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Olsson, Gustaf

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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GUSTAF OLSSON

DEPARTMENT OF AUTOMATIC CONTROL
LUND INSTITUTE OF TECHNOLOGY
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Gustaf Olsson

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Gustaf Olsson

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The activated sludge process is recognized as the major unit process in many wastewater treatment plant systems. It has been demonstrated that atuomatic control of such a process under normal circumstances gives superior effluent quality compared with manual control. Moreover energy is saved by automatic control.

The dissolved oxygen profile can provide crucial information for the estimation of biological activity, necessary for the control of the process. Both in processes for only carbonaceous removal and in fully nitrifying processes it can be used as an important detector of disturbances.

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Modeling and control of the activated sludge process

Gustaf Olsson
Department of Automatic Control
Lund Institute of Technology
Lund, Sweden

During recent years there has been an increasing demand for better operation of wastewater treatment plants in order to guarantee satisfactory effluent quality at minimal cost. The renewed interest in instrumentation and control comes after a period of huge investments in sewer networks and treatment plants. Several factors have contributed to the potential for better operation and control, such as cheap computing power, improving sensors and better knowledge of process dynamics and control.

The activated sludge process is recognized as the most common and major unit process for the reduction of municipal and industrial waste. Although its dynamics is complex the potential for control is far from exhausted. Already with commercially available instrumentation today its operation can be significantly improved.

In the process heterotrophic microorganisms react with organic pollutants in the wastewater and with oxygen dissolved in the water to produce more cell mass, carbon dioxide and water. Nitrifying organisms oxidize ammonia-nitrogen in the water to form nitrite, nitrate and more cell mass. The reactor effluent flows to a sedimentation basin, where the solids are separated from the liquid. A portion of the concentrated sludge is recycled in order to maintain enough mass of viable organisms in the system and a reasonable food-to-mass ratio.

Some typical disturbance patterns and control difficulties are summarized here. A detailed discussion is made in (1). Hydraulic disturbances are significant in amplitude. Diurnal variations as well as shock loads from rain storms or melting snow may cause major upsets. Significant disturbances also appear from internal sources like primary pumps, back-washing of deep bed filters or return sludge flow rate changes. The amplitudes are such, that quasi-stationary of linear control methods are seldom adequate.

Concentration and composition changes of the influent wastewater create tremendous control problems. The number of components in the sewage water is so large and the concentrations generally so low, that the measurement problems seem prohibitive. Microbial composition and concentrations in the reactor can be significantly

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changed, sometimes very fast, sometimes gradually. As a result the pollutant elimination will be affected and the process may turn into undesirable operational conditions. These properties of the process imply, that disturbance detection and parameter and state estimation are the major control problems.

The process dynamics is complex. Typical response times vary from a few seconds up to weeks and months. Nonlinear phenomena are common due to large disturbance amplitudes. Measurement and transport time delays cannot be neglected. Sensor location is important due to spatial distributions. As living organisms are part of the system, not only parameters but the structure of the system dynamics can be changed during the operation.

Dissolved oxygen (DO) concentration is a key variable in the operation. It affects the economy and is also closely related to the biological activity of the organisms in the sludge. The main emphasis in this paper is to show how the DO concentration distribution in a non-homogeneous aerator can be used for the estimation of the activity of both heterotrophic and nitrifying organisms.

The paper is organized as follows. A brief review of the activated sludge dynamics and DO control is made. Then the properties of DO profiles in organic removal are discussed. In the last section it is shown, that the DO profile concept can be favourably used in reactors with combined organic and nitrogen removal, and the implications for control are discussed.

Activated sludge dynamics

Large efforts have been spent to develop highly structured models of activated sludge dynamics. The results in this paper are based on models derived elsewhere (1-4). The models consider the flow regime in the aerator, oxygen dynamics, cell growth and basal metabolism. It also includes degradation of pollutants - both organic carbon and nitrogen - as well as the solubilization of particulate degradable organic carbon.

Organic waste removal. It is assumed that the organic waste is degraded into the following steps:
(i) substrate penetration of the cell membrane
(ii) metabolism of the mass stored in the floc phase, the "growth" phase
(iii) decay of the organisms to inert mass

Typical response times are of the order 15-30 minutes (i), days (ii), and several days (iii). The net microorganism growth rate is a key design parameter and its reciprocal is termed sludge age or mean cell residence time. An adequate control has to take into consideration, that the growth rate is time-varying (5).

Nitrification. In biological nitrification ammonium nitrogen is oxidized into nitrite by means of Nitrosomonas species, and nitrite is oxidized to nitrate by the Nitrobacter species.

The first reaction is slower than the second one, so the resulting effluent nitrite concentration will be small. Nitrate is the final oxidation state if no denitrification takes place in the aerator. In the oxidation of ammonium nitrogen alcalinity is lost. About half of it could be restored if the system is designed for denitrification as well.

The growth rates of Nitrosomonas and Nitrobacter species are assumed to follow the so called Monod kinetics with respect to ammonia and nitrite concentrations respectively as well to oxygen. The growth rates are much more sensitive to pH, toxic and temperature changes than the heterotrophic organisms. Moreover, the growth rates are significantly smaller than for heterotrophic organisms. Therefore a fully nitrifying plant requires much longer mean cell residence times than plants designed for only carbonaceous removal.

Dissolved oxygen. The structure of the DO material balance in a reactor can be divided into three parts, the hydraulic transport of DO, the production related to the air supply and the consumption (uptake rate) due to organism growth and decay. The hydraulic transport of DO is negligible in comparison with the oxygen transfer (production).

The oxygen uptake rate terms are considered in more detail. Here they are represented by four terms, oxygen uptake rate due to heterotrophic growth (r_1), oxygen consumption rate by organism decay (r_2), oxygen uptake rate due to Nitrosomonas (r_3) and Nitrobacter (r_4) respectively. The specific carbonaceous oxygen uptake rate (SCOUR) is defined by (6)

$$SCOUR = (r_1 + r_2)/\text{cell mass}$$

and the specific nitrogeneous oxygen uptake rate (SNOUR) in analogous way by

$$SNOUR = (r_3 + r_4)/\text{cell mass}$$

In a fully nitrifying reactor SNOUR is of the same order of magnitude as SCOUR. Consequently, full nitrification will almost double the air demand.

The DO dynamics include phenomena in widely different time scales, from fractions of hours to weeks. This means, that a control system designed for the control of DO as a physical variable has to gradually change its parameters.

Process identification and parameter estimation has been applied in water quality and wastewater treatment systems (7-9). The overall oxygen transfer coefficient can be determined on-line. The hydraulic dispersion has been identified by manipulation of the influent flow rate or the return sludge flow rate (9).

Reactor model. The structured model of the activated sludge process includes the following concentration variables: soluble organic substrate, stored mass, ammonia nitrogen, nitrite and nitrate nitrogen. Organisms are represented by viable Heterotrophs, Nitrosomonas and Nitrobacter. Inert (non-viable) nitrifying bacteria are lumped together with the non-viable heterotrophic organisms. Dissolved oxygen is included, but alcalinity, pH and gas changes are neglected, as non-covered aerators are used.

The concentration dynamics is described by (5),

$$\frac{\partial c}{\partial t} = E \frac{\partial^2 c}{\partial z^2} - v \cdot \frac{\partial c}{\partial z} + f_1(c) - f_2(c)$$

where $c = c(z,t)$ = a space and time variable concentration
E = dispersion coefficient
v = stream velocity
f_1 = production rate
f_2 = consumption rate

Dissolved oxygen control

DO dynamics and control is of vital importance for the operation of an activated sludge system. The relation between DO and biological activity will be summarized here.

The choice of an adequate DO concentration. The desired DO concentration is a compromize between economy demands and hydraulic and biological demands. Moreover, in a non-homogeneous reactor a proper spatial distribution has to be determined.

Aerobic organism growth demands a certain amount of DO concentration. In the aerator the growth of specific types of organisms should be favoured. At low DO concentrations heterotrophic organisms may be inhibited while filamentous organisms are favoured, resulting in bulking sludge. The DO demand of nitrifying organisms is higher than that of heterotrophic organisms. Consequently in a nitrifying reactor bulking sludge seldom appears.

To find the proper degree of mixing is complex. It is related to both DO concentration, floc size, floc formation as well as hydraulic dispersion and bulking sludge formation. Experiments seem to indicate that the sludge volume index (SVI) will increase sharply for an increasing air supply. The reason for this is unclear (10). Either it is due to the addition of oxygen as such or by the increasing mixing. The air supply thus has to be optimized between the growth limitation and the SVI increase.

Nitrates can be used as complements or alternatives to oxygen, both for energy saving and for the treatment of industrial wastes. This is the background for the Kraus modification of the activated sludge process. Similarly an anoxic zone in the inlet area of the aerator can be applied (11).

DO control. Most of available commercial DO control systems today are based on an analog PI controller and one DO probe. Quite often they give unsatisfactory result due to difficult process and measurement noise, time delays in the plant and insufficient measurement information. Unsuitable actuators are common, but actuator limitations can be overcome easier with digital control.

A typical result from direct digital control of the Käppala plant outside Stockholm is shown in fig 1. The DO concentration target is 3 mg/l. The controlled concentration (curve B) has an average value of 3.0 mg/l with a standard deviation of 0.28 mg/l. Encouraging and remarkable results of DO control have been achieved recently (12), where two aeration basins were compared in parallel, one manually and the other automatically controlled. With automatic control energy was saved and significant improvements of the water quality were obtained. Further practical DO control experiences are reported in (13 - 15).

The biodegradable load to the reactor can be indicated by the air flow rate if a DO control system is active. In fig 2 dry mass of COD from municipal sewage is compared to such an air flow signal in Käppala.

Dissolved oxygen concentration profiles with organic removal

The spatial variation of concentrations in a non-homogeneous reactor will increase the control complexity. However, the concentration profiles provide extra information. The immediate problem of locating the DO probes suitably must be considered, which was remarked already in 1964 (16): "there is no one position in the tank which is representative of the whole tank all the time. This means that a one-point control system applied to a piston-flow plant is likely to be, at best, a compromise...".

DO profile characterization. In an aerator with a uniform air supply distribution the DO concentration has a typical profile, fig 3. The oxygen content is close to zero at the inlet but is often in excess close to the outlet. As the influent wastewater is mixed with recycled sludge the soluble substrate is captured quickly by the floc. Within 30 minutes it is significantly reduced. No oxygen is needed for this process. Stored mass is consumed as a result of cell growth, and the DO uptake rate is proportional to the growth rate. As the stored mass concentration decreases towards the outlet, the growth rate will decrease. Consequently the DO consumption at the outlet is mainly due to cell decay.

As most organism are satisfied with 2-3 mg/l of DO the natural question arises, how to define a suitable DO concentration target. Normally the air flow distribution cannot be controlled but only the total air flow. An analysis of DO profiles and systematic ways to define desired setpoints were made in (5, 17).

Five features of the DO profile are important, fig 3:
(i) the position of the maximum slope, which is related to the organic or hydraulic load. It is pushed towards the outlet by an increasing load, which can be compensated by an increasing air

supply.
(ii) the value of the maximum slope, which is approximately proportional to the value of the maximum specific growth rate.
(iii) the DO concentration at the outlet, which is relatively high if the growth is close to completion.
(iv) the slope of the profile at the outlet, which is directly related to the completion of the cell growth. For incomplete reactions the slope will be significantly positive. Otherwise it is almost horizontal, and its value reflects only the endogeneous respiration.
(v) the curvature of the profile down-stream, quantified by a second derivative. It should be negative, and its sign and value are related to the organic load, the growth rate and the degree of reaction completion.

The slope (iv) is a much more relevant information for DO control than the absolute value of the DO concentration at the reactor end. This explains, why many plants demand high excess DO concentrations at the outlet. Moreover, the air flow demand is primarily related to the DO profile slope than to the concentration value at the outlet.

The qualitative features of the DO profile are the same, even if the dispersion coefficient E is increasing. All gradients are decreasing until they approach zero for the extreme case, a CSTR.

DO profile dynamics. The dynamical characteristics of the DO profile are illustrated by simulation of a plant, consisting of an aerator with four CSTR in series, each one having organic removal but no nitrification. The return sludge concentration is assumed constant, which is a reasonable assumption as long as the return sludge flow rate is constant and the settler sludge buffer is positive.

Both the influent flow rate and the biochemical oxygen demand (BOD) have been varied 25 % around their average values in 24 hour periods. As they are assumed to be in phase with each other, the resulting organic load varies a factor of three during the period.

Without any DO control the DO concentrations decrease for an increasing load and vice versa, figs 4 and 5. Fig 5 shows, how the DO profile is pushed towards the outlet as a result of increasing load. To parametrize the profile, we define two variables, the "slope" between the two last subreactors,

$$d_{43} = DO(4) - DO(3)$$

and an estimate of the second spatial derivative of the profile of the three last subreactors,

$$d_{42} = DO(4) - 2 \cdot DO(3) + DO(2)$$

where DO(i) is the DO concentration in subreactor i. The value of

d_{42} should be negative, but tends to positive values for high loads, fig 6, and is very sensitive to the biodegradable load. The slope d_{43} is also correlated to the load change (figs 4 and 6).

As SCOUR is an alternative measure of biodegradable load, it has been illustrated in fig 7 for the same simulation. The SCOUR profile (fig 8) is closely related to the DO profile (fig 6). The latter, however, is directly measurable, and the oxygen transfer coefficient does not have to be estimated.

DO profile during control. The sensitivity of the DO concentration to load changes is largest in subreactor 3, so DO(3) has been chosen for control. With a discrete time controller supplied with a feed-forward signal from the influent flow rate the total air supply to the four subreactors was controlled to keep DO(3) as constant as possible, fig 9. Even if the regulator is not optimally tuned, the improvement of the aerator performance as seen by the DO profile is significant.

The load variations are detected by the air flow rate (fig 9) as well as by d_{43} and d_{42}, fig 10. The slope is now less positive and d_{42} is satisfactory (negative) all the time. As the profile parameters are more directly related to the oxygen uptake rates, they are better indicators of the biodegradable load than the air supply, particularly when the control signal is limited.

The DO control experiment, fig 1, can further verify the results. The air flow rate (D) is clearly correlated to the DO profile slope (C). The slope is obtained by subtraction of two noisy signals, but the difference is large enough to give satisfactory accuracy.

Dissolved oxygen profiles with combined organic removal and nitrification

The general appearance of a DO profile is similar as before when nitrification takes place (16). The analysis of the profile and its interpretation, however, is different. The different time scales of the growth rates of nitrifying and heterotrophic organisms is used in the analysis in order to separate the different phenomena.

Characterization of a satisfactory DO profile. A typical steady-state simulation of DO profiles in a plug flow reactor will illustrate the ideas. Ammonia-nitrogen from the influent flow is consumed by both nitrifying and heterotrophic organisms, fig 11. In a completed reaction the NH_4-N approaches zero before the outlet. The Nitrosomonas oxygen demand is shown in fig 12. The characteristic break of the oxygen demand is caused by the disappearance of NH_4-N. As the nitrite is oxidized to nitrate a sharp break appears in both the nitrite concentration and the oxygen demand due to Nitrobacter growth, figs 11 and 12.

With the long mean cell residence time, necessary to complete the nitrification, the oxygen demand due to heterotrophic growth has its maximum early. If no nitrification would occur, the corresponding DO profile would have its characteristic break close to the inlet, fig 13. The amplitudes of SCOUR and SNOUR are similar in the first part of the reactor, but the SNOUR has a clear break, which makes it possible to separate carbonaceous and nitrogeneous oxygen demands.

Disturbances of the DO profile. The result of different types of disturbances in operational conditions or influent flow characteristics have been studied extensively by simulation. The DO profile behaves qualitatively as for carbonaceous removal (5), but the resulting control action may be different with nitrification. A load increase in terms of higher influent flow rate or a larger BOD or ammonia concentration will push the break of the profile towards the outlet. A BOD increase will favour more heterotrophic growth, thus increasing SCOUR. This limits the oxygen available for nitrification. An incomplete reaction is noted as increasing ammonium and nitrite concentrations at the outlet as well as by an increasing DO slope at the outlet. A decrease of the sludge age or insufficient air flow rate or decrease in temperature will make the nitrification chain of reactions incomplete. This will be noted in the profile in a similar way as a load change.

Implications for control. If the DO concentration has a non-homogeneous profile at least three DO probes are needed to monitor the profile changes. They give clear indications of variations in the biological activity. The control of the air flow is crucial, not only for the economy but for the effluent water quality. For on-line control the DO probes are sufficient indicators of external disturbances, but the measurements can be regularly cross-checked with alcalinity, nitrite or nitrate measurements of the effluent. By controlling the alcalinity by nitrification the cost for chemical dosage in post-precipitation plants can be significantly reduced.

Acknowledgment

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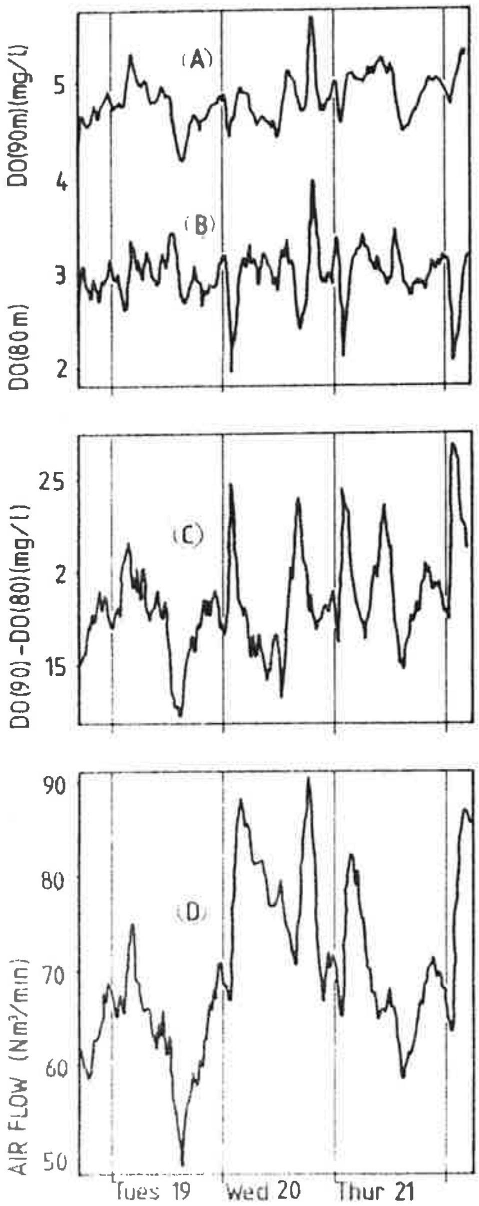

Fig 1. DO control at Käppala. The DO at 80 m downstream is controlled (B) and DO at 90 m is only recorded (A). The slope (C=A-B) is correlated with the air flow rate (D).

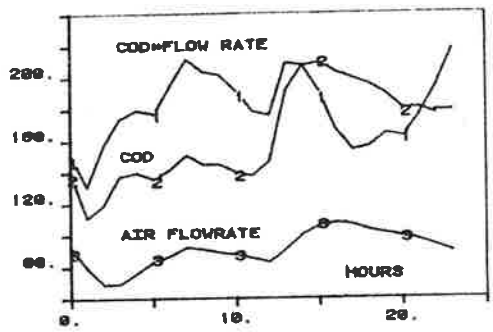

Fig 2. DO control at Käppala with hourly data of COD concentration, dry mass flow of COD and air flow rate.

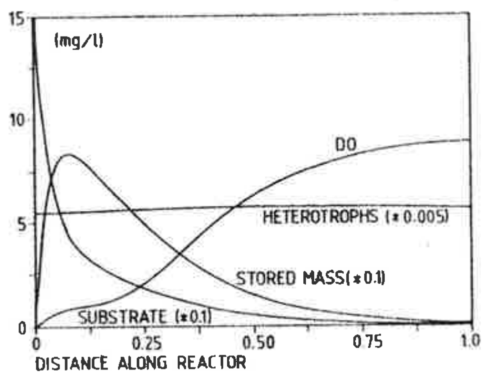

Fig 3. Typical concentration profiles in a plug flow aerator with organic removal.

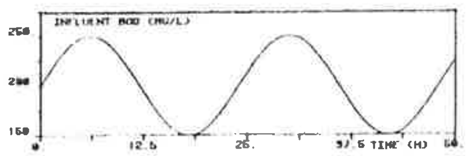

Fig 4. Influent BOD disturbance (in phase with the flow rate disturbance).

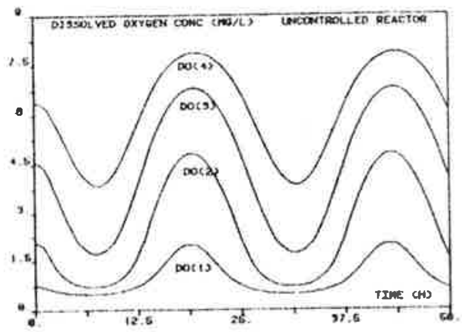

Fig 5. The DO concentrations of the uncontrolled reactor, disturbed by the diurnal load changes.

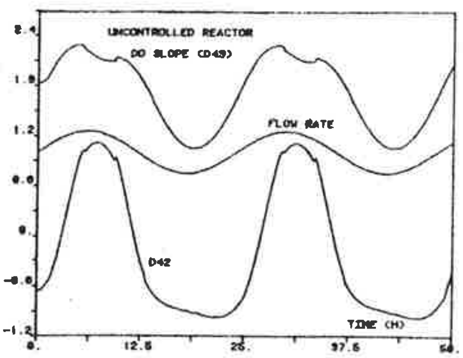

Fig 6. The DO profile parameters d_{43} and d_{42} and the influent flow rate of the uncontrolled reactor.

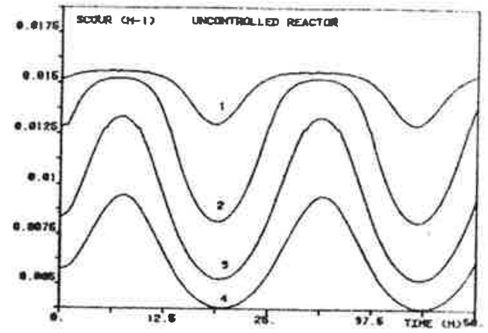

Fig 7. SCOUR of the four subreactors in the uncontrolled reactor.

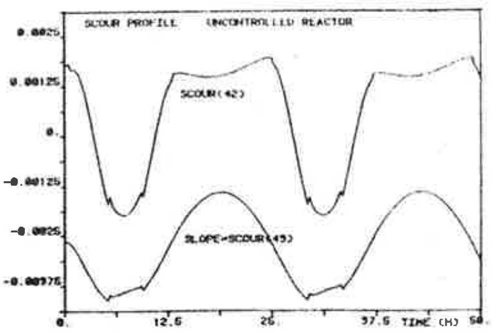

Fig 8. **The SCOUR profile parameters of the uncontrolled reactor. SCOUR(43) = SCOUR(4) - SCOUR(3), SCOUR(42) = SCOUR(4) - 2·SCOUR(3) + SCOUR(2).**

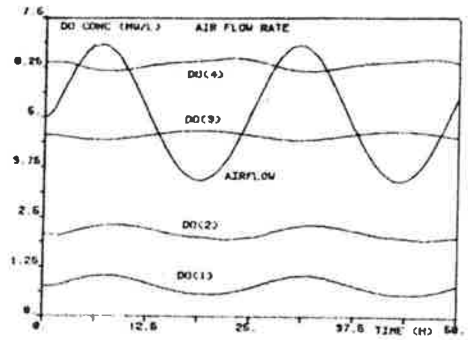

Fig 9. The aerator with DO control of DO(3), showing the total air flow rate and the DO concentrations.

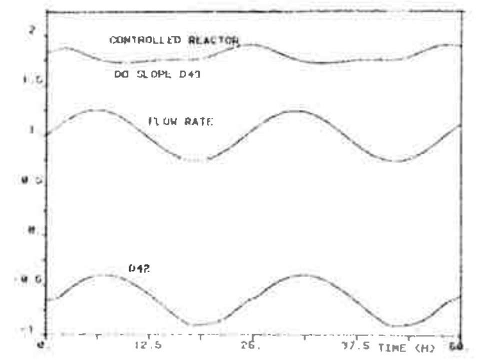

Fig 10. Same simulation as fig 9.. DO profile parameters and the influent flow rate.

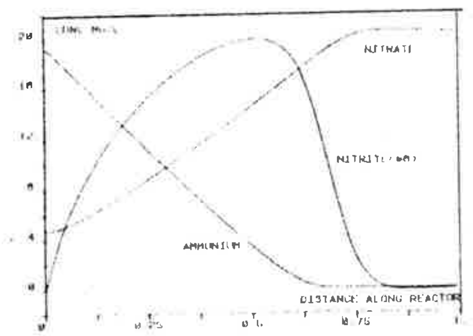

Fig 11. Concentration profiles of ammonium, nitrite and nitrate in a plug flow reactor.

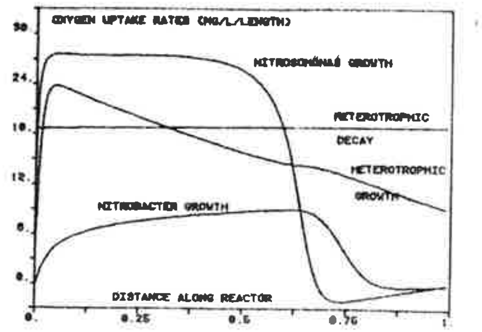

Fig 12. Steady-state spatial distribution of different oxygen uptake rates in a plug flow reactor.

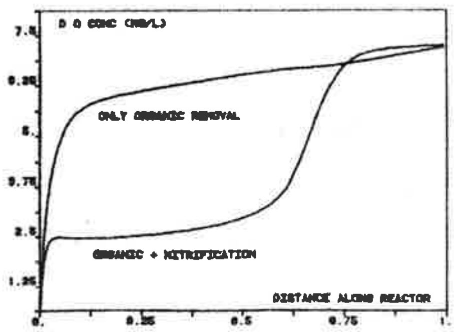

Fig 13. DO profiles in a plug flow reactor with both full nitrification and with no nitrification.