

# Simultaneous Biological Nitrogen and Phosphate Removal from Wastewater in a Modified Phostrip Process

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## Abstract

Results of experiments aimed at achieving simultaneous nitrogen and phosphate removal in the Phostrip process are reported. It is shown that this may be achieved, without compromising the phosphate removing ability of the process, by including a denitrification stage which utilizes only swage organics. However, a modified Bardenpho process with anaerobic treatment but no separation of the phosphate-rich supernatant was more successful in removing phosphates. The modified Phostrip process may find useful application in instances where the composition of influent sewage is not favourable to purely biological phosphate removal.

## Introduction

Levin *et al.* (1972a,1975) developed and patented the Phostrip process for phosphate removal during biological sewage treatment. This process (Fig. 1a) consists of a conventional activated sludge process modified to strip the secondary sludge of its phosphate content by acid and/or anaerobic treatment. Before recycling, the treated sludge is separated from the phosphate-rich supernatant liquor. The latter, which comprises only a fraction of the total influent flow, is treated with lime, or other chemicals, to precipitate the phosphate concentrated into this stream. The chemical demand is greatly reduced in this man-

ner, which makes the Phostrip process economically attractive when compared with some alternative processes for the chemical removal of phosphates.

Levin *et al.* (1972b) further developed this process to include denitrification. To achieve this the process was operated at a sufficiently long sludge age, or low loading rate, to ensure nitrification of ammoniacal nitrogen in the aeration reactor.

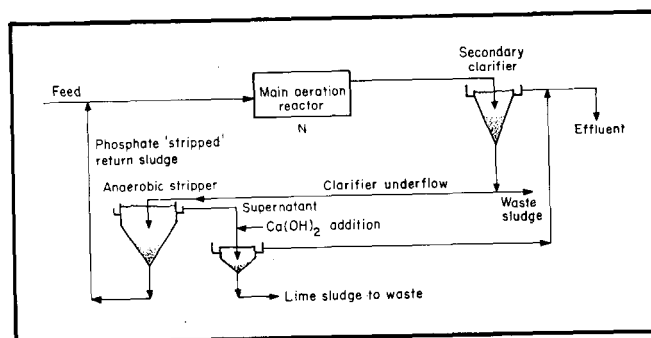


Figure 1(a)  
Schematic flowsheet of Phostrip process

The denitrification step was arranged in a manner similar to that first proposed by Wuhrmann (1964) and is illustrated diagrammatically in Figure 1b. Nitrified mixed liquor from the aeration reactor was passed into a stirred reactor from which air was excluded. The respiratory requirements of the sludge were met by utilising residual dissolved oxygen, followed by subsequent reduction of nitrates. While under oxygen limiting conditions in the denitrification reactor the sludge released part of the phosphate which had been taken up under aeration. The effluent from the denitrification reactor was subjected to aeration to ensure re-uptake or released phosphate and to improve the settling properties of the sludge. The sludge withdrawn from the secondary clarifier was stripped of its phosphate content and recycled in the manner described above for the normal Phostrip process.

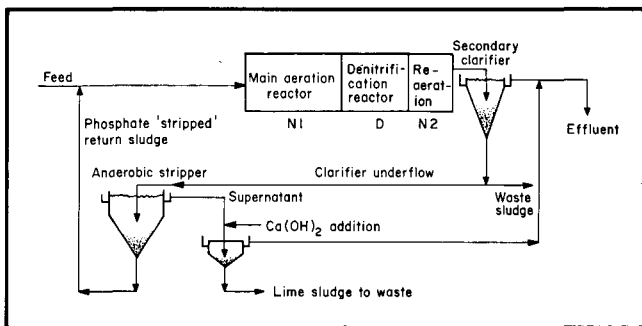


Figure 1(b)

Schematic flowsheet of Phostrip process after modification to include denitrification

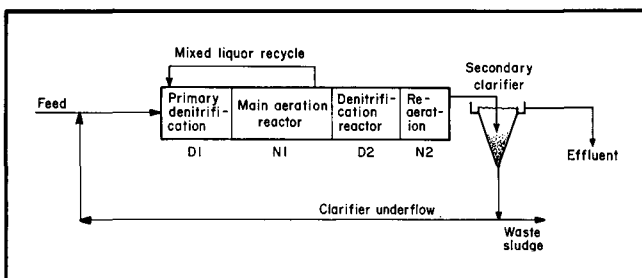


Figure 1(c)

Schematic flowsheet of Bardenpho process

Denitrification rate in the Wuhrmann process is controlled by endogenous respiration rates, which in turn depend on sludge age or sludge loading rate. At high sludge age, such as is required to ensure nitrification, the endogenous activity, and hence potential denitrification rate, is low. Various process modifications have been proposed to rectify this disadvantage. Of these the suggestion by Johnson and Schoepfner (1964) is most noteworthy. They propose bypassing about 15 per cent of the influent flow directly into the denitrification reactor. The organic substrates present in this sewage sidestream greatly enhanced the denitrification rate. This procedure has the drawback that the ammoniacal nitrogen present in the sewage sidestream cannot be denitrified and appears in the effluent as nitrate after nitrification in the final aeration reactor.

While attempting to improve nitrogen removal in the Balakrishnan-Eckenfelder (1970) process, Barnard (1973) developed a process in which high denitrification rates were combined with full nitrification. In this process (Fig. 1c) the denitrification reactor was placed ahead of the aeration stage to receive influent sewage, secondary sludge and nitrified mixed liquor which was recycled directly from the aeration stage at a high rate. Nitrogen removal was further improved by including a secondary denitrification stage, much along the lines of the Wuhrmann process. Further work by Barnard (1975) led to the recognition of the importance of an anaerobic\* stage to induce enhanced biological phosphate uptake in subsequent aerobic conditions.

In biological phosphate removal there is an, at this stage not yet precisely definable, upper limit of removal which apparently depends primarily on the amount of phosphate accumulated in the micro-organisms. The sludge age and other parameters, such as the influent sewage composition and substrate concentration, which control sludge growth also influence this upper limit. In some instances the composition of sewage, particularly in respect of its COD:P ratio, may be such that the attainment of low phosphate residuals in the effluent from a purely biological process is impossible because at a low COD:P ratio sludge growth will be insufficient to remove all phosphates. It is not yet possible to define the COD:P ratio below which complete phosphate removal by purely biological processes will no longer be possible. From unpublished experimental work it appears that at a COD:P ratio of about 50:1 complete phosphate removal by biological means is still possible in the modified Bardenpho process. When the COD:P ratio of the sewage to be treated is wider than 50, phosphate stripping of the sludge prior to recycling, as in the Phostrip process, may be advantageous. The aim of this investigation was to test the feasibility of including denitrification in the Phostrip process in such a manner that high denitrification rates and full nitrification may be ensured. This modified Phostrip process with high lime precipitation of phosphate in a small sidestream was compared with an alternative, purely biological, modified Bardenpho process configuration using no chemicals.

## Laboratory Units and Methods

All experiments described were performed in a temperature controlled room at 20 °C. The modified Phostrip process (Fig. 1d) consisted of a denitrification reactor (D, 6,8 dm<sup>3</sup>), a main aeration stage, which was split into two separate consecutive basins (N1 and N2, 4,8 dm<sup>3</sup> and 5,6 dm<sup>3</sup> respectively), a clari-

\*In this paper 'anaerobic' denotes a state in which both oxygen and nitrate and/or nitrite are either completely absent or present in very low concentrations only.

fier and a phosphate stripping stage. Because of the small scale of operation, it was found difficult to effect phosphate release and separation of the phosphate-depleted recycled sludge and phosphate-rich supernatant in one clarifier. Release of phosphate, therefore, was effected in two separate anaerobic reactors (A1 and A2, 5,5 dm<sup>3</sup> each). Separation of sludge and phosphate-rich supernatant was effectively achieved in a separated anaerobic clarifier. The small side-stream of effluent from the phosphate stripping stage, constituting only 20 per cent of the total effluent from the plant, was accumulated in a closed container to determine the lime demand for complete phosphate precipitation. In full scale practice the chemically treated side-stream with very low phosphate content, dilutes the main effluent stream. To make the processes more directly comparable the effluent phosphate concentrations reported here have been adjusted for this effect. To do this, complete removal of phosphate in the 20 per cent sidestream was assumed and the measured phosphate concentration in the main effluent stream reduced by a factor calculated from the actual measured volumes of the sidestream and main effluent container.

At the inlet, the ratio of the flow of recycled phosphate stripped sludge to influent sewage flow was 1:1. Nitrified mixed

liquor was withdrawn from the second aeration reactor and recycled into the denitrification reactor at 5,7 times the influent sewage flowrate. The mixed liquor recycle rate was not optimized in these experiments and since only 74 per cent of the nitrified mixed liquor leaving the second aeration reactor was recycled to the denitrification reactor with these recycle rates, only 74 per cent denitrification of nitrates was to be expected from this mode of operation.

The unit was seeded to about 2 000 mg/dm<sup>3</sup> MLSS, with sludge obtained from a pilot plant which incorporated anaerobic treatment and in which efficient biological phosphate removal was being achieved (Simpkins and McLaren, 1978). Settled sewage, as available at the local sewage treatment plant (Daspoort, Pretoria, S. Africa) and which originated mainly from domestic (80%) and light industrial sources (20%), was used as feedstock. The chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and total phosphate content of the feedstock was adjusted, by dilution and addition of NH<sub>4</sub>HCO<sub>3</sub> and K<sub>2</sub>HPO<sub>4</sub> where required, to concentrations of approximately 500 mg/dm<sup>3</sup> COD, 50 mg/dm<sup>3</sup> TKN and 10 mg/dm<sup>3</sup> of PO<sub>4</sub>-P. A fresh sewage batch was used every 3 or 4 d (twice a week) and a uniform feedrate of 36 dm<sup>3</sup>/d was maintained. To ensure nitrification a sludge age of 15 d (which was also the sludge age in the pilot plant from which the sludge was obtained) was maintained by wasting the appropriate volume of mixed liquor directly from each reactor every day. After a sludge acclimatization period, during which only the influent and effluent were sampled, the unit was intensively monitored for two weeks. During this period a sample, filtered through Whatman 2V paper, was taken daily from each reactor and analysed for chemical oxygen demand, phosphate and nitrate content.

The lime demand of a composite sample of the stripper supernatant, collected over a three-day period, was determined in a jar test with a six-paddle flocculator. Increasing quantities of lime (Merk, analytical reagent grade) were added to aliquots of the stripper supernatant, flash-mixed at 90 r/min for 1 min and followed by flocculation at 40 r/min for 10 minutes, at which time the pH in each jar was measured. The precipitate was allowed to settle for 30 min, after which the orthophosphate content was determined in samples filtered through Whatman 2V paper.

At the end of the two-week experimental period the sludge was drained from the modified Phostrip plant (Fig. 1d) and used in the alternative (modified Bardenpho) process (Fig. 1e). In this instance the two anaerobic reactors which received the sludge recycle and feed, were placed ahead of the denitrification stage and the sludge stripper separator was eliminated. No other changes were made and identical reactor volumes, the same sludge age and feedstock as before were used during this phase of the experiment. A period of six days was allowed for sludge stabilization followed by monitoring for a further 17 days. In this instance the ratio of sludge recycle to influent wastewater was also 1:1, but the rate at which nitrified mixed liquor was recycled was 4,0 times the influent flowrate. Thus, in this case, only 66 per cent of the nitrified mixed liquor leaving the second aeration reactor was recycled and therefore only 66 per cent denitrification of nitrates was to be expected.

All analyses for COD, TKN and total phosphate-P carried out on the feedstock was performed according to the manual procedures described in Standard Methods (1965). Analyses for COD, ammonia-N, orthophosphate-P and nitrate plus nitrite-N in filtered samples were done by automated (Auto-Analyzer) methods described in the Analytical Guide (1974).

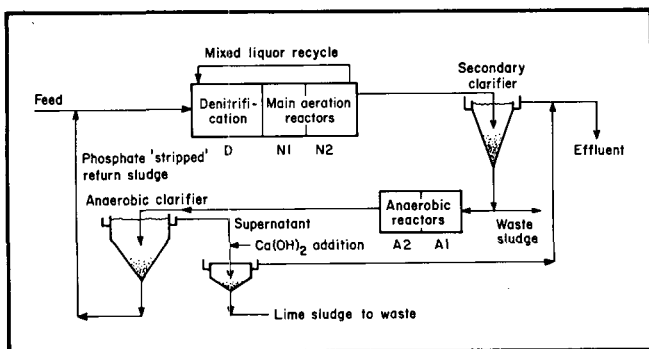


Figure 1(d)

Schematic flowsheet of the modified Phostrip process used in the first part of this investigation

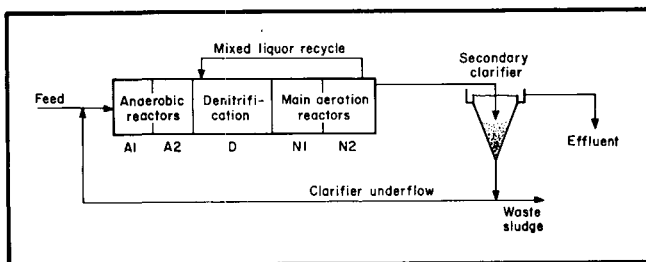


Figure 1(e)

Schematic flowsheet of the process used in the second part of this investigation

## Results

The mean values of all analyses performed on the influent, effluent and filtered reactor contents obtained from the modified Phostrip process during the experimental period are listed in Table 1, which also lists reactor volumes. The results obtained

with the alternative (Bardenpho) process are given in similar format in Table 2. The effluent quality over the whole experimental period is illustrated in Figure 2 with respect to COD, ammonia-N, nitrite plus nitrate-N and orthophosphate-P. Results pertaining to the lime demand test on a composite sample of stripper supernatant are given in Figure 3.

**TABLE 1**  
REACTOR VOLUMES AND MEAN RESULTS OF THE MODIFIED PHOSTRIP PROCESS DURING THE EXPERIMENTAL PERIOD. (ALL ANALYTICAL RESULTS ARE GIVEN IN mg/dm<sup>3</sup>)

Parameter	Influent	Reactor					Composite stripper supern.	Composite final effluent	% Removal
		Denitri-fication	1st Aerobic	2nd Aerobic	1st Anaerobic	2nd Anaerobic			
Volume (dm <sup>3</sup> )	36 d <sup>-1</sup>	6,8	4,8	6,5	5,5	5,5	7,2 d <sup>-1</sup>	—	
Actual retention time (h)	—	0,60	0,42	0,57	3,06	3,06	—	—	
Total PO <sub>4</sub> -P	10,5	—	—	—	—	—	—	—	
o-PO <sub>4</sub> -P	—	3,5	2,4	2,0	6,1	11,1	10,7	1,9	82*
NO <sub>3</sub> +NO <sub>2</sub> -N	—	1,8	4,5	6,1	0,6	0,6	1,1	5,8	
TKN-N	45,8	—	—	—	—	—	—	1,6	84**
NH <sub>3</sub> -N	—	—	—	—	—	—	—	0,4	
COD	494	37	35	35	39	41	39	37	93

\* % Phosphate removal = (total P influent - ortho P effluent).100/total P influent.

\*\* % Nitrogen removal = (TKN influent - all forms of nitrogen in effluent).100/TKN influent.

**TABLE 2**  
REACTOR VOLUMES AND MEAN RESULTS OF THE MODIFIED BARDENPHO PROCESS DURING THE EXPERIMENTAL PERIOD. (ALL ANALYTICAL RESULTS ARE GIVEN IN mg/dm<sup>3</sup>)

Parameter	Influent	Reactor					Composite final effluent	% Removal
		1st Anaerobic	2nd Anaerobic	Denitri-fication	1st Aerobic	2nd Aerobic		
Volume (dm <sup>3</sup> )	36 d <sup>-1</sup>	5,5	5,5	6,8	4,8	6,5	—	
Actual retention time (h)	—	1,88	1,88	0,78	0,55	0,74	—	
Total PO <sub>4</sub> -P	12,0	—	—	—	—	—	—	
o-PO <sub>4</sub> -P	—	16,4	21,9	6,9	2,2	0,4	0,6	95*
NO <sub>3</sub> +NO <sub>2</sub> -N	—	0,6	0,5	1,5	9,0	7,2	6,6	
TKN-N	43,1	—	—	—	—	—	1,7	81**
NH <sub>3</sub> -N	—	—	—	—	—	—	0,5	
COD	46,9	57	53	49	48	49	54	88

\* % Phosphate removal = (total P influent - ortho P effluent).100/total P influent

\*\* % Nitrogen removal = (TKN influent - all forms of nitrogen in effluent).100/TKN influent.

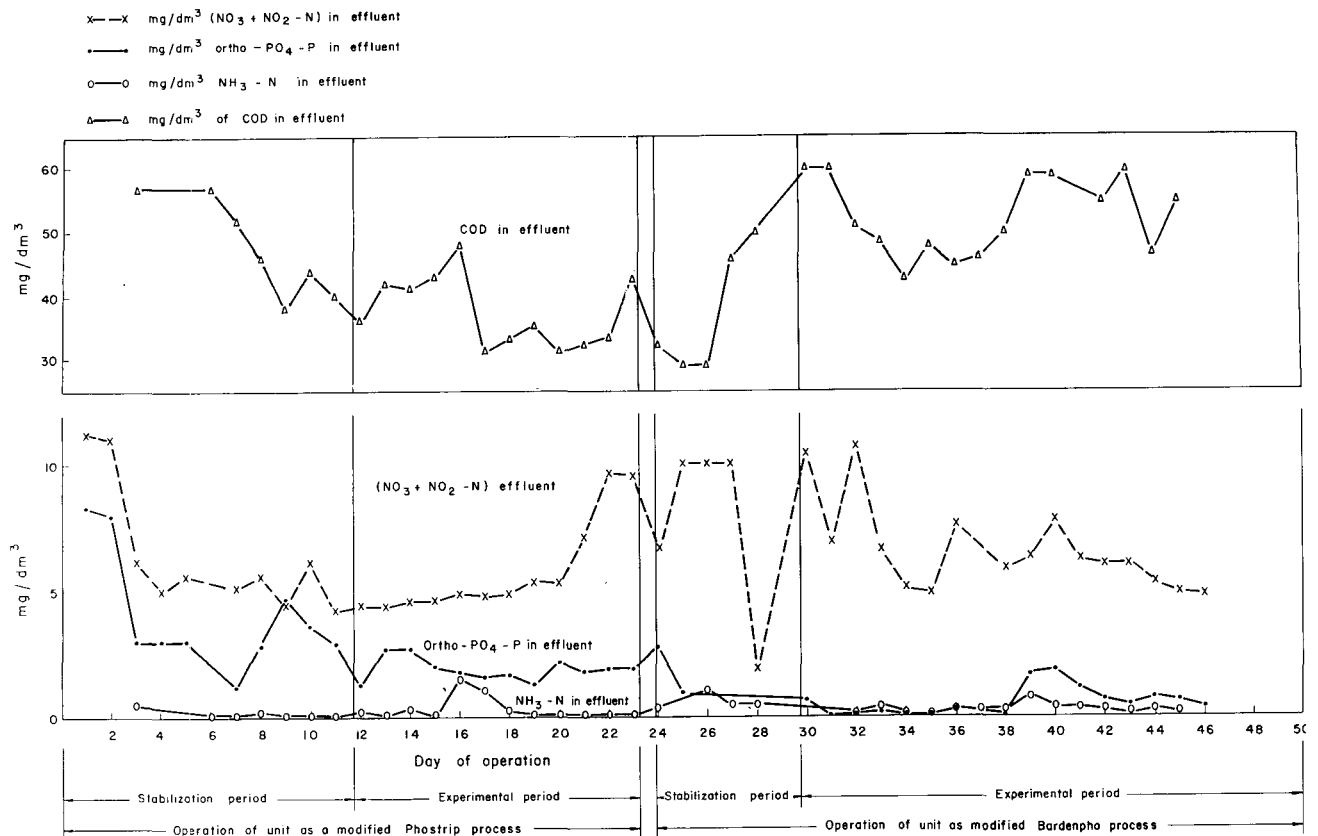


Figure 2  
 Effluent concentration of COD ( $\Delta - \Delta$ ), ammonia ( $o - o$ ), ortho phosphate ( $\cdot - \cdot$ ) and nitrate plus nitrite-N ( $\times - \times$ ) obtained

## Discussion

The total reactor volume (excluding the phosphate sludge separator) nominal aeration time, sludge age and feedstock were similar in the two process configurations investigated. The performance, therefore, may be directly compared, with due consideration for the small difference in A-recycle ratio and the small variation in feed composition. However, there were differences, particularly when the actual residence time in the various reactors was compared (Tables 1 & 2).

## COD Removal

Both processes attained the high COD removals generally expected from activated sludge processes operated at long sludge ages on the predominantly domestic sewage used here (Simpkins and McLaren, 1978). The 31 per cent longer exposure of sludge to anaerobic conditions (6.72 as compared to 4.54 h) and the 12 per cent higher in-reactor denitrification ratio applied in the case of the modified Phostrip unit (74% as against 66%) may account for its marginally (6%) higher COD removal. However,

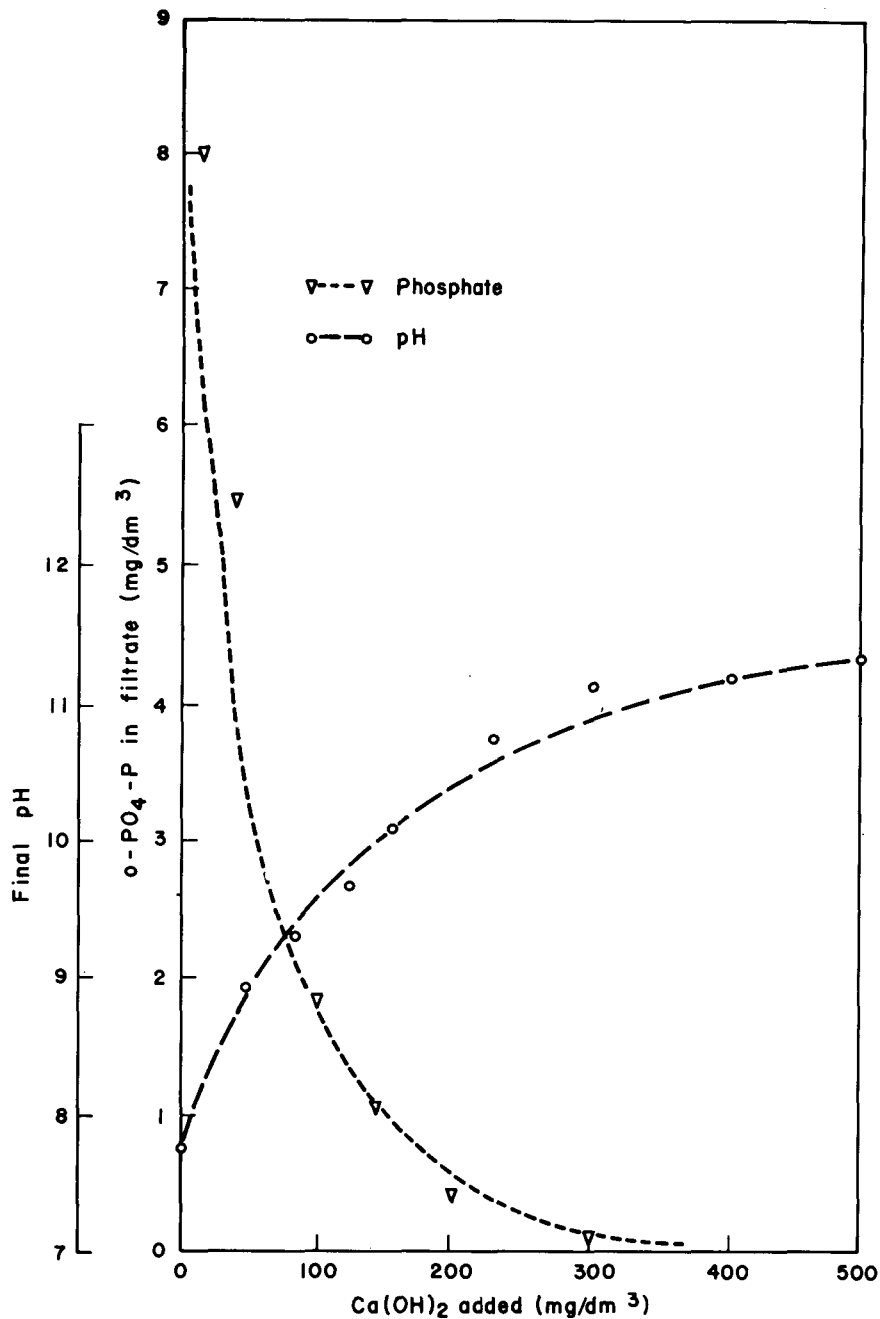


Figure 3  
Lime demand of stripper supernatant

variations in biodegradability of COD were not measured, accordingly, no distinction can be drawn between the two processes in so far as their COD removal ability is concerned. Both are adequate in terms of attaining the "general standard".

#### Nitrification/Denitrification

Less than 0,5 mg/dm<sup>3</sup> of ammonia-N was generally measured in the final effluent of both processes (Fig. 2). This indicated satisfactory nitrification. As in the case of COD removal, the 12

per cent higher denitrification recycle may account for the marginally higher ammonia removal in the modified Phostrip process. But, again the two processes appear equally efficacious in this regard.

In the modified Phostrip process the nitrifying organisms in the sludge were able to survive exposure to anaerobic and/or anoxic\* conditions for 6,7 h and yet achieve complete nitrification when aerated for less than one hour. In this instance the aerobic sludge age was 4,65 d and the temperature 20 °C. At lower temperatures the long exposure to anaerobic con-

\*'Anoxic' denotes a state in which nitrate and/or nitrite are present at significant levels, but the oxygen tension is very low.

ditions may require an increase in the aerobic sludge age to ensure complete nitrification.

Substantial denitrification was obtained, irrespective of whether the unit was operated as a modified Phostrip or as a modified Bardenpho process, in which effluent nitrate plus nitrite-N concentrations of 5,8 and 6,6 mg/dm<sup>3</sup> respectively were attained. Here the 12 per cent difference is precisely accounted for by the 12 per cent difference in denitrification recycle percentages (74% as against 66%).

In both processes about 0,6 mg/dm<sup>3</sup> of nitrate plus nitrite-N was measured in each of the anaerobic reactors, despite conditions favourable to rapid, complete denitrification, i.e. high influent COD and limitation of air access. At relatively high nitrate concentrations, denitrification in suspended culture is a zero order reaction with respect to nitrate concentration (Christensen and Harremoes, 1977). Where the objective is to reach very low nitrate concentrations, as is required for anaerobic conditions, Monod type kinetics should be applied, for which a saturation constant of about 0,1 mg/dm<sup>3</sup> of nitrate-N has been reported by Moore and Schroeder (1971). Considering the abovementioned factors nitrate plus nitrite-N concentration would be expected to reach levels as low as 0,1 mg/dm<sup>3</sup> in the anaerobic reactors. Some interference may have occurred in the analytical method used or possibly the residual nitrate may have become unavailable for denitrification.

### Phosphate Removal

Phosphate removal in the activated sludge process is best discussed in terms of some index other than the traditional 'percentage removal'. The phosphate removal index,  $\Delta P/\Delta COD$ , was first introduced by Mulbarger *et al.* (1971) and the concept was further developed by Marsden and Marais (1976), who stated that any value of  $\Delta P/\Delta COD$  greater than about 0,008 at 15 d sludge age was indicative of enhanced phosphate removal. Phosphate removal in the modified Phostrip process (Fig. 1d) amounted to 82 per cent of the influent total phosphates concentration to give an effluent containing 1,9 mg/dm<sup>3</sup> of orthophosphate-P. The phosphate removal index was  $\Delta P/\Delta COD = 0,019$ , compared to 0,027 for the modified Bardenpho configuration (Fig. 1e) in which instance about 95 per cent of the influent total-P was removed, leaving only 0,6 mg/dm<sup>3</sup> of orthophosphate-P in the effluent.

A much higher degree of phosphate solubilization occurred in the anaerobic reactors (22 mg/dm<sup>3</sup> of phosphate-P) when this stage was placed ahead of the denitrification reactor in the modified Bardenpho process than in the case of the modified Phostrip unit (11 mg/dm<sup>3</sup> of phosphate-P). The relevance of these high levels of phosphate release under anaerobic conditions to subsequent enhanced uptake in the aeration stage is not yet clear. However, a high degree of phosphate release is clearly indicative of the ability of the sludge to take up large amounts of phosphate. This view is confirmed by the fact that phosphate release under anaerobic conditions in processes exhibiting enhanced phosphate removal has often been noted before (Barnard, 1975; Fuhs and Chen, 1975; McLaren and Wood, 1976; Simpkins and McLaren, 1978).

### Lime Demand

The results of the lime demand test on the stripper supernatant from the modified Phostrip process are shown in Figure 3. Addi-

tion of about 300 mg/dm<sup>3</sup> of lime raised the pH of the supernatant to about 11, and consequently precipitated practically all phosphates. As the laboratory process was operated 300 mg/dm<sup>3</sup> of lime in the stripper supernatant was equivalent to 69 mg/dm<sup>3</sup>, in the influent flow. This represents a saving in chemicals of 80 per cent when compared with lime treatment of the whole flow. Such savings are actually experienced in full scale work (Peirano, 1977). In practice the lime requirements may probably be reduced by e.g. recycling lime sludge as seed for calcium phosphate precipitation. No optimization of lime dosage was done in these experiments.

### Conclusions

The results obtained lead to the following conclusions:

- (i) The Phostrip process, with chemical stripping of sidestream phosphates, can readily be modified to achieve a high degree of nitrogen removal, using only influent sewage organics as hydrogen donors, without impairing its normal phosphate removal characteristics.
- (ii) Excellent phosphate removal and a high degree of nitrogen removal through nitrification/denitrification have been demonstrated in a modified Bardenpho process requiring no chemical addition.
- (iii) There is merit in further investigating both processes to derive optimal reactor sizes and recycle flow rates to suit normal diurnal variations in influent flow and substrate.
- (iv) A modified Phostrip process may find useful application in instances where the influent sewage has such a composition as to impair the efficacy of the purely biological modified Bardenpho process.

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