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ANOXIC PHOSPHATE UPTAKE IN THE DEPHANOX PROCESS

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ABSTRACT

The innovative nutrient removal process scheme DEPHANOX proved to be very efficient because it maximises the utilisation of organic substrate for phosphorus and nitrogen removal. The process solves the competition for organic substrates among Poly-P organisms and denitrifiers as well as the problem of overgrowing of slow nitrifiers by faster organotrophs, typical of activated sludge. In experiments, DEPHANOX showed better P removal efficiency than a JHB configuration, working with a very low influent COD/TKN ratio. This paper reports the results of a simulation study that has been carried out to better understand the behaviour of the two configurations with a wide variety of influent wastewater characteristics and under dynamic conditions.

The results of the simulation confirmed the high P removal capacity of the DEPHANOX configuration with low influent COD/TKN ratios. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Wastewater treatment; biological phosphate removal; denitrification; activated sludge model No. 2; anoxic conditions; anoxic dephosphatation; DEPHANOX; JHB.

INTRODUCTION

The occurrence of denitrifying phosphorus removing bacteria (DPB) has been clearly demonstrated in several studies (Bortone *et al.* 1996; Meinhold *et al.* 1998). It has been shown that DPB have similar capacities and characteristics as fully aerobic PAO (Polyphosphate Accumulating Organisms). Kuba *et al.* (1996) have reported a stoichiometric mass balance of the required COD, consumed oxygen and produced sludge for P and N removal in single sludge conventional systems, alternating anaerobic/anoxic/aerobic conditions, and in two-sludge systems, alternating anaerobic/anoxic condition with a separate oxic phase. From the stoichiometric calculation, it follows that, for the same amount of removed nutrient, 50% of the COD requirement, 30% of the oxygen consumption and and 50% of the sludge production can be saved using the two-sludge systems.

Moreover, this kind of plant is particularly suitable for low COD/TKN ratio wastewater, where the lack of carbon affects the nutrient removal efficiency. It has been experimentally proven that optimal performances can be obtained with only 3.4 COD/N ratio (Kuba *et al.* 1996), while in conventional systems COD/N ratio should be higher than 4.5, up to 8.6 to take into account the aerobic COD "loss" in oxic condition.

It can be stated that plant configurations that exert selective pressure in favour of DPB are strongly recommended, since the competition between PAO and denitrifiers can be drastically reduced.

In Fig. 1, the innovative process scheme (DEPHANOX) is presented. Raw municipal wastewater is introduced into an anaerobic tank (1) where phosphate is released from Poly-P bacteria and most of the organic substrate is bio-sorbed in activated sludge flocs. A downstream settler (2) separates activated sludge with organic substrate (both extra and intracellular) from ammonia-rich supernatant. The liquid stream then goes to a biofilm reactor (3) where nitrification occurs. The organic-substrate-rich sludge bypasses nitrification and is resuspended with the nitrified effluent from (3) in the anoxic stage (4). Here nitrates are removed by denitrifying bacteria and also utilised by Poly-P bacteria as electron acceptors for enhanced P-uptake. A post-aeration step (5) allows nitrogen gas stripping from the sludge and favours a complete regeneration of Poly-P bacteria (complete oxidation of intracellular storage products like PHB) before final settling (6).

This process proved to be very efficient because it drives the utilisation of organic substrate either for phosphorus or for nitrogen removal. The process solves the competition for organic substrates among Poly-P organisms and denitrifiers as well as the problem of overgrowing of slow nitrifiers by faster organotrophs, typical of activated sludge.

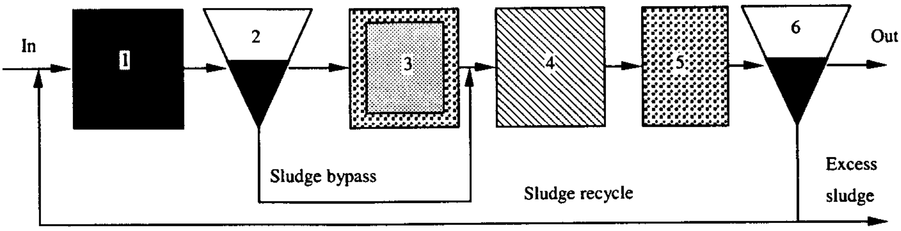

Figure 1. Innovative nitrification-denitrification-enhanced biological P removal (NDEBPR) plant configuration: 1) Anaerobic P-release; 2) Sludge and settleable organic matter separation; 3) Fixed-film nitrification; 4) Denitrification combined with luxury P-uptake; 5) Re-aeration; 6) Final settler

To make the configuration more competitive with regard to the high investment cost due to the presence of two settlers, the anaerobic reactor and the first settler were substituted with a "UASB-like" reactor, that can easily handle the function of separating a well clarified COD-poor supernatant from a dense COD-rich sludge. In previous work (Bortone *et al.* 1996), an experimental comparison of DEPHANOX efficiencies with those of a NDEBPR conventional configuration was carried out. The configuration of the "reference" reactor was set up according to the Johannesburg (JHB) flow scheme (Fig.2).

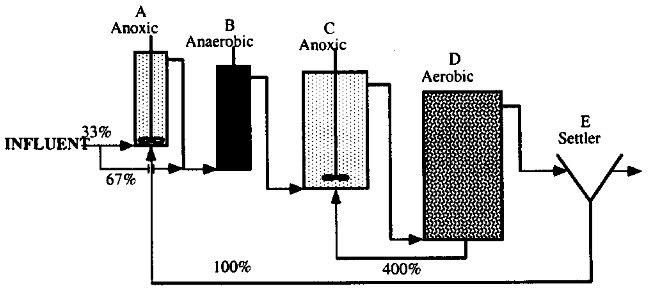

Figure 2. JHB lab-scale plant.

The DEPHANOX and JHB lab-scale plant operational parameters were comparable for the whole experimental campaign. The comparison tests were carried out with municipal wastewater with a low COD/TKN ratio (average 3.8; average influent COD concentration of 233 mg/L). This very low COD/TKN is quite common for Italian municipal wastewater and this can make the complete removal of nutrients in the effluent difficult. The relatively high concentration of nitrates, caused by the incomplete denitrification, negatively influences the biological P removal. For this reason the JHB configuration was chosen as reference flow scheme, since it includes a return sludge denitrifying compartment to avoid the presence of nitrates in the anaerobic compartment. This allows us to achieve high removal efficiency even in spite of the low influent COD/TKN ratio. The removal efficiencies in both plants were comparable. The most significant difference was found in P removal. The low influent COD/TKN ratio did not allow the complete depletion of nitrates in the JHB anaerobic compartment, that worked in fact as an anoxic reactor. Effluent COD concentrations were below 50 mg L^{-1} in both reactors; furthermore, full nitrification capacity was always reached, as witnessed by effluent ammonia concentrations which were always lower than 1 mg/L. Differences were observed in effluent nitrate concentrations: on average, they were higher in the DEPHANOX effluent (20 mg/L) than in JHB (15 mg/L). As already reported, the DEPHANOX configuration allowed us to keep effluent P concentrations always lower than 1 mg L^{-1} (influent P concentration 4.5 mg/L), while JHB effluent presented significantly higher values (average 2.7 mg/L) (Fig. 3).

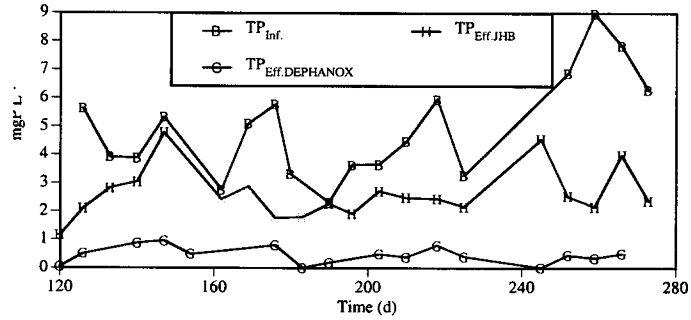

Figure 3. Influent and effluent concentrations in DEPHANOX and JHB.

This paper reports the results of a simulation study that has been carried out to better understand the behaviour of the two configurations with a wide variety of influent wastewater characteristics and under dynamic conditions.

MATERIAL AND METHODS

The IAWQ Model N.2 (Henze *et al.*, 1995) was modified for Anoxic P and implemented in AQUASIM® (Reichert , 1994) and MatLab/Simulink®.

An η_g slowing factor was used to simulate the lower efficiency yield and/or lower population density of denitrifying PAO. The settlers were modelled as ideal separators, having full capacity for solid entrapment. Some simplifications were also introduced in the model of the DEPHANOX biofilm reactor, that was modelled in fact as a CSTR. This CSTR was supposed to be fed with only soluble components, due to the full separation efficiency of the first settler, and the biomass was considered to be fully retained without any solid wash-out. Those ideal conditions gave rise to obtain full nitrification capacity with a simultaneous high removal efficiency of the soluble organic carbon entering the reactor with the first settler supernatant. It has to be highlighted that those simplifications and assumptions were considered acceptable since during the experimental laboratory run the biofilm reactor volume was never limiting plant performance. The kinetic constants and the stoichiometric parameters were made equal for DEPHANOX and JHB configurations,whereas the sludge ages, the reactor volumes, and the flow rates were identical to experimental conditions (Bortone *et al.*, 1996). The dynamic simulations were carried out with hypothetical daily influent fluctuations and with different COD/TKN ratios. Simulations were carried out using the average dynamic parameter values until steady state conditions were reached (almost 50 days); later dynamic daily fluctuations were introduced for a 2.5 days period using AQUASIM and for 30 days using MatLab/Simulink.

RESULTS AND DISCUSSION

In Figures 4 and 5 the daily influent fluctuations used for AQUASIM simulation are reported.

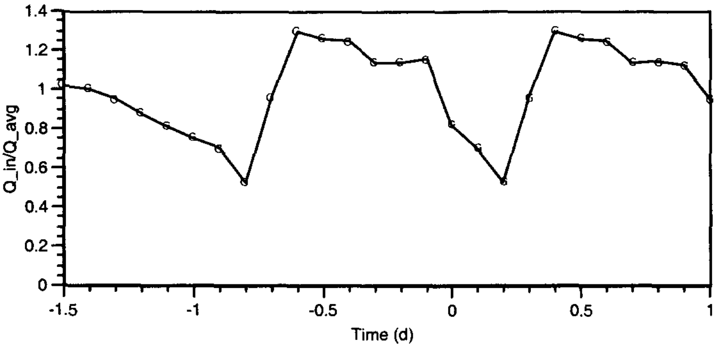

Figure 4. Simulated daily Influent Flow Rate ratio (Q_in/Q_avg) (Simulation was started 50 days before reaching the steady state condition; -1.5 d is the time when daily fluctations were introduced).

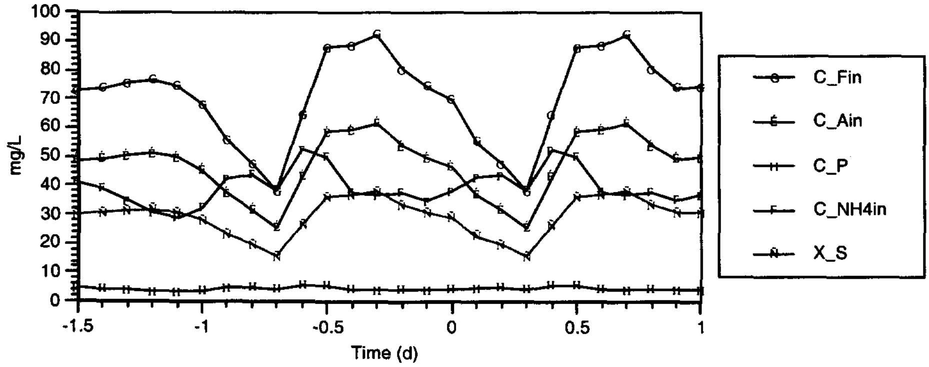

Figure 5. Daily fluctuations of the influent concentration: C_Ain= VFA; C_F=Fermentable COD; C_P=Phosphorus; C_NH4=Ammonia; X_S= Slowly degradable COD.

The first DEPHANOX simulation run (Fig. 6) was carried out with a low influent COD/TKN ratio equal to 4, as in the previously mentioned laboratory experimental run. As reported before, since biomass was considered to be fully retained in the DEPHANOX biofilm reactor, PAO and heterotrophic organisms, in this reactor, were not considered in the simulation (React 2, X_PAO and X_H=0).

As it can be noticed in Fig. 6, the simulated PAO concentrations are higher than heterotrophs, demonstrating the high capacity of the DEPHANOX process in selecting polyphosphate microorganisms even in spite of the low COD/TKN ratio.

This higher concentration of PAO allows us to obtain a very high P removal efficiency with an effluent P concentration always close to zero (Fig. 7). P is fully anoxically removed in the Anoxic Reactor (React4). Due to the activity of DNPAO, the denitrification process also shows a quite high efficiency with an effluent average value of 15 mg/L. Moreover, the process conditions allow us to avoid the presence of nitrate in the anaerobic reactor. These results can be qualitatively compared to the experimental ones, where DEPHANOX effluent concentrations were always below 1 mg/L (Bortone *et al.*, 1996).

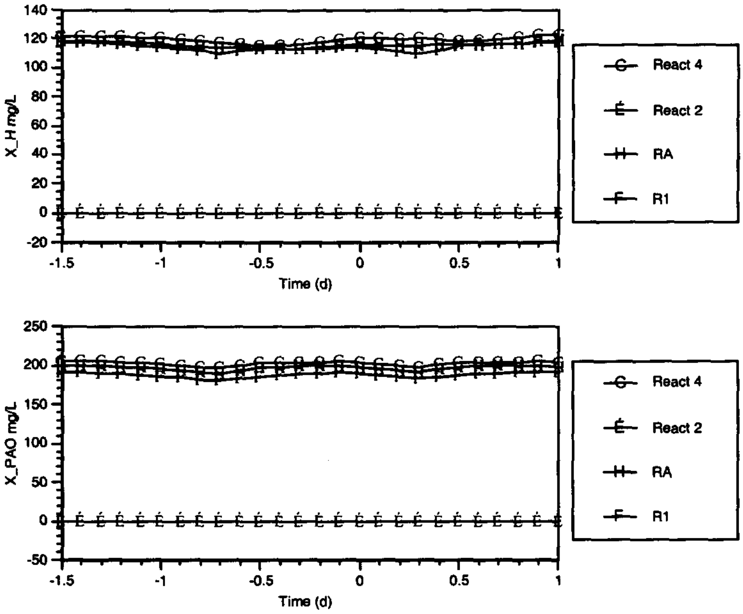

Figure 6. Simulated PAO and heterotroph concentration in the DEPHANOX compartments (influent COD/TKN ratio = 4). React 4=Post-denitrification and luxury anoxic P uptake reactor; React 2= Nitrification Biofilm reactor; R1=Anaerobic reactor; RA= Reareation Reactor; X_H= Heterotrophs; X_PAO= Phosphorus Accumulating Organisms

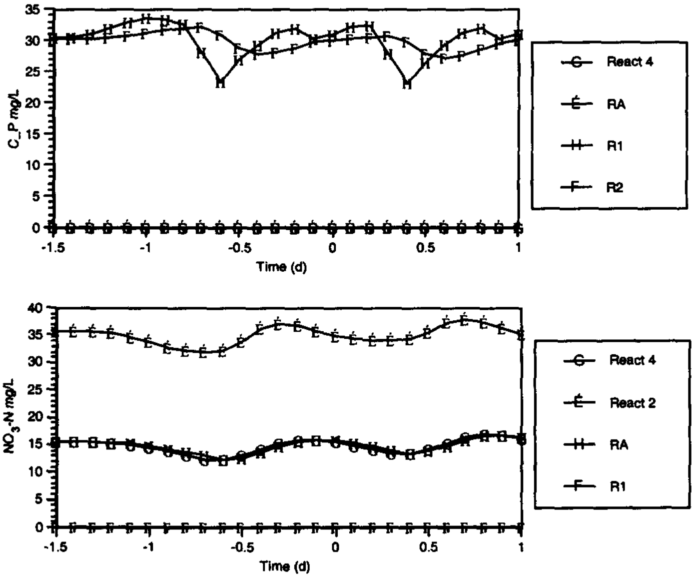

Figure 7. Simulated PO_4-P and NO_3-N concentration in the DEPHANOX plant (COD/TKN = 4). DEPHANOX Compartments: React 4=Post-denitrificazione and luxury anoxic P uptake reactor; React 2= Nitrification Biofilm reactor ; R1=Anaerobic reactor; RA= Reareation Reactor (C_P= PO_4-P)

On the other hand, JHB shows a different behaviour. As in the lab scale plant, the influent flow rate was split into two parts: 33% in the sludge denitrification reactor and 67% in the anaerobic reactor.

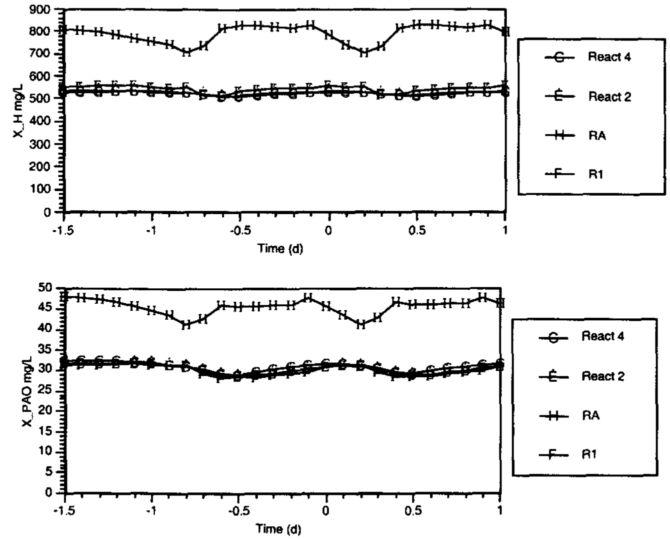

Figure 8. Simulated PAO and heterotroph concentration in the JHB Compartments (COD/TKN=4). JHB Compartments: React 4=Oxidation-Nitrification and luxury aerobic P uptake reactor; React 2= Predenitrification reactor; R1=Anaerobic reactor; RA= Return Sludge Predenitrification Reactor

The low COD/TKN ratio doesn't facilitate the PAO growth. In fact, the PAO concentration is very low, 1/5-1/6 of the DEPHANOX figures (Fig. 8). A possible reason is given by the simulated data reported in Fig. 9. As it can be seen, the nitrate concentration in the JHB anaerobic reactor increases during a part of the simulated period. In spite of the presence of the return sludge denitrification compartment, under these process conditions and with these wastewater characteristics, the presence of nitrates in the anaerobic reactor can not be avoided. This leads to the failure of the enhanced biological phosphate removal process.

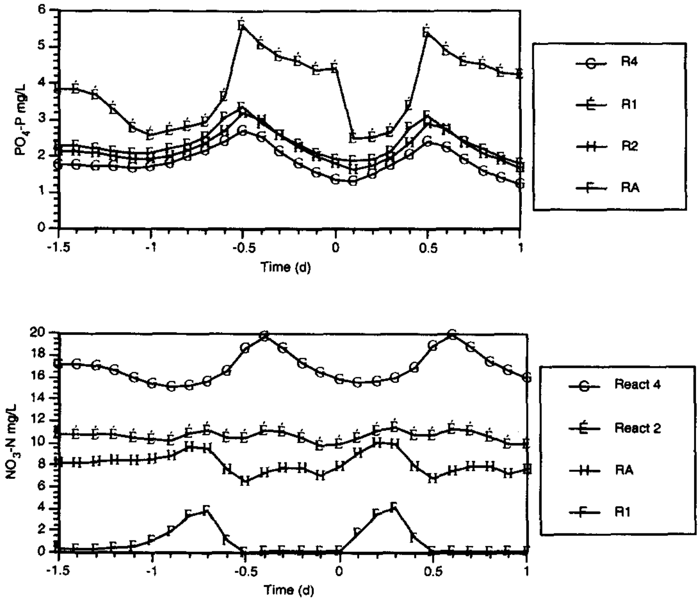

Figure 9. Simulated PO_4-P and NO_3-N concentration in the JHB plant (COD/TKN = 4). JHB Compartments: React 4=Oxidation-Nitrification and luxury aerobic P uptake reactor; React 2= Predenitrification reactor; R1=Anaerobic reactor; RA= Return Sludge Predenitrification Reactor

The simulation was then carried out with a COD/TKN ratio of 10. This influent characteristic allows us to accumulate a higher PAO concentration in the JHB configuration (Fig.10). As a consequence, the higher simulated COD/TKN ratio allows us to achieve a very low concentration of nitrates in the anaerobic reactor (R1) and, therefore, enhanced P removal (Fig.11).

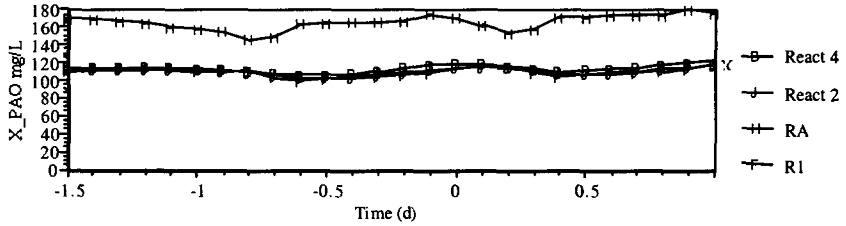

Figure 10. Simulated PAO and heterotroph concentration in the JHB Compartments (COD/TKN=10). JHB Compartments: React 4=Oxidation-Nitrification and luxury aerobic P uptake reactor; React 2= Predenitrification reactor; R1=Anaerobic reactor; RA= Return Sludge Predenitrification Reactor

The higher COD/TKN ratio allows a higher PAO concentration also in the DEPHANOX configuration (average 350 mg/L). In Fig. 12, it can be noticed that in spite of the higher COD availability, anoxic P uptake is incomplete; P is fully anoxically removed only when nitrates are not limiting (see nitrate in Fig. 12). This demonstrates that the reaeration compartment is strictly needed in the DEPHANOX configuration, because in the case of full depletion of nitrates in the anoxic tank, P removal can be completed only under aerobic conditions in the reaeration compartment. A large series of different influent COD/TKN and TKN/PO4-P ratios has been simulated using the model implemented in Mat/Lab-Simulink®. The results of those simulations confirmed the previous conclusions: DEPHANOX shows a better efficiency working at a low COD/TKN ratio. This can be also noticed in Fig. 13, where DEPHANOX P removal efficiency becomes significantly higher than in the JHB with decreasing COD/TKN ratios. Figure 14 shows the relationship between the influent COD/TKN-TKN/PO4-P ratios and the anoxic P removal efficiency in the DEPHANOX configuration. This relationship has been obtained keeping constant COD and P values and only modifying the influent P value. As can be noticed, even at very low COD/TKN ratios, the DEPHANOX anoxic P removal efficiency can be kept higher than 90% when TKN/PO4-P is also high, or in other words the electron acceptor is not limiting anoxic P uptake.

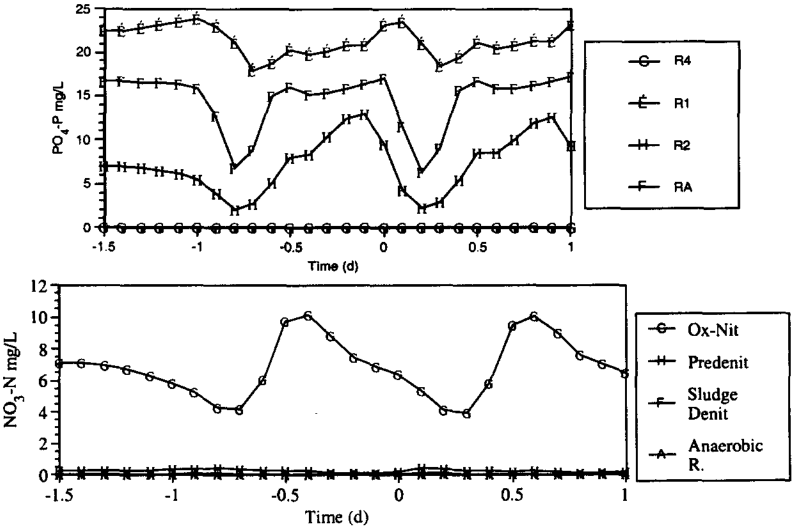

Figure 11. Simulated PO_4-P and NO_3-N concentration in the JHB plant (COD/TKN = 10). JHB Compartments: React 4=Oxidation-Nitrification and luxury aerobic P uptake reactor; React 2= Predenitrification reactor; R1=Anaerobic reactor; RA= Return Sludge Predenitrification Reactor

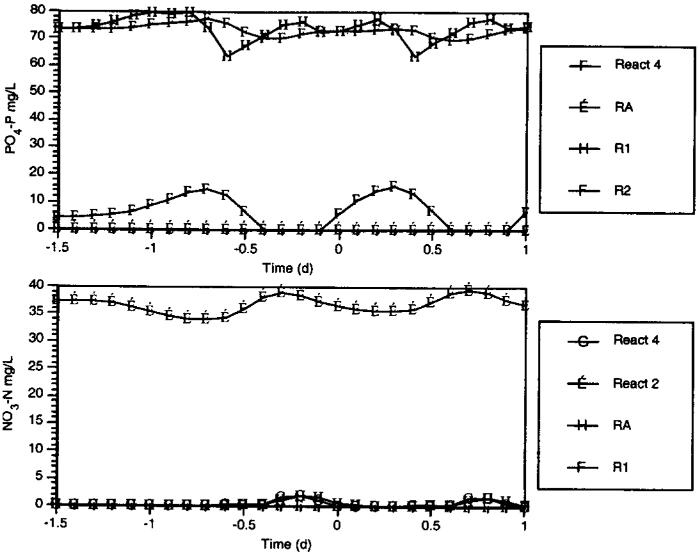

Figure 12. Simulated PO_4-P and NO_3-N concentration in the DEPHANOX plant (COD/TKN = 10). DEPHANOX Compartments: React 4=Post-denitrificazione and luxury anoxic P uptake reactor; React 2= Nitrification Biofilm reactor; R1=Anaerobic reactor; RA= Reareation Reactor

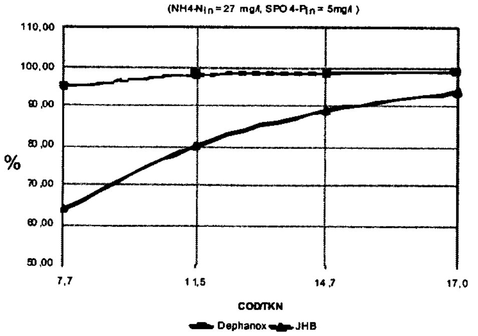

Figure 13. DEPHANOX and JHB P removal efficiency versus COD/TKN ratios.

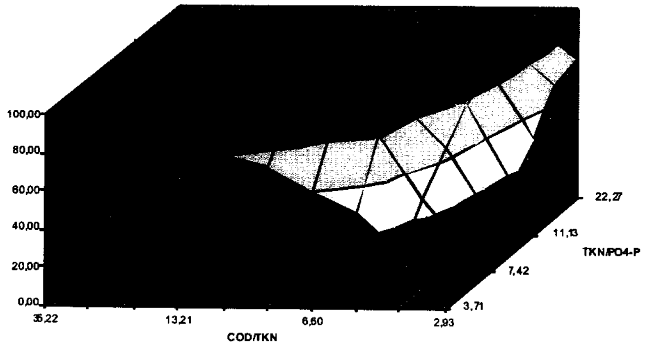

Figure 14. DEPHANOX anoxic P removal efficiency vs COD/TKN and TKN/PO_4-P ratios (COD and TKN constant).

CONCLUSIONS

The simulation studies have demonstrated a high capacity and stability of the DEPHANOX configuration with low influent COD/TKN ratios. In all simulated conditions, DEPHANOX showed to be reliable in keeping a high PAO concentration. The simulations have also demonstrated that the reaeration tank is necessary to complete the luxury P uptake in case of a lack of nitrate (electron acceptors) in the denitrification reactor.

On the basis of this consideration, further research work is being carried out to design and validate an "on-line" control system to regulate redox potential in the denitrification reactor, with the objective to have only one combined reactor for denitrification and reaeration where air is switched on only if nitrates are depleted.

REFERENCES

Bortone, G., Saltarelli, R., Alonso, V., Sorm, R., Wanner, J. and Tilche A. (1996). Biological anoxic phosphorus removal -The DEPHANOX process. *Wat. Sci. Tech.*, **34**(1-2), 119-128.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M. C. and Marais, G. v. R. (1995). Activated sludge model No. 2. Scientific and Technical Report No. 3, IAWQ, London, England.

Kuba, T., van Loosdrecht, M. C. M. and Heijnen, J. J. (1996). Phosphorus and nitrogen removal with minimal COD requirement by integration of denitrifying dephosphatation and nitrification in a two-sludge system. *Wat. Res.*, **30**(7), 1702-1710.

Meinhold, J., Filipe, C. D. M., Daigger, G. and Isaacs, S. (1998). Characterization of the Denitrifying Fraction of Phosphate Accumulating Organisms in Biological Phosphate removal. Proceedings of "Modelling and Microbiology of Activated Sludge Processes". Kollekolle, Copenhagen, March, 16-18.

Reichert, P. (1994). Concept underlying a computer program for the identification and simulation of aquatic system. Swiss Federal Institute for Environmental Science and Technology (EAWAG) CH-8600 Duberdorf, Switzerland.