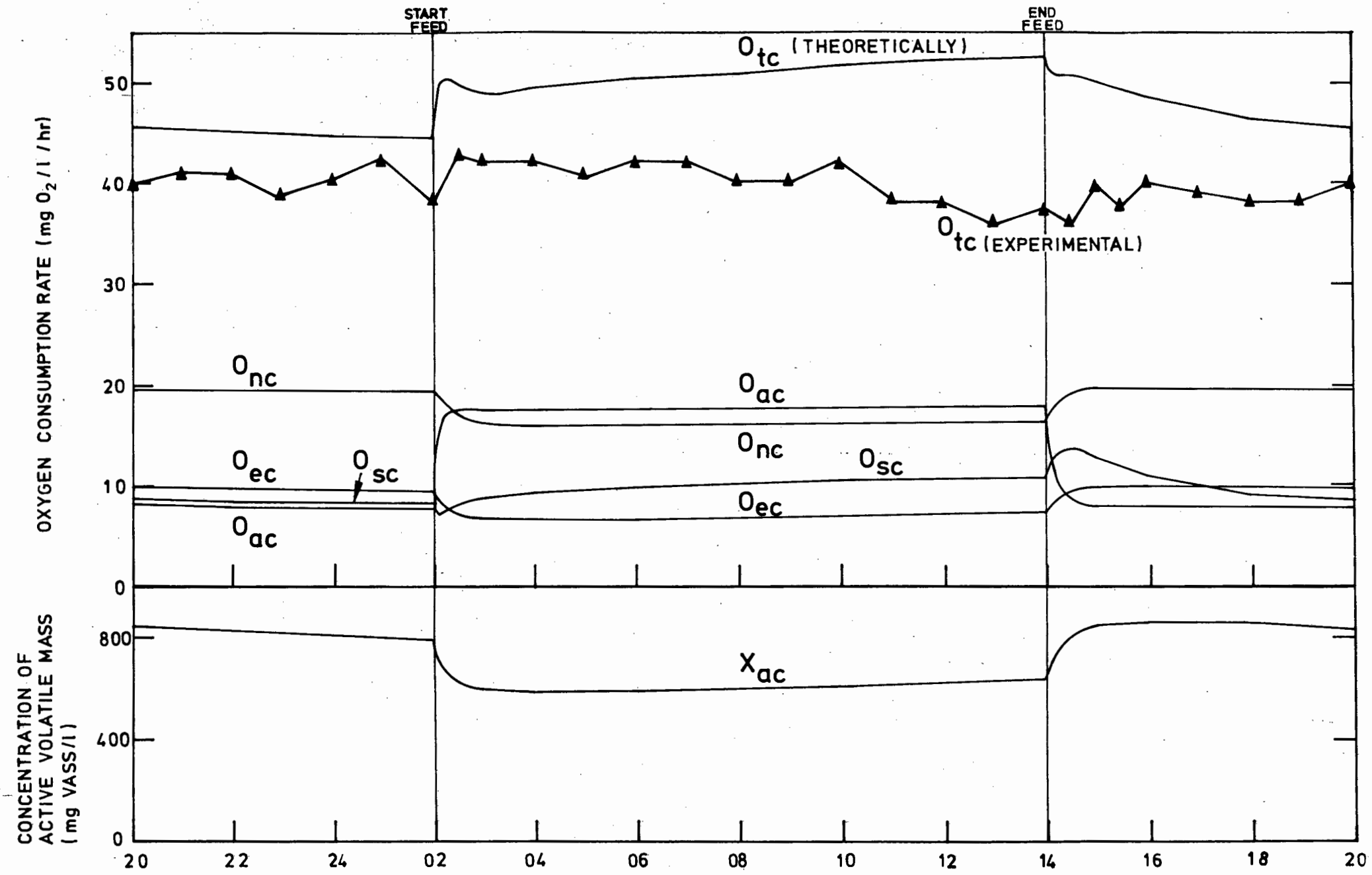


Fig. 4.27 *Comparison of how the oxygen consumption rates for adsorption, synthesis, endogenous respiration and nitrification predicted by the partial enmeshment adsorption model vary with the predicted VASS concentration in the contact reactor.*

the increase in O_{ec} and O_{nc} giving rise to the theoretically predicted sharp upward trend in O_{tc} immediately subsequent to the switching off of the square wave flow.

In the case of the adsorption hypothesis, analysed in Fig. 4.27, the drop in the oxygen consumption rate for endogenous respiration, O_{ec}, and nitrification, O_{nc}, is not enough to cancel out the sharp increase in the oxygen consumption rate for adsorption, O_{ac}, while O_{sc} only increases very gradually as the concentration of X_{ac} builds up in the process. This, according to the adsorption hypothesis, results in the square wave shaped cyclicity in the total oxygen demand in the contact reactor.

The fact that neither of the above two cyclic responses predicted by the bi-substrate and adsorption hypotheses accurately reflect the constant response observed experimentally in the contact reactor is probably due to the inherent deficiencies in the experimental procedures for measuring the oxygen consumption rate. Unfortunately, due to the extreme sensitivity of the oxygen consumption rate in the contact reactor, the experimentally observed values of O_{tc} cannot be divided up satisfactorily into their constituent components in the same way as the theoretical values can.

It is very likely that the sharp localised peak predicted by the bi-substrate hypothesis just after the cessation of the square wave feed can be missed by the experimental testing procedure, but it is less likely that the more prolonged peak predicted by the adsorption hypothesis will escape detection experimentally. In the experimental investigation no special care was taken to pick up the localised peak predicted by the bi-substrate hypothesis because at the time the bi-substrate model had not yet been properly calibrated and was predicting a square wave cyclicity more severe than that predicted by the adsorption theory. It was only after the data generated in the investigation was used to calibrate the bi-substrate model that an awareness of the possible existence of the localised peak arose. In retrospect it would have been preferable to have applied a square wave loading pattern more severe than that used and to have monitored more thoroughly the period immediately after the termination of the square wave flow.

Because the oxygen consumption rate in the contact reactor is dominated by the requirements for assimilation of soluble COD and nitrification, it is not affected by the degree of enmeshment of particulate COD by the sludge floc. Hence, whereas it would appear that the bi-substrate hypothesis provides a more accurate prediction of the oxygen consumption rate in the contact reactor than the adsorption hypothesis, it is not possible to establish from this parameter whether the partial enmeshment version of the bi-substrate model is preferable to the full enmeshment version. The analysis of the oxygen consumption rate in the stabilization reactor does, however, allow a decision to be made about which of the two versions is preferable.

(b) In the stabilization reactor:

In the stabilization reactor both the adsorption and the bi-substrate full enmeshment models predict virtually identical values for the oxygen consumption rate, but the theoretical values are approximately 12% higher than the experimentally observed values (Fig. 4.22 and 4.23). The partial enmeshment versions of the adsorption and bi-substrate models also predict identical values, but there are far closer to the experimentally observed values than the full enmeshment versions, the overprediction only being about 6% (Fig. 4.24 and 4.25). The reason that partial enmeshment versions give better predictions for the oxygen consumption rate in the stabilization reactor is that it allows particulate unassimilated COD to escape from the system in the effluent, thus diminishing the COD load on the stabilization reactor. From Table 4.14 it is evident that the process oxygen demand for nitrification, O_{np}, is overpredicted by all four models, whereas the oxygen consumption rate for carbonaceous degradation, O_{cp}, is very accurately predicted by the partial enmeshment bi-substrate model. Because most of the biological activity takes place in the stabilization reactor, the trends in the average process oxygen consumption rates mentioned above are likely to be also evident in the stabilization reactor.

The plotted experimental and theoretical partial enmeshment bi-substrate values of O_{ns}, O_{cs} and O_{ts} are shown in Fig. 4.28. It can be seen that the correspondence between the experimental and theoretical values of O_{cs} is considerably better than that for the O_{ts} values. During the base flow period O_{cs} is underpredicted whereas O_{ns} is

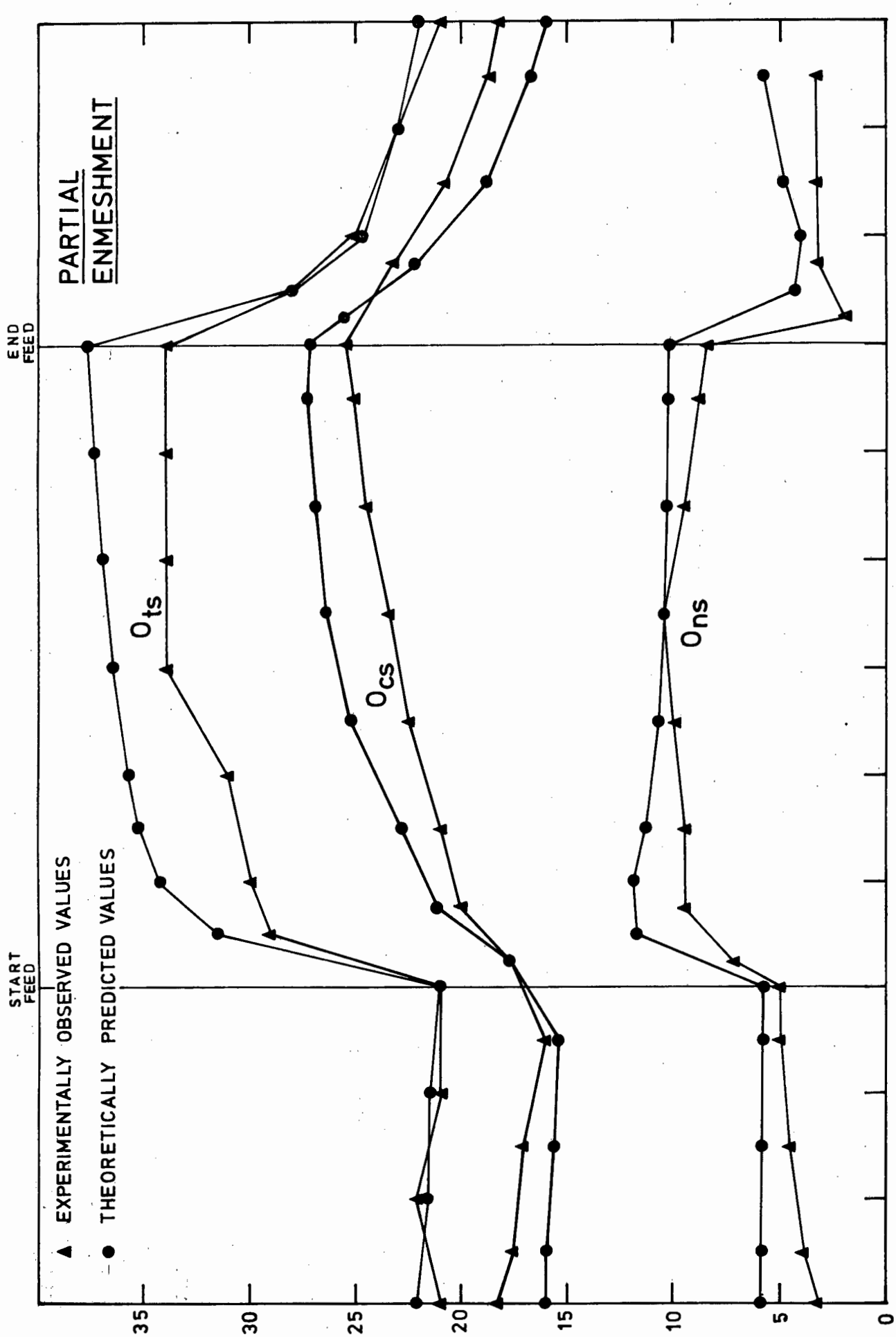


Fig. 4.28 *Comparison between the oxygen consumption rates for carbonaceous degradation and nitrification predicted by the partial enmeshment bi-substrate model and those observed experimentally in the stabilization reactor.*

overpredicted. This means that when O_{ns} and O_{cs} are added together to form O_{ts} they tend to cancel one another out, and the total oxygen consumption rate is thus apparently accurately predicted under base flow conditions. However, during the square wave flow period both O_{ns} and O_{cs} are overpredicted which results in O_{ts} being overpredicted.

In the case of the full enmeshment bi-substrate model; theoretical values of O_{ns}, O_{cs} and O_{ts} are plotted with the experimentally observed values in Fig. 4.29, and it can be seen that the carbonaceous oxygen consumption rate is overpredicted to a much large extent than by the partial enmeshment version.

The detailed analysis of the oxygen consumption rates in the contact and stabilization reactors discussed above strongly support the partial enmeshment bi-substrate model as the one which most accurately predicts the oxygen consumption rates in the CSP.

(3) TKN Concentrations

All four versions of the model very accurately predict the experimentally observed filtered TKN concentrations in the contact reactor. The average values, N_{tc}, in Table 4.14 are all within 4% of the experimentally observed values, and Figs. 4.22 to 4.25 all show an excellent correspondence between experimentally observed and theoretically predicted values. Thus this parameter is of no use in establishing the relative merits of the four versions of the model; the same comment applies to the TKN concentration in the stabilisation reactor: The predicted values all stay virtually constant at 2,3 mg/ℓ throughout the cycle whereas the experimentally observed values are randomly scattered round 4,2 mg/ℓ. This difference can easily arise due to a larger quantity of very slowly biodegradable TKN than is usually found in Strandfontein sewage, being present in the batch of sewage used for the test.

(4) Nitrate Concentration

The nitrate concentration in the contact and stabilization reactor is the one parameter which the partial enmeshment versions do not predict as well

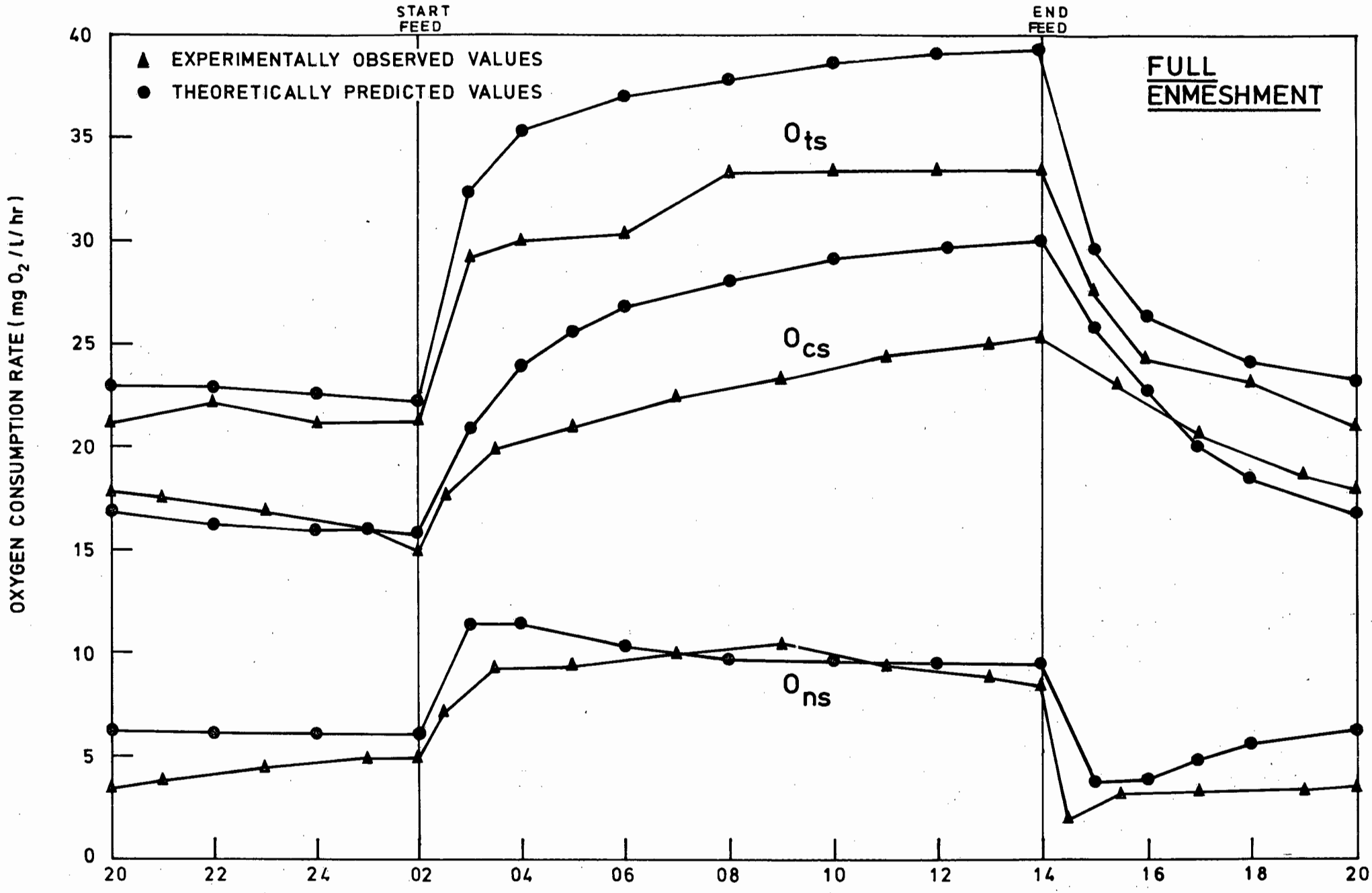


Fig. 4.29 *Comparison between the oxygen consumption rates for carbonaceous degradation and nitrification predicted by the full enmeshment bi-substrate model and those observed experimentally in the stabilization reactor.*

as the full enmeshment versions. In Figs. 4.22 to 4.25, whereas the cyclic behavioural pattern observed experimentally is similar to that predicted by all four versions of the model, the predicted values are all much higher than those observed. Moreover, the full enmeshment versions (Fig. 4.22 and 4.23) are much closer to the observed values than the partial enmeshment versions (Fig. 4.24 and 4.25). In Table 4.14 the average nitrate concentration values are overpredicted by approximately 30% by the partial enmeshment versions and 20% by the full enmeshment versions.

The problem of obtaining closer fits for predicted and observed nitrate values has also been encountered by Ekama and Marais (1978): Throughout the development of the general model the nitrification aspect has been the one most prone to inconsistency between experimental and theoretical values. The reasons for this are probably the following: (i) the model accepts a very simplistic approach to the competition between the heretotrophs and the autotrophs for the use of the available TKN, (ii) nitrification is due only to two organisms, *nitrosomonas* and *nitrobacter*, instead of the wide spectrum of organisms associated with COD reduction. Consequently nitrification tends to be sensitive to temperature and pH and the presence of toxins, (iii) each of the sewage batches will have a composition unique to itself which, due to (ii) above gives rise to a different nitrification response. In the particular batch on which this 24 hour test was performed, for example, the TKN level in the stabilization reactor was consistently higher then observed on average over a period of time in prior batches. In this particular test the experimentally measured sludge concentrations and TKN lost in the effluent was higher than that predicted by the model (Table 4.14). Consequently there was less TKN available for nitrification, and hence the measured nitrates were lower than those predicted. Unless the 24 hour test is repeated a large number of times it is unlikely that an explicit statement regarding the error in the model predictions can be made.

Taking an overall view, the analysis of the square wave data would seem to indicate that the partial enmeshment bi-substrate model is the most reliable of the four models discussed in describing the response of the CSP.

4.5.1.2 Sine Wave Pattern

Full enmeshment version:

An analysis of the sine wave experimental data in terms of the full enmeshment assumption established that the additional loss of sludge in the effluent effectively reduced the sludge age from 6 to 5,6 days. Both the adsorption and bi-substrate models were run assuming full enmeshment and a sludge age of 5,6 days. The predicted and experimentally observed results can be compared in Figs. 4.30 and 4.31.

Partial enmeshment version:

For the partial enmeshment version of the adsorption and bi-substrate models, the sludge age was maintained at 6 days, and a comparison between the predicted and experimentally observed results can be made from the plots in Figs. 4.32 and 4.33.

Discussion

In Table 4.15 the averaged experimentally observed parameter values and those predicted by all four versions of the model are listed. In general the sine wave data confirms the trends which were evident in the square wave data and are discussed below under a number of headings.

COD concentrations:

The unfiltered COD concentrations in the effluent are most accurately predicted by the partial enmeshment version of both the adsorption and bi-substrate models (Figs. 4.32 and 4.33). The filtered COD concentrations in the contact reactor however, confirm the finding in the square wave analysis that the partial enmeshment adsorption model is unable to predict the observed cyclic behaviour of the filtered COD concentrations in the contact reactor. In contrast, the bi-substrate version predicts a cyclic response in the filtered COD values in the contact reactor, although the predicted values are slightly lower than those observed.

In the stabilization reactor all four versions accurately predict the COD concentrations and this parameter does not therefore provide evidence for or against any of the versions. However, taking account of the behaviour in the contact

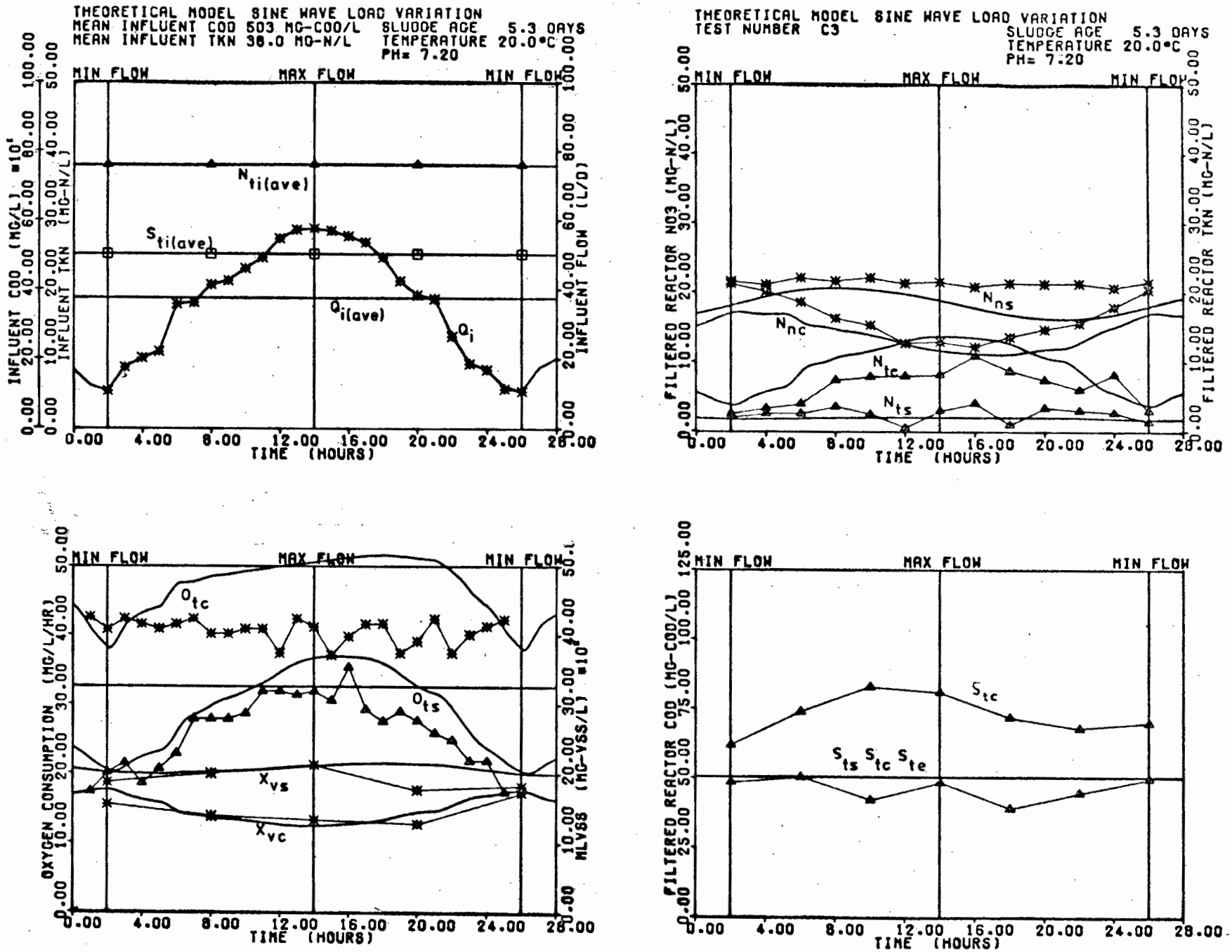


Fig. 4.30 *Comparison between the response predicted by the adsorption full enmeshment model and that observed experimentally for a CSP unit subjected to a sine wave cyclic loading pattern.*

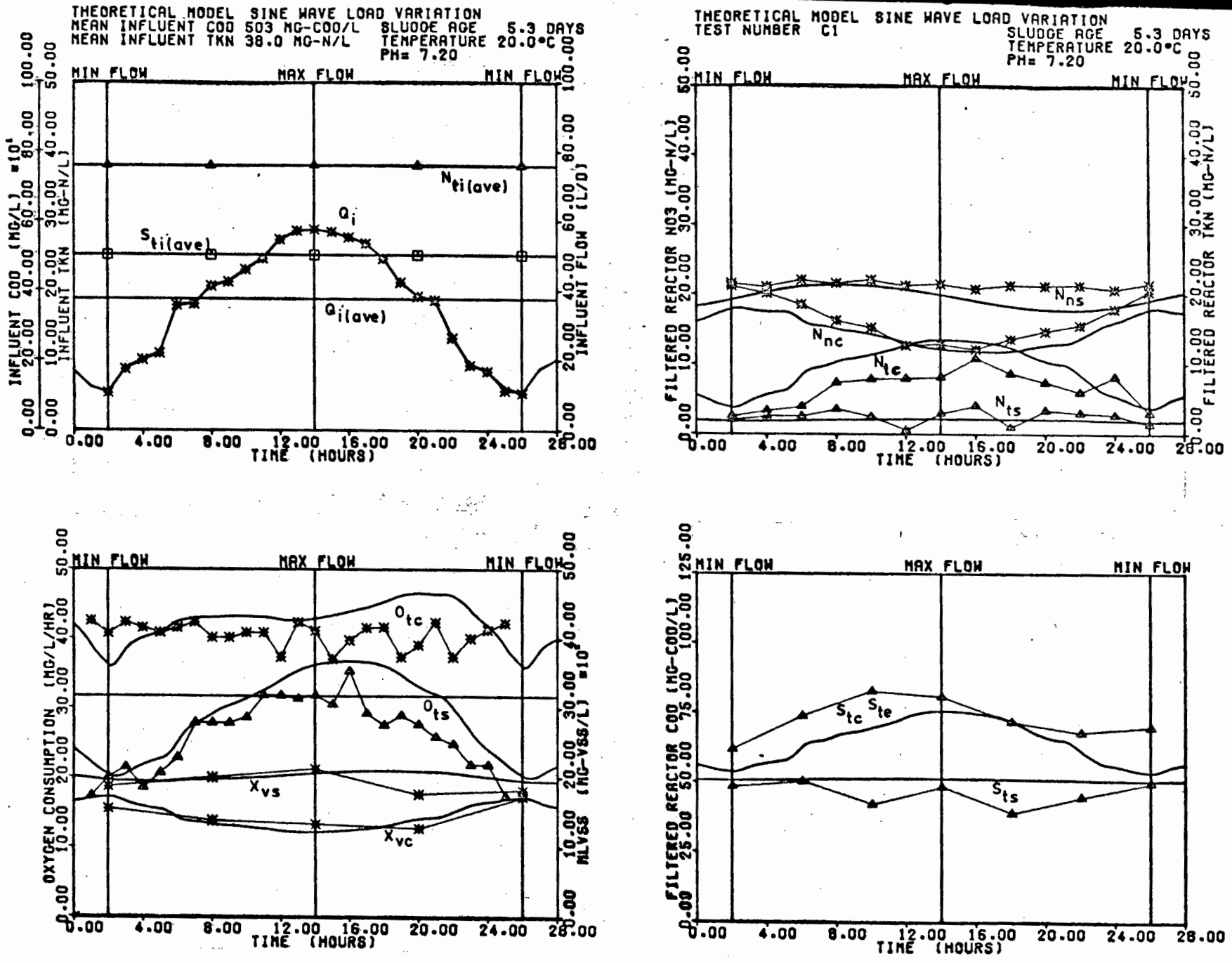


Fig. 4.31 *Comparison between the response predicted by the bi-substrate full enmeshment model and that observed experimentally for a CSP unit subjected to a sine wave cyclic loading pattern.*

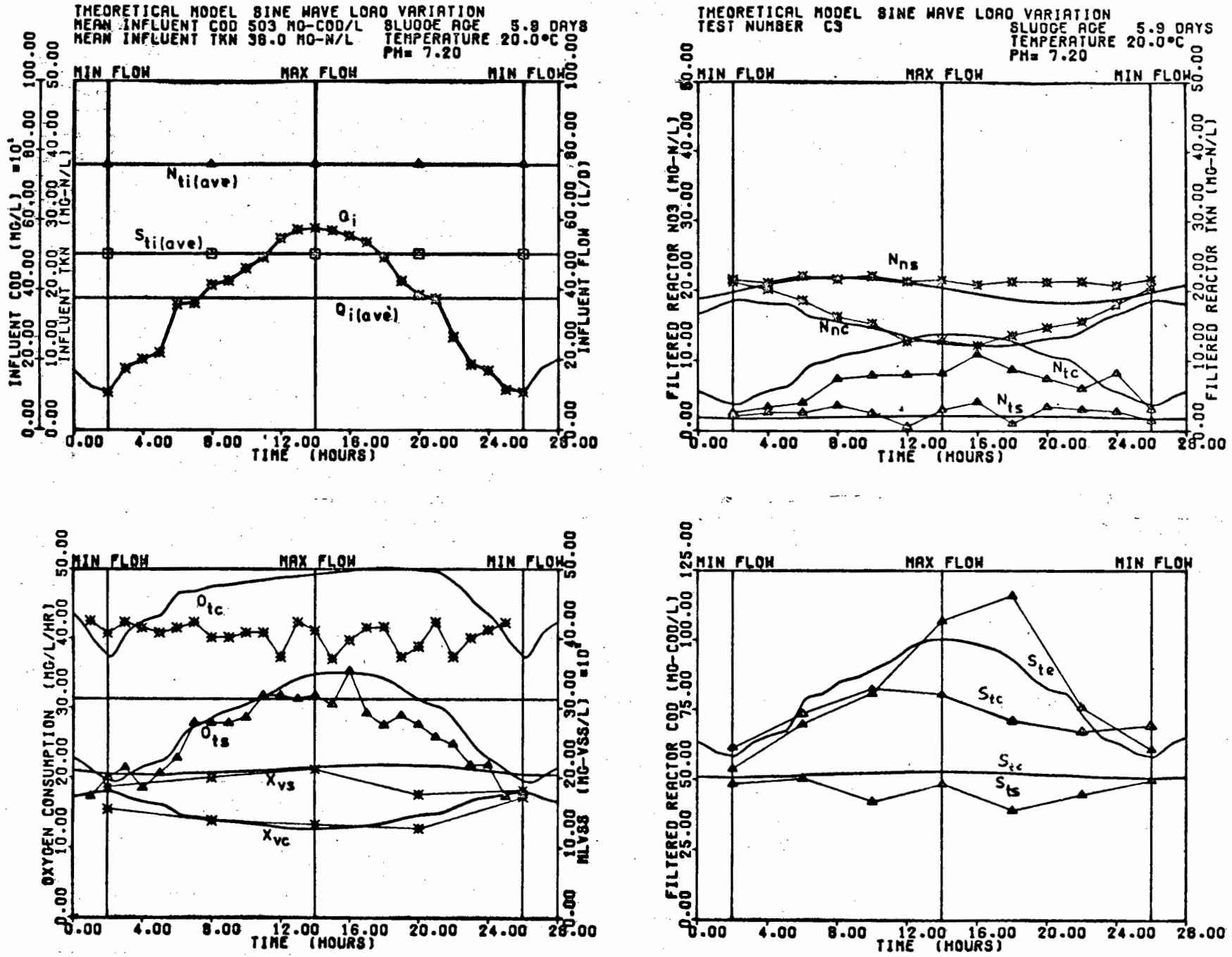


Fig. 4.32 *Comparison between the response predicted by the adsorption partial enmeshment model and that observed experimentally for a CSP unit subjected to a sine wave cyclic loading pattern.*

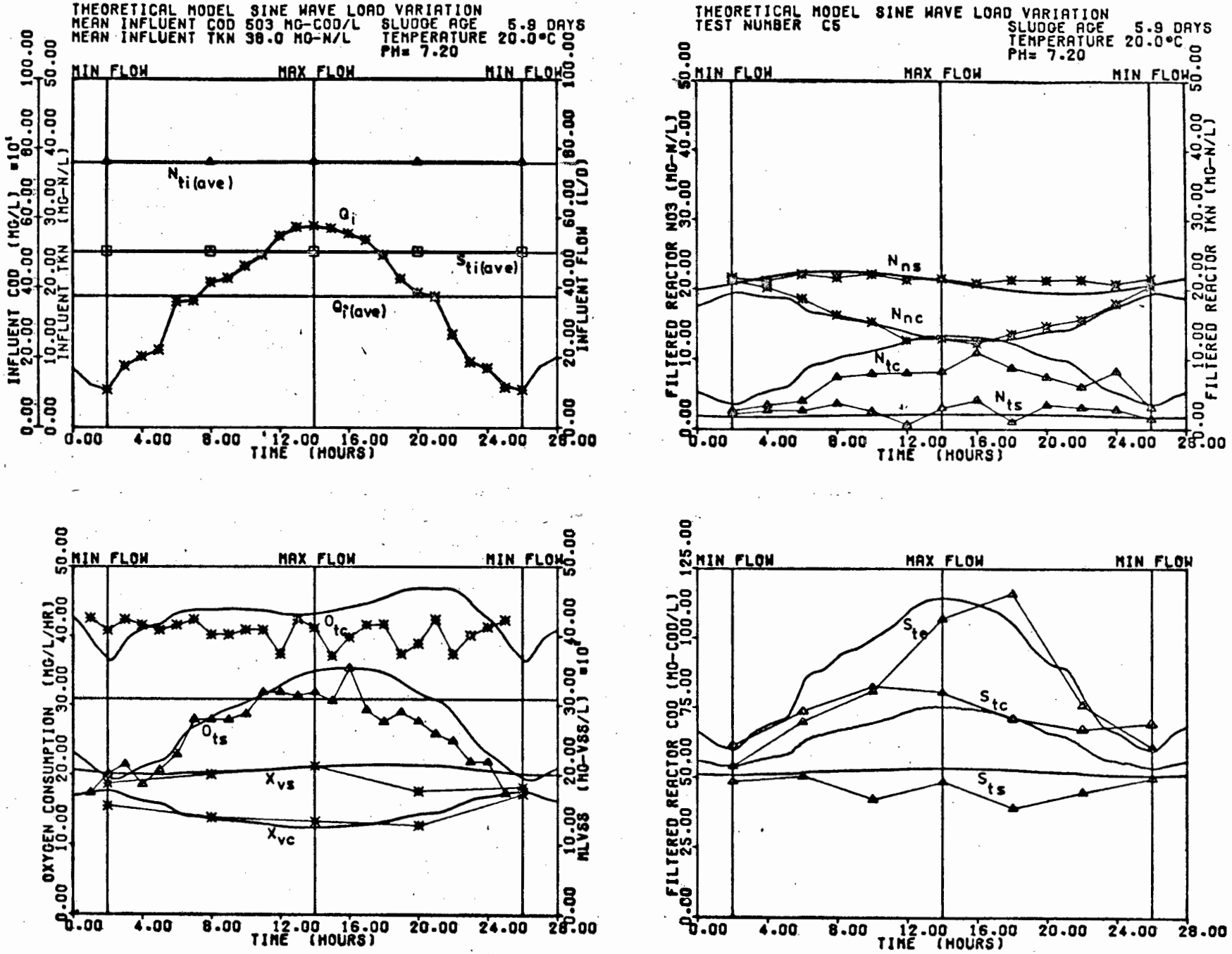


Fig. 4.33 *Comparison between the response predicted by the bi-substrate partial enmeshment model and that observed experimentally for a CSP unit subjected to a sine wave cyclic loading pattern.*

reactor described in the previous paragraph, the partial enmeshment bi-substrate model can be seen to give the best overall predictions of the COD concentrations in the CSP.

VSS concentrations:

As in the case of the square wave data, the VSS concentration in the reactors is not a useful parameter in establishing the relative merits of the four models. Figs. 4.30 to 4.33 show that the correspondence between the experimental values and the predicted values is excellent, with the exception of the one value at 2000 hours. However, this value can be ignored as it was most likely due to an experimental error.

Oxygen consumption rates:

The behaviour pattern of both the predicted and experimentally observed oxygen consumptions rates in the contact and stabilization reactors for the sine wave feed pattern is very similar to that for the square wave feed pattern.

The experimentally observed rates in the contact reactor remain essentially constant throughout the cycle, whereas the two models both predict a slight cyclicity. As with the square wave feed, the adsorption model predicts an oxygen consumption rate cycle (Figs. 4.30 and 4.32) which closely follows the sine wave feed pattern, whereas the bi-substrate model predicts a less pronounced cyclicity, (Figs.4.31 and 4.33) having a peak about one quarter of a cycle out of phase with the sine wave feed pattern. The bi-substrate predictions are much closer to the observed values than the adsorption predictions. The slight cyclicity predicted by the bi-substrate model would be very difficult to establish experimentally and the fact that it was not observed during this test cannot be considered as evidence against the bi-substrate hypothesis.

All the models overpredict the oxygen consumption rate in the stabilization reactor in exactly the same fashion as for the square wave feed pattern. The data in Table 4.15 shows that the full enmeshment versions of both the adsorption and bi-substrate models overpredict the average experimentally observed values by approximately 9% while the partial enmeshment versions of the models overpredict it by 5%.

Table 4.15 Comparison of parameter values averaged over full cycle for the sine wave cyclic test

Parameter	Experimental	Bi-substrate with full enmeshment	Adsorption with full enmeshment	Bi-substrate with partial enmeshment	Adsorption with partial enmeshment
X_{vc}	1422	1405	1445	1447	1472
X_{vs}	1945	2015	2072	2078	2113
X_{vp}	1872	1929	1984	1990	2023
MX_{vw}	4723	5042	5186	4763	4845
O_{tc}	41	42,8	47,9	43,5	46,8
O_{ts}	27,5	29,8	30,0	28,8	28,7
O_{np}	7,5	6,9	6,5	7,4	7,1
O_{cp}	21,9	24,8	26,0	23,5	24,2
O_{tp}	29,4	31,6	32,5	30,9	31,3
S_{tc}	74	65	50	65	50
S_{ts}	48	51	50	53	50
MS_{te}*	87	-	-	98	88
MS_{te}	78	69	50	-	-
N_{tc}	6,9	9,7	9,9	9,5	9,9
N_{ts}	2,6	2,0	2,0	2,0	2,0
MN_{te}	8,6	11,0	11,2	10,9	11,4
N_{nc}	16,0	14,4	13,8	15,6	15,0
N_{ns}	21,4	19,6	18,5	21,1	20,2
MN_{ne}	15	12,9	13,2	15,4	14,8

X_{vc}, X_{vs} and X_{vp} = the average sludge concentrations in the contact reactor, stabilization reactor and overall process respectively (mg/ℓ)

MX_{vw} = total mass of sludge wasted daily (mg/day)

O_{tc}, O_{ts} = the average mass of oxygen utilized in the contact and stabilization reactors respectively (mg/ℓ/hr)

O_{np}, O_{cp}, O_{tp} = the average process oxygen utilization rates for nitrification, carbonaceous degradation and the total, respectively (mg/ℓ/hr)

S_{tc}, S_{ts} = the average filtered COD concentrations in the contact and stabilization reactors respectively.

MS_{te}*, MS_{te} = the respective average unfiltered and filtered masses of COD leaving the system per litre of effluent.

N_{ti}, N_{ts} = average filtered TKN concentration in the contact and stabilization reactors respectively (mg/ℓ).

MN_{te} = the average unfiltered TKN mass leaving the system per litre of effluent.

N_{nc}, N_{ns} = the average concentrations of nitrate in the contact and stabilization reactors respectively.

MN_{ne} = the average mass of nitrate leaving the system per litre of effluent.

Nitrification:

The sine wave data bears out the comments made earlier about the unpredictability of the nitrification process. Consider only the partial enmeshment bi-substrate model. In the square wave test the TKN concentration in the contact reactor was closely predicted but the concentrations in the stabilization reactor underpredicted by 2 mg/ℓ. The nitrate concentrations in both reactors were overpredicted by at least 20%. In this set of data the average value of the TKN concentration in the contact reactor is overpredicted by 38% (2,6 mg/ℓ) and the concentration in the stabilization reactor is accurately predicted, (Table 4.15). The average nitrate concentrations in the two reactors are predicted within 2% of the experimental values. Furthermore, Fig. 4.33 shows that there is an excellent correlation between the cyclic behaviour of the experimental and theoretical nitrate concentrations.

It is evident from comparing square wave and sine wave responses that the nitrification kinetics are very sensitive to extraneous influences which cannot be identified simply by examining the data. It must therefore be expected that random fluctuations of the TKN and nitrate concentrations will be exhibited between sets of data.

The analysis of the sine wave data is not as complete as that of the square wave data as it was accepted that the partial enmeshment bi-substrate model is the most reliable one. The predicted response of this model when applied to the sine wave data is not at variance with the acceptance of the partial enmeshment bi-substrate model and in fact confirms that the model is reliable.

The reliability of the partial enmeshment bi-substrate model in predicting the response of the CSP is confirmed further by the time invariant investigation.

4.5.2 Time invariant Flow and Load Conditions

4.5.2.1 Unit run at 20°C and 6 day nominal sludge age

For the full enmeshment version of the adsorption and bi-substrate models the actual sludge age was calculated to be 5,1 days. Both the adsorption and the bi-substrate models were run for a sludge age of 5,1 days with full enmeshment and for a sludge age of 6 days with partial enmeshment of 40%. The predicted average results together with the experimental observations are shown in Table 4.16.

COD concentrations:

Of the four versions of the model the partial enmeshment bi-substrate model once again predicts the COD values in the contact reactor, stabilization reactor and the effluent most accurately and the shortcomings of the adsorption model in predicting the effluent quality of the CSP are once again demonstrated.

VSS concentrations:

All four versions of the model overpredict the VSS concentrations, but the partial enmeshment version of both the adsorption and bi-substrate models overpredicts the values more than the full enmeshment version.

This large discrepancy is surprising in the light of the previously analysed data. The problem appears to lie with the experimental data, because the average experimental process VSS concentrations (X_{vp}) for the square wave and sine wave given in Tables 4.14 and 4.15 compare well with one another but are both about 13% higher than the results observed for the steady feed tests. Theoretically these should be the same because the sludge age, process loadings and reactor volumes were identical for all three tests series. An explanation for this discrepancy may possibly be found in the nature of the sewage itself.

The sewage used in this series of tests was initially collected from the Strandfontein sewer at approximately midday, but because of the high TKN load in this sewage it was decided for the subsequent series of tests to collect the sewage later in the day when the TKN concentration was lower. The high TKN concentration may have been associated with an industrial waste which had a low inert COD fraction, which then would have resulted in the low VSS concentrations observed experimentally. A lower value of f_{up}, when applied in the model shows not only a drop in the predicted VSS value, but it also narrows the gap between the X_{vp} values predicted by the full and partial enmeshment versions of the model. When f_{up} was reduced from 0,09 to 0,05 the MLVSS in the two reactors was far more accurately predicted by all four versions of the model. In the partial enmeshment version of the model, the value of X_{vp} is more sensitive to the value of f_{up} because the effective sludge age is 6 days for the partial enmeshment as opposed to 5,1 days for the full enmeshment version.

Oxygen consumption rate:

The oxygen consumption rate in the contact reactor is closely predicted by all the models with the partial enmeshment bi-substrate model being

Table 4.16 Average daily results for unit run under steady feed conditions at a nominal sludge age of 6 days and at 20°C

Parameter	Experimental	Adsorption with full enmeshment	Bi-substrate with full enmeshment	Adsorption with partial enmeshment	Bi-substrate with partial enmeshment
S_{ti}	512	512	512	512	512
S_{ts}	54	51	52	53	53
S_{tc}	62	51	65	53	65
S_{te}	90	51	65	80	87
N_{ti}	56	56	56	56	56
N_{ts}	1,7	2,3	2,4	2,3	2,3
N_{tc}	11	14,6	14,4	14,4	13,9
N_{te}	15	14,6	14,4	14,4	13,9
N_{ns}	36	36	37	38	38
N_{nc}	27	27	28	29	29
X_{vs}	1772	1949	1914	2115	2093
X_{vc}	1301	1383	1358	1496	1480
X_{vp}	1706	1866	1833	2025	2003
O_{ts}	32	34,1	34,2	33,5	33,7
O_{tc}	61	62,6	57,3	64,2	61,7
O_{tp}	36	38,2	37,5	38,0	37,8
O_{cp}	23	25,1	24,2	24,3	23,8
O_{np}	13	13,1	13,3	13,7	14,0

slightly better than the rest. The oxygen consumption rate in the stabilization reactor is slightly overpredicted by all the models, with the partial enmeshment versions being marginally more accurate than the full enmeshment versions. However, all these values are so close to one another that it can be concluded that all four versions of the model satisfactorily predict the oxygen consumption rate for the CSP under steady feed conditions.

Nitrification:

The nitrification process is relatively well described by all the models. They all overpredict the TKN concentrations in the contact reactor but the TKN concentration is relatively well predicted in the stabilization reactor. The nitrate concentrations in both the reactors are accurately predicted by the full enmeshment versions of both the adsorption and bi-substrate models, whereas the partial enmeshment versions overpredict the values by approximately 6%.

4.5.2.2 Unit run at 20°C and 10 day nominal sludge age

For the full enmeshment version of the adsorption and bi-substrate models the actual sludge age was calculated to be 9,7 days. Both the adsorption and the bi-substrate models were run on the computer for a sludge age of 9,7 days with full enmeshment, and for a sludge age of 10 days with partial enmeshment of 40%. The theoretical and experimental data are shown in Table 4.17.

COD concentrations:

The experimental COD concentrations in the contact and stabilization reactors and in the effluent are not accurately predicted by the model. In the stabilization reactor the filtered COD concentration is overpredicted relative to the observed experimental values. This would indicate that the soluble unbiodegradable fraction of the Strandfontein sewage, f_{us}, used during the investigation is not in fact all unbiodegradable but contains a percentage of organic material which is very slowly biodegradable. The decrease in the Food/Micro-organism ratio brought about by the use of a longer sludge age, coupled with the longer retention time in the reactors as a result of the lower influent and recycle flows resulted in more of the very slowly biodegradable soluble fraction of the influent being assimilated in the process. Although the bi-substrate hypothesis also underpredicts the filtered COD concentration in the contact reactor, it accurately predicts the difference between the filtered COD concentrations in the contact and stabilization reactors. Thus the soluble biodegradable COD concentration in the contact reactor (i.e. $S_{tc} - S_{ts}$) is accurately predicted by the bi-substrate hypothesis.

Table 4.17 Average daily results for a unit run under steady feed conditions at a nominal sludge age of 10 days and at 20°C.

Parameter	Experimental	Adsorption with full enmeshment	Bi-substrate with full enmeshment	Adsorption with partial enmeshment	Bi-substrate with partial enmeshment
S_{ti}	496	496	496	496	496
S_{ts}	42	50	50	51	51
S_{tc}	52	50	61	51	61
S_{te}	61	50	61	76	82
N_{ti}	47	47	47	47	47
N_{ts}	4,8	1,8	1,9	1,9	1,9
N_{tc}	10,5	10,7	10,4	10,9	10,4
N_{te}	12,0	10,7	10,4	10,9	10,4
N_{ns}	29	31	32	31	32
N_{nc}	22	24	25	25	25
X_{vs}	2073	2046	2018	2024	2008
X_{vc}	1478	1425	1406	1411	1399
X_{vp}	1990	1956	1929	1936	1920
O_{ts}	21	22	22	21	21
O_{tc}	42	51	48	49	48
O_{tp}	24	26	26	25	25
O_{cp}	17	18	18	17	17
O_{np}	7	8	8	8	8

The partial enmeshment versions of the adsorption and bi-substrate models both overpredict the unfiltered COD concentrations in the effluent. This behaviour is to be expected due to the fact that, with the longer hydraulic retention times in the contact reactor, the enmeshment during a 10 day sludge age experiment should be more efficient than during the shorter sludge age tests. The increase in the enmeshment efficiency as the sludge age is increased should be taken into account in the design of a CSP plant. The enmeshment fraction is not constant, but increases with the sludge age although the relationship

for the efficiency with respect to sludge age is not yet qualified. The nature of the CSP configuration therefore results in the effluent quality of the process being more sensitive to sludge age than a CMAS process.

VSS concentrations:

All four versions of the model predict the VSS concentrations in the contact and stabilization reactors to be within 3% of the experimentally observed values. This parameter again, therefore, is of no use in assessing the relative merits of the various versions of the model.

Oxygen consumption rates:

All four versions of the model overpredict the oxygen consumption rate in the contact reactor (Table 4.17). This is possibly due to the lower nitrification rate in the process illustrated by the experimental nitrifucation data. The experimental values of the oxygen consumption rate in the stabilization reactor are excellently predicted by all four versions of the model, with the partial enmeshment version of the adsorption and bi-substrate model being marginally better than the full enmeshment versions (Table 4.17). There is, however, very little to choose between the capability of the four versions of the model in predicting the oxygen consumption rate for the CSP at 10 days sludge age and 20°C.

Nitrification:

The sewage influent in this series of tests appears to have had a greater concentration of very slowly biodegradable TKN than that in the 6 day sludge age series. The residual TKN concentration measured in the stabilization reactor is 4,8 (Table 4.17) which is more than double that predicted by all four versions of the model, and very much higher than that observed during the six day sludge age series. This is contrary to expectations as the nitrification Food/Micro-organism ratio is lower than at 6 days sludge age and the hydraulic retention times in the reactors are longer.

Discussion:

The experimental data shown in Tables 4.18 and 4.19 cannot be meaningfully compared to the theoretically predicted values because, as established in Section 4.4.1.3, it does not constitute a mass balance. A mass balance is a fundamental prerequisite for establishing the authenticity of a set of experimental data, and if this prerequisite is not satisfied the data must be discarded. However, because this has been a recurring problem in experimental investigations into the activated sludge process at low temperatures it may be useful to analyse the data with a view to explaining why hitherto it has been impossible to achieve a mass balance for units run at low temperature.

Table 4.18

Average daily results for a unit run under steady feed conditions at a nominal sludge age of 6 days and at 12°C with nitrification

Parameter	Experimental	Adsorption with full enmeshment	Bi-substrate with full enmeshment	Adsorption with partial enmeshment	Bi-substrate with partial enmeshment
S_{ti}	510	510	510	510	510
S_{ts}	49	51	55	51	56
S_{tc}	55	51	79	51	79
S_{te}	69	51	79	113	128
N_{ti}	50	50	50	50	50
N_{ts}	6	2,5	2,7	2,8	2,9
N_{tc}	13,5	15,4	15,5	15,7	15,7
N_{te}	14,9	15,4	15,5	15,7	15,7
N_{ns}	29	29	30	31	32
N_{nc}	22	20	21	22	22
X_{vs}	2206	2212	2149	2129	2123
X_{vc}	1531	1580	1521	1526	1476
X_{vp}	2112	2123	2061	2045	2032
O_{ts}	25	34	33	31	31
O_{tc}	33	32	28	30	26
O_{tp}	26	34	32	31	30
O_{np}	10,5	9,7	10,0	10,4	10,6
O_{cp}	15,5	23,8	22,2	20,7	19,7

There are four factors which could explain the inability to achieve a mass balance for data obtained at low temperatures, and these are discussed below under the following headings: (1) The effluent COD concentration, (2) The oxygen consumption rates, (3) the COD/VSS ratio, P, (4) The VSS concentration.

Table 4.19
Average daily results for a unit run under steady feed conditions at a nominal sludge age of 6 days at 12°C without nitrification

Parameter	Experimental	Adsorption with full enmeshment	Bi-substrate with full enmeshment	Adsorption with partial enmeshment	Bi-substrate with partial enmeshment
S_{ti}	503	503	503	503	503
S_{ts}	64	50	54	50	55
S_{tc}	69	50	77	50	78
S_{te}	75	50	77	111	125
N_{ti}	54	54	54	54	54
N_{ts}	41	36	37	38	39
N_{tc}	41	40	41	42	42
N_{te}	43	40	41	42	42
N_{ns}	0	0	0	0	0
N_{nc}	0	0	0	0	0
X_{vs}	2124	2242	2179	2107	2059
X_{vc}	1545	1598	1540	1516	1460
X_{vp}	2043	2152	2090	2024	1975
O_{ts}	13,6	24	23	21	20
O_{tc}	24,4	22	18	19	16
O_{tp}	15	24	22	20	19

(1) The effluent COD concentration:

The imbalance observed in the COD results at low temperatures could be due to the fact that the mass of COD leaving the system in the effluent is very much higher than that measured. In order to achieve 100% COD

mass recovery for the set of data shown in Table 4.18, the COD concentration in the effluent would have to be 141 mg COD/ℓ. The measured COD concentration in the effluent is 69 mg COD/ℓ. At the same time the 12°C tests were being carried out another identical unit was being run at 20°C, and the data from the 20°C unit produced excellent COD mass balances. The COD concentration testing for both units was done at the same time in a random fashion, using the same chemicals and with the samples all on the same distillation tray. It would seem impossible that an error of the magnitude required to give a balance could be made consistently for the 12°C effluent samples when at the same time to 20°C samples were being tested correctly. Hence it can be stated with a certain amount of confidence that the problem does not lie with the measurement of the COD concentration in the effluent.

(2) The oxygen consumption rates:

Initially it was thought that the problem lay with the measurement of the oxygen consumption rates. This supposition was supported by the fact that the theoretical model reasonably accurately predicted the experimentally observed values of all the parameters except the oxygen consumption rate in the contact and stabilization reactors (Tables 4.18 and 4.19). However, when the measured process oxygen consumption rate was divided up into its carbonaceous and nitrification constituents, as follows, it was found to be accurate:

The experimental process nitrification oxygen consumption rate is calculated from the mass of nitrates leaving the system in the effluent and is found to be 10,5 mg O_2/ℓ/hr. Thus the process carbonaceous oxygen consumption rate is found to be 15,5 mg O_2/ℓ/hr. Now when the unit was run without nitrification the carbonaceous oxygen consumption rate was measured as 15,0 mg O_2/ℓ/hr, which is essentially the same as that calculated from the experimental data for the unit run with nitrification. Therefore the nitrification oxygen consumption rate was measured accurately when the unit was being run with nitrification, and thus it seems reasonable to assume that all the oxygen consumptions rates were also measured accurately.

If it is accepted that the oxygen consumption rates were correctly measured during the cold temperature tests, then it is evident from Tables 4.18 and 4.19 that all versions of the model substantially over-predict the carbonaceous oxygen demand, and thus the biological activity in the process. It would appear that the Arrhenius constants for the temperature dependency of the carbonaceous kinetic constants proposed by Ekama and Marais (1978) and adopted in this investigation in Eqs. (3.23, 3.32, 3.33, 3.37) are too low, and that the carbonaceous biological activity is retarded to a greater extent by low temperatures than previously realised. Hence at low temperatures the activated sludge process behaves to a large extent as a bio-flocculation process with a high proportion of the influent COD leaving the system with the wasted sludge in an unassimilated form. Therefore, to achieve a COD mass balance either the COD/VSS ratio of the wasted sludge is higher at 12°C than at 20°C, or the VSS concentration in the waste flow is measured incorrectly at 12°C.

(3) The COD/VSS ration, P:

If it is assumed that the measured effluent COD concentration, oxygen consumption rates and VSS concentrations are correct, then to achieve a mass balance the COD/VSS ratio, P, must be equal to approximately 2. This value is higher than any found in the literature, and no reference could be found indicating that P is temperature dependent. The fact that the sludge contains a large proportion of unassimilated COD was thought to be unlikely to affect the value of P because Ekama and Marais (1978) found that the sludge obtained from centrifuging raw sewage had a P value very similar to that for activated sludge. Thus it seems that the value of P is unlikely to change sufficiently with temperature to allow for a mass balance to be achieved. However, the possibility cannot be definitely ruled out without further intensive investigation into the problem.

(4) The VSS concentrations:

Assuming that all the other parameters are measured correctly, and that P = 1,48 at 12°C, in order to achieve a mass balance the VSS concen-

tration in the sludge waste flow from the contact reactor would have to be 2124 VSS/ℓ, which constitutes an increase of 39%. The equivalent VSS concentration in the stabilization reactor would have to be 3060. As for the other parameters already considered, it seems unlikely that a mistake of this magnitude could have been made in measuring the VSS concentrations in the 12°C unit when the VSS concentrations in the 20°C unit were being correctly measured at the same time. The only alternative is that the fault lies in the nature of the VSS itself: If the biological activity at 12°C is as low as is indicated by the measured oxygen consumption rates, then the sludge will contain a very high fraction of unassimilated COD, and the VSS concentration will build up to the level required to produce a mass balance i.e. 2124 mg VSS/ℓ. However, it may just be possible that while the VSS sample is being dried in an oven at 105°C, approximately 25% of the volatile mass may be driven off and only approximately 1500 mg VSS/ℓ remains in the sample. When the test is performed on the sludge from the 20°C unit the sludge is more stable and contains a much smaller fraction of the more volatile unassimilated COD, thus producing a more accurate result. One argument against this hypothesis is that even at 20°C one would tend not to achieve balances at <u>both</u> very short sludge ages and at very long sludge ages.

The possible inaccuracy in the VSS test would also cast doubt on the finding of Ekama and Marais that the P value for raw sewage sludge is approximately the same as for activated sludge because this finding involved performing the VSS test on raw unassimilated COD. However, it is possible that the P value for sludges containing high fractions of unassimilated COD may be higher than for sludges containing low fractions of unassimilated COD. Although the matter certainly requires a thorough investigation, a preliminary conclusion may be made that the difficulty in achieving a mass balance for an activated sludge plant run at low temperatures may be due to a combination of two factors: (1) the value of P increases with the fraction of unassimilated COD in the sludge, and (2) the standard VSS test becomes inaccurate when a high fraction of unassimilated COD is present in the sludge. This conclusion is extremely tentative and serves more as an

hypothesis to be discarded, accepted or modified in the light of an experimental investigation oriented towards testing the hypothesis.

The analysis of the experimental data does, however establish that all four versions of the model accurately predict the experimentally observed nitrification response of the CSP at 12°C (Table 4.18). Thus the Arrhenius constants adopted for the temperature dependency of the nitrification kinetic constants can be considered to be accurate.

4.5.3 The Model Kinetic Constants

The kinetic constants used in this theoretical analysis of the CSP are all given in Table 4.13. It was found that good correspondence was obtained between the adsorption model and the experimental data without changing the values of any of the constants proposed by Ekama and Marais (1978). Thus the model can be considered general enough to cover the CSP within the limitations discussed § 4.5.2.

With regard to the bi-substrate model, initially it was calibrated by compairing the predictions of the general model with the 24 hour square wave feed data for the CMAS units at 2,5 and 20 day sludge ages published by Ekama and Marais (1978). This calibration procedure gave the same values for the kinetic constants given in Table 4.13 with the exception of the maximum specific growth rate constant for the soluble substrate, K_{ms}. This constant, i.e. K_{ms} was initially given the value of 8. However when this value was used in predicting the response of the CSP to cyclic loading conditions, the oxygen consumption rate in the contact reactor displayed a very marked cyclicity which was not observed experimentally. Using the CSP data to recalibrate the bi-substrate model, a value of $K_{ms} = 3$ was found to give the best results. This value was subsequently checked by applying it in the general model and compairing the predictions obtained with the experimentally observed data of Ekama and Marais. Figures 4.34 and 4.35 show that the correspondence between the CMAS square wave observations and the values theoretically predicted by the recalibrated bi-substrate model is very good indeed. It would appear that the CMAS process is not as sensitive to K_{ms} as the CSP, so that a wide variation in K_{ms} leads to minor changes

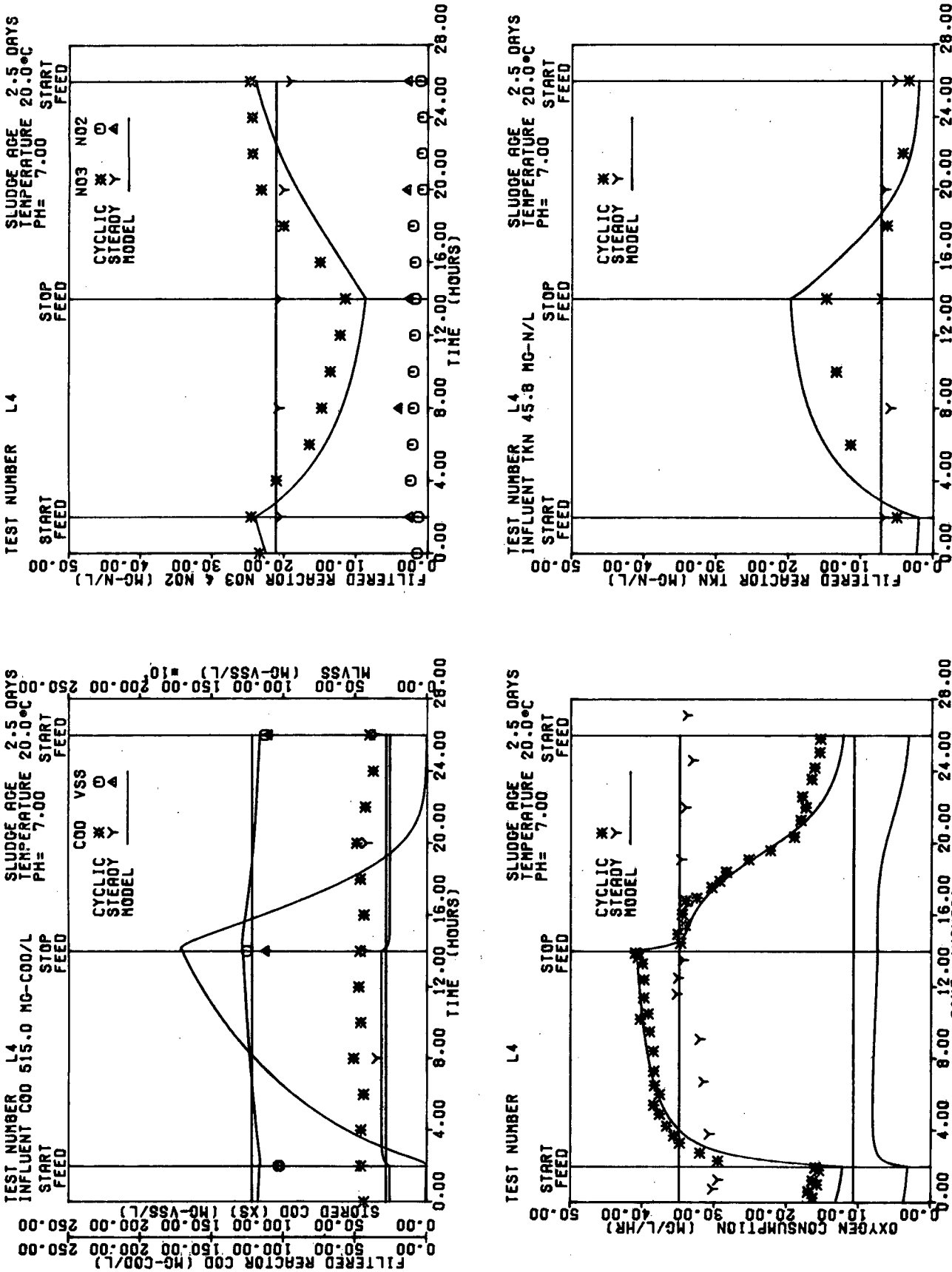


Fig. 4.34 *Comparison between the response predicted by the recalibrated bi-substrate general model and that observed experimentally for a CMAS unit subjected to a square-wave loading pattern.*

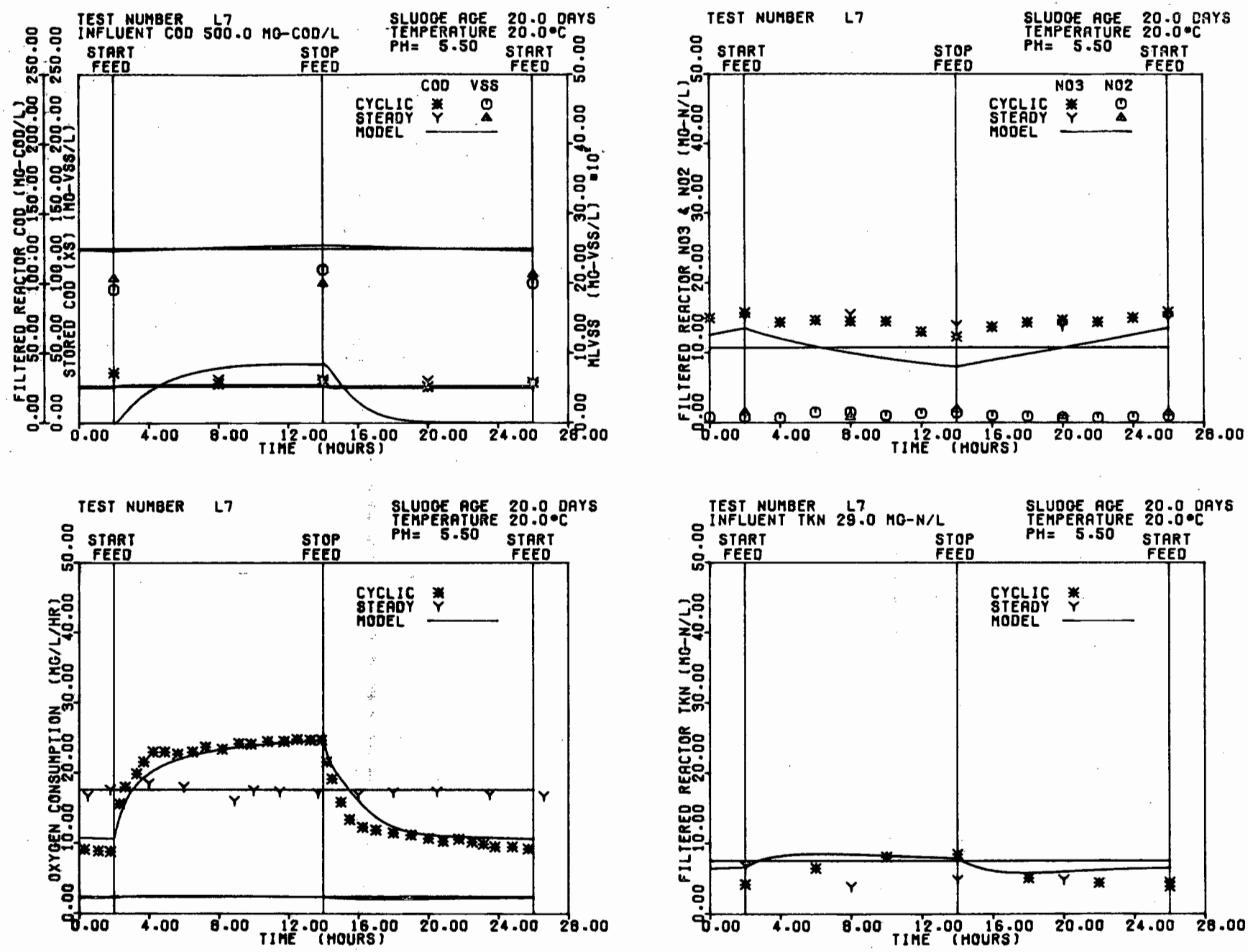


Fig. 4.35 *Comparison between the response predicted by the recalibrated bi-substrate general model and that observed experimentally for a CMAS unit subjected to a square wave loading pattern.*

in the predicted CMAS response. Thus it can be concluded that the CSP value for K_{sm} constitute an improved evaluation and should be applied in the general model.

During the course of the investigation the additional constant, f_{ssb}, was introduced to define the fraction of the unadsorped particulate COD which remains unenmeshed in the contact reactor. It was found that f_{ssb} varied with sludge age and the length of retention time in the contact reactor. However, the best overall fit was achieved for a value of $f_{ssb} = 0,6$. It must be noted that this constant only has relevance to the CSP. In a CMAS or ordinary series reactor process the total retention time prior to solid/liquid separation in the settling tank is so long that most of the particulate COD has either been adsorped or enmeshed and very little escapes in the effluent. Therefore the constant f_{ssb} has not been introduced into the general Ekama and Marais model, and does not affect the predictions in Figs. (4.34 and 4.35).

4.6 CONCLUSIONS

The experimental investigation described in this chapter and the analysis of the data generated lead to the following conclusions:

1. Under cyclic loading the bi-substrate hypothesis is superior to the adsorption hypothesis in predicting the COD behaviour in the reactors and effluent, and in predicting the oxygen consumption rate in the contact reactor. Consequently, the bi-substrate hypothesis appears to be preferable to the adsorption hypothesis.

2. In the bi-substrate model the partial enmeshment version provides a more satisfactory explanation of the difference between the filtered and unfiltered COD concentrations in the effluent than the full enmeshment version. The observed process carbonaceous oxygen consumption rate is also more accurately predicted by the partial enmeshment version than by the full enmeshment version.

3. Prediction of the nitrification response of the CSP is subject to the same difficulties as experienced with the CMAS process in that the nitrification rate is very sensitive to the quality of the influent sewage. Thus the response of the experimental CSP unit varied considerably and it was only possible to develop mean constants for the model to give a best overall prediction of a whole series of experimental tests.

4. At 12°C the bi-substrate partial enmeshment model tends to overpredict the observed carbonaceous oxygen consumption rate of the CSP. The causes for this overprediction could not be established conclusively as it was not possible to obtain an experimental COD balance at 12°C. It was concluded that there appears to be an inherent error in one of the experimental tests as performed at present which only manifests itself at low temperatures. However it would appear that the Arhenius constants used to define the temperature dependency of the carbonaceous biodegradation are too low. This aspect should be the subject of an intensive investigation.

In general it is concluded that the response of the CSP to cyclic and time invariant feed conditions at 20°C is best described by the bi-substrate partial enmeshment model.

C H A P T E R F I V E

DESIGN OF THE CONTACT STABILIZATION PROCESS

Application of the theory of the CSP is best illustrated by considering a design example.

It must be realized that in South Africa the CSP is not likely to be accepted as a feasible process for final treatment of wastewater before discharge into natural waterways, because the effluent from this process usually has unacceptably high concentrations of biodegradable COD and TKN. However because of the small aeration volume required by the process relative to other processes, it could find application as a method for reducing the total COD load before discharging to a municipal sewer. In order to illustrate this approach, consider the following hypothetical example:

A small burrough adjoining a large city discharges its effluent into a sewer outfall which leads to one of the smaller purification plants serving the city. Subsequent to the construction of this main purification plant a starch manufacturing industry has grown up in the burrough resulting in a large increase in the COD load contributed by the flow from the burrough. No provision was made for this increase in the design of the main plant. The plant has become overloaded and the city authorities are insisting that the COD load in the effluent from the burrough must be reduced prior to its discharge into the sewer outfall. Furthermore it is required that the treatment adopted include nitrification so as to maintain a reasonably low TKN/COD ratio in the influent to the main plant.

The COD in the effluent from the starch factory is predominantly of a particulate nature and because there is very little suitable land available on which to establish the treatment works, it is decided to install

a contact stabilization plant.

It is considered that with a judicious choice of sludge age the required reduction of COD load can be obtained even if the wasted sludge is discharged into the sewer with the treated effluent. The discharge of the sludge into the sewer will have three advantages: (1) It removes the necessity for expensive on site sludge treatment; (2) It will enhance dentrification in the sewer when the nitrate in the nitrified effluent is mixed with the sludge and the raw sewage in the sewer outfall; (3) It will improve the settling characteristics of the sewage in the primary settling tanks at the main works.

A series of 24 hour tests are carried out on the sewage to establish the load and flow pattern. A representative set of data is given in Table 5.1. Note that the COD load, MCOD, is just about 1000 kg COD/d. The permitted load is 500 kg COD/d, hence the load must be halved, at least, by the CSP designed.

Design Procedure

The sewage to be treated is analysed and its characteristics given below

Characteristics of the sewage

Symbol	Value	Units
f_{bs}	0,15	mg COD/mg COD
f_{us}	0,06	mg COD/mg COD
f_{up}	0,08	mg VSS/mg COD
f_{un}	0,02	mg N/mg N
f_{na}	0,75	mg N/mg N

A sludge age of 6 days is chosen as this should be long enough to ensure at least the halving of the energy load. Furthermore it should be long enough to ensure nitrification all year round. A sludge recycle rate

Table 5.1 Daily cyclic flow and load characteristics of the sewage generated

Time	Flow Kℓ/day	COD mg/ℓ	TKN mgN/ℓ	M(COD) kg/d	M(TKN) kgN/d
0400	412	943	73,9	389	30
0500	372	729	67,6	282	25
0600	353	600	57,1	212	20
0700	334	544	51,2	182	17
0800	326	446	45,1	145	15
0900	392	643	49,2	252	19
1000	602	1337	113,6	805	68
1100	728	1766	122,4	1285	89
1200	822	2001	125,8	1645	103
1300	855	2173	123,6	1858	106
1400	873	2250	113,1	1964	99
1500	849	2241	112,7	1903	96
1600	817	2229	112,4	1821	92
1700	751	2177	108,8	1635	82
1800	703	2040	106,1	1434	75
1900	678	1954	98,6	1325	67
2000	667	1869	91,4	1246	61
2100	628	1749	88,9	1098	56
2200	585	1629	85,9	953	50
2300	556	1543	85,0	858	47
2400	546	1466	84,6	800	46
0100	529	1354	82,5	716	44
0200	494	1239	80,5	612	40
0300	445	1101	77,8	490	35
0400	412	943	73,9	389	30
Mean	596,5	1502	89,9	996	58

of 2 is chosen for the plant as this will ensure a relatively high nitrification efficiency and will also result in a short sludge retention time in the settling tank which will minimise the risk of denitrification in the tank during the hot summer months.

With the very high particulate COD load in the influent, it is decided to use an α value of 0,2 . This will result in a slightly larger plant (about 5%) than if $\alpha = 0,1$ was chosen, but it is considered that COD lost in the effluent due to partial enmeshment will be reduced by the higher X_{vc}/S_{ip} ratio in the contact reactor.

The steady state Eqs. (3.50 to 3.52) are now utilized to <u>estimate</u> the mass of sludge produced in the process, $M(X_{vp})$.

The total mass of biodegradable COD in the influent, MS_{bi} is given by

$$M(S_{bi}) = M(S_{ti})(1 - f_{us} - f_{up}\ P)$$
$$= 996\ (1 - 0,06 - 0,08.1,48)\ kg/d$$
$$= 818\ kg/d$$

Assume for the purpose of this estimate that all the biodegradable COD is oxidised in the process:

from Eq. (3.50)

$$M(X_{ap}) = \frac{Y_h\ (MS_{bi})\ R_s}{1 + b_h .\ R_s}$$
$$= \frac{0,43\ .\ 818\ .\ 6}{1 + 0,24\ .\ 6}$$
$$= 865\ kg\ VASS$$

from Eq. (3.51)

$$M(X_{ep}) = f\ .\ b_h\ .\ M(X_{ap})\ .\ R_s$$
$$= 0,2\ .\ 0,24\ .\ 865\ .\ 6$$
$$= 249\ kg\ VSS$$

from Eq. (3.52)

$$M(X_{ip}) = R_s \cdot M(S_{pi})$$

$$= 6 \cdot 0.08 \cdot 996$$

$$= 478 \text{ kg VSS}$$

Therefore

$$M(X_{vp}) = 865 + 249 + 478$$

$$= 1592 \text{ kg VSS}$$

To achieve good settling at this relatively short sludge age the volatile sludge concentration in the contact reactor should not exceed approximately 2600 mg/ℓ under the peak flow conditions.

As a first approximation, assume the sludge wastage flow $w = 0$

and try $X_{vc} = 2400 \text{ mg/ℓ}$

From Eq. (3.12)

$$X_{vp} = X_{vc}(1 + r - w)/(\alpha + r - \alpha w)$$

$$= 2400 (1 + 2 - 0)/(0,2 + 2 - 0)$$

$$= 3273 \text{ mg/ℓ}$$

$$\therefore V_p = \frac{1592 \times 10^6}{3273}$$

$$= 48\ 6\ 400$$

$$\text{Now } w = (1 + r)[1 + QR_s(\alpha + r)/V_p] - (3.17)$$

$$= (1 + 2)/[1 + 596\ 500.6(0,2 + 2)/486\ 400]$$

$$= 0,175$$

The reactor volumes can now be calculated

$$V_c = V_p \cdot \alpha (1 + r - w)/(\alpha + r - \alpha w) \quad - \quad (3.10)$$

$$= 486\ 400.0{,}2\ (1 + 2 - 0{,}175)/(0{,}2 + 2 - 0{,}2.0{,}175)$$

$$= 126\ 900 \quad \ell$$

$$V_s = V_p \cdot r (1 - \alpha)/(\alpha + r - \alpha w) \quad - \quad (3.9)$$

$$= 486\ 400 \cdot 2\ (1 - 0{,}2)/(0{,}2 + 2 - 0{,}2.0{,}175)$$

$$= 359\ 500 \quad \ell$$

Checking the approximate sludge concentrations in the reactors

$$X_{vc} = X_{vp} (\alpha + r - \alpha w)/(1 + r - w) \quad - \quad (3.12)$$

$$= 3273\ (0{,}2 + 2 - 0{,}2.0{,}175)/(1 + 2 - 0{,}175)$$

$$= 2508$$

$$X_{vs} = X_{vp} (\alpha + r - \alpha w)/r \quad - \quad (3.13)$$

$$= 3273\ (0{,}2 + 2 - 0{,}2.0{,}175)/2$$

$$= 3543$$

These are satisfactory.

The actual hydraulic retention time in the contact reactor is given by

$$r_{hc} = \frac{V_c}{Q(1+r)} \times 24$$

$$= \frac{126\ 900 \cdot 24}{596\ 500 \cdot 3}$$

$$= 1{,}7 \text{ hrs}$$

This is a relatively long contact time (approximately twice the retention time obtained if $\alpha = 0{,}1$ is used) but in view of the high con-

centration of particulate COD this is considered desirable to improve the enmeshment of the unadsorped particulate COD by the sludge. The choice of the fraction of unadsorped particulate COD which becomes enmeshed in the contact reactor is one parameter which has not been quantified during this investigation. It has been shown that the fraction is effected by contact time and the X_{vc}/S_{ip} ratio (see § 4.5.2.2). However, exactly how this parameter will behave under full scale conditions is impossible to predict without a pilot plant investigation. In this example the plant has been specifically designed to achieve a high enmeshment efficiency in the contact reactor, and so it is assumed that 40% of the unadsorbed particulate COD remains unenmeshed in the sludge flow during the contact period, i.e. $f_{ssb}=0,4$.

The wasted sludge will be pumped continuously from the contact reactor by a positive displacement pump and will be mixed with the process effluent prior to discharge into the sewer outfall.

Step 1 of the design procedure set out in § 3.5.1 has now been completed. Suitable values of V_c and V_s have been selected and these, together with the hourly flow, COD and TKN concentrations can be fed into the computer to obtain the predicted cyclic response of the plant.

Figure 5.1 shows the predicted response of the CSP plant to this cyclic loading pattern given in Table 5.1; the most important parameter responses are listed in Table 5.2 .

To establish the total daily equivalent COD load introduced into the main sewer outfall from the CSP, the total mass of sludge wasted, $M(X_{vw})$ must be calculated. Because the sludge is wasted continuously over 24 hrs it can be assumed that the average concentration of the wasted sludge is equal to the average concentration in the contact reactor.

$$M(X_{vw}) = w \cdot Q \cdot X_{vc}(ave)$$

$$= 0,175 \cdot 596 \cdot 10^{3} \cdot 2674 \cdot 10^{-6}$$

$$= 279 \text{ Kg}$$

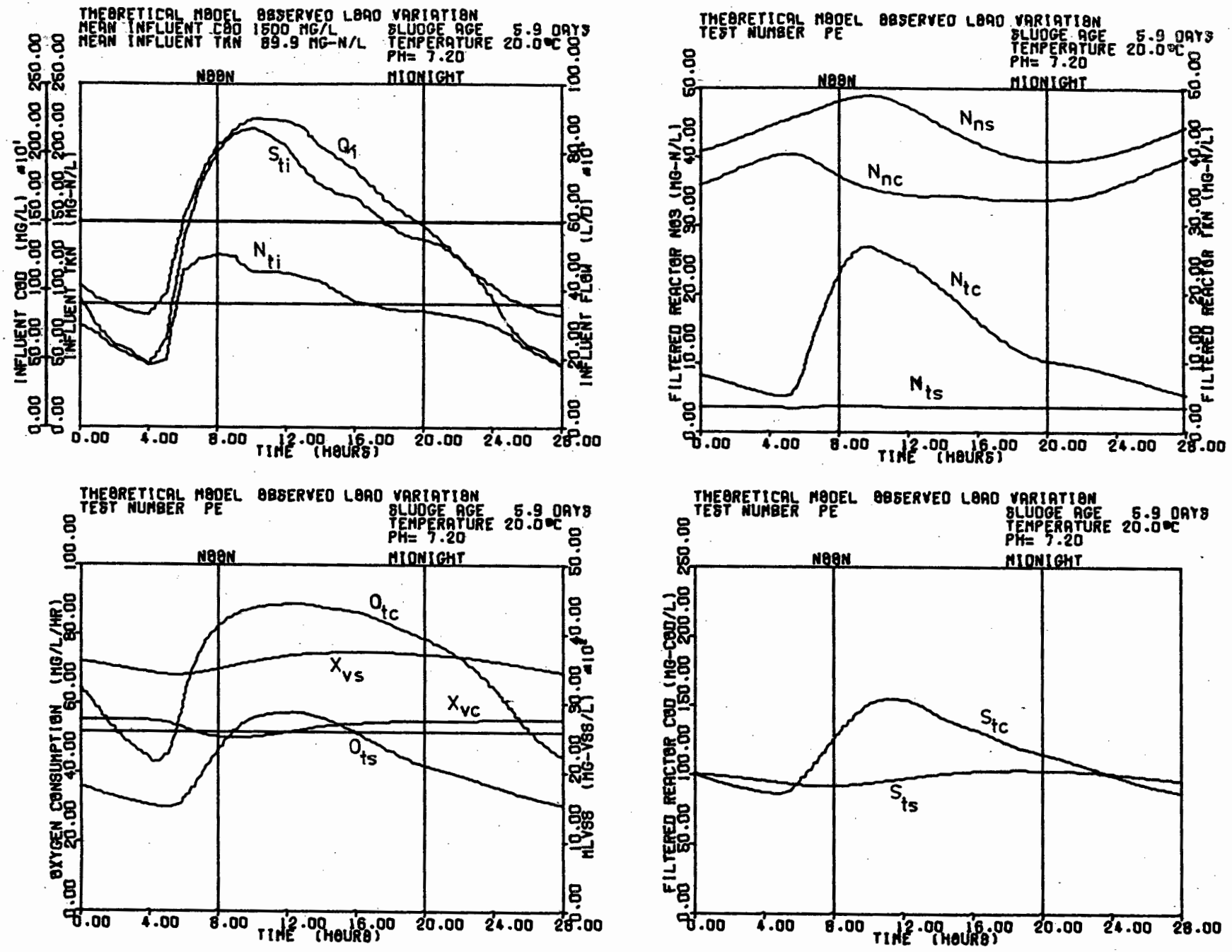


Fig. 5.1 *Theoretical response of the CSP plant predicted by the bi-substrate partial enmeshment model.*

Table 5.2 The predicted response of the main parameters to the influent cycle in Table 5.1

Time	Flow Kℓ/d	X_{vc} mg/ℓ	X_{vs} mg/ℓ	S_{te} mg/ℓ	$M(S_{te})$ Kg/d	O_{tc} mg/ℓ/hr	O_{ts} mg/ℓ/hr	N_{ne} mg/ℓ	MN_{ne} Kg/d
0400	412	2757	3603	100	41	64	36	36	15
0500	372	2763	3563	95	35	58	34	37	14
0600	353	2763	3521	92	32	52	33	38	13
0700	334	2758	3479	89	30	48	32	39	13
0800	326	2750	3439	87	28	44	31	40	13
0900	392	2715	3408	87	34	45	30	40	16
1000	602	2631	3413	95	57	61	32	40	24
1100	728	2550	3450	109	79	76	39	39	28
1200	822	2505	3498	126	104	82	46	37	30
1300	855	2496	3551	140	120	86	52	35	30
1400	873	2512	3602	151	132	88	56	35	31
1500	849	2542	3649	155	132	88	57	35	30
1600	817	2579	3687	154	126	89	57	34	28
1700	751	2624	3713	150	113	89	57	34	26
1800	703	2665	3727	142	100	88	56	34	24
1900	678	2692	3734	137	93	87	54	34	23
2000	667	2706	3740	133	89	86	51	34	23
2100	628	2718	3740	128	80	85	49	34	21
2200	585	2731	3732	122	71	83	46	34	20
2300	556	2742	3718	118	66	81	44	34	19
2400	546	2746	3702	115	63	79	42	34	19
0100	529	2744	3687	111	59	76	40	34	18
0200	494	2743	3666	108	53	73	39	34	17
0300	445	2750	3638	104	46	69	37	35	16
0400	412	2758	3606	100	41	64	36	36	15
Mean	596	2674	3611	123	74	74	44	36	21

The total mass of COD leaving the CSP in the effluent, $M(S_{te})$, can be obtained from Table 5.3 . Therefore, the total equivalent mass of COD entering the main outfall after treatment is given by

Eq. COD mass = 279 x 1,48 + 74

= 487 kg COD/d

The equivalent COD mass leaving the plant (i.e. 487 kg/d) is less than the maximum allowed into the sewer, hence the design complies with the requirement that the influent COD load be reduced by at least half. From Table 5.2 the maximum sludge concentration in the contact reactor is 2763 mg/ℓ . This is higher than the concentration initially stipulated for good settling, but as this concentration occurs during the low flow period of the cycle (when the settling tank in effect is overdesigned) no settling problems should arise.

It will be seen from Figure 5.1 that the oxygen consumption rate response in the contact reactor displays a relatively severe cyclicity compared to that reported for the experimental units. The reason for this is that with a value of $\alpha = 2$ the retention time in the contact reactor is relatively long, consequently the cyclicity of the flow has a correspondingly smaller effect on the sludge concentration in the contact reactor. Less active sludge mass is "washed out" of the reactor, hence the oxygen consumption rate shows a more marked response to the cyclic loading of the plant. As the aeration capacity in the contact reactor has to be designed to cater for the peak load oxygen consumption rate, this is an undesirable feature of the design. However this effect has to be weighted up against the specific advantage deliberately built into the design. The reason the retention time in the contact reactor was lengthened was to improve the enmeshment efficiency of the unadsorped particulate COD by the sludge flow. The extent to which this objective has been achieved can be calculated by subtracting the soluble unbiodegradable COD fraction $M(S_{ue})$ from $M(S_{te})$ (with a contact time of 1,7 hrs the concentration of soluble biodegradable COD in the effluent is negligible).

$$M(S_{ue}) = M(S_{ti}) \cdot f_{us}$$

$$= 996 \cdot 0{,}06$$

$$= 60 \text{ kg/day}$$

Thus the mass of particulate COD leaving the system in the effluent is given by

$$M(S_{pe}) = M(S_{te}) - M(S_{ue})$$

$$= 74 - 60$$

$$= 14 \text{ kg/day}$$

General Remarks

In order that the model can be utilized to its full potential as a design tool to optimise the design of the CSP, a more accurate description of the behaviour of f_{ssb} relative to retention time in the contact reactor must be established by means of pilot plant studies. Once this is determined the model can be used to adjust α until an optimum balance is achieved between the degree of cyclicity of the oxygen consumption rate in the contact reactor and the mass of particulate COD leaving the system in the effluent.

As in the design of all activated sludge plants, at this stage of our knowledge, a factor of safety should be introduced because no design method yet devised can be considered completely satisfactory. For instance in the example considered above it would be advisable to increase the volume of the plant slightly over that calculated - in the event that the energy reduction achieved is not as high as predicted, the sludge age then could be increased without increasing the sludge concentration in the contact reactor to levels unacceptably high for efficient settling.

The fact that the cyclic oxygen consumption rate can be evaluated constitutes a significant improvement over the design by means of the imperial models discussed in Chapter Two.

C H A P T E R S I X

CONCLUSIONS

The original objective of this thesis was to check experimentally the two hypotheses on activated sludge kinetics advanced by Ekama and Marais (1978) i.e. the adsorption and bi-substrate hypothesis respectively. The contact stabilization process (CSP) was selected as the one presenting a most severe test of the predictive power of any hypothesis on activated sludge kinetics, and the most likely therefore to establish the superiority of the one hypothesis over the other.

From a comparison of the experimentally observed and theoretically predicted data it was concluded that an additional factor had to be taken into account before a valid comparison could be made - whereas the general activated sludge theory accepted a rapid and complete enmeshment of influent particulate COD, in the contact reactor the experimental data indicated incomplete enmeshment in the short contact time available. When allowance was made for partial enmeshment in the predicted response of the system it was concluded that the bi-substrate hypothesis was superior to the adsorption one.

Theoretical analyses of plant behaviour indicated that the nitrification response is particularly sensitive to slight changes in the nitrification rate constants. This was borne out by the experimental results where it was found that virtually every sewage batch showed different nitrification response characteristics. It was concluded that consistentcy in nitrification response would only be obtained if artificial substrates were utilised.

The kinetic constants defining the bi-substrate hypothesis initially were taken to be the same as those determined from the experimental data of Ekama and Marais. Under the extreme conditions in the CSP

it was found that only one of these constants, the maximum specific growth rate utilizing solube substrate, K_{ms}, had to be modified in order to obtain good correspondence between the experimental data and theoretical predictions. The use of this modified constant in the general activated sludge theory had inconsequential effects on the predictions, and can therefore be taken to constitute an improved evaluation as it allows for the general theory to be extended over a greater range of processes.

The model appears to be sufficiently reliable to be used as a tool for analysing a design under any proposed cyclic conditions.

Due to the partial enmeshment in the contact reactor there is a relatively high COD concentration in the effluent. As nitrification is also partial in the contact reactor, the TKN concentration in the effluent tends to be high. These two behaviour characteristics make the process unsuitable for application as a final treatment method in South Africa. It may however find application as an intermediate treatment facility to reduce high COD concentrations before discharge to a sewer system.

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A P P E N D I X A

TABULATION OF EXPERIMENTAL DATA

1. Note

(1) All COD concentrations are given in mg COD/ℓ
(2) All VSS concentrations are given in mg VSS/ℓ
(3) All TKN and Nitrate concentrations are given in mg N/ℓ
(4) All oxygen consumption rates are given in mg O/ℓ/hr
(5) All pumping rates are given in ℓ/d

2. Index of Tables

TABLE A.1 DAILY EXPERIMENTAL RESULTS

FOR R_s = 6 days

T = 20°C

DATE	COD				VSS		OD		TKN				NITRATES		
	IN	EFF	STAB	CONT	STAB	CONT	CONT	STAB	IN	EFF	STAB	CONT	EFF	STAB	CONT
5.5	482	48	32	55	1644	1488	57	33	74	15	2,9	19	39	53	41
6.5	552	95	40	51	1743	1238	59	38	68	21	3,7	15	39	56	37
7.5	526	87	44	71	1716	1276	55	35	69	20	2,8	17	41	52	42
8.5	534	89	59	87	1541	1046	60	31	75	20	0,0	12	34	42	31
9.5	482	120			1650	1443	58	29	75	18	4,6	17	29	37	28
10.5	510	91	53	67	1817	1421	56	30	62	19	4,4	14	26	37	27
11.5	486	71	79	55	1864	1312	66	39	84	18	1,7	9	27	55	41
12.5	550	72	56	68	1872	1378	62	36	73	25	0,0	17	34	54	40
13.5	527	91	44	52	2064	1513	66	34	79	16	0,0	10	43	23	37
14.5	455	81	48	52	1787	1212	63	31	76	15	0,0	12	35	45	24
15.5	507	81	64	64	1825	1322	59	24	41	9	0,0	8	29	30	18
16.5	483	93	56	72	1799	1121	58	24	40	10	3,0	9	20	20	19
17.5	515	89	60	72	1871	1379	68	35	42	12	0,0	8	21	23	18
18.5	499	111	63	47	1867	1377	64	30	40	12	1,8	7	17	24	18
19.5	547	117	36	68	1854	1292	53	28	43	10	0,0	10	17	26	19
20.5	533	59	50	58	1906	1336	60	32	38	7	1,4	11	17	27	22
21.5	462	103	68	100	1719	1192	65	35	45	10	3,0	8	20	29	24
22.5	582	88	24	48	1625	1144	57	29	46	8	1,8	8	21	27	21
23.5	530	128	64	48	1762	1276	57	29	47	11	2,5	10	20	25	20
24.5	530	104	80	48	1826	1380	67	35	45	12	0,0	10	18	23	22
25.5	482	86	45	45	1706	1186	57	33	40	16	0,0	10	19	28	21
26.5	518	80	67	74	1625	1148	60	33	43	21	2,8	11	20	30	24
27.5	493	77	58	67	1674	1438	65	35	43	12	2,8	10	22	34	27
Mean	512	90	54	62	1772	1301	61	32	56	15	1,7	11	26	36	27

Process parameters are given in Tables 4.1 and 4.2

Data is plotted in Figs 4.4 to 4.7 inclusive

TABLE A.2 DAILY EXPERIMENTAL RESULTS

FOR R_s = 10 days

T = 20°C

DATE	COD				VSS		OD		TKN				NITRATES		
	IN	EFF	STAB	CONT	STAB	CONT	CONT	STAB	IN	EFF	STAB	CONT	EFF	STAB	CONT
23.5	430	67	45	58	1996	1356	43	22	52	14,8	5,1	13,4	23	37	26
24.5	550	57	51	70	2282		44	25	53	15,2	-	11,6	25	35	26
25.5	480	57	47	70	2264	1719	46	24	58	15,7	5,0	14,5	25	34	25
26.5	499	62	49	62	2313	1631	42	22	51	14,5	5,8	11,9	25	36	27
27.5	520				2137	1584	40	21	51	14,8	6,9	12,7	26	38	29
28.5	556	73	55	55	2192	1614	45	22	51	13,8	4,0	10,3	27	39	29
29.5	515	64	58	55	2099	1488	43	23	51	15,6	6,6		24	33	26
30.5	504				1951	1309	37	19	51		4,7	13,5	21	34	26
31.5	451	73	46	55	2085	1478	35	17	34	10,6	1,9	7,5	21	27	20
7.6	551	53	35	50	2111	1614	38	17	36	10,2	2,9	9,3	17	24	19
2.6	464		36	49	2200	1561	40	20	50	14,2	7,5	13,1	17	22	17
3.6	492	64	33	48	2150	1593	42	19	36	12,6	4,1	9,8	17	23	18
4.6	478	62	40		2007	1401	41	19	44	11,0	5,5	10,2	18	24	19
5.6	531	67	35	45	2154	1536	44	21	42	10,9	6,6	8,6	19	25	19
6.6	509	44	32		2190	1583	47	22	44	12,4	10,2	12,3	18	26	17
7.6	488	76	45	51	2105	1549	40	22	48	13,1	4,1	10,8	18	26	18
8.6	437	68	46	56	1963	1559	41	20	47	13,5	4,1	11,3	18	27	20
9.6	520	60	45	41	2106	1559	42	22	53	11,0	1,7	10,4	21	29	23
10.6	460	60	42	41	1944	1454	38	21	40	10,5	2,6	10,9	19	25	20
11.6	522	44	42	48	1889	1312	36	17	43	9,0	5,1	7,5	18	24	19
12.6	496	64	32	29	1934	1371	39	17	42	11,3	5,8	10,1	18	24	19
13.6	490	54	48	48	1882	1242			43	9,4	5,2	10,5	17	21	16
14.6	530	49	30	40	1857	1202	52	16	42	7,2	3,9	6,4	17	19	16
15.6	469	54	48	48	2014	1380	47	23	53	10,5	2,1	6,2	19	31	23
16.6	456	59	34	69	1998	1380	49	23	54	10,5	2,8	10,2	25	36	28
Mean	496	61	42	51	2073	1478	42	21	46	12,2	4,8	10,5	20	28	21

Process parameters are given in Tables 4.5 and 4.6

Data is plotted in Figs 4.8 to 4.11 inclusive

TABLE A.3 DAILY EXPERIMENTAL RESULTS FOR Rs = 6 days With Nitrification
T = 12°C

	COD				VSS		TKN				NITRATES			CD	
DATE	1	E	S	C	S	C	1	E	S	C	E	S	C	S	C
25.4	492	80	38	54	1963	1337	44	11,1	5,3	8,8	16	25	19	23	32
26.4	510	77	70	86	1999	1337	59	13,3	4,6	13,5	17	27	18	25	31
27.4	509	64	58	61	2088	1428	58	12,2	3,0	11,2	18	26	20	25	30
28.4	505	52	46	52	2025	1389	59	13,3	8,3	14,9	21	31	24	24	30
29.4	492	62	46	43	2107	1436	49	20,9	1	14,1	25	36	29	29	30
30.4	559	71	52	65	2120	1460	50	8,2	1,8	14,5	25	36	29	28	33
1.5	472	62	34	37	2145	1461	61	9,4	2,1	12,5	26	36	27	25	31
2.5	523	59	43	81	1930	1318	60	25,0		15,0	25	29	22	26	32
3.5											25		28		
4.5	521	75	49	56	2131	1468	67	22,5		20,7	27	36	30	31	35
5.5	522	94	62	71	2294	1543	68	19,6		20,7	32	37	30	32	37
6.5	576	135	49	65	2281	1609	34		7,7		27	37		32	39
7.5	479	84	52	46	2277	1639	32	16,3	8,2	13,4	15	28	14	23	31
8.5	537	72	34	44	2213	1496	32	14,1	6,9	9,5	16	17	18	25	30
9.5	537	67	61	54	2188	1530	46	15,2	8,0	11,6	19	25	20	21	26
10.5	501		45	51	2025	1428	49	14,0	5,3	12,4	18	26	19	20	26
11.5	489	70	52	55	2195	1510	50	14,6	3,7	11,2	19	26	19	24	32
12.5	511	48	36	45	2143	1464	41	14,8	7,7	14,0	20	26	20	25	33
13.5	485	66	44	48	2291	1610	48	13,7	6,2	11,6	19	27	13	26	35
14.5	532	59	75	63	2276	1509	50	13,5	14,2	18,5	17	17	21		
15.5	503	52	42,3	39	2363	1714	51		5,0		22	27	21	22	34
16.5	475	63	44	50	2278	1617	47	13,3	5,0	9,7		27		19	26
17.5	503	72	50	53	2212	1505	44	12,2	3,5	11,1	23	29	22	24	36
18.5	491	60	47	53	2202	1571	41	17,7	4,3	12,6	21	30	22	19	27
19.5	415	44	44	53	2346	1581	48	13,3	5,0	6,9	21	29	21	23	32
20.5	556	60	50	44	2346	1594	55	7,6	5,3	14,8	22	30	22	28	41
21.5	512	41	44	44	2286	1535	54	12,2	5,8	12,3	21	30	22	28	35
22.5	529	80	51	51	2369	1647	50	15,2	7,7	16,2	22	31	22	25	38
23.5	512	70	48	64	2314	1581	56	17,7	8,7	17,8	22	28	20	27	35
24.5	543	70	48	61	2284	1778	56	17,3	4,0	9,6	23	33	25	21	30
25.5	472	70		48	2042	1369	48	16,7	6,2	15,5	23	32	24	22	35
26.5	523	78	59	66	2223	1545	53	15,2	5,8	14,4	23	32	22	22	37
27.5	484	87	58	68	2429	1775	51	16,7	7,3	14,7	25	30	22	24	32
28.5	560				2426	1728	46	16,3	5,8	14,7	23	29	22	26	35
MEAN	510	69	49	55	2206	1531	50	14,9	6	13,5	22	29	22	25	33

Process parameters are given in Tables 4.1 and 4.2
Data is plotted in Figs. 4.12 to 4.15 inclusive

TABLE A.4 DAILY EXPERIMENTAL RESULTS

FOR R_s = 6 days, T = 12°C } without nitrification

DATE	COD				VSS		OD		TKN			
	IN	EFF	STAB	CONT	STAB	CONT	STAB	CONT	IN	EFF	STAB	CONT
13.6	499	70	61	74	2158	1533	14	24	40	31	28	30
14.6	552	59	66	56	2139	1822	18	35	54	32	27	30
15.6	488	70	67	77	2260	1608	14	24	57	34	35	39
16.6	459	91	72	75	2178	1586	14	30	51	43	35	33
17.6	548	78	56	82	1949	1612	15	26	53	45	40	37
18.6	488	69	46	53	2270	1570	13	26	42	44	44	42
19.6	452	70	58	58	2290	1578	13	20	42	45	34	36
20.6	396	71	-	71	2076	1348			61	44	44	45
21.6	504	83	70	83	2074	1480	12	24	57	46	46	52
22.6	539	86	66	55	2088	1536	12	20	58	50	54	55
23.6	509	78	-	29	2070	1678	12	21	66	53	53	51
24.6	493	78	74	74	1936	1462	12	18	62	44	46	45
Mean	503	75	64	69	2124	1545	14	24	54	43	41	41

Process parameters are given in Tables 4.1 and 4.2

Data is plotted in Figs 4.16 to 4.19 inclusive

TABLE A.5 EXPERIMENTAL OBSERVATIONS FOR 24 HOUR TEST.

Time	Pump Rate ℓ/d	COD			TKN			NITRATE			VSS		O.D.	
		C	S	E	C	S	E	C	S	E	C	S	C	S
0000	11	62	49	54	2,6	2,1	5,7	21	22	19	1569	1883	43	18
1000	18												41	20
2000	20	51	55	52	3,4	2,6	5,3	20	21	20			43	22
3000	22												42	19
4000	36	74	51	70	4,0	2,6	6,3	19	22	20			41	21
5000	36												42	23
6000	41	77	51	67	7,4	3,6	6,3	16	22	16	1400	2014	43	28
7000	43												40	28
8000	46	83	43	81	7,9	2,5	9,3	15	22	15			40	28
9000	49												41	29
1000	54	90	54	97	8,0	0,6	10,3	13	21	13			41	32
1100	57												38	32
1200	58	81	49	107	8,2	3,0	11,3	13	22	13	1345	2138	43	32
1300	57												41	32
1400	55	83	56	81	10,4	4,1	9,9	12	21	13			37	31
1500	54												40	36
1600	49	72	39	116	8,7	1,0	8,7	14	21	13			42	29
1700	43												42	28
1800	39	75	43	97	7,4	3,4	8,1	15	21	14	1290	1779	38	29
1900	37												39	28
2000	27	68	45	76	6,0	2,4	7,4	16	21	15			43	26
2100	19												38	25
2200	17	67	43	77	8,2	2,7	4,6	18	21	17			40	22
2300	12												41	22
2400	11	70	50	61	3,0	1,4	5,0	20	22	19	1737	1819	42	18

Flow Pattern : Sine Wave

Process parameter given in Tables 4.1 and 4.2

S_{ti} = 503 mg COD/ℓ

N_{ti} = 38 mg N/ℓ

Raw sewage ex Strandfontein, Cape Town

Rs = 6 days

T = 20° C

pH = 7,2

Experimental data plotted in Fig. 4.20

TABLE A.6 EXPERIMENTAL OBSERVATIONS FOR 24 HOUR TEST.

Time	Pump Rate ℓ/d	COD (mg/ℓ			TKN (mg/ℓ			NITRATE (mg/ℓ			VSS (mg/ℓ		O.D. (mg/ℓ/hr)	
		C	S	E	C	S	E	C	S	E	C	S	C	S
0000		56	53	63	8,7	4,0	9,4	18	22	18	1580	1940	42	21
0100	18												38	22
0200		55	53	81	8,6	4,0	11,9	18	23	18	1580	1960	43	21
0250													42	26
0300		86	61	108	15,2	3,9	13,0	14	22	17	1240	1970	41	29
0350														
0400		97	51	90	15,7	3,9	15,4	13	22	14			43	31
0500													42	31
0600		88	57	112	16,3	4,6	16,6	14	22	13			42	31
0700	54												40	32
0800		96	57	112	16,2	5,4	19,2	15	25	14	1270	2120	40	34
0900													42	34
1000		73	52	113	16,3	4,3	19,0	15	24	14			38	34
1100													38	34
1200		79	48	100	14,7	4,7	17,6	15	23	14	1350	2160	36	34
1300													38	34
1400		92	56	102	14,3	5,0	18,2	15	23	13	1330	2170	36	34
1450													39	29
1500		55	50	102	8,7	3,2	16,2	20	23	14	1670	2050	38	28
1550													40	26
1600		61	52	78	8,3	3,6	13,7	20	23	15			39	25
1700													38	23
1800		65	50	72	7,9	3,7	11,3	20	23	17			38	23
1900	18												38	21
2000		65	54	80	7,6	3,9	9,9	20	23	18	1640	2040	40	21
2100													41	22
2200		61	51	69	7,7	4,0	9,7	17	21	18			38	22
2300													40	22
2400		56	53	63	8,7	4,0	9,4	18	22	18	1580	1940	42	21

Flow Pattern : Square Wave

Process parameters given in Tables 4.1 and 4.2

S_{ti} = 500 mg COD/ℓ

N_{ti} = 46 mg N/ℓ

Raw sewage ex Strandfontein, Cape Town.

Rs = 6 days

T = 19,5° C

pH = 7,2

Experimental data plotted in Fig. 4.21

TABLE A.7 TEMPERATURE AND pH READINGS TAKEN DURING 24 HOUR SQUARE WAVE TEST

TIME	TEMPERATURE				pH	
	CONTACT	STAB	BASE FLOW	SQUARE FLOW	CONTACT	STAB
0000	19,5	19,25	21,0		7,5	7,2
0100	19,5	19,25	20,0			
0200	19,5	19,00	20,0	19,5	7,6	7,2
0300	19,5	19,25	20,0	20,5		
0400	19,5	19,25	20,0	19,5	7,6	7,2
0500	19,5	19,25	20,0	19,5		
0600	19,5	19,25	20,0	20,0	7,5	7,2
0700	19,5	19,25	20,5	20,0		
0800	19,5	19,25	20,5	20,0	7,5	7,3
0900	19,5	19,5	20,5	20,0		
1000	19,5	19,5	20,0	20,0	7,5	7,2
1100	19,75	19,5	20,0	20,0		
1200	19,75	19,5	20,0	20,0	7,3	7,3
1300	19,75	19,5	20,5	20,0		
1400	19,75	19,5	20,5	20,0	7,4	7,3
1500	19,75	19,5	20,0			
1600	19,75	19,5	20,0		7,4	7,4
1700	19,5	19,5	20,0			
1800	19,5	19,5	20,0		7,4	7,2
1900	19,5	19,5	20,0			
2000	19,5	19,5	20,0		7,4	7,2
2100	19,5	19,5	20,0			
2200	19,5	19,5	20,0		7,4	7,2
2300	19,5	19,5	20,0			
2400	19,5	19,5	20,0		7,4	7,2

A P P E N D I X B

LISTING OF COMPUTER PROGRAMS

These programs were adapted from the general model of Ekama and Marais (1978), which included for denitrification.

Computer programs in Fortran IV and V, performing the following functions in the contact stabilization model are listed below. The model listed is based on the bi-substrate hypothesis and contains an option for partial enmeshment.

1. MAIN PROGRAM FOR CONTACT STABILIZATION PROCESS (CYCLIC)

1.1 Description

This program calculates the space-time varying response behaviour of the contact stabilization process. For an exposition of the properties of the program see Section 3.5.

The program utilizes five subroutines - CONTAC, STABIC, PARNTC, SETLEC and CHAR, and their respective functions are given in the Tables above. To take account of the extra mass loadings on the system when both the influent flow and sewage strengths vary diurnally, the steady state solution is adjusted by a factor [see lines (4.22 to 4.27)].

1.2 Input of Data

All the input data is read in at lines 120 to 134 and at 228 to 231. Except for the first line, all the data is read in free format. An example of the input data layout for this program is given in data element CYDATA1 (page B.41). From this data the program calculated the theoretical response waves for the sine wave 24 hour test shown in Fig. 4.30. The nomenclature is given in comment statements in the program - lines 1 - 80, 149 - 225 and 438 - 484.

For all loading patterns

Data Card 1 (line 122)

Column 1 TYPE - whether sine, square wave or general load wave pattern.

2 RESULT - output numerically, graphically or both.

3 - 6 KOM - start time of 24 hour cycle. For square wave this should be two hours before feed commencement. For sine wave the peak flow occurs 14 hours after this value. This is essential for compatibility between this program and the plot program.

7 - 8 TN - test number.

9 NITDEN - whether process includes denitrification, or not.

11 - 15 CRIT - convergence criterion - maximum error, as a fraction of the particular integral, between two consecutive days results.

For sine wave loading pattern

Data Card 2 (line 126) - 3,14159

Data Card 3 (line 127)

Average influent flow COD, TKN and nitrate concentrations and their respective amplitudes.

Data Card 4 (line 130)

Kinetic constants.

Data Card 5 (line 131)

Kinetic constants.

Data Card 6 (line 132)

Sludge age, recycle ratio, number of reactors in series, number of integration steps per day, then sewage characteristics and more kinetic constants.

Data Card 7 (line 133)

Temperature and pH dependency coefficients, temperature and pH of mixed liquor.

Data Card 8 (line 134)

Time of sludge wastage period commencement, time of sludge wastage period termination, and the volume of the reactor. Note that ICSD and ISSD must both fall within the selected 24 hour cycle*.

---

* Sludge wastage cannot occur when the influent flow rate is less than the calculated waste flow rate. Should this occur the waste flow rate is set equal to the influent flow rate. This adjustment will, in effect, increase the sludge of the process.

For square wave loading pattern

Data Card 2 (line 129)

Volume of influent per day, influent COD, TKN and NO_3 concentrations during peak flow period, base flow rate, influent COD, TKN and NO_3 concentrations during base flow period, length of peak flow period.

Data Cards 3 to 7

Same as Cards 4 to 8 for sine wave pattern*.

For general load pattern

Data Cards 2 to 6

Same as Cards 4 to 8 for sine wave pattern*.

Data Cards 6 to n (lines 228 to 231)

Hourly values for influent flow, COD, TKN and NO_3 concentrations - 25 values for each are required, the first and last of each being the same.

2. THEORETICAL RESPONSE WAVE PLOTTING PROGRAM (PLOTTER)

This program, called PLOTTER, is listed on p. B.32. It is based on the CALCOMP plotting software. The programme reads the theoretical response calculated by CYCLIC and produces a diagram of the theoretical response waves, e.g. Fig. 4.30. The input data required by this program is read in at lines 21, 23, 25, 31, 35, 45 and 52. The input data required at line 21 is given in PLATA (p. B.41) and is used for drawing the outlines on the diagram. The remaining input data is all generated and written in the required format in a temporary file by CYCLIC. This is done in CYCLIC at lines 953 to 1021 and required that temporary unit number 18 is assigned to the runstream.

---

* See footnote on previous page

This program requires on subroutine (other than the CALCOMP software) i.e. EOT (p. B.40). This subroutine is required if the final diagrams are to be written to magnetic tape to allow the diagrams to be plotted on different plotting hardware. It is an assembler routine which marks the tape with an End of File marker after each execution of the program.

3. EXPERIMENTAL RESPONSE WAVE PLOTTING PROGRAM (GRAFS)

This program called GRAFS is listed on p. B.36. It is also based on the CALCOMP plotting software. The program reads the experimental data observed during a 24 hour test and produces a diagram of the experimental response waves, e.g. Fig. 4.20. The input data required by this program is read in at lines 22 to 53. The data required at line 23 of the program is given in PLATA (p. B.41) and is used for drawing the outlines on the diagram, in the same fashion as PLOTTER. The remaining input data constitutes the experimentally observed data during a 24 hour test. An example of the input data layout is given in element CYPDATA1 (p. B.42) and is the experimental data observed during the sine wave test (Fig. 4.20).

A description of the input data follows.

Data Card 1 (Format 101, line 26)

Column 1 TYPE - whether sine, square or general load wave pattern (see lines 148 to 151 of SERIES.CYCLIC)

2 - 5 SAGE - sludge age

6 - 8 ICOD - influent COD concentration

9 - 12 ITKN - influent TKN concentration

13 - 16 TEMP - temperature

17 - 20 PH - pH of the mixed liquor

21 - 22 TN - test number

23 - 24 NR - number of reactors

25 NITDEN - whether system includes denitrification or not (see lines 203 - 205 of CYCLIC)

Data Cards 2 to 62 (lines 27 to 53)

All these data are read in at free format. See Table B.1 for an explanation of the symbols and how the data are read in.

This program also requires the EOT subroutine for the same reason as PLOTTER.

Table B.1

Input data layout for SERIES.GRAFS

Process Variable		Number of Data	Times at which Data were measured		Values of Data measured in Reactors	
			Time Array	Read at Line	Value Array	Read at Line
MLVSS (mg VSS/ℓ)		N1	TNI (I)	28	RXVP (J,I)	40
COD (mg COD/ℓ)		N2	TN2 (I)	29	RSTP (J,I)	41
TKN (mg N/ℓ)		N3	TN3 (I)	30	RNTP (J,I)	42
NH3 (mg N/ℓ)		N11	TN11 (I)	31	RNH3P (J,I)	43
NO3 (mg N/ℓ)		N4	TN4 (I)	32	RNO3P (J,I)	44
Oxygen consumption rate (mg O/ℓ/hr)	Reactor					
	1	N5	TN5 (I)	33	TOP 1 (I)	45
	2	N5	TN5 (I)	33	TOP 2 (I)	46
	3	N6	TN6 (I)	34	TOP 3 (I)	47
	4	N6	TN6 (I)	34	TOP 4 (I)	48
	5	N7	TN7 (I)	35	TOP 5 (I)	49
	6	N7	TN7 (I)	35	TOP 6 (I)	50
Influent load	Flow (ℓ/d)	N8	TN8 (I)	36	QP (I)	51
	COD (mg/ℓ)	N9	TN9 (I)	37	TOP (I)	52
	TKN (mg N/ℓ)	N10	TN10 (I)	38	CNIP (I)	53

```
CONTAX*CONTACTBS(1).CYCLIC
      1       C  DYNAMIC STATE MODEL OF CONTACT-STABILIZATION ACTIVATED SLUDGE PROCESS
      2       C  ------------------------------------------------------------------
      3       C              (INCLUDING ADSORPTION AND STORAGE OF COD, AND NITRIFICATION)
      4       C
      5       C           CALCULATION CHARACTERISTICS
      6       C           --------------------------
      7       C           THIS PROGRAMME REQUIRES THE FOLLOWING CORE STORAGE CAPACITY:-
      8       C            FOR ND=241 AND NF=4*(ND-1)+1 AND NEE=NE+1
      9       C            STORAGE=10*NE+23 KILOWORDS
     10       C            DOUBLING ND INCREASES STORAGE REQUIREMENT BY 1.75
     11       C            APPROX. CALCULATION CPU TIME ON A UNIVAC 1106 COMPUTER
     12       C            FOR 100 ITERATIONS:-
     13       C            CPU TIME (SECONDS) =50*NE+30
     14       C
     15       C         PROCSS = LOGICAL NUMBER FO RDESCRIBING PROCESS TYPE
     16       C              IF = 0   PROGRAMME VALID FOR AERATED LAGOON PROCESS
     17       C              IF = 1 PROGRAMME VALID FOR ACTIVATED SLUDGE WITH RECYCLE
     18       C         RESULT = LOGICAL NUMBER TO DIRECT OUTPUT
     19       C              IF = 1     PRINT RESULTS
     20       C              IF = 2     PLOT RESULTS
     21       C              IF = 0     PLOT AND PRINT RESULTS
     22       C              TN = NUMBER OF TEST CALCULATION
     23       C            CRIT = MAXIMUM ERROR ALLOWED BETWEEN CONSECUTIVE DAYS'
     24       C                   VALUES OF PROCESS VARIABLES TO TEST FOR CONVERGENCE
     25       C             KOM = TIME AT WHICH TIME BASE COUNTER COMMENCES
     26       C              KO = TIME BASE VARIABLE
     27       C               M = CYCLE NUMBER MONITOR
     28       C               D = NUMBER OF INTERGRATION STEPS PER DAY
     29       C              DT = INTERGRATION STEP LENGTH
     30       C              DD = NUMBER OF INTERGRATION STEPS PER DAY FOR NITRIFICATION
     31       C             DDT = INTERGRATION STEP LENGTH FOR NITRIFICATION
     32       C             RDT = RATIO OF INTERGRATION STEP LENGTHS
     33       C              KH = NUMBER OF TIME STEPS PER HOUR
     34       C              HK = NO. OF INTERVALS PER DAY  OF SLUDGE WASTAGE
     35       C
     36       C         NOTE
     37       C         ----
     38       C            NITROGEN CONCENTRATIONS MEASURED IN MG-N/L WITH TKN TEST
     39       C            COD CONCENTRATIONS MEASURED IN MG/L OF COD
     40       C            VSS CONCENTRATIONS MEASURED IN MG/L OF VSS
     41       C            OXYGEN CONSUMPTIONS IN MG/L/HOUR
     42       C            UNIT OF MASS IS THE MG
     43       C            UNIT OF VOLUME IS THE L
     44       C            UNIT OF TIME IS THE DAY
     45       C            SYMBOL S REFERS TO COD
     46       C            SYMBOL X REFERS TO VSS
     47       C            SYMBOL N REFERS TO NITROGEN
     48       C            SYMBOL O REFERS TO OXYGEN
     49       C
     50       C            KINETIC CONSTANTS
     51       C            -----------------
     52       C            AN EXTRA T OR 20 INDICATES VALUES AT T OR 20 DEG. C
     53       C             KV = MAX. RATE OF COD TRANSFER FROM SEWAGE INTO STORAGE
     54       C             KR = RATE OF CONVERSION OF ORGANIC N TO SALINE NH3
     55       C             KM = MAX. RATE OF  ORGANISM SYNTHESIS FROM STORED COD
     56       C             KS = SATURATION COEF. FOR COD  UTILIZATION
     57       C             UM = MAXIMUM GROWTH RATE OF NITRIFYING ORGANISMS
     58       C             KN = SATURATION COEF. FOR NH3  UTILIZATION
     59       C             BH = ENDOGENOUS RESPIRATION RATE
     60       C             BN = ENDOGENOUS RESPIRATION RATE FOR NITRIFICATION
     61       C           THEA = TEMPERATURE DEPENDENCY CONSTANT FOR ADSORPTION OF COD
```

```
C           THES = TEMPERATURE DEPENDENCY CONSTANT FOR SYNTHESIS
C           THEE = TEMPERATURE DEPENDENCY CONSTANT FOR ENDOG. RESPIRATION
C           PHIN = PH DEPENDENCY CONSTANT FOR NITRIFICATION
C           THEN = TEMPERATURE DEPENDENCY CONSTANT FOR NITRIFICATION
C           THEZ = CONSTANT FOR NO TEMPERATURE DEPENDENCY
C             YH = YIELD OF ORGANISMS FROM COD UTILIZED
C             YN = ACTIVE MASS YIELD OF NITRIFYING ORGANISMS FROM AMMONIA
C              F = UNBIODEG. FRACTION OF ORGANISM
C             FR = MAXIMUM FRACTION OF STORED COD (AS VSS) TO ACTIVE
C                  ORGANISM MASS
C             FN = FRACTION OF CARBONACEOUS CELL MASS AS N
C            FNS = FRACTION OF NITROGEN ASSOCIATED WITH STORED COD
C              P = COD EQUIVALENT OF VSS
C            FCA = FRACTOIN OF COD REQUIRED FOR COD ADSORPTION
C            FOE = FRACTION OF N RELEASED BY ENDOGENOUS RESPIRATION
C                  AS ORGANIC NITROGEN
C            FOS = FRACTION OF NITROGEN REQUIRED FOR CELL SYNTHESIS
C                  AS ORGANIC NITROGEN
C
C
C       DIMENSION STATEMENTS
C       --------------------
C
      PARAMETER NE=2
      PARAMETER ND=241
      PARAMETER NF=961
      DOUBLE PRECISION DT,DDT,RDT
      COMMON/BLOCC1/SBS(NE,NF),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
     1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,NF),NH3(NE,NF),
     2NO3(NE,NF),SBP(NE,ND)
      COMMON/BLOCC2/Q(NE,ND),V(NE),SBI(ND),SUI(ND),SCIS(NE,NF),
     1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),
     2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(NF),SCIP(NE,ND),
     3SCVO(NE,ND),NNIT(NE,NF)
      REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
      REAL NUI,NONI,NH3I,NO3I,NNIT
      REAL NU,NON,NH3,NO3
      INTEGER D,DD,HK,TYPE,RESULT,TN
      DIMENSION STI(ND),STQ(ND)
      REAL NTI(ND),NTQ(ND),NO3Q(ND),NXII(ND)
      REAL NTIAV,NUIAV,NONIAV,NO3IAV,NH3IAV,NXIIAV
      REAL NTQAV,NO3QAV
      REAL NTIMAX,NO3IAX,NTQMAX,NO3QAX
      REAL NTIO,NTIOO,NO3IO,NO3IOO,LFP
      DIMENSION RA(NE),RN(NE)
      REAL KV20,KMP20,KSP20,KMS20,KSS20,KNMAX,KN20,KR20
      DIMENSION STOSBP(NE,ND),STOXV(NE,ND),STNO3(NE,ND)
      DIMENSION KO(ND),WQ(ND),OS(NE,ND),OE(NE,ND),
     1OC(NE,ND),ON(NE,ND),OT(NE,ND),ST(NE,ND),RXS(NE,ND)
      REAL NT(NE,ND)
      DIMENSION SBSAV(NE),OSAV(NE),OEAV(NE),OCAV(NE),
     1ONAV(NE),OTAV(NE),STAV(NE),SUAV(NE),SBPAV(NE),
     2XAAV(NE),XEAV(NE),XSAV(NE),XIAV(NE),XVAV(NE),
     3XNAV(NE),RXSAV(NE)
      REAL NONAV(NE),NTAV(NE),NO3AV(NE),NH3AV(NE),NUAV(NE),NSWAV(NE)
C
C           INPUT OF DATA
C           -------------
  100 FORMAT ( )
  101 FORMAT(2I1,I4,A2,I1,F5.3)
      READ 101,TYPE,RESULT,KOM,TN,NITDEN,CRIT
      IF(TYPE.EQ.1) GO TO 111
```

```
      IF(TYPE.EQ.2) GO TO 112
      IF(TYPE.EQ.3) GO TO 113
  111 READ 100,PI
      READ 100,QO,STIO,NTIO,NO3IO,VARQ,VARSTI,VARNTI,VNO3I
      GO TO 113
  112 READ 100,VF,STIO,NTIO,NO3IO,BQ,STIOO,NTIOO,NO3IOO,LFP
  113 READ(8,100) KV20,KMP20,KSP20,KMS20,KSS20,UMAX,KNMAX,BH20,BN20,
     1YH,YN,F,P,FN,FOE,FSSB
      READ 100,RS,SR,ALF,NR,D,FUS,FUP,UN,SN,KR20,FOS,FCA,FR
      READ 100,THEA,THES,THEE,PHIN,THEN,THEZ,TEMP,PH
      READ 100,ICSD,ISSD,VP
      KH=D/24
      NL=D+1
      NLL=D+2
      NJ=4
      DD=NJ*D
      NK=DD+1
      NKK=DD+2
C
C          SEWAGE CHARACTERISTICS
C          ----------------------
C         TYPE = LOGICAL NUMBER DESCRIBING INFLUENT LOAD PATTERN
C           IF = 1    SINE WAVE LOAD PATTERN
C           IF = 2    SQUARE WAVE LOAD PATTERN
C           IF = 3    GENERAL LOADING PATTERN
C            Q = INFLUENT FLOW
C          STI = TOTAL INFLUENT COD
C          NTI = TOTAL INFLUENT TKN
C          STQ = TOTAL INFLUENT COD LOAD
C          NTQ = TOTAL INFLUENT TKN LOAD
C         NO3Q = TOTAL INFLUENT NO3 LOAD
C         NONI = INFLUENT ORGANIC NITROGEN CONCENTRATION
C         NH3I = INFLUENT AMMONIA CONCENTRATION
C         NO3I = INFLUENT NITRATE CONCENTRATION
C          NUI = UNBIODEGRADABLE FRACTION OF SEWAGE N
C         NXII = UNSABLE N IN INERT MATERIAL IN INFLUENT
C          XII = UNBIODEG. SOLID FRACTION OF SEWAGE COD AS VSS
C          SBI = BIODEG. FRACTION OF SEWAGE COD
C          SUI = UNBIODEG. SOLUBLE FRACTION OF SEWAGE COD
C          FUS = FRACTION OF SOLUBLE UNBIODEG. COD
C          FUP = FRACTION OF SOLID UNBIODEG. COD AS VSS
C           UN = UNBIODEGRADABLE FRACTION OF N
C           SN = FRACTION OF TKN AS AMMONIA
C           QO = AVERAGE INFLUENT FLOW FOR SINE WAVE PATTERN
C         STIO = INFLUENT COD CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C         NTIO = INFLUENT TKN CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C        NO3IO = INFLUENT NO3 CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C        STIOO = INFLUENT COD CONCENTRATION DURING BASE FLOW PERIOD
C        NTIOO = INFLUENT TKN CONCENTRATION DURING BASE FLOW PERIOD
C       NO3IOO = INFLUENT NO3 CONCENTRATION DURING BASE FLOW PERIOD
C        NM,NN = LIMITS OF PEAK FLOW PERIOD
C         QMAX = MAXIMUM FLOW VALUE OF THE DAY
C        STIMAX = MAXIMUM COD CONCENTRATION VALUE OF THE DAY
C        NTIMAX = MAXIMUM TKN CONCENTRATION VALUE OF THE DAY
C        NO3IAX = MAXIMUM NO3 CONCENTRATION VALUE OF THE DAY
C        STQMAX = MAXIMUM COD LOAD VALUE OF THE DAY
C        NTQMAX = MAXIMUM TKN LOAD VALUE OF THE DAY
C        NO3QAX = MAXIMUM NO3 LOAD VALUE OF THE DAY
C           LFP = LENGTH OF FEED PERIOD (SQUARE WAVE)
```

```
C            PQ = PEAK FLOW RATE IN SQUARE WAVE PATTERN
C            BQ = BASE FLOW RATE IN SQUARE WAVE PATTERN
C            VF = VOLUME OF FEED PER DAY
C        VARSTI = AMPLITUDE OF INPUT COD CONC. WAVE (SINE WAVE)
C        VARNTI = AMPLITUDE OF INPUT TKN CONC. WAVE (SINE WAVE)
C         VNO3I = AMPLITUDE OF INPUT NO3 CONC. WAVE (SINE WAVE)
C          VARQ = AMPLITUDE OF INFLUENT FLOW WAVE (SINE WAVE)
C        VARSTL = AMPLITUDE OF INFLUENT COD LOAD WAVE (SINE WAVE)
C        VARNTL = AMPLITUDE OF INFLUENT TKN LOAD WAVE (SINE WAVE)
C        VRNO3L = AMPLITUDE OF INFLUENT NO3 LOAD WAVE (SINE WAVE)
C
C           PROCESS CHARACTERISTICS
C           -----------------------
C
C        NITDEN = LOGICAL NUMBER DESCRIBING PROCESS OPERATION
C             IF = 1  PROCESS INCLUDES NITRIFICATION ONLY
C             IF = 2  PROCESS INCLUDES NITRIFICATION AND DENITRIFICATION
C          TEMP = OPERATING TEMPERATURE OF MIXED LIQUOR
C            PH = OPERATING PH OF MIXED LIQUOR
C           RSM = MINIMUM SLUDGE AGE FOR NITRIFICATION
C            RN = NOMINAL HYDRAULIC RETENTION TIME IN REACTORS
C            RA = ACTUAL HYDRAULIC RETENTION TIME IN REACTORS
C           TRN = TOTAL HYDRAULIC RETENTION TIME OF PROCESS
C            SR = SLUDGE UNDERFLOW RECYCLE RATIO TO AVERAGE INFLUENT FLOW
C            QR = SLUDGE UNDERFLOW RECYCLE RATE
C           WQR = SLUDGE WASTAGE FLOW RATIO
C            NR = NUMBER OF REACTORS IN SERIES
C           ALF = FRACTIONAL DISTRIBUTION OF SLUDGE BETWEEN THE
C                 CONTACT AND STABILIZATION REACTORS
C          ICSD = TIME AT WHICH SLUDGE WASTAGE COMMENCES
C          ISSD = TIME AT WHICH SLUDGE WASTAGE TERMINATES
C             V = VOLUME OF REACTOR
C            VP = TOTAL VOLUME OF PROCESS
C            RS = SLUDGE AGE
C            WQ = SLUDGE WASTE FLOW
C      N.B.  THE SLUDGE WASTE FLOW MAY NEVER BE GREATER THAN
C              THE INFLUENT FLOW AT ANY INERVAL OF THE DAY
C        I.E.  THE EFFLUENT FLOW FROM A REACTOR MAY NEVER BE LESS
C              THAN ZERO AT ANY INTERVAL OF THE DAY
C
      IF(TYPE.EQ.1) GO TO 115
      IF(TYPE.EQ.2) GO TO 116
      READ(8,100) (Q(1,I),I=1,NL,KH)
      READ(8,100) (STI(I),I=1,NL,KH)
      READ(8,100) (NTI(I),I=1,NL,KH)
      READ(8,100) (NO3I(I),I=1,NL,KH)
      IF(TYPE.EQ.3) GO TO 117
  115 DO 8 I=1,NL,KH
      KL=(I-1)/KH
      DUM=SIN(2*PI*(KL-8)/24)
      Q(1,I)=Q0*(1+VARQ*DUM)
      STI(I)=STI0*(1+VARSTI*DUM)
      NTI(I)=NTI0*(1+VARNTI*DUM)
      NO3I(I)=NO3I0*(1+VNO3I*DUM)
    8 CONTINUE
C
C        INTERPOLATION OF STI, NO3I, Q AND NTI AT REQUIRED INTERVALS
C        -----------------------------------------------------------
C
  117 DO 25 I=1,24
      KI=KH*I+1
      KJ=KH*(I-1)+1
```

```
      DIFSTI=(STI(KI)-STI(KJ))/KH
      DIFFQ=(Q(1,KI)-Q(1,KJ))/KH
      DIFNTI=(NTI(KI)-NTI(KJ))/KH
      DNO3I=(NO3I(KI)-NO3I(KJ))/KH
      DO 25 J=2,KH,1
      KK=KJ+J-1
      STI(KK)=STI(KJ)+(J-1)*DIFSTI
      Q(1,KK)=Q(1,KJ)+(J-1)*DIFFQ
      NTI(KK)=NTI(KJ)+(J-1)*DIFNTI
      NO3I(KK)=NO3I(KJ)+(J-1)*DNO3I
   25 CONTINUE
      GO TO 118
  116 PQ=BQ+(VF-BQ)*24.0/LFP
      DO 24 I=1,NL,1
      NTI(I)=NTI00
      STI(I)=STI00
      Q(1,I)=BQ
   24 NO3I(I)=NO3I00
      NM=2*KH+1
      NN=NM+LFP*KH-1
      DO 23 I=NM,NN,1
      STI(I)=STI0
      Q(1,I)=PQ
      NTI(I)=NTI0
      NO3I(I)=NO3I0
   23 CONTINUE
  118 DO 1 I=1,NL
      STQ(I)=STI(I)*Q(1,I)
      NTQ(I)=NTI(I)*Q(1,I)
      NO3Q(I)=NO3I(I)*Q(1,I)
      SUI(I)=FUS*STI(I)
      NUI(I)=UN*NTI(I)
      XII(I)=FUP*STI(I)
      NXII(I)=XII(I)*FN
      NH3I(I)=SN*NTI(I)
      NONI(I)=NTI(I)-NUI(I)-NXII(I)-NH3I(I)
    1 SBI(I)=STI(I)*(1.0-FUS-FUP*P)
C
C       CALCULATION OF AVERAGE SEWAGE CHARACTERISTICS
C         ---------------------------------------------
C
      SUMQ=0
      SUMSTI=0
      SUMNTI=0
      SNO3I=0.0
      QMAX=0.0
      STIMAX=0.0
      SUMSTQ=0.0
      STQMAX=0.0
      SUMNTQ=0.0
      NTQMAX=0.0
      NTIMAX=0.0
      SNO3Q=0.0
      NO3QAX=0.0
      NO3IAX=0.0
      DO 2 I=1,0,1
      SUMNTI=SUMNTI+NTI(I)
      SNO3I=SNO3I+NO3I(I)
      SUMSTI=SUMSTI+STI(I)
      SUMSTQ=SUMSTQ+STQ(I)
      SUMNTQ=SUMNTQ+NTQ(I)
      SNO3Q=SNO3Q+NO3Q(I)
```

```
      IF(STQ(I).GT.STQMAX) STQMAX=STQ(I)
      IF(NTQ(I).GT.NTQMAX) NTQMAX=NTQ(I)
      IF(NO3Q(I).GT.NO3QAX) NO3QAX=NO3Q(I)
      IF(Q(1,I).GT.QMAX) QMAX=Q(1,I)
      IF(STI(I).GT.STIMAX) STIMAX=STI(I)
      IF(NTI(I).GT.NTIMAX) NTIMAX=NTI(I)
      IF(NO3I(I).GT.NO3IAX) NO3IAX=NO3I(I)
    2 SUMQ=SUMQ+Q(1,I)
      QAV=SUMQ/D
      STQAV=SUMSTQ/D
      NTQAV=SUMNTQ/D
      NO3QAV=SNO3Q/D
      IF(TYPE.EQ.2) GO TO 119
      NTIAV=SUMNTI/D
      STIAV=SUMSTI/D
      NO3IAV=SNO3I/D
      GO TO 120
  119 STIAV=STQAV/VF
      NTIAV=NTQAV/VF
      NO3IAV=NO3QAV/VF
  120 SBIAV=STIAV*(1.0-FUS-FUP*P)
      SUIAV=FUS*STIAV
      NUIAV=NTIAV*UN
      XIIAV=FUP*STIAV
      NXIIAV=FN*XIIAV
      NH3IAV=SN*NTIAV
      NONIAV=NTIAV-NXIIAV-NUIAV-NH3IAV
      QR=SR*QAV
      IF(TYPE.EQ.2) GO TO 121
      VARSTL=STQMAX/STQAV-1.00
      VARNTL=NTQMAX/NTQAV-1.00
      VRNO3L=NO3QAX/NO3QAV-1.00
      IF(VRNO3L.LT.0.0) VRNO3L=0.0
      IF(TYPE.EQ.1) GO TO 121
      VARQ=QMAX/QAV-1.00
      VARSTI=STIMAX/STIAV-1.00
      VARNTI=NTIMAX/NTIAV-1.00
      VNO3I=NO3IAX/NO3IAV-1.00
      IF(VNO3I.LT.0.0) VNO3I=0.0
C
C             CALCULATE PROCESS DESIGN PARAMETERS
C             -----------------------------------
C
  121 TRNS=VP/QAV
      WQR=TRNS*(1.0+SR)/(RS*ALF+RS*SR+TRNS)
      V(1)=VP*ALF*(1.0+SR-WQR)/(ALF+SR-ALF*WQR)
      V(2)=VP*SR*(1.0-ALF)/(ALF+SR-ALF*WQR)
      VP=V(1)+V(2)
      RA(1)=V(1)/(QAV+QR)*24.0
      RA(2)=V(2)/(QR)*24.0
      RN(1)=V(1)/QAV*24.0
      RN(2)=RA(2)
      TRN=RN(1)+RN(2)
C
C             RELATE STEP INTERVALS TO THE TIME BASE
C             --------------------------------------
C
      II=0
      KN=1440/D
      KH1=KH+1
      DO 27 I=1,NL,1
      JE=I-1
```

```
      IF(JE.EQ.0) GO TO 30
      KO(I)=KO(I-1)+KN
      GO TO 31
   30 KO(I)=KOM
   31 II=II+1
      IF (II.EQ.KH1) KO(I)=KO(I)+40
      IF (II.EQ.KH1) II=1
      IF (KO(I).EQ.2400) KO(I)=0
      IF(KO(I).EQ.ICSD) IC=I-1
      IF(KOM.EQ.ICSD) IC=1
      IF(KO(I).EQ.ISSD) IS=I
      WQ(I)=0.00
   27 CONTINUE
      HK=IS-IC
      DO 28 I=IC,IS,1
      WQ(I)=WQR*QAV*D/HK
   28 CONTINUE
      DO 29 I=1,NL,1
      Q(2,I)=Q(1,I)-WQ(I)
      IF(Q(2,I).GT.0.00) GO TO 29
      Q(2,I)=0.00
      WQ(I)=Q(1,I)
   29 CONTINUE
C
C             ADJUST TEMPERATURE AND PH DEPENDENT CONSTANTS
C             ---------------------------------------------
C
      IF(PH.LT.8.0) UM20=UMAX
      IF(PH.LT.7.2) UM20=UMAX*(PHIN)**(PH-7.20)
      IF(PH.LT.8.0) KN20=KNMAX
      IF(PH.LT.7.2) KN20=KNMAX*(PHIN)**(7.20-PH)
      UMT=UM20*(THEN)**(TEMP-20.0)
      KNT=KN20*(THEN)**(TEMP-20.0)
      KSPT=KSP20*(THEZ)**(TEMP-20.0)
      KMPT=KMP20*(THES)**(TEMP-20.0)
      KSST=KSS20*(THEZ)**(TEMP-20.0)
      KMST=KMS20*(THEA)**(TEMP-20.0)
      KRT=KR20*(THEE)**(TEMP-20.0)
      KVT=KV20*(THEA)**(TEMP-20.0)
      BHT=BH20*(THEE)**(TEMP-20.0)
      BNT=BN20*(THEE)**(TEMP-20.0)
      RSM=1.0/((UMT/(1.0+(KNT/(SN*NTIAV))))-BNT)
      FNS=NONIAV/SBIAV
C
C              CALCULATE INITIAL CONDITIONS (PARTICULAR INTEGRAL)
C*****************************************************************
      CALL PARNTC(YH,FCA,RS,BHT,KVT,TRNS,KMPT,KSPT,KMST,KSST,
     1P,F,FN,FNS,KRT,KNT,BNT,UMT,YN,
     2SBIAV,SU1AV,XIIAV,NUIAV,NONIAV,NTIAV,NO3IAV)
C*****************************************************************
      FACT=STQAV/(STIAV*QAV)
      XA(1,1)=FACT*XA(1,1)
      XS(1,1)=FACT*XS(1,1)
      XE(1,1)=FACT*XE(1,1)
      XI(1,1)=FACT*XI(1,1)
      XV(1,1)=FACT*XV(1,1)
      CRITXV=CRIT*XV(1,1)
      IF(CRITXV.LT.CRIT) CRITXV=CRIT
      CRISBP=CRIT*SBP(1,1)
      IF(CRISBP.LT.CRIT) CRISBP=CRIT
      CRINO3=CRIT*NO3(1,1)
      IF(CRINO3.LT.CRIT) CRINO3=CRIT
```

```
C
C          GENERAL NOTATION FOR PROCESS VARIABLES IN REACTOR
C          -------------------------------------------------
C
C          SBP = BIODEGRADABLE PARTICULATE COD
C          SBS = BIODEGRADABLE SOLUBLE COD
C           SU = UNBIODEGRADABLE COD
C           ST = TOTAL COD
C           XS = STORED COD
C           XA = ACTIVE ORGANISMS
C           XE = INERT RESIDUE FROM DECAYING ORGANISMS
C           XI = INERT MATERIAL FROM SEWAGE
C           XN = ACTIVE NITROSOMONAS
C           XV = TOTAL VSS
C           OA = OXYGEN CONSUMPTION RATE FOR ADSORPTION OF COD
C           OS = OXYGEN CONSUMPTION RATE FOR SYNTHESIS
C           OE = OXYGEN CONSUMPTION RATE FOR ENDOGENOUS RESPIRATION
C           OC = TOTAL CARBONACEOUS OXYGEN CONSUMPTION RATE
C           ON = OXYGEN CONSUMPTION FOR NITRIFICATION
C           OT = TOTAL OXYGEN CONSUMPTION RATE
C          NSW = NITROGEN REMOVED IN SLUDGE WASTAGE PER DAY
C           NT = TOTAL TKN IN REACTOR
C           NU = UNBIODEGRADABLE TKN IN REACTOR
C          NON = ORGANIC NITROGEN CONCENTRATION  IN REACTOR
C          NH3 = AMMONIA CONCENTRATION IN REACTOR
C          NO3 = NITRATES CONCENTRATION IN REACTOR
C          RXS = RATE OF CHANGE OF STORED COD (AS MG-VSS/L/D)
C          SCI = ENERGY ENTERING STORAGE FROM LIQUID PHASE (MG-COD/L)
C         SCVO = ENERGY REMOVED FROM STORAGE DUE TO CELL SYNTHESIS (MG-VSS/L)
C
C          THE SUFFIX 'AV' AFTER A SYMBOL INDICATES DAILY AVERAGE
C           VALUES FOR VARIABLES IN INFLUENT OR REACTORS
C          THE SUFFIX 'R' AFTER A SYMBOL INDICATES
C           VALUES FOR VARIABLES IN RECYCLE
C          THE SUFFIX 'P' AFTER A SYMBOL INDICATES VALUES
C           FOR VARIABLES CARRIED OVER TO PLOTTER ROUTINES
C          THE SUFFIX 'MAV' AFTER A SYMBOL INDICATES DAILY AVERAGE
C           VALUES OF VARIABLES FOR PROCESS
C
C         BALC = PERCENTAGE COD RECOVERY
C        TCODI = TOTAL COD MASS INPUT
C        TCODO = TOTAL COD MASS OUTPUT
C        TWCOD = TOTAL COD MASS IN WASTE FLOWS FROM REACTORS
C         WCOD = COD MASS IN WASTE FLOW FROM REACTOR
C         ECOD = TOTAL COD MASS IN EFFLUENT
C         BALN = PERCENTAGE NITROGEN RECOVERY
C         TNTI = TOTAL NITROGEN MASS INPUT
C         TNTO = TOTAL NITROGEN MASS OUTPUT
C          TWN = TOTAL NITROGEN MASS IN WASTE FLOWS FROM REACTORS
C           WN = NITROGEN MASS IN WASTE FLOW FROM REACTOR
C           EN = TOTAL NITROGEN MASS IN EFFLUENT
C
C
      DO 9 J=1,NR,1
      IF(J.EQ.1) GO TO 3
      IF(J.EQ.2) GO TO 4
    3 DUM1=(ALF+SR-ALF*WQR)/(1.0+SR-WQR)
      DUM2=(1.0+SR-WQR)/SR
      GO TO 13
    4 DUM2=(ALF+SR-ALF*WQR)/(1.0+SR-WQR)
      DUM1=(1.0+SR-WQR)/SR
   13 SBP(J,1)=SBP(1,1)*DUM2
```

```
496             SBS(J,1)=SBS(1,1)*DUM2
497             SU(J,1)=SU(1,1)
498             XS(J,1)=XS(1,1)*DUM2
499             XA(J,1)=XA(1,1)*DUM1
500             XE(J,1)=XE(1,1)*DUM1
501             XI(J,1)=XI(1,1)*DUM1
502             XV(J,1)=XV(1,1)*DUM1
503             NON(J,1)=NON(1,1)*DUM2
504             NU(J,1)=NU(1,1)
505             NH3(J,1)=NH3(1,1)*DUM2
506             XN(J,1)=XN(1,1)*DUM1
507             NO3(J,1)=NO3(1,1)*DUM1
508           9 CONTINUE
509             DO 5 I=1,NL,1
510             SBP(NR,I)=SBP(NR,1)
511             SU(NR,I)=SU(NR,1)
512             XS(NR,I)=XS(NR,1)
513             XA(NR,I)=XA(NR,1)
514             XE(NR,I)=XE(NR,1)
515             XI(NR,I)=XI(NR,1)
516             NON(NR,I)=NON(NR,1)
517             NU(NR,I)=NU(NR,1)
518             IA=NJ*(I-1)
519             DO 5 IJ=1,NJ,1
520             IB=IA+IJ
521             IF(IB.GE.NKK) GO TO 5
522             SBS(NR,IB)=SBS(NR,1)
523             NH3(NR,IB)=NH3(NR,1)
524             NO3(NR,IB)=NO3(NR,1)
525             XN(NR,IB)=XN(NR,1)
526           5 CONTINUE
527             DO 10 J=1,NR,1
528             DO 10 I=1,NL
529             STOSBP(J,I)=SBP(J,1)
530             STNO3(J,I)=NO3(J,1)
531             STOXV(J,I)=XV(J,1)
532          10 CONTINUE
533             DT=1./D
534             DDT=1./DD
535             RDT=DDT/DT
536             M=0
537          17 J=1
538       C*****************************************************************
539             CALL CONTAC(D,DT,J,QR,FR,FCA,KVT,KMPT,KSPT,KMST,KSST,
540            1P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT)
541       C*****************************************************************
542             CALL SETLEC(NL,J,QR,NJ,NKK,FSSB)
543       C*****************************************************************
544             J=J+1
545       C*****************************************************************
546             CALL STABIC(D,DT,J,QR,FR,FCA,KVT,KMPT,KSPT,KMST,KSST,
547            1P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT)
548       C*****************************************************************
549             DO 12 J=1,NR,1
550             DO 12 I=1,NL
551             IB=NJ*(I-1)+1
552             IF(DABS(SBP(J,I)-STOSBP(J,I)).GE.CRISBP) GO TO 14
553             IF(DABS(NO3(J,IB)-STNO3(J,I)).GE.CRINO3) GO TO 14
554             IF (DABS(XV(J,1)-STOXV(J,I)).GE.CRITXV) GO TO 14
555          12 CONTINUE
556             GO TO 15
557          14 M=M+1
```

```
      IF (M.GE.500) GO TO 15
      DO 16 J=1,NR,1
      DO 16 I=1,NL
      IB=NJ*(I-1)+1
      STOSBP(J,I)=SBP(J,I)
      STNO3(J,I)=NO3(J,IB)
      STOXV(J,I)=XV(J,I)
   16 CONTINUE
      DO 6 J=1,NR,1
      SBP(J,I)=SBP(J,NL)
      SBS(J,I)=SBS(J,NK)
      XS(J,I)=XS(J,NL)
      XA(J,I)=XA(J,NL)
      XE(J,I)=XE(J,NL)
      XI(J,I)=XI(J,NL)
      SU(J,I)=SU(J,NL)
      NU(J,I)=NU(J,NL)
      NON(J,I)=NON(J,NL)
      NH3(J,I)=NH3(J,NK)
      XN(J,I)=XN(J,NK)
      NO3(J,I)=NO3(J,NK)
      XV(J,I)=XV(J,NL)
    6 CONTINUE
      GO TO 17
   15 CONTINUE
      DO 26 J=1,NR,1
      DO 26 I=1,NL
      JA=I-1
      IF (JA.EQ.0) JA=0
      JB=I+1
      IF (JB.EQ.NLL) JB=2
      JD=I
      IF(JD.EQ.NL) JD=1
      IB=NJ*(I-1)+1
      JC=IB
      IF(JC.EQ.NK) JC=1
      RXS(J,I)=(XS(J,JB)-XS(J,JA))/(DT*2.0)
      ST(J,I)=SU(J,I)+SBS(J,IB)+FSSB*SBP(J,I)
      NT(J,I)=NON(J,I)+NU(J,I)+NH3(J,JC)
      OS(J,I)=(1.0-P*YH)*(P*SCVO(J,JD)/DT+SCIS(J,JC)/DDT)/24.0
      OE(J,I)=((1.0-F)*BHT*P*XA(J,I))/24.0
      OC(J,I)=OS(J,I)+OE(J,I)
      ON(J,I)=4.57*NNIT(J,JC)/(DDT*24.0)
      OT(J,I)=OC(J,I)+ON(J,I)
   26 CONTINUE
C
C     CALCULATION OF AVERAGE RESULTS FROM DYNAMIC MODEL
C     -------------------------------------------------
C         EXAMPLE:  XVAV = AVERAGE XV
C
      SUMXVT=0.0
      SUMXAM=0.0
      SUMXEM=0.0
      SUMXIM=0.0
      SUMXSM=0.0
      SUMXNM=0.0
      SUMOSM=0.0
      SUMOCM=0.0
      SUMOEM=0.0
      SUMONM=0.0
      SUMOTM=0.0
      DO 22 J=1,NR,1
```

```
      SUMNU=0.0
      SUMXA=0.0
      SUMXE=0.0
      SUMXI=0.0
      SUMSBP=0.0
      SUMSBS=0.0
      SUMXV=0.0
      SUMXS=0.0
      SUMXN=0.0
      SUMOC=0.0
      SUMOE=0.0
      SUMOS=0.0
      SUMON=0.0
      SUMSU=0.0
      SUMRXS=0.0
      SUMNON=0.0
      SUMNH3=0.0
      SUMNT=0.0
      SUMNO3=0.0
      SUMOT=0.0
      DO 21 I=1,D
      IB=NJ*(I-1)+1
      SUMNU=SUMNU+NU(J,I)
      SUMXA=SUMXA+XA(J,I)
      SUMXE=SUMXE+XE(J,I)
      SUMXI=SUMXI+XI(J,I)
      SUMSBP=SUMSBP+SBP(J,I)
      SUMSBS=SUMSBS+SBS(J,IB)
      SUMXV=SUMXV+XV(J,I)
      SUMXN=SUMXN+XN(J,IB)
      SUMXS=SUMXS+XS(J,I)
      SUMOC=SUMOC+OC(J,I)
      SUMOE=SUMOE+OE(J,I)
      SUMOS=SUMOS+OS(J,I)
      SUMON=SUMON+ON(J,I)
      SUMSU=SUMSU+SU(J,I)
      SUMRXS=SUMRXS+RXS(J,I)
      SUMNO3=SUMNO3+NO3(J,IB)
      SUMNON=SUMNON+NON(J,I)
      SUMNH3=SUMNH3+NH3(J,IB)
      SUMNT=SUMNT+NT(J,I)
      SUMOT=SUMOT+OT(J,I)
   21 CONTINUE
      NUAV(J)=SUMNU/D
      XAAV(J)=SUMXA/D
      XEAV(J)=SUMXE/D
      XIAV(J)=SUMXI/D
      SBPAV(J)=SUMSBP/D
      SBSAV(J)=SUMSBS/D
      XVAV(J)=SUMXV/D
      XSAV(J)=SUMXS/D
      XNAV(J)=SUMXN/D
      OCAV(J)=SUMOC/D
      OEAV(J)=SUMOE/D
      OSAV(J)=SUMOS/D
      ONAV(J)=SUMON/D
      SUAV(J)=SUMSU/D
      RXSAV(J)=SUMRXS/D
      STAV(J)=SUAV(J)+SBSAV(J)+SBPAV(J)
      OTAV(J)=SUMOT/D
      NO3AV(J)=SUMNO3/D
      NONAV(J)=SUMNON/D
```

```
      NH3AV(J)=SUMNH3/D
      NTAV(J)=SUMNT/D
      SUMXVT=SUMXVT+XVAV(J)*V(J)
      SUMXAM=SUMXAM+XAAV(J)*V(J)
      SUMXEM=SUMXEM+XEAV(J)*V(J)
      SUMXIM=SUMXIM+XIAV(J)*V(J)
      SUMXSM=SUMXSM+XSAV(J)*V(J)
      SUMXNM=SUMXNM+XNAV(J)*V(J)
      SUMOSM=SUMOSM+OSAV(J)*V(J)
      SUMOEM=SUMOEM+OEAV(J)*V(J)
      SUMOCM=SUMOCM+OCAV(J)*V(J)
      SUMONM=SUMONM+ONAV(J)*V(J)
      SUMOTM=SUMOTM+OTAV(J)*V(J)
   22 CONTINUE
      ENIT=0.0
      ECOD=0.0
      SUMWS=0.0
      SUMNSW=0.00
      WCOD=0.0
      WNIT=0.0
      DO 7 I=1,D,1
      IB=NJ*(I-1)+1
      ECOD=ECOD+Q(NR,I)*ST(1,I)*DT
      ENIT=ENIT+Q(NR,I)*(NT(1,I)+NO3(1,IB))*DT
      SUMWS=SUMWS+XV(1,I)*WQ(I)*DT
      SUMNSW=SUMNSW+(FN*(XA(1,I)+XE(1,I)+XI(1,I))+FNS*XS(1,I))
     1*WQ(I)*DT
      WCOD=WCOD+(ST(1,I)+(1.0-FSSB)*SBP(1,I))*WQ(I)*DT
      WNIT=WNIT+(NT(1,I)+NO3(1,IB))*WQ(I)*DT
    7 CONTINUE
      NSWAV=SUMNSW/QAV
      RSAV=SUMXVT/SUMWS
      XAMAV=SUMXAM/VP
      XEMAV=SUMXEM/VP
      XIMAV=SUMXIM/VP
      XSMAV=SUMXSM/VP
      XVMAV=SUMXVT/VP
      XNMAV=SUMXNM/VP
      OSMAV=SUMOSM/VP
      OCMAV=SUMOCM/VP
      OEMAV=SUMOEM/VP
      ONMAV=SUMONM/VP
      OTMAV=SUMOTM/VP
C
C       CHECK MASS BALANCES ON COD AND NITROGEN
C       ---------------------------------------
C  1.   COD
C  -------
      TCODI=STQAV
      TCODO=P*SUMWS+SUMOCM*24.0+WCOD+ECOD
      BALC=TCODO*100.0/TCODI
C  2.   NITROGEN
C  ------------
      TNTI=NTQAV
      TNTO=NSWAV*QAV+WNIT+ENIT
      BALN=TNTO*100.0/TNTI
C
C       OUTPUT AND FORMAT STATEMENTS
C       ----------------------------
C
      WRITE(5,201) (TEMP,PH,YH,BHT,KVT,YN,THEN,F,FCA,FN,KNT,PHIN,
     1THEE,P,FOE,UMT,BNT,FOS,KRT,KSPT,THEZ,KMPT,THEA,THES,
```

```
     2KMST,KSST,FR,FNS,RSM,RS)
201  FORMAT(1H1,20X,22('*'),/,1H ,20X,22('*'),/,
     11H ,20X,'** WITH COD STORAGE **',/,1H ,20X,22('*'),/,
     11H ,20X,22('*'),/,
     11HO,10X,'KINETIC CONSTANTS',/,1H ,10X,17('-'),/,
     21H ,5X,'PROCESS OPERATING TEMPERATURE=',F5.1,1X,'DEG. C',/,
     31H ,28X,'AND PH=',F5.2,/,1HO,5X,'HETEROTROPHS',28X,'AUTOTROPHS',/,
     41H ,5X,12('-'),28X,10('-'),/,1H ,6X,'YH=',F5.3,4X,'BH=',F5.3,4X,
     5'KV=',F5.3,8X,'YN=',F5.3,6X,'THEN=',F5.3,/,1H ,7X,'F=',F5.3,3X,
     6'FCA=',F5.3,4X,'FN=',F5.3,8X,'KN=',F5.2,6X,'PHIN=',F5.3,/,
     75X,'THEE=',F5.3,5X,'P=',F5.3,3X,'FOE=',F5.3,8X,'UM=',F5.3,
     28X,'BN=',F5.3,/,
     86X,'FOS=',F5.3,4X,'KR=',F5.3,3X,'KSP=',F5.1,6X,'THEZ=',F5.3,/,
     16X,'KMP=',F5.3,2X,'THEA=',F5.3,2X,'THES=',F5.3,/,
     26X,'KMS=',F5.3,3X,'KSS=',F5.1,/,
     27X,'FR=',F5.3,3X,'FNS=',F5.3,/,
     91HO,5X,'MINIMUM SLUDGE AGE FOR NITRIFICATION=',F5.2,1X,'DAYS',/,
     11H ,5X,'OPERATING SLUDGE AGE OF PROCESS=',F5.2,1X,'DAYS')
      WRITE(5,202) (FUP,FUS,SN,UN,QAV,STQAV,NTQAV,STIAV,SBIAV,SUIAV,
     1XIIAV,NTIAV,NH3IAV,NONIAV,NUIAV,NO3IAV)
202  FORMAT(1HO,10X,'AVERAGE COMPOSITION OF SEWAGE',/,
     11H ,10X,29('-'),/,1HO,5X,'SOLID INERT FRACTION OF INFLUENT COD=',
     2F5.3,/,1H ,5X,'SOLUBLE INERT FRACTION OF INFLUENT COD=',F5.3,/,
     31H ,5X,'AMMONIA TO TKN FRACTION=',F5.3,/,
     41H ,5X,'INERT TKN FRACTION=',F5.3,/,1HO,4X,'QAV=',E9.5,
     15X,'STQAV=',E9.5,5X,'NTQAV=',E9.5,/,
     51H ,5X,'STI=',F7.2,5X,'SBI=',F7.2,4X,'SUI=',F6.2,
     64X,'XII=',F6.2,/,1H ,5X,'NTI=',F6.2,4X,'NH3I=',F6.2,
     74X,'NONI=',F5.2,5X,'NUI=',F5.2,5X,'NO3I=',F5.2)
      IF(TYPE.EQ.1) GO TO 122
      IF(TYPE.EQ.2) GO TO 123
122  WRITE(5,205) (VARQ,VARSTI,VARNTI,VNO3I,VARSTL,VARNTL,VRNO3L)
205  FORMAT(1HO,10X,'SINE WAVE INFLUENT FLOW AND FEED PATTERN',/,
     11H ,10X,40('-'),/,
     41HO,10X,'AMPLITUDE OF FLOW WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     51H ,10X,'AMPLITUDE OF COD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     61H ,10X,'AMPLITUDE OF TKN WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     71H ,10X,'AMPLITUDE OF NO3 WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF COD LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF TKN LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF NO3 LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)')
      GO TO 124
123  WRITE(5,206) (LFP,PQ,BQ,VF)
206  FORMAT(1HO,10X,'SQUARE WAVE INFLUENT FLOW AND FEED PATTERN',/,
     11H ,10X,42('-'),/,
     11H ,10X,'LENGTH OF FEED PERIOD (HRS)=',F5.2,/,
     21H ,10X,'PEAK FLOW (L/D)=',E9.5,/,
     31H ,10X,'BASE FLOW (L/D)=',E9.5,/,
     41H ,10X,'VOLUME OF FEED PER DAY (LITRES)=' E9.5)
124  WRITE(5,203) TRN,VP,M,RSAV,SR,WQR
203  FORMAT(1H1,10X,21('-'),/,1H ,10X,'DAILY AVERAGE RESULTS',/,
     11H ,10X,21('-'),/,
     11HO,5X,'TOTAL HYDRAULIC RETENTION TIME=',F8.3,1X,'HOURS',/,
     11H ,5X,'TOTAL VOLUME=',E9.5,1X,'LITRES',/,
     21H ,5X,'NO. OF DAYS TO REACH DYNAMIC STEADY STATE=',I3,/,
     21H ,5X,'SLUDGE AGE =',F5.2,1X,'DAYS',/,
     31H ,5X,'UNDERFLOW SLUDGE RECYCLE RATIO =',F4.2,/,
     41H ,5X,'SLUDGE WASTE FLOW RATIO =',F7.5)
      WRITE(5,244) (TCODI,TCODO,BALC,TNTI,TNTO,BALN)
244  FORMAT(1HO,10X,'MASS BALANCES ON COD AND NITROGEN',/,
     11H ,10X,33('-'),/,
     21HO,5X,'TOTAL COD MASS INPUT=',1X,E13.6,1X,'(MG-COD/D)',/,
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      21H ,5X,'TOTAL COD MASS OUTPUT=',1X,E13.6,1X,'(MG-COD/D)',/,
      31H ,5X,'PERCENTAGE COD RECOVERY=',1X,F7.3,1X,'(%)',/,
      21H ,5X,'TOTAL NITROGEN MASS INPUT=',1X,E13.6,1X,'(MG-N/D)',/,
      21H ,5X,'TOTAL NITROGEN MASS OUTPUT=',1X,E13.6,1X,'(MG-N/D)',/,
      31H ,5X,'PERCENTAGE NITROGEN RECOVERY=',1X,F7.3,1X,'(%)')
       IF(RESULT.EQ.2) GO TO 125
       WRITE(5,300)
  300 FORMAT(1H0,30X,'TANK  1',6X,'TANK  2',
     26X,'TANK  3',6X,'TANK  4',6X,'TANK  5',6X,'TANK  6',
     36X,'MEAN',/,1H ,30X,7('-'),6X,7('-'),6X,7('-'),6X,7('-'),
     46X,7('-'),6X,7('-'),6X,4('-'))
       WRITE(5,301) ((XAAV(J),J=1,NR,1),XAMAV)
       WRITE(5,302) ((XSAV(J),J=1,NR,1),XSMAV)
       WRITE(5,303) ((XEAV(J),J=1,NR,1),XEMAV)
       WRITE(5,304) ((XIAV(J),J=1,NR,1),XIMAV)
       WRITE(5,305) ((XVAV(J),J=1,NR,1),XVMAV)
       WRITE(5,319) ((XNAV(J),J=1,NR,1),XNMAV)
       WRITE(5,313) ((OSAV(J),J=1,NR,1),OSMAV)
       WRITE(5,308) ((OEAV(J),J=1,NR,1),OEMAV)
       WRITE(5,314) ((OCAV(J),J=1,NR,1),OCMAV)
       WRITE(5,315) ((ONAV(J),J=1,NR,1),ONMAV)
       WRITE(5,316) ((OTAV(J),J=1,NR,1),OTMAV)
       WRITE(5,321) (SBPAV(J),J=1,NR,1)
       WRITE(5,320) (SBSAV(J),J=1,NR,1)
       WRITE(5,324) (SUAV(J),J=1,NR,1)
       WRITE(5,311) (STAV(J),J=1,NR,1)
       WRITE(5,306) (NONAV(J),J=1,NR,1)
       WRITE(5,310) (NH3AV(J),J=1,NR,1)
       WRITE(5,323) (NUAV(J),J=1,NR,1)
       WRITE(5,312) (NTAV(J),J=1,NR,1)
       WRITE(5,307) (NO3AV(J),J=1,NR,1)
       WRITE(5,322) (V(J),J=1,NR,1)
       WRITE(5,317) (RA(J),J=1,NR,1)
       WRITE(5,318) (RN(J),J=1,NR,1)
  301 FORMAT(1H ,8X,'XA    (MG-VSS/L)',2X,7(E13.5))
  302 FORMAT(1H ,8X,'XS    (MG-VSS/L)',2X,7(E13.5))
  303 FORMAT(1H ,8X,'XE    (MG-VSS/L)',2X,7(E13.5))
  304 FORMAT(1H ,8X,'XI    (MG-VSS/L)',2X,7(E13.5))
  305 FORMAT(1H ,8X,'XV    (MG-VSS/L)',2X,7(E13.5))
  319 FORMAT(1H ,8X,'XN    (MG-VSS/L)',2X,7(E13.5))
  313 FORMAT(1H ,8X,'OS   (MG-O/L/HR)',2X,7(E13.5))
  308 FORMAT(1H ,8X,'OE   (MG-O/L/HR)',2X,7(E13.5))
  314 FORMAT(1H ,8X,'OC   (MG-O/L/HR)',2X,7(E13.5))
  315 FORMAT(1H ,8X,'ON   (MG-O/L/HR)',2X,7(E13.5))
  316 FORMAT(1H ,8X,'OT   (MG-O/L/HR)',2X,7(E13.5))
  321 FORMAT(1H ,8X,'SBP   (MG-COD/L)',2X,6(E13.5))
  320 FORMAT(1H ,8X,'SBS   (MG-COD/L)',2X,6(E13.5))
  324 FORMAT(1H ,8X,'SU    (MG-COD/L)',2X,6(E13.5))
  311 FORMAT(1H ,8X,'ST    (MG-COD/L)',2X,6(E13.5))
  306 FORMAT(1H ,8X,'NON     (MG-N/L)',2X,6(E13.5))
  310 FORMAT(1H ,8X,'NH3     (MG-N/L)',2X,6(E13.5))
  323 FORMAT(1H ,8X,'NU      (MG-N/L)',2X,6(E13.5))
  312 FORMAT(1H ,8X,'NT      (MG-N/L)',2X,6(E13.5))
  307 FORMAT(1H ,8X,'NO3     (MG-N/L)',2X,6(E13.5))
  322 FORMAT(1H ,8X,'VOL     (LITRES)',2X,6(E13.5))
  317 FORMAT(1H ,8X,'AHRT     (HOURS)',2X,6(E13.5))
  318 FORMAT(1H ,8X,'NHRT     (HOURS)',2X,6(E13.5))
       DIMENSION IFMT(5)
       DATA IFMT/'((2OX,',I4,',O,'(E13.5',')))'/
       IFMT(3)=INUMC(NR,O)
       WRITE(5,399) (KO(I),STQ(I),NTQ(I),Q(1,I),SBI(I),STI(I),
     INTI(I),SUI(I),NUI(I),XII(I),NH3I(I),NONI(I),WQ(I),
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```
     2I=1,NL,KH)
399 FORMAT(1H1,10X,'DYNAMIC INPUTS',/,1H ,10X,14('-'),/,
    11H ,1X,'TIME',1X,'COD LOAD',1X,'TKN LOAD',3X,'FLOW',6X,'SBI',6X,
    2'STI',6X,'NTI',6X,'SUI',6X,'NUI',6X,'XII',5X,'NH3I',5X,'NONI',
    37X,'WQ',/,
    31H ,1X,4('-'),1X,8('-'),1X,8('-'),3X,4('-'),6X,3('-'),6X,3('-'),
    46X,3('-'),6X,3('-'),6X,3('-'),6X,3('-'),5X,4('-'),5X,4('-'),
    57X,2('-'),/,
    5(1H ,2X,I4,12(E9.4)))
      WRITE(5,400)
400 FORMAT(1H1,10X,21('-'),/,1H ,10X,'DAILY DYNAMIC RESULTS',/,
    11H ,10X,21('-'),/,
    11HO,20X,'TIME',5X,'TANK  1',6X,'TANK  2',
    26X,'TANK  3',6X,'TANK  4',6X,'TANK  5',6X,'TANK  6',/,
    31H ,20X,4('-'),5X,7('-'),6X,7('-'),6X,7('-'),6X,7('-'),
    46X,7('-'),6X,7('-'))
      WRITE(5,401)
401 FORMAT(1HO,3X,'XA    (MG-VSS/L)')
      WRITE(5,IFMT) (KO(I),(XA(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,402)
402 FORMAT(1HO,3X,'XS    (MG-VSS/L)')
      WRITE(5,IFMT) (KO(I),(XS(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,403)
403 FORMAT(1HO,3X,'XE    (MG-VSS/L)')
      WRITE(5,IFMT) (KO(I),(XE(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,404)
404 FORMAT(1HO,3X,'XI    (MG-VSS/L)')
      WRITE(5,IFMT) (KO(I),(XI(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,405)
405 FORMAT(1HO,3X,'XV    (MG-VSS/L)')
      WRITE(5,IFMT) (KO(I),(XV(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,419)
419 FORMAT(1HO,3X,'XN    (MG-VSS/L)')
      DO 34 I=1,NL,KH
      IB=NJ*(I-1)+1
 34   WRITE(5,IFMT) (KO(I),(XN(J,IB),J=1,NR,1))
      WRITE(5,406)
406 FORMAT(1HO,3X,'OS   (MG-O/L/HR)')
      WRITE(5,IFMT) (KO(I),(OS(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,410)
410 FORMAT(1HO,3X,'OE   (MG-O/L/HR)')
      WRITE(5,IFMT) (KO(I),(OE(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,407)
407 FORMAT(1HO,3X,'OC   (MG-O/L/HR)')
      WRITE(5,IFMT) (KO(I),(OC(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,408)
408 FORMAT(1HO,3X,'ON   (MG-O/L/HR)')
      WRITE(5,IFMT) (KO(I),(ON(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,409)
409 FORMAT(1HO,3X,'OT   (MG-O/L/HR)')
      WRITE(5,IFMT) (KO(I),(OT(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,411)
411 FORMAT(1HO,3X,'SBP   (MG-COD/L)')
      WRITE(5,IFMT) (KO(I),(SBP(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,418)
418 FORMAT(1HO,3X,'SBS     (MG-N/L)')
      DO 33 I=1,NL,KH
      IB=NJ*(I-1)+1
 33   WRITE(5,IFMT) (KO(I),(SBS(J,IB),J=1,NR,1))
      WRITE(5,420)
420 FORMAT(1HO,3X,'SU    (MG-COD/L)')
      WRITE(5,IFMT) (KO(I),(SU(J,I),J=1,NR,1),I=1,NL,KH)
```

```
      WRITE(5,412)
  412 FORMAT(1HO,3X,'ST    (MG-COD/L)')
      WRITE(5,IFMT) (KO(I),(ST(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,413)
  413 FORMAT(1HO,3X,'NON     (MG-N/L)')
      WRITE(5,IFMT) (KO(I),(NON(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,421)
  421 FORMAT(1HO,3X,'NU      (MG-N/L)')
      WRITE(5,IFMT) (KO(I),(NU(J,I),J=1,NR,1),I=1,NL,KH)
      WRITE(5,415)
  415 FORMAT(1HO,3X,'NH3     (MG-N/L)')
      DO 35 I=1,NL,KH
      IB=NJ*(I-1)+1
   35 WRITE(5,IFMT) (KO(I),(NH3(J,IB),J=1,NR,1))
      WRITE(5,414)
  414 FORMAT(1HO,3X,'NT      (MG-N/L)')
      WRITE(5,IFMT) (KO(I),(NT(J,I),J=1,NR,I),I=1,NL,KH)
      WRITE(5,416)
  416 FORMAT(1HO,3X,'NO3     (MG-N/L)')
      DO 36 I=1,NL,KH
      IB=NJ*(I-1)+1
   36 WRITE(5,IFMT) (KO(I),(NO3(J,IB),J=1,NR,1))
      IF(RESULT.EQ.1) GO TO 126
C
C           FORMATS FOR PLOTTER ROUTINE
C           ---------------------------
C
      PARAMETER NDD=281
      DIMENSION PL(NDD),OTP(NDD),OTSP(NDD),QP(NDD),
     1XVP(NDD),STP(NDD),STISP(NDD),QSP(NDD),STIP(NDD),
     2ONP(NDD),ONSP(NDD)
      REAL NTP(NDD),NTIP(NDD),NO3P(NDD),NTISP(NDD),NH3P(NDD)
  125 N1=28*KH
      N2=28*KH+1
      WRITE(18,510) (RSAV,STIAV,NTIAV,TEMP,TN,NR,PH,NITDEN)
  510 FORMAT(F4.1,F5.1,2F4.1,A2,I2,F4.2,I1)
      WRITE(18,511) N2,TYPE,QMAX,STIMAX,NTIMAX
  511 FORMAT(2I4,F12.2,F8.2,F6.2)
  512 FORMAT(2F5.2)
      IF(TYPE.EQ.1) GO TO 37
      IF(TYPE.EQ.2) GO TO 38
   37 WRITE(18,512) VARSTL,VARNTL
      GO TO 39
   38 WRITE(18,512) LFP
   39 DO 501 I=1,N2,1
      OTSP(I)=OTMAV
      QSP(I)=QAV
      ONSP(I)=ONMAV
      STISP(I)=STIAV
  501 NTISP(I)=NTIAV
      PL(1)=0.0
      DO 502 I=1,N1,1
  502 PL(I+1)=PL(I)+DT*24.0
      DO 503 I=1,D,1
      QP(I)=Q(1,I)
      NTIP(I)=NTI(I)
  503 STIP(I)=STI(I)
      DO 504 KL=NL,N2,1
      I=KL-D
      QP(KL)=Q(1,I)
      NTIP(KL)=NTI(I)
  504 STIP(KL)=STI(I)
```

```
      992            DO 505 K=1,N2,1
      993        505 WRITE(18,513) (PL(K),OTSP(K),QSP(K),ONSP(K),QP(K),
      994           1STISP(K),NTISP(K),STIP(K),NTIP(K))
      995        513 FORMAT(1H ,2F7.2,E9.5,F7.2,E9.5,4F7.2)
      996            DO 506 J=1,NR,1
      997            DO 507 I=1,D,1
      998            IB=NJ*(I-1)+1
      999            OTP(I)=OT(J,I)
     1000            NTP(I)=NT(J,I)
     1001            NO3P(I)=NO3(J,IB)
     1002            XVP(I)=XV(J,I)
     1003            NH3P(I)=NH3(J,IB)
     1004            ONP(I)=ON(J,I)
     1005        507 STP(I)=ST(J,I)
     1006            DO 508 KL=NL,N2,1
     1007            I=KL-D
     1008            IB=NJ*(I-1)+1
     1009            OTP(KL)=OT(J,I)
     1010            NTP(KL)=NT(J,I)
     1011            NO3P(KL)=NO3(J,IB)
     1012            XVP(KL)=XV(J,I)
     1013            NH3P(KL)=NH3(J,IB)
     1014            ONP(KL)= ON(J,I)
     1015        508 STP(KL)=ST(J,I)
     1016            DO 509 K=1,N2,1
     1017        509 WRITE(18,514) (OTP(K),STP(K),ONP(K),NTP(K),XVP(K),
     1018           1NO3P(K),NH3P(K))
     1019        514 FORMAT(1H ,7F7.2)
     1020        506 CONTINUE
     1021            ENDFILE 18
     1022        126 STOP
     1023            END

$PRT,S CONTAX*CONTACTBS.CONTAC
```

```
CONTAX*CONTACTBS(1).CONTAC
      C*************************************************************************
            SUBROUTINE CONTAC(D,DT,J,QR,FR,FCA,KVT,KMPT,KSPT,KMST,KSST,
           IP,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT)
      C*************************************************************************
      C              THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF THE
      C                FIRST REACTOR IN A SERIES UNDER AEROBIC CONDITIONS
      C*************************************************************************
            PARAMETER NE=2
            PARAMETER ND=241
            PARAMETER NF=961
            INTEGER D
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/BLOCC1/SBS(NE,NF),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,NF),NH3(NE,NF),
           2NO3(NE,NF),SBP(NE,ND)
            COMMON/BLOCC2/Q(NE,ND),V(NE),SBI(ND),SUI(ND),SCIS(NE,NF),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(NF),SCIP(NE,ND),
           3SCVO(NE,ND),NNIT(NE,NF)
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NNIT
            REAL NU,NON,NH3,NO3
            DO 11 I=1,D,1
            DUMA=DT*Q(J,I)/V(J)
            DUMB=DT*QR/V(J)
            DUMC=DT*(QR+Q(J,I))/V(J)
            IA=NJ*(I-1)
            DO 12 IJ=1,NJ,1
            IB=IA+IJ
            SCIS(J,IB)=KMST*SBS(J,IB)/(KSST+SBS(J,IB))*XA(J,I)*DDT
            SBS(J,IB+1)=SBS(J,IB)+DUMA*RDT*FCA*SBI(I)-SCIS(J,IB)
           1+RDT*DUMB*SBS(NR,IB)-RDT*DUMC*SBS(J,IB)
         12 CONTINUE
            IB=NJ*I
            BRAK=FR-(XS(J,I)/XA(J,I))
            IF(BRAK.GT.0.00) GO TO 40
            BRAK=0.00
            XS(J,I)=FR*XA(J,I)
         40 XV(J,I)=XS(J,I)+XA(J,I)+XE(J,I)+XI(J,I)
            SCIP(J,I)=DT*KVT*BRAK*SBP(J,I)*XA(J,I)
            SBP(J,I+1)=SBP(J,I)+DUMA*(1.0-FCA)*SBI(I)-SCIP(J,I)
           1+DUMB*SBP(NR,I)-DUMC*SBP(J,I)
            IF(SBP(J,I+1).LT.0.0) SBP(J,I+1)=0.0
            SCVO(J,I)=KMPT/(KSPT+XS(J,I)*P)*XA(J,I)*XS(J,I)*DT
            XS(J,I+1)=XS(J,I)+SCIP(J,I)/P-SCVO(J,I)
           1+DUMB*XS(NR,I)-DUMC*XS(J,I)
            SU(J,I+1)=SU(J,I)+DUMA*SUI(I)
           1+DUMB*SU(NR,I)-DUMC*SU(J,I)
            NU(J,I+1)=NU(J,I)+DUMA*NUI(I)
           1+DUMB*NU(NR,I)-DUMC*NU(J,I)
            XA(J,I+1)=XA(J,I)+YH*(SCVO(J,I)*P+SCIS(J,IB)/RDT)
           1-BHT*XA(J,I)*DT+DUMB*XA(NR,I)-DUMC*XA(J,I)
            XE(J,I+1)=XE(J,I)+F*BHT*XA(J,I)*DT
           1+DUMB*XE(NR,I)-DUMC*XE(J,I)
            XI(J,I+1)=XI(J,I)+DUMA*XII(I)
           1+DUMB*XI(NR,I)-DUMC*XI(J,I)
            NON(J,I+1)=NON(J,I)+DUMA*NONI(I)
           1-DT*KRT*XA(J,I)*NON(J,I)
           1+DUMB*NON(NR,I)-DUMC*NON(J,I)
           2+(FOE*FN*(1.0-F)*BHT*XA(J,I))*DT-FOS*FN*YH*(P*SCVO(J,I)
           3+SCIS(J,IB)/RDT)
```

```
     3-FNS*(SCIP(J,I)/P-SCVO(J,I))
      XV(J,I+1)=XS(J,I+1)+XA(J,I+1)+XE(J,I+1)+XI(J,I+1)
      IA=NJ*(I-1)
      DO 11 IJ=1,NJ,1
      IB=IA+IJ
      NNIT(J,IB)=DDT*UMT/YN*NH3(J,IB)*XN(J,IB)/(KNT+NH3(J,IB))
      TNH3=NH3(J,IB)+RDT*DUMA*NH3I(I)+DDT*KRT*XA(J,I)*NON(J,I)
     1+RDT*DUMB*NH3(NR,IB)-RDT*DUMC*NH3(J,IB)
     1+DDT*(1.0-FOE)*FN*(1.0-F)*BHT*XA(J,I)
     1-(1.0-FOS)*FN*YH*(P*SCVO(J,I)*RDT+SCIS(J,IB))-NNIT(J,IB)
      IF(TNH3.GT.0.0) GO TO 43
      NH3(J,IB+1)=0.0
      NO3(J,IB+1)=NO3(J,IB)+RDT*DUMA*NO3I(I)+NNIT(J,IB)
     1+RDT*DUMB*NO3(NR,IB)-RDT*DUMC*NO3(J,IB)+TNH3
      GO TO 44
   43 NH3(J,IB+1)=TNH3
      NO3(J,IB+1)=NO3(J,IB)+RDT*DUMA*NO3I(I)+NNIT(J,IB)
     1+RDT*DUMB*NO3(NR,IB)-RDT*DUMC*NO3(J,IB)
   44 XN(J,IB+1)=XN(J,IB)+YN*NNIT(J,IB)-BNT*XN(J,IB)*DDT
     1+RDT*DUMB*XN(NR,IB)-RDT*DUMC*XN(J,IB)
   11 CONTINUE
      RETURN
      END
$PRT,S CONTAX*CONTACTBS.STABIC
```

```
CONTAX*CONTACTBS(1).STABIC
      C*****************************************************************
            SUBROUTINE STABIC(D,DT,J,QR,FR,FCA,KVT,KMPT,KSPT,KMST,KSST,
           IP,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT)
      C*****************************************************************
      C              THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF THE
      C               2ND TO NTH REACTORS IN A SERIES UNDER AEROBIC CONDITIONS
      C*****************************************************************
            PARAMETER NE=2
            PARAMETER ND=241
            PARAMETER NF=961
            INTEGER D
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/BLOCC1/SBS(NE,NF),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,NF),NH3(NE,NF),
           2NO3(NE,NF),SBP(NE,ND)
            COMMON/BLOCC2/Q(NE,ND),V(NE),SBI(ND),SUI(ND),SCIS(NE,NF),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(NF),SCIP(NE,ND),
           3SCVO(NE,ND),NNIT(NE,NF)
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NNIT
            REAL NU,NON,NH3,NO3
            DUM=DT*QR/V(J)
            DO 18 I=1,D,1
            IA=NJ*(I-1)
            DO 12 IJ=1,NJ,1
            IB=IA+IJ
            SCIS(J,IB)=KMST*SBS(J,IB)/(KSST+SBS(J,IB))*XA(J,I)*DDT
            SBS(J,IB+1)=SBS(J,IB)-SCIS(J,IB)
           1+DUM*RDT*(SBS(J-I,IB)-SBS(J,IB))
         12 CONTINUE
            IB=NJ*I
            BRAK=FR-(XS(J,I)/XA(J,I))
            IF(BRAK.GT.0.00) GO TO 45
            BRAK=0.00
            XS(J,I)=FR*XA(J,I)
         45 XV(J,I)=XS(J,I)+XA(J,I)+XE(J,I)+XI(J,I)
            SCIP(J,I)=DT*KVT*BRAK*SBP(J,I)*XA(J,I)
            SBP(J,I+1)=SBP(J,I)-SCIP(J,I)
           1+DUM*(SBPR(I)-SBP(J,I))
            IF(SBP(J,I+1).LT.0.0) SBP(J,I+1)=0.0
            SCVO(J,I)=KMPT/(KSPT+XS(J,I)*P)*XA(J,I)*XS(J,I)*DT
            XS(J,I+1)=XS(J,I)+SCIP(J,I)/P-SCVO(J,I)
           1+DUM*(XSR(I)-XS(J,I))
            IF(XS(J,I+1).LT.0.0) XS(J,I+1)=0.0
            SU(J,I+1)=SU(J,I)+DUM*(SU(J-1,I)-SU(J,I))
            NU(J,I+1)=NU(J,I)+DUM*(NU(J-1,I)-NU(J,I))
            XA(J,I+1)=XA(J,I)+YH*(SCVO(J,I)*P+SCIS(J,IB)/RDT)
           1-BHT*XA(J,I)*DT+DUM*(XAR(I)-XA(J,I))
            XE(J,I+1)=XE(J,I)+F*BHT*XA(J,I)*DT
           1+DUM*(XER(I)-XE(J,I))
            XI(J,I+1)=XI(J,I)+DUM*(XIR(I)-XI(J,I))
            NON(J,I+1)=NON(J,I)-KRT*XA(J,I)*NON(J,I)*DT
           1+DUM*(NON(J-1,I)-NON(J,I))
           2+(FOE*FN*(1.0-F)*BHT*XA(J,I))*DT-FOS*FN*YH
           3*(P*SCVO(J,I)+SCIS(J,IB)/RDT)
           3-FNS*(SCIP(J,I)/P-SCVO(J,I))
            XV(J,I+1)=XS(J,I+1)+XA(J,I+1)+XE(J,I+1)+XI(J,I+1)
            IA=NJ*(I-1)
            DO 18 IJ=1,NJ,1
            IB=IA+IJ
```

```
      NNIT(J,IB)=DDT*UMT/YN*NH3(J,IB)*XN(J,IB)/(KNT+NH3(J,IB))
      TNH3=NH3(J,IB)+DDT*KRT*XA(J,I)*NON(J,I)
     1+RDT*DUM*(NH3(J-1,IB)-NH3(J,IB))
     1+DDT*(1.0-FOE)*FN*(1.0-F)*BHT*XA(J,I)
     1-(1.0-FOS)*FN*YH*(P*SCVO(J,I)*RDT+SCIS(J,IB))-NNIT(J,IB)
      IF(TNH3.GT.0.0) GO TO 46
      NH3(J,IB+1)=0.0
      NO3(J,IB+1)=NO3(J,IB)+NNIT(J,IB)+TNH3
     1+RDT*DUM*(NO3(J-1,IB)-NO3(J,IB))
      GO TO 47
   46 NH3(J,IB+1)=TNH3
      NO3(J,IB+1)=NO3(J,IB)+NNIT(J,IB)
     1+RDT*DUM*(NO3(J-1,IB)-NO3(J,IB))
   47 XN(J,IB+1)=XN(J,IB)+YN*NNIT(J,IB)-BNT*XN(J,IB)*DDT
     1+RDT*DUM*(XNR(IB)-XN(J,IB))
   18 CONTINUE
      RETURN
      END
$PRT,S CONTAX*CONTACTBS.PARNTC
```

```
CONTAX*CONTACTBS(1).PARNTC
      1       C*********************************************************************
      2             SUBROUTINE PARNTC(YH,FCA,RS,BHT,KVT,TRNS,KMPT,KSPT,KMST,KSST,
      3            1P,F,FN,FNS,KRT,KNT,BNT,UMT,YN,
      4            2SBIAV,SUIAV,XIIAV,NUIAV,NONIAV,NTIAV,NO3IAV)
      5       C*********************************************************************
      6       C              THIS SUBROUTINE CALCULATES THE STEADY STATE
      7       C               SOLUTION ( PARTICULAR INTEGRAL )
      8       C*********************************************************************
      9             PARAMETER NE=2
     10             PARAMETER ND=241
     11             PARAMETER NF=961
     12             REAL NUIAV,NONIAV,NTIAV,NO3IAV
     13             REAL NH3MAX,NSW
     14             COMMON/BLOCC1/SBS(NE,NF),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
     15            1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,NF),NH3(NE,NF),
     16            2NO3(NE,NF),SBP(NE,ND)
     17             COMMON/BLOCC2/Q(NE,ND),V(NE),SBI(ND),SUI(ND),SCIS(NE,NF),
     18            1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),
     19            2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(NF),SCIP(NE,ND),
     20            3SCVO(NE,ND),NNIT(NE,NF)
     21             REAL KVT,KMPT,KSPT,KMST,KSSI,KRT,KNT
     22             REAL NUI,NONI,NH3I,NO3I,NNIT
     23             REAL NU,NON,NH3,NO3
     24             DUM=(1.0/RS+BHT)/(YH*KVT)
     25             SBS(1,1)=FCA*DUM
     26             SBP(1,1)=(1.0-FCA)*DUM
     27             XA(1,1)=YH*(SBIAV-DUM)*RS/(TRNS*(1.0+BHT*RS))
     28             DUM1=KSPT+XA(1,1)*RS*(KMPT-KVT*SBP(1,1))
     29             DUM2=-KVT*XA(1,1)*SBP(1,1)*RS*KSPT
     30             XS(1,1)=(-DUM1+SQRT((DUM1)**2-4*DUM2))/(2*P)
     31             XE(1,1)=F*BHT*XA(1,1)*RS
     32             XI(1,1)=XIIAV*RS/TRNS
     33             XV(1,1)=XA(1,1)+XS(1,1)+XE(1,1)+XI(1,1)
     34             SU(1,1)=SUIAV
     35             NU(1,1)=NUIAV
     36             NSW=(FN*(XA(1,1)+XE(1,1)+XI(1,1))+FNS*XS(1,1))*TRNS/RS
     37             NON(1,1)=(NONIAV+TRNS*((1.0-F)*FN*BHT*XA(1,1)-FNS*XS(1,1)))/
     38            1(1.0+KRT*XA(1,1)*TRNS)
     39             NH3MAX=NTIAV-NSW-NU(1,1)-NON(1,1)
     40             NH3(1,1)=KNT*(BNT+1.0/RS)/(UMT-BNT-1.0/RS)
     41             IF(NH3(1,1).GT.NH3MAX) NH3(1,1)=NH3MAX
     42             IF(NH3(1,1).LE.0.0) NH3(1,1)=NH3MAX
     43             XN(1,1)=YN*(NH3MAX-NH3(1,1))*RS/(TRNS*(1.0+BNT*RS))
     44             NO3(I,1)=NO3IAV+NH3MAX-NH3(1,1)
     45             RETURN
     46             END

@PRT,S CONTAX*CONTACTBS.SETLEC
```

```
CONTAX*CONTACTBS(1).SETLEC
      1       C*********************************************************************
      2             SUBROUTINE SETLEC(NL,J,QR,NJ,NKK,FSSB)
      3       C*********************************************************************
      4       C               THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF THE
      5       C                SETTLING TANK
      6       C*********************************************************************
      7             PARAMETER NE=2
      8             PARAMETER ND=241
      9             PARAMETER NF=961
     10             COMMON/BLOCC1/SBS(NE,NF),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
     11            1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,NF),NH3(NE,NF),
     12            2NO3(NE,NF),SBP(NE,ND)
     13             COMMON/BLOCC2/Q(NE,ND),V(NE),SBI(ND),SUI(ND),SCIS(NE,NF),
     14            1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),
     15            2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(NF),SCIP(NE,ND),
     16            3SCVO(NE,ND),NNIT(NE,NF)
     17             REAL NUI,NONI,NH3I,NO3I,NNIT
     18             REAL NU,NON,NH3,NO3
     19             DO 13 I=1,NL,1
     20             DUM=(QR+Q(J+1,I))/QR
     21             XAR(I)=XA(J,I)*DUM
     22             XSR(I)=XS(J,I)*DUM
     23             XER(I)=XE(J,I)*DUM
     24             XIR(I)=XI(J,I)*DUM
     25             SBPR(I)=(1.0-FSSB)*SBP(J,I)*DUM+FSSB*SBP(J,I)
     26             IA=NJ*(I-1)
     27             DO 13 IJ=1,NJ,1
     28             IB=IA+IJ
     29             IF(IB.GE.NKK) GO TO 13
     30             XNR(IB)=XN(J,IB)*DUM
     31          13 CONTINUE
     32             RETURN
     33             END

@PRT,S CONTAX*CONTACTBS.CHAR
```

```
CONTAX*CONTACTBS(1).CHAR
      1              COMPILER(FLD=ABS)
      2        C FUNCTION TO PUT CHARACTER REPRESENTATION OF INUM INTO INUMC
      3              FUNCTION INUMC(INUM,IZ)
      4              DIMENSION ICH(11)
      5              DATA ICH/'0','1','2','3','4','5','6','7','8','9',' '/
      6              DATA NBPC/6/,NCPW/6/
      7              IBIT=0
      8              IST=0
      9              IDIV=10**(NCPW-1)
     10              INUMT=INUM
     11        10    IDUM=INUMT/IDIV
     12              IF(IST.GT.0) GO TO 30
     13              IF(IDUM.GT.0) GO TO 20
     14              IDUM=IDUM+1
     15              IF(IZ.EQ.0) IDUM=11
     16              GO TO 40
     17        20    IST=1
     18        30    INUMT=INUMT-IDUM*IDIV
     19              IDUM=IDUM+1
     20        40    FLD(IBIT,NBPC,IDUMC)=FLD(0,NBPC,ICH(IDUM))
     21              IBIT=IBIT+NBPC
     22              IDIV=IDIV/10
     23              IF(IDIV.GT.0) GO TO 10
     24              INUMC=IDUMC
     25              RETURN
     26              END

@PRT,S CONTAX*CONTACTBS.PLOTTER
```

```
CONTAX*CONTACTBS(1).PLOTTER
      1              PARAMETER M=2
      2              PARAMETER N=300
      3              INTEGER TYPE,TN,P
      4              DIMENSION IBUF(5000)
      5              DIMENSION TEMPER(3),SLAGE(4),INFCOD(5),INFTKN(5),TNUM(3),
      6             1PHATCH(2)
      7              DIMENSION AA(5),BB(5),CC(5),DD(5),EE(5),FF(5),GG(5),PP(5)
      8              DIMENSION PT(N),TOP(N),TOSP(N),ONP(N),XVP(N),STP(N),
      9             2QP(N),QSP(N),SOP(N),SOSP(N),ONSP(N)
     10              DIMENSION CNTP(N),CNISP(N),CNO3P(N),CNIP(N),CNH3P(N)
     11              DIMENSION RTOP(M,N),RONP(M,N),RSTP(M,N),RXVP(M,N),
     12             1RNTP(M,N),RNO3P(M,N),RNH3P(M,N)
     13              DATA TEMPER/'TEMPER','ATURE ','      C'/
     14              DATA PHATCH/'  PH= ','        '/
     15              DATA SLAGE/'SLUDGE',' AGE  ','     D','AYS   '/
     16              DATA INFCOD/'MEAN I','NFLUEN','T COD ','     MG','-COD/L'/
     17              DATA INFTKN/'MEAN I','NFLUEN','T TKN ','      M','G-N/L '/
     18              DATA TNUM/'TEST N','UMBER ','        '/
     19              DATA P/025/
     20          100 FORMAT ( )
     21              READ(8,100) (AA(I),BB(I),CC(I),DD(I),EE(I),FF(I),GG(I),
     22             1PP(I),I=1,4,1)
     23              READ(18,110) (SAGE,ICOD,ITKN,TEMP,TN,NR,PH,NITDEN)
     24          110 FORMAT(A4,A5,2A4,A2,I2,A4,I1)
     25              READ(18,101) NO1,TYPE,QMAX,STIMAX,CNTIMX
     26          101 FORMAT(2I4,F12.2,F8.2,F6.2)
     27              WRITE(5,102) NO1,TYPE
     28          102 FORMAT(1X,'PLOT',I4,1X,'POINTS',4X,I4)
     29          103 FORMAT(F5.2)
     30              IF(TYPE.EQ.2) GO TO 703
     31          702 READ(18,103) VARL
     32              WRITE(5,104) VARL
     33          104 FORMAT(1X,'AMPLITUDE OF SINE WAVE=',F5.2)
     34              GO TO 704
     35          703 READ(18,103) CLFP
     36              WRITE(5,105) CLFP
     37          105 FORMAT(1X,'LENGTH OF FEED PERIOD OF SQUARE WAVE=',F5.2)
     38          704 FLD(0,24,SLAGE(3))=FLD(0,24,SAGE)
     39              FLD(0,24,TEMPER(3))=FLD(0,24,TEMP)
     40              FLD(0,24,PHATCH(2))=FLD(0,24,PH)
     41              FLD(0,18,INFCOD(4))=FLD(0,18,ICOD)
     42              FLD(0,24,INFTKN(4))=FLD(0,24,ITKN)
     43              FLD(6,12,TNUM(3))=FLD(0,12,TN)
     44              DO 150 I=1,NO1,1
     45          150 READ(18,107) (PT(I),TOSP(I),QSP(I),ONSP(I),QP(I),
     46             1SOSP(I),CNISP(I),SOP(I),CNIP(I))
     47          107 FORMAT(1H ,2F7.2,E9.5,F7.2,E9.5,4F7.2)
     48              PT(NO1+1)=0.0
     49              PT(NO1+2)=4.0
     50              DO 152 J=1,NR,1
     51              DO 152 I=1,NO1,1
     52          152 READ(18,106) (RTOP(J,I),RSTP(J,I),RONP(J,I),RNTP(J,I),
     53             1RXVP(J,I),RNO3P(J,I),RNH3P(J,I))
     54          106 FORMAT(1H ,7F7.2)
     55              CALL PLOTS(IBUF,5000,17)
     56              CALL FACTOR(0.5)
     57        C     CALL PLOTS(0,0,17)
     58        C     CALL NEWPEN(1)
     59        C     CALL FACTOR(1.27)
     60              CALL PLOT(0.0,4.0,-3)
     61              TOSP(NO1+1)=0.0
```

```
      TOSP(NO1+2)=25.0
      ONSP(NO1+1)=0.0
      ONSP(NO1+2)=25.0
      CALL AXIS(0.0,0.0,29HOXYGEN CONSUMPTION  (MG/L/HR),
     1+29,5.00,90.0,0.0,25.00)
      JUMP=1
      GO TO 300
C     CALL LINE(PT,ONSP,NO1,1,0, )
401   CALL LINE(PT,TOSP,NO1,1,0, )
      DO 201 J=1,NR,1
      DO 202 I=1,NO1,1
      TOP(I)=RTOP(J,I)
202   ONP(I)=RONP(J,I)
      TOP(NO1+1)=0.0
      TOP(NO1+2)=25.0
      ONP(NO1+1)=0.0
      ONP(NO1+2)=25.0
C     CALL LINE(PT,ONP,NO1,1,0, )
201   CALL LINE(PT,TOP,NO1,1,0, )
      CALL PLOT(7.00,7.00,-3)
      QP(NO1+1)=0.00
      QSP(NO1+1)=0.00
      IF(QMAX.GT.1000.0) GO TO 260
      QP(NO1+2)=20.0
      QSP(NO1+2)=20.0
      CALL AXIS(0.00,0.00,20HINFLUENT FLOW  (L/D),
     1-20,5.00,90.0,0.00,20.00)
      GO TO 261
260   QP(NO1+2)=20000.0
      QSP(NO1+2)=20000.0
      CALL AXIS(0.00,0.00,20HINFLUENT FLOW  (L/D),
     1-20,5.00,90.0,0.00,20000.00)
261   CALL PLOT(-7.50,0.00,-3)
      SOP(NO1+1)=0.0
      SOSP(NO1+1)=0.0
      IF(STIMAX.GT.1010.0) GO TO 262
      SOP(NO1+2)=200.0
      SOSP(NO1+2)=200.0
      CALL AXIS(0.0,0.0,20HINFLUENT COD  (MG/L),
     1+20,5.00,90.0,0.0,200.0)
      GO TO 263
262   SOP(NO1+2)=500.0
      SOSP(NO1+2)=500.0
      CALL AXIS(0.0,0.0,20HINFLUENT COD  (MG/L),
     1+20,5.00,90.0,0.0,500.0)
263   CNIP(NO1+1)=0.00
      CNISP(NO1+1)=0.00
      IF(CNTIMX.GT.51.0) GO TO 264
      CNIP(NO1+2)=10.0
      CNISP(NO1+2)=10.0
      CALL AXIS(0.0,0.0,22HINFLUENT TKN  (MG-N/L),
     1-22,5.00,90.0,0.00,10.00)
      GO TO 265
264   CNIP(NO1+2)=20.00
      CNISP(NO1+2)=20.00
      CALL AXIS(0.0,0.0,22HINFLUENT TKN  (MG-N/L),
     1-22,5.00,90.0,0.00,20.00)
265   CALL PLOT(0.50,0.00,-3)
      JUMP=2
      GO TO 300
402   CALL SYMBOL(0.00,5.74,0.14,INFCOD,0.00,30)
      CALL SYMBOL(0.00,5.54,0.14,INFTKN,0.00,30)
```

```
124             CALL LINE(PT,QSP,NO1,1,0, )
125             CALL LINE(PT,QP,NO1,1,0, )
126             CALL LINE(PT,SOSP,NO1,1,0, )
127             CALL LINE(PT,SOP,NO1,1,0, )
128             CALL LINE(PT,CNISP,NO1,1,0, )
129             CALL LINE(PT,CNIP,NO1,1,0, )
130             CALL PLOT(16.00,-7.00,-3)
131             CALL AXIS(0.00,0.00,17HMLVSS  (MG-VSS/L),
132            1-17,5.00,90.0,0.00,1000.0)
133             CALL PLOT(-7.00,0.00,-3)
134             CALL AXIS(0.0,0.0,31HFILTERED REACTOR COD (MG-COD/L),
135            1+31,5.00,90.0,0.0,20.00)
136             JUMP=3
137             GO TO 300
138         403 DO 211 J=1,NR,1
139             DO 212 I=1,NO1,1
140             STP(I)=RSTP(J,I)
141         212 XVP(I)=RXVP(J,I)
142             XVP(NO1+1)=0.0
143             XVP(NO1+2)=1000.0
144             STP(NO1+1)=0.0
145             STP(NO1+2)=20.0
146             CALL LINE(PT,STP,NO1,1,0, )
147         211 CALL LINE(PT,XVP,NO1,1,0, )
148             CALL PLOT(7.00,7.00,-3)
149             IF(NITDEN.EQ.2) GO TO 180
150             CALL AXIS(0.00,0.00,29HFILTERED REACTOR TKN (MG-N/L),
151            1-29,5.00,90.00,0.00,10.0)
152             CALL PLOT(-7.00,0.00,-3)
153             CALL AXIS(0.0,0.0,29HFILTERED REACTOR NO3 (MG-N/L),
154            1+29,5.00,90.0,0.0,10.0)
155             GO TO 181
156         180 CALL AXIS(0.00,0.00,29HFILTERED REACTOR TKN (MG-N/L),
157            1-29,5.00,90.00,0.00,5.00)
158             CALL PLOT(-7.00,0.00,-3)
159             CALL AXIS(0.0,0.0,29HFILTERED REACTOR NO3 (MG-N/L),
160            1+29,5.00,90.0,0.0,5.00)
161         181 JUMP=4
162             GO TO 300
163         404 DO 221 J=1,NR,1
164             DO 222 I=1,NO1,1
165             CNTP(I)=RNTP(J,I)
166             CNH3P(I)=RNH3P(J,I)
167         222 CNO3P(I)=RNO3P(J,I)
168             IF(NITDEN.EQ.2) GO TO 183
169             CNO3P(NO1+1)=0.0
170             CNO3P(NO1+2)=10.0
171             CNH3P(NO1+1)=0.0
172             CNH3P(NO1+2)=10.0
173             CNTP(NO1+1)=0.0
174             CNTP(NO1+2)=10.00
175             GO TO 184
176         183 CNO3P(NO1+1)=0.0
177             CNO3P(NO1+2)=5.0
178             CNH3P(NO1+1)=0.0
179             CNH3P(NO1+2)=5.0
180             CNTP(NO1+1)=0.0
181             CNTP(NO1+2)=5.00
182         184 CALL LINE(PT,CNTP,NO1,1,0, )
183       C     CALL LINE(PT,CNH3P,NO1,1,0, )
184         221 CALL LINE(PT,CNO3P,NO1,1,0, )
185             GO TO 301
```

```
  186          300 CALL AXIS(0.0,0.0,13HTIME  (HOURS),-13,7.00,
  187             10.0,0.0,4.00)
  188              IF(FLD(0,6,TN).EQ.P) GO TO 707
  189              IF(TYPE.NE.2) GO TO 553
  190              CALL LINE(AA,BB,2,1,0, )
  191              CC(1)=AA(1)+12.0
  192              CC(2)=AA(2)+12.0
  193              POS=CC(1)/4.0-0.28
  194              CALL LINE(CC,BB,2,1,0, )
  195              CALL LINE(DD,BB,2,1,0, )
  196              CALL SYMBOL(2.60,5.94,0.14,26HSQUARE WAVE LOAD VARIATION,
  197             10.00,26)
  198              CALL SYMBOL(0.15,5.24,0.14,5HSTART,0.00,5)
  199              CALL SYMBOL(POS,5.24,0.14,4HSTOP,0.00,4)
  200              CALL SYMBOL(6.15,5.24,0.14,5HSTART,0.00,5)
  201              CALL SYMBOL(0.22,5.05,0.14,4HFEED,0.00,4)
  202              CALL SYMBOL(POS,5.05,0.14,4HFEED,0.00,4)
  203              CALL SYMBOL(6.22,5.05,0.14,4HFEED,0.00,4)
  204              GO TO 601
  205          553 CALL LINE(AA,BB,2,1,0, )
  206              CALL LINE(CC,BB,2,1,0, )
  207              CALL LINE(DD,BB,2,1,0, )
  208              CALL SYMBOL(2.60,5.94,0.14,24HSINE WAVE LOAD VARIATION,0.0,24)
  209              CALL SYMBOL(0.00,5.05,0.14,8HMIN FLOW,0.0,8)
  210              CALL SYMBOL(3.00,5.05,0.14,8HMAX FLOW,0.0,8)
  211              CALL SYMBOL(6.00,5.05,0.14,8HMIN FLOW,0.0,8)
  212              GO TO 601
  213          707 AA(1)=8.00
  214              AA(2)=AA(1)
  215              CC(1)=AA(1)+12.00
  216              CC(2)=AA(2)+12.00
  217              CALL LINE(AA,BB,2,1,0, )
  218              CALL LINE(CC,BB,2,1,0, )
  219              CALL SYMBOL(2.60,5.94,0.14,23HOBSERVED LOAD VARIATION,0.0,23)
  220              CALL SYMBOL(1.72,5.05,0.14,4HNOON,0.0,4)
  221              CALL SYMBOL(4.50,5.05,0.14,8HMIDNIGHT,0.0,8)
  222          601 IF(JUMP.EQ.1) GO TO 552
  223              IF(JUMP.EQ.2) GO TO 551
  224              IF(JUMP.EQ.3) GO TO 550
  225              IF(JUMP.EQ.4) GO TO 550
  226          551 CALL LINE(PP,BB,2,1,0, )
  227              IF(JUMP.EQ.2) GO TO 550
  228          552 CALL LINE(EE,BB,2,1,0, )
  229          550 CALL LINE(FF,GG,2,1,0, )
  230              CALL SYMBOL(4.50,5.74,0.14,SLAGE,0.00,24)
  231              CALL SYMBOL(4.50,5.54,0.14,TEMPER,0.00,18)
  232              CALL SYMBOL(4.22,5.34,0.14,PHATCH,0.00,12)
  233              CALL SYMBOL(6.80,5.64,0.07,1,0.0,-1)
  234              CALL SYMBOL(0.00,5.94,0.14,17HTHEORETICAL MODEL,0.00,17)
  235              IF(JUMP.EQ.2) GO TO 603
  236              CALL SYMBOL(0.00,5.74,0.14,TNUM,0.00,18)
  237          603 IF(JUMP.EQ.1) GO TO 401
  238              IF(JUMP.EQ.2) GO TO 402
  239              IF(JUMP.EQ.3) GO TO 403
  240              IF(JUMP.EQ.4) GO TO 404
  241          301 CALL PLOT(11.00,-12.27,999)
  242        C     CALL EOT
  243              STOP
  244              END
@PRT,S CONTAX*CONTACTBS.GRAFS
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```
CONTAX*CONTACTBS(1).GRAFS
      1              PARAMETER M=6
      2              PARAMETER N=40
      3              INTEGER TYPE,TN,P
      4              DIMENSION IBUF(5000)
      5              DIMENSION TEMPER(3),SLAGE(4),INFCOD(5),INFTKN(5),TNUM(3),
      6             1PHATCH(2)
      7              DIMENSION AA(5),BB(5),CC(5),DD(5),EE(5),FF(5),GG(5),PP(5)
      8              DIMENSION TN1(N),TN2(N),TN3(N),TN4(N),TN5(N),TN6(N),
      9             1TN7(N),TN8(N),TN9(N),TN10(N),TN11(N)
     10              DIMENSION QP(N),SOP(N),XVP(N),STP(N)
     11              DIMENSION CNTP(N),CNO3P(N),CNIP(N),CNH3P(N)
     12              DIMENSION RNTP(M,N),RSTP(M,N),RXVP(M,N),RNO3P(M,N),RNH3P(M,N)
     13              DIMENSION TOP1(N),TOP2(N),TOP3(N),TOP4(N),
     14             1TOP5(N),TOP6(N)
     15              DATA TEMPER/'TEMPER','ATURE ','      C'/
     16              DATA PHATCH/'  PH= ','       '/
     17              DATA SLAGE/'SLUDGE',' AGE  ','      D','AYS    '/
     18              DATA INFCOD/'MEAN I','NFLUEN','T COD ','     MG','-COD/L'/
     19              DATA INFTKN/'MEAN I','NFLUEN','T TKN ','      M','G-N/L '/
     20              DATA TNUM/'TEST N','UMBER ','      '/
     21              DATA P/025/
     22          100 FORMAT ( )
     23              READ(8,100) (AA(I),BB(I),CC(I),DD(I),EE(I),FF(I),GG(I),
     24             1PP(I),I=1,4,1)
     25              READ(8,101) (TYPE,SAGE,ICOD,ITKN,TEMP,PH,TN,NR,NITDEN)
     26          101 FORMAT(I1,A4,A3,3A4,A2,I2,I1)
     27              READ(8,100) (N1,N2,N3,N4,N5,N6,N7,N8,N9,N10,N11)
     28              READ(8,100) (TN1(I),I=1,N1,1)
     29              READ(8,100) (TN2(I),I=1,N2,1)
     30              READ(8,100) (TN3(I),I=1,N3,1)
     31              READ(8,100) (TN11(I),I=1,N11,1)
     32              READ(8,100) (TN4(I),I=1,N4,1)
     33              READ(8,100) (TN5(I),I=1,N5,1)
     34              READ(8,100) (TN6(I),I=1,N6,1)
     35              READ(8,100) (TN7(I),I=1,N7,1)
     36              READ(8,100) (TN8(I),I=1,N8,1)
     37              READ(8,100) (TN9(I),I=1,N9,1)
     38              READ(8,100) (TN10(I),I=1,N10,1)
     39              DO 250 J=1,NR,1
     40              READ(8,100) (RXVP(J,I),I=1,N1,1)
     41              READ(8,100) (RSTP(J,I),I=1,N2,1)
     42              READ(8,100) (RNTP(J,I),I=1,N3,1)
     43              READ(8,100) (RNH3P(J,I),I=1,N11,1)
     44          250 READ(8,100) (RNO3P(J,I),I=1,N4,1)
     45              READ(8,100) (TOP1(I),I=1,N5,1)
     46              READ(8,100) (TOP2(I),I=1,N5,1)
     47              READ(8,100) (TOP3(I),I=1,N6,1)
     48              READ(8,100) (TOP4(I),I=1,N6,1)
     49              READ(8,100) (TOP5(I),I=1,N7,1)
     50              READ(8,100) (TOP6(I),I=1,N7,1)
     51              READ(8,100) (QP(I),I=1,N8,1)
     52              READ(8,100) (SOP(I),I=1,N9,1)
     53              READ(8,100) (CNIP(I),I=1,N10,1)
     54              WRITE(5,99) TYPE
     55           99 FORMAT(1H ,3X,I1)
     56              QMAX=0.00
     57              DO 102 I=1,N8,1
     58              IF(QP(I).GT.QMAX) QMAX=QP(I)
     59          102 CONTINUE
     60              SOMAX=0.00
     61              DO 103 I=1,N9,1
```

```
      IF(SOP(I).GT.SOMAX) SOMAX=SOP(I)
  103 CONTINUE
      CNIMAX=0.00
      DO 104 I=1,N10,1
      IF(CNIP(I).GT.CNIMAX) CNIMAX=CNIP(I)
  104 CONTINUE
      FLD(0,24,SLAGE(3))=FLD(0,24,SAGE)
      FLD(0,24,PHATCH(2))=FLD(0,24,PH)
      FLD(0,24,TEMPER(3))=FLD(0,24,TEMP)
      FLD(0,18,INFCOD(4))=FLD(0,18,ICOD)
      FLD(0,24,INFTKN(4))=FLD(0,24,ITKN)
      FLD(6,12,TNUM(3))=FLO(0,12,TN)
      TN9(N9+1)=0.0
      TN9(N9+2)=4.0
      TN8(N8+1)=0.0
      TN8(N8+2)=4.0
      TN10(N10+1)=0.0
      TN10(N10+2)=4.0
C     CALL PLOTS(0,0,17)
      CALL PLOTS(IBUF,5000,17)
C     CALL NEWPEN(1)
C     CALL FACTOR(1.27)
      CALL FACTOR(0.50)
      CALL PLOT(0.0,4.0,-3)
      CALL AXIS(0.0,0.0,29HOXYGEN CONSUMPTION  (MG/L/HR),
     1+29,5.00,90.0,0.0,25.00)
      JUMP=1
      GO TO 300
  401 TN5(N5+1)=0.0
      TN5(N5+2)=4.0
      TN6(N6+1)=0.0
      TN6(N6+2)=4.0
      TN7(N7+1)=0.0
      TN7(N7+2)=4.0
      TOP1(N5+1)=0.0
      TOP1(N5+2)=25.0
      TOP2(N5+1)=0.0
      TOP2(N5+2)=25.0
      TOP3(N6+1)=0.0
      TOP3(N6+2)=25.0
      TOP4(N6+1)=0.0
      TOP4(N6+2)=25.0
      TOP5(N7+1)=0.0
      TOP5(N7+2)=25.0
      TOP6(N7+1)=0.0
      TOP6(N7+2)=25.0
      CALL LINE(TN5,TOP1,N5,1,+1,11)
      CALL LINE(TN5,TOP2,N5,1,+1,2)
      CALL LINE(TN6,TOP3,N6,1,+1,3)
      CALL LINE(TN6,TOP4,N6,1,+1,4)
      CALL LINE(TN7,TOP5,N7,1,+1,5)
      CALL LINE(TN7,TOP6,N7,1,+1,9)
      CALL PLOT(7.00,7.00,-3)
      QP(N8+1)=0.0
      IF(QMAX.GT.1000.0) GO TO 260
      QP(N8+2)=20.0
      CALL AXIS(0.00,0.00,20HINFLUENT FLOW  (L/D),
     1-20,5.00,90.0,0.00,20.00)
      GO TO 261
  260 QP(N8+2)=20000.0
      CALL AXIS(0.00,0.00,20HINFLUENT FLOW  (L/D),
     1-20,5.00,90.0,0.00,20000.00)
```

```
124         261 CALL PLOT(-7.50,0.00,-3)
125             SOP(N9+1)=0.00
126             IF(SOMAX.GT.1010.0) GO TO 262
127             SOP(N9+2)=200.0
128             CALL AXIS(0.0,0.0,20HINFLUENT COD  (MG/L),
129            1+20,5.00,90.0,0.0,200.0)
130             GO TO 263
131         262 SOP(N9+2)=500.0
132             CALL AXIS(0.0,0.0,20HINFLUENT COD  (MG/L),
133            1+20,5.00,90.0,0.0,500.0)
134         263 CNIP(N10+1)=0.00
135             IF(CNIMAX.GT.51.0) GO TO 264
136             CNIP(N10+2)=10.0
137             CALL AXIS(0.0,0.0,22HINFLUENT TKN  (MG-N/L),
138            1-22,5.00,90.0,0.00,10.00)
139             GO TO 265
140         264 CNIP(N10+2)=20.00
141             CALL AXIS(0.0,0.0,22HINFLUENT TKN  (MG-N/L),
142            1-22,5.00,90.0,0.00,20.00)
143         265 CALL PLOT(0.50,0.00,-3)
144             JUMP=2
145             GO TO 300
146         402 CALL SYMBOL(0.00,5.74,0.14,INFCOD,0.00,30)
147             CALL SYMBOL(0.00,5.54,0.14,INFTKN,0.00,30)
148             CALL LINE(TN8,QP,N8,1,+1,11)
149             CALL LINE(TN9,SOP,N9,1,+1,0)
150             CALL LINE(TN10,CNIP,N10,1,+1,2)
151             CALL PLOT(16.00,-7.00,-3)
152             CALL AXIS(0.00,0.00,17HMLVSS  (MG-VSS/L),
153            1-17,5.00,90.0,0.00,1000.0)
154             CALL PLOT(-7.00,0.00,-3)
155             CALL AXIS(0.0,0.0,31HFILTERED REACTOR COD (MG-COD/L),
156            1+31,5.00,90.0,0.0,20.00)
157             JUMP=3
158             GO TO 300
159         403 TN1(N1+1)=0.0
160             TN1(N1+2)=4.0
161             TN2(N2+1)=0.0
162             TN2(N2+2)=4.0
163             DO 211 J=1,NR,1
164             DO 212 I=1,N2,1
165         212 STP(I)=RSTP(J,I)
166             DO 213 I=1,N1,1
167         213 XVP(I)=RXVP(J,I)
168             XVP(N1+1)=0.0
169             XVP(N1+2)=1000.0
170             STP(N2+1)=0.0
171             STP(N2+2)=20.0
172             CALL LINE(TN2,STP,N2,1,+1,2)
173         211 CALL LINE(TN1,XVP,N1,1,+1,11)
174             CALL PLOT(7.00,7.00,-3)
175             IF(NITDEN.EQ.2) GO TO 180
176             CALL AXIS(0.00,0.00,29HFILTERED REACTOR TKN (MG-N/L),
177            1-29,5.00,90.00,0.00,10.0)
178             CALL PLOT(-7.00,0.00,-3)
179             CALL AXIS(0.0,0.0,29HFILTERED REACTOR NO3 (MG-N/L),
180            1+29,5.00,90.0,0.0,10.0)
181             GO TO 181
182         180 CALL AXIS(0.00,0.00,29HFILTERED REACTOR TKN (MG-N/L),
183            1-29,5.00,90.00,0.00,5.00)
184             CALL PLOT(-7.00,0.00,-3)
185             CALL AXIS(0.0,0.0,29HFILTERED REACTOR NO3 (MG-N/L),
```

```
     1+29,5.00,90.0,0.0,5.00)
  181 JUMP=4
      GO TO 300
  404 TN3(N3+1)=0.0
      TN3(N3+2)=4.0
      TN4(N4+1)=0.0
      TN4(N4+2)=4.0
      TN11(N11+1)=0.0
      TN11(N11+2)=4.0
      DO 221 J=1,NR,1
      DO 222 I=1,N3,1
  222 CNTP(I)=RNTP(J,I)
      DO 223 I=1,N4,1
  223 CNO3P(I)=RNO3P(J,I)
      DO 224 I=1,N11,1
  224 CNH3P(I)=RNH3P(J,I)
      IF(NITDEN.EQ.2) GO TO 183
      CNO3P(N4+1)=0.0
      CNO3P(N4+2)=10.0
      CNTP(N3+1)=0.0
      CNTP(N3+2)=10.00
      CNH3P(N11+1)=0.0
      CNH3P(N11+2)=10.00
      GO TO 184
  183 CNO3P(N4+1)=0.0
      CNO3P(N4+2)=5.0
      CNTP(N3+1)=0.0
      CNTP(N3+2)=5.00
      CNH3P(N11+1)=0.0
      CNH3P(N11+2)=5.00
  184 CALL LINE(TN3,CNTP,N3,1,+1,2)
C     CALL LINE(TN11,CNH3P,N11,1,+1,0)
  221 CALL LINE(TN4,CNO3P,N4,1,+1,11)
      GO TO 301
  300 CALL AXIS(0.0,0.0,13HTIME  (HOURS),-13,7.00,
     10.0,0.0,4.00)
      IF(FLD(0,6,TN).EQ.P) GO TO 707
      IF(TYPE.NE.2) GO TO 553
      CALL LINE(AA,BB,2,1,0, )
      CC(1)=AA(1)+12.0
      CC(2)=AA(2)+12.0
      POS=CC(1)/4.0-0.28
      CALL LINE(CC,BB,2,1,0, )
      CALL LINE(DD,BB,2,1,0, )
      CALL SYMBOL(2.60,5.94,0.14,26HSQUARE WAVE LOAD VARIATION,
     10.00,26)
      CALL SYMBOL(0.15,5.24,0.14,5HSTART,0.00,5)
      CALL SYMBOL(POS,5.24,0.14,4HSTOP,0.00,4)
      CALL SYMBOL(6.15,5.24,0.14,5HSTART,0.00,5)
      CALL SYMBOL(0.22,5.05,0.14,4HFEED,0.00,4)
      CALL SYMBOL(POS,5.05,0.14,4HFEED,0.00,4)
      CALL SYMBOL(6.22,5.05,0.14,4HFEED,0.00,4)
      GO TO 601
  553 CALL LINE(AA,BB,2,1,0, )
      CALL LINE(CC,BB,2,1,0, )
      CALL LINE(DD,BB,2,1,0, )
      CALL SYMBOL(2.60,5.94,0.14,24HSINE WAVE LOAD VARIATION,0.0,24)
      CALL SYMBOL(0.00,5.05,0.14,8HMIN FLOW,0.0,8)
      CALL SYMBOL(3.00,5.05,0.14,8HMAX FLOW,0.0,8)
      CALL SYMBOL(6.00,5.05,0.14,8HMIN FLOW,0.0,8)
      GO TO 601
  707 AA(1)=8.00
```

```
      AA(2)=AA(1)
      CC(1)=AA(1)+12.00
      CC(2)=CC(1)
      CALL LINE(AA,BB,2,1,0, )
      CALL LINE(CC,BB,2,1,0, )
      CALL SYMBOL(2.60,5.94,0.14,23HOBSERVED LOAD VARIATION,0.0,23)
      CALL SYMBOL(1.72,5.05,0.14,4HNCON,0.0,4)
      CALL SYMBOL(4.50,5.05,0.14,8HMIDNIGHT,0.0,8)
  601 IF(JUMP.EQ.1) GO TO 552
      IF(JUMP.EQ.2) GO TO 551
      IF(JUMP.EQ.3) GO TO 550
      IF(JUMP.EQ.4) GO TO 550
  551 CALL LINE(PP,BB,2,1,0, )
      IF(JUMP.EQ.2) GO TO 550
  552 CALL LINE(EE,BB,2,1,0, )
  550 CALL LINE(FF,GG,2,1,0, )
      CALL SYMBOL(4.50,5.74,0.14,SLAGE,0.00,24)
      CALL SYMBOL(4.50,5.54,0.14,TEMPER,0.00,18)
      CALL SYMBOL(4.22,5.34,0.14,PHATCH,0.00,12)
      CALL SYMBOL(6.80,5.64,0.07,1,0.0,-1)
      CALL SYMBOL(0.00,5.94,0.14,17HEXPERIMENTAL DATA,0.00,17)
      IF(JUMP.EQ.2) GO TO 603
      CALL SYMBOL(0.00,5.74,0.14,TNUM,0.00,18)
  603 IF(JUMP.EQ.1) GO TO 401
      IF(JUMP.EQ.2) GO TO 402
      IF(JUMP.EQ.3) GO TO 403
      IF(JUMP.EQ.4) GO TO 404
  301 CALL PLOT(11.00,-12.27,999)
C     CALL EOT
      STOP
      END
```

```
CONTAX*CONTACTBS(1).EOT
      1       $(1)        AXR$
      2       EOT*
      3                   L,U         AO,IOP
      4                   ER          IOW$
      5                   J           1,X11
      6       $(0)
      7       IOP         I$OT        '17           ',WEE$
      8                   END
```

```
CONTAX*CONTACTBS(1).CYDATA1
      1       321000C110.001
      2       0.135,2.50,100.0,3.00,20.0,0.650,1.0,0.24,0.04,0.45,0.10,0.20
      3       1.48,0.10,1.00,0.00
      4       5.4,1.92,0.10,2,240,0.100,0.090,0.00,0.75,0.015,0.00,0.234,1.00
      5       1.200,1.100,1.029,2.350,1.123,1.000,20.0,7.20
      6       1000,1000,14.3
      7       16.99,12.34,10.75,17.58,20.26,22.11,35.88,36.30,41.38,42.60
      8       46.08,49.32,54.72,57.24,57.60,56.88,55.44,53.64,49.32,42.48
      9       38.52,37.50,27.00,19.08,16.99
     10       503.0,503.0,503.0,503.0,503.0,503.0,503.0,503.0,503.0,503.0
     11       503.0,503.0,503.0,503.0,503.0,503.0,503.0,503.0
     12       503.0,503.0,503.0,503.0,503.0,503.0,503.0,503.0
     13       38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0
     14       38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0,38.0
     15       0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
     16       0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
```

```
CONTAX*CONTACTBS(1).PLATA
      1       2.00,0.00,14.00,26.00,28.00,0.00,50.00,0.00
      2       2.00,50.00,14.00,26.00,28.00,28.00,50.00,0.00
      3       0.00,0.00,0.00,0.00,0.00,0.00,0.00,0.00
      4       4.00,10.00,4.00,4.00,4.00,4.00,10.00,4.00
```

```
CONTAX*CONTACTBS(1).CYPDATA1
     1        35.4050338.020.07.20C1 21
     2        5,7,13,13,25,1,1,25,5,5,1
     3        2.0,8.0,14.0,20.0,26.0
     4        2.0,6.0,10.0,14.0,18.0,22.0,26.0
     5        2.0,4.0,6.0,8.0,10.0,12.0,14.0,16.0,18.0,20.0,22.0,24.0,26.0
     6        0.0
     7        2.0,4.0,6.0,8.0,10.0,12.0,14.0,16.0,18.0,20.0,22.0,24.0,26.0
     8        1.0,2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0,11.0,12.0,13.0,14.0,15.0,16.0,17.0
     9        18.0,19.0,20.0,21.0,22.0,23.0,24.0,25.0,26.0
    10        0.0
    11        0.0
    12        2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0,11.0,12.0,13.0,14.0,15.0,16.0,17.0
    13        18.0,19.0,20.0,21.0,22.0,23.0,24.0,25.0,26.0
    14        2.0,8.0,14.0,20.0,26.0
    15        2.0,8.0,14.0,20.0,26.0
    16        1569.0,1400.0,1345.0,1290.0,1740.0
    17        48.7,50.6,42.4,48.7,39.4,45.0,50.0
    18        2.6,3.4,4.0,7.4,7.9,8.0,8.2,10.9,8.7,7.4,6.0,8.2,3.0
    19        0.0
    20        21.2,20.2,18.6,16.3,15.3,12.7,12.9,12.2,13.6,14.7,15.6,17.9,20.4
    21        1883.0,2014.0,2138.0,1779.0,1837.0
    22        62.0,74.0,83.0,81.0,72.0,68.0,70.0
    23        2.1,2.6,2.6,3.6,2.5,.6,3.0,4.1,1.0,3.4,3.0,2.7,1.4
    24        0.0
    25        21.6,21.1,22.1,21.6,22.1,21.3,21.5,20.8,21.3,21.2,21.3,20.7,21.5
    26        42.7,40.9,42.5,41.7,41.0,41.7,42.5,40.3,40.3,41.0,41.0,37.5,42.5,41.3,37.2,39.9
    27        41.7,41.8,37.5,39.2,42.5,37.5,40.2,41.4,42.4
    28        17.5,20.2,21.6,18.7,20.8,23.0,28.0,28.0,28.0,28.8,32.0,32.0,31.5,32.0,30.7,35.5
    29        29.4,27.7,29.1,27.8,26.0,25.0,22.0,22.0,17.5
    30        0.0
    31        0.0
    32        0.0
    33        0.0
    34        10.8,17.6,20.3,22.1,35.9,36.3,41.4,42.6,46.1,49.3,54.7,57.2,57.6,56.9,55.4,53.6
    35        49.3,42.5,38.5,37.4,26.6,18.7,17.0,11.5,10.8
    36        503.0,503.0,503.0,503.0,503.0
    37        38.0,38.0,38.0,38.0,38.0
```

APPENDIX C

EXAMINATIONS WRITTEN TO COMPLETE THE REQUIREMENTS OF THE DEGREE

	EXAMINATION	YEARS PASSED	CREDIT RATING	SYMBOL OBTAINED
CE 522	Aquatic Chemistry	June 1978	$7\frac{1}{2}$	1
CE 513	Wastewater Treatment	July 1978	$7\frac{1}{2}$	1
CE 502	Low Cost Sanitation	December 1978	5	1*
THESIS	CONTACT STABILIZATION ACTIVATED SLUDGE PROCESS		20	
		TOTAL	40	
		NO OF CREDITS REQUIRED	40	

* PROVISIONAL RESULT

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION : JUNE 1978

CE 522 : AQUATIC CHEMISTRY

Answer ALL questions.

1 (a).

$5{,}10^{-4}$ mole/l of NH_3 and 10^{-3} moles/l of CO_2 are added to pure water. ($pk_{NH_4^+} = 9{,}10$; $pk_{H_2CO_3} = 6{,}37$; $pk_{HCO_3^-} = 10{,}33$).

i. Determine the pH established in the mixture.

ii. Discuss (using appropriate sketches) the buffer capacity of this mixed system.

(b).

Write brief notes of not more than 100 words on the following topics :-

i. Alkalimetric titrations and buffer capacity.

ii. Equivalence points and equivalent solution.

iii. Mass parameters for weak acid systems in water.

iv. Stabilized water.

2 (a).

Analysis of a water gives Alkalinity 30 ppm (as $CaCO_3$), pH 6,2, $\mu = 0{,}005$ and temperature $20^{\circ}C$.

It is required to strip the carbonate species from the water by removing CO_2 under reduced pressures. Determine the pH of the water after CO_2 has been stripped. What mass concentration of CO_2 is removed ?

(b).

Waters from two sources are blended as in the table given below.

(Assume all these waters have the same conic strength and temperature i.e. 0,005 and $20^{\circ}C$ respectively).

i. Determine the condition of the blend.

ii. Is the blend stable ?

iii. If the blend is not stable, enumerate the alternative methods one could employ to obtain a stable blend.

WATER	SOURCE	pH	Alk. (ppm on $CaCO_3$)	Ca ($CaCO_3$)	PARTS IN BLEND
A	Groundwater	6,4	70	75	2
B	Softened water	11,1	50	50	3

3. Analysis of a water from a dolomitic region gives :
Ca 300 ; Alk 200 ; Mg 100 (all in ppm expressed as $CaCO_3$) ;
pH 6,90 ; μ = 0,01 and temperature 20°C.

It is required that after softening and stabilization the magnesium and calcium concentrations are 20 and 140 ppm as $CaCO_3$ respectively.

i. Determine the mass concentrations of $Ca(OH)_2$ and Na_2CO_3 required in the softening process.

ii. Determine the mass concentrations of $Ca(OH)_2$ and CO_2 required to restabilize the water.

iii. Sketch the plant layout.

4 (a).

Analysis of a typical Cape water after colour removal gives :
Total Alkalinity 0, HCO_3 Acidity 12, Ca^{++} 4 (all in ppm as $CaCO_3$) and pH = 5,4.

i. Is this analysis in any way contradictory ?

ii. If so, what is the probable source of error and what is the most likely initial condition of the water ?

4 (b).

It is required to stabilize the water in (a) above using lime and CO_2, determine the required dosages of these chemicals. Comment critically on the pros and cons of the final condition of the water.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION - JULY 1978

CE 513 - WASTEWATER TREATMENT

To be collected after 09h00 on 28th July 1978 and returned before 17h00 on 31st July 1978. The attached affidavit to be signed by the student on receipt of the examination script.

ANSWER ALL QUESTIONS

QUESTION 1

An activated sludge plant is to be built for a town with a population of about 20 000 people. The data listed in the table below is available as representative of the flow and load conditions to be expected at the main sewer outfall of the town. At present the process is to be operated on the completely mixed principle including nitrification. The wastewater is well buffered and has a pH of about 7,2. As the wastewater principally is of domestic origin, assume a specific growth rate of nitrosomonas (μ_{nm}) of 0,50 per day.

RAW SEWAGE

TIME	FLOW (Mℓ/d)	COD (mgCOD/ℓ)	TKN (mgN/ℓ)
0600	1,10	248	30,2
0800	2,35	213	24,9
1000	4,60	412	55,1
1200	5,85	567	60,5
1400	5,70	625	54,9
1600	5,00	620	54,9
1800	4,50	576	51,8
2000	4,25	536	45,3
2200	3,95	480	42,8
2400	3,80	442	42,3
0200	3,40	389	35,8
0400	2,00	323	31,1
0600	1,10	248	30,2

a) Assuming steady state conditions :

i) Design the plant for summer conditions (20°C) at a sludge age of 15 days and an MLVSS concentration of 4000 mgVSS/ℓ.

ii) Check your design for winter conditions (12°C).

iii) Make a comparison, in tabular form, of the average effluent quality, oxygen demand and sludge concentration during summer and winter months.

iv) Estimate the minimum factor of safety with respect to nitrification.

b) Estimate from the influent loading variations given in the Table, the peak and minimum total oxygen requirements during summer and winter.

c) Assume that instead of a single reactor, three reactors of equal volume are built. Describe qualitatively with the aid of sketches, how the process variables such as oxygen demand, nitrate, TKN, filtered COD and MLVSS concentrations vary over the day through the plant at 20°C.

QUESTION 2

The waste sludge of the above plant is to be thickened by flotation to 4%, prior to aerobic digestion. Design the flotation system, presenting your final design in the form of sketches to scale on graph paper.

QUESTION 3

Design an aerobic digestor for the thickened sludge on the basis that the digested sludge may not be discharged to the drying beds unless the active fraction is less than 25%. The design may be based on steady state conditions at 20°C. Nitrification must be included in your design.

QUESTION 4

As an alternative scheme to that given in Questions 1,2 and 3 above, investigate a design of an activated sludge process at 20°C, operating at a very long sludge age, so that thickened waste sludge (also by flotation) may be directly cischarged to the drying beds (i.e. active fraction of the sludge less than 25%) without the use of aerobic digestion. Do not design the flotation system.

a) Assuming steady state conditions, determine ;

i) the required sludge age; and

ii) the reactor volume given that X_v is also 4 000 mgVSS/ℓ.

b)

i) Compare the oxygen and volume requirements of the two schemes (exclude the flotation plant in the comparison as both schemes require this unit process).

ii) Which of the two schemes is the better in terms of phosphorus removal ? Discuss with the aid of calculations.

c) Write down briefly your conclusions on the comparison of the two schemes.

QUESTION 5 ...../3

QUESTION 5

For an activated sludge plant, determine the average total power requirements of the aeration of the mixed liquor, for the following conditions. The volume of the aeration basin is 1,65 Mℓ and the average total oxygen demand is 48 mgO/ℓ/hr. Assuming that mechanical aerators are to be used with an oxygen transfer rate of 2,44 KgO/Kwh under standard conditions, what power, measured at the shaft, needs to be supplied for the following conditions?

At the proposed site :

Atmospheric pressure = 725 mm Hg ;

Temperature = 21°C ; an oxygen concentration in the reactor of 3 MgO/ℓ, (to ensure nitrification) is to be maintained.

The α and β values for the mixed liquor are estimated to be 0,8 and 0,9 respectively.

QUESTION 6

A cannery has an effluent flow of about 1 500 m^3/d during the main canning season. The daily averaged BOD is approximately 700 mg/d; phosphorus and nitrogen concentrations are negligible. The cannery operates at peak production for about 4 months of the year during the summer when the flow and BOD given above are applicable. For the rest of the year the load and flow are less. An aerated lagoon system has been proposed to treat the waste stream. It is essential that the effluent from the system must have volatile solids and BOD concentrations as low as possible, but no settling rank or maturation pond system following the treatment works are envisaged.

With the objective of satisfying the conditions above, design and compare the following two solutions :

i) A single lagoon with a retention time of 10 days;

ii) A system of two lagoons in series, the first having a retention time of 2,5 days; the second a retention time of 7,5 days.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

DECEMBER EXAMINATION 1978

CE 502 - LOW COST SANITATION

Do ALL Questións

QUESTION 1

a. Discuss the biochemical and feacal bacterial degradation kinetics in facultative ponds, with particular reference to wind, temperature and radiation effects and the influence of raw and anaerobic pretreated influents.

b. Discuss the design of a septic tank-french drain disposal system for waste waters from individual houses.

QUESTION 2

Write an essay on the problems associated with the provision of water supply and an acceptable form of sanitation for low cost housing areas. The discussion should include a comparison of the different forms of sanitation that have been used in Africa.

QUESTION 3

Discuss the approach you would take and the factors to be considered when investigating sub-soil conditions for a low cost high density housing project.

/2....

QUESTION 4

Design an oxidation pond system to treat the effluent from a low cost housing township in the lowveld of the Transvaal.

Present population	10 000
Estimated future population	15 000
Sanitation provision	Regular waterborne flush system to sewers
Estimated waste flow/capita/day	50 - 90ℓ
Estimated BOD_5 contribution per capita/day	0,04 kg

The pond system is to consist of (a) a grit channel
(b) Open anaerobic lagoons
(c) Primary, secondary and tertiary facultative ponds.

Design the system making your own estimates of the factors required in the design. Provision to minimize odours from the anaerobic lagoon is to be built into the design.

QUESTION 5

a. List the conditions that must be satisfied for data to be normal distributed.

b. Under what conditions do you expect data to be log-normal distributed ? Illustrate with at least 3 examples giving your evaluation of the causes in each case.

c. Give the various measures of central tendency of a distribution and discuss their efficiency.

A random sample of 20 apples was taken from all the apples picked from a single tree, listed below in ranked arbitrary mass units.

11, 14, 15, 18, 18, 20, 20, 22, 22, 22,
26, 26, 27, 30, 30, 32, 36, 38, 40, 70

If you would wish to compare this tree's production with another, what measure of central tendency would you select ? If you would wish to determine the average mass of the apples of this tree would you use the same measure ? Determine with the aid of graphical statistics the answers to your selected measures.

/3....

QUESTION 5 (continued)

d. The following two sets of data were obtained on the concentration of E.coli in the effluent from a facultative oxidation pond during the winter and summer season respectively.

Winter : < 300, 400, 17 000, 12 000, 2500,
1000, 700, > 20 000, 6000, 3500,
2500, 1400, 9000, 7000, 1400,
> 20 000, 4000.

Summer : 440, 800, 1000, 1260, 1600,
1800, 2400, 2800, 4000, 6000.

Test using graphical statistical techniques if the selected statistical mean values of these two distributions are significantly different at 96% level of significance.
