Gilbert V. Levin, George J. Topol, and Alexandra G. Tarnay

Bacteria in a commercial sewage plant can now be trained to dispose of phosphates.

Biological removal of phosphates from wastewater

Biological method for phosphate removal

Because of the success and economy of biological treatment for removal of organic components, use of microorganisms to remove phosphorus from wastewater is especially interesting. This paper reports a pilot study of the PhoStrip process for phosphorus removal. It is primarily a biological process and promises significantly lower operating costs than conventional methods.

The process has been reported in various stages of its development (*1–4*), most of it done in laboratory flasks (*1–4*).

In essence, the process is based on the finding that the aeration of mixed liquor can *induce* activated sludge microorganisms to take up dissolved phosphorus. This "luxury uptake" of phosphorus is in excess of the amount required for growth. If the air supply is turned off, the phosphorus previously taken up is released into the liquid phase. However, when aeration is recommenced, the microorganisms again take up the dissolved phosphorus.

The process shown in Figure 1 is based on these findings. Aeration induces the microorganisms to take up dissolved phosphorus, and the relatively phosphorus-free effluent from the secondary clarifier is discharged into the stream. The set-

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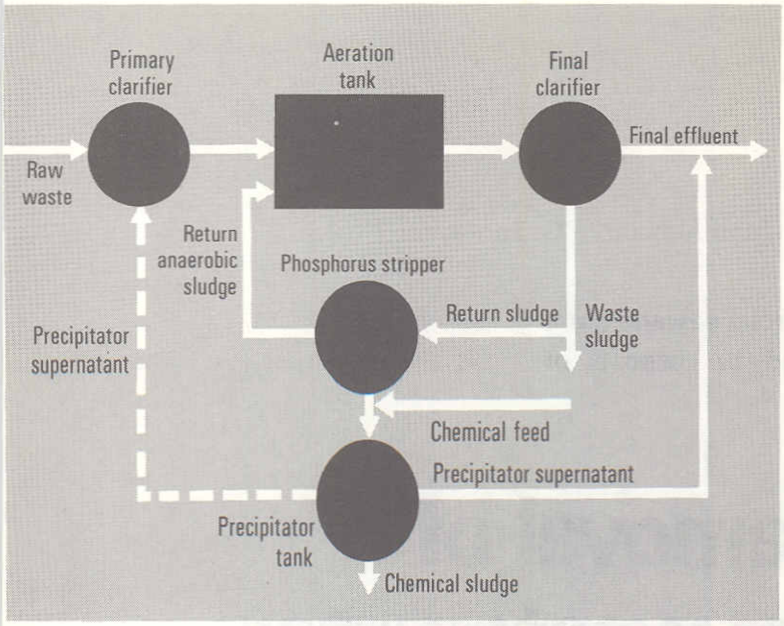

Figure 1. Schematic of biological process for phosphorus removal

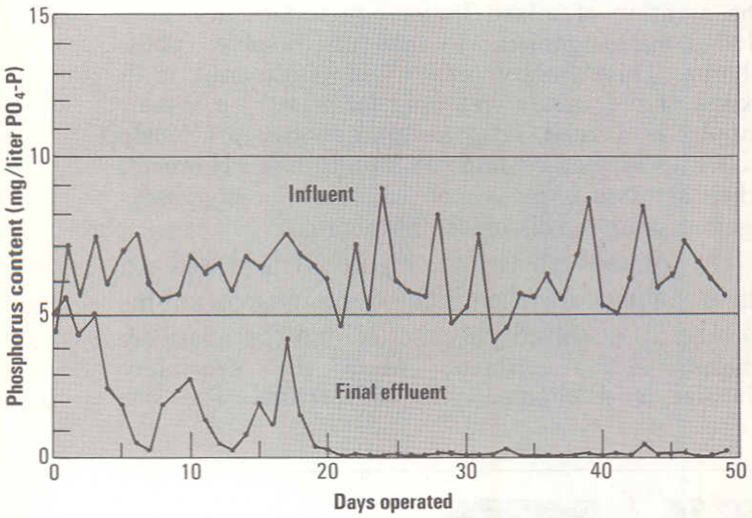

Figure 2. Pilot plant results with synthetic wastewater using biological process for phosphorus removal

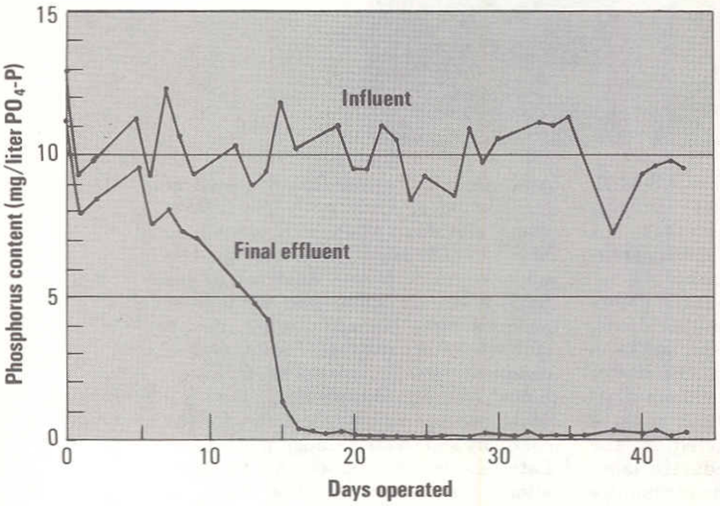

Figure 3. Pilot plant results with Baltimore primary effluent using biological process for phosphorus removal

tled sludge is removed from the secondary clarifier and transferred into the anaerobic tank (an open tank similar to a conventional sludge thickener). Here the organisms consume the oxygen remaining from aeration and release dissolved phosphorus. Further settling occurs in this tank, producing a phosphorus-rich supernatant that is removed for chemical precipitation of the phosphorus. Finally, the sludge at the bottom of the anaerobic tank, relieved of that portion of the phosphorus extracted with the supernatant, is returned to mix with raw wastewater at the head end of the aeration tank for the start of another cycle. The process had never been tested on a continuous-flow basis or in a plant designed for it. The question remained as to whether it could achieve and sustain phosphorus removals of the magnitude required for a practical process.

To investigate this question, a pilot plant was constructed and first run in the conventional activated sludge mode with a synthetic wastewater consisting of a dog food slurry to which ammonium dibasic phosphate was added to give a total orthophosphate phosphorus concentration of 10 mg/liter. After normal activated sludge operation had been maintained for several weeks, an anaerobic tank was added to the system, which was then operated for biological removal of phosphorus (*5*). Influent and effluent dissolved orthophosphate concentrations were monitored. After a startup period, orthophosphate removal began to increase dramatically, passing the hoped-for 80 percent removal level to achieve an average of 98 percent removal for the 28-day test period (Figure 2).

Next, the PhoStrip process was tried on domestic wastewater. Daily tank truck deliveries of primary effluent with Baltimore's Back River wastewater treatment plant were made to the pilot plant. As shown in Figure 3, the results closely paralleled those with synthetic wastewater, achieving an average removal of orthophosphate of 97 percent over the 31-day test period.

The next step in the development of the method was to run the pilot plant "onstream" at a wastewater treatment plant to expose the process to influent wastewater quality fluctuation and winter temperatures. The closest suitable source of domestic wastewater was at Blue Plains, the District of Columbia's water pollution control plant. D.C.'s Department of Environmental Services agreed to permit installation and operation of a pilot plant at its plant, which treats the wastewater from Washington, D.C., and parts of nearby Maryland and Virginia. The District's Department of Environmental Services also offered to monitor the tests and to conduct independent sampling and laboratory analyses.

The pilot plant

The pilot plant consists of an aerating section, final clarifier, anaerobic phosphorus stripping tank, pumps, and a control panel with accessories. The design was developed to simulate, as closely as possible, a full-scale operation in the smallest practicable size permitting full operational control.

The aerating section, consisting of six vertical Plexiglas cylinders connected in series, reproduces the plug-flow pattern of long aerating tanks of conventional activated sludge plants. Each cylinder is 4.5 ft tall and 8 in. in diameter, and contains 10 gallons of mixed liquor. Air is introduced at the bottom of each cylinder through a short length of perforated tubing.

The control panel provides individual valves and flow meters for independent control of the aeration rate in each aerating cylinder. The panel also contains adjustable timers for positive control of the pilot plant influent, sludge flow to the anaerobic phosphorus stripping tank, and return of thickened sludge from the phosphorus stripping tank to the head of the aerating section. The pumps are of the positive displacement, progressive cavity type.

The final clarifier has a capacity of 20 gallons and is provided with a conical bottom for sludge withdrawal. Effluent from the last aerating cylinder flows into the clarifier by gravity through a sloping overflow tube. A stilling well is provided in the clarifier to dampen the turbulence of inflowing mixed liquor.

The anaerobic phosphorus stripping tank is a 15 gallon polyethylene tank with a slow-moving paddle mechanism. The stirring rate is designed to permit gradual thickening of the sludge just as in the case of a conventional sludge thickener. The concentrated organisms release phosphorus as orthophosphate; the gentle stirring facilitates the transfer of the phosphorus from the sludge to the supernatant, which leaves the system as a stream of concentrated phosphorus. The phosphorus-depleted sludge is returned by pump to the aeration tank where it again takes up phosphorus from incoming wastewater.

During the tests, excess sludge was wasted from the anaerobic tank underflow. The flow pattern for phosphorus removal is depicted in Figure 4. Figure 5 is a photograph of the installation. The influent fed to the PhoStrip process for phosphorus removal was obtained from the primary effluent channel of the District of Columbia Blue Plains wastewater treatment plant.

The pilot plant was attended daily. Sampling, measurements, and maintenance routines were established and followed throughout the program.

In addition to the daily readings and grab sampling, composite samples were obtained through the cooperation of the District of Columbia Water Pollution Control Division personnel. "Standard Methods" were used for analytical procedures.

Operations

The pilot plant was placed in the PhoStrip mode and was operated under conditions that were proven by previous in-house work to effect a high degree of phosphorus removal.

The startup period provided adequate time for sludge acclimation and for the operating personnel to become familiar with the routine sampling and measurement procedures. Simple tests such as sludge settling, pH, DO, and preliminary orthophosphate analyses were performed on site. Samples were delivered daily to the Biospherics laboratory for the other assays. Pilot plant control was maintained through various flow adjustments and by the wasting of excess sludge to keep the solids at the desired level.

The pilot plant was operated to maintain the design parameters given in Table 1 in which the actual

Table 1. Operating parameters

Parameter	Quantity: Design	Quantity: Actual (avg or range for test period)
Feed	10.0 gph	10.0 gph
Aeration rate	Min rate to maintain adequate mixing	Coarse bubble aeration at avg of 3.18 cu ft/gal
Aeration period	6.0 hr	6.0 hr
MLSS	1200 mg/liter	1260 mg/liter
Return sludge flow to stripper	1.50 gph	1.57 gph
Anaerobic detention period	10.0 hr	10.4 hr
Return anaerobic sludge flow	0.75 gph	0.71 gph
Stripper supernatant flow	0.75 gph	0.82 gph
Waste sludge flow	To maintain MLSS at 1200 mg/liter	0.04 gph
Temperature	Ambient	12°-16°C

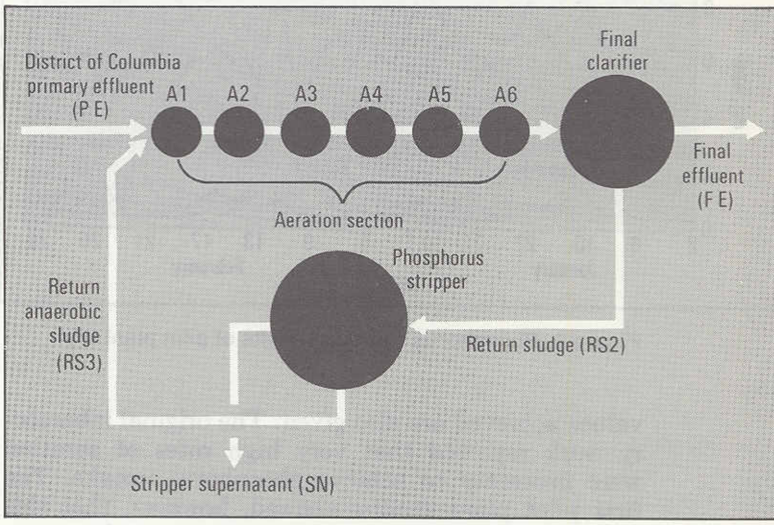

Figure 4. Pilot plant flow pattern for District of Columbia pilot test of PhoStrip process

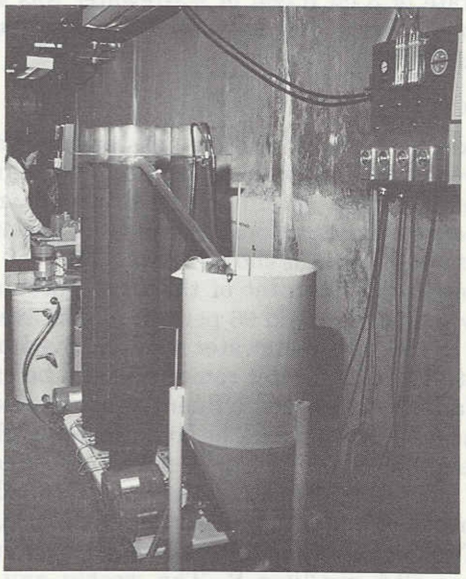

Figure 5. District of Columbia pilot plant installation

Table 2. Phosphorus removable data

Time period, 1972	Raw waste total phosphorus (mg/liter)	Final effluent[a] total phosphorus: Unfiltered removal (mg/liter)	(%)	Filtered removal (mg/liter)	(%)	Final effluent orthophosphate[b] (as P) (mg/liter)	Stripper supernatant total phosphorus (mg/liter)
Jan 12–18	6.8	0.26	96.2	...	...	0.04	56.4
Jan 19–25	7.1	0.80	88.8	0.39	94.5	0.05	52.6
Jan 26–Feb 1	7.1	0.80	88.8	0.21	97.1	0.06	48.4
Feb 2–8	6.8	0.76	88.8	0.24	96.5	0.06	55.2
Feb 9–15	6.8	0.70	89.7	0.21	96.9	0.06	48.6
Feb 16–22	6.0	0.76	87.4	0.35	94.2	0.20	56.7
Feb 23–29	6.7	0.80	88.1	0.30	95.5	0.04	56.8
Overall average	6.7	0.69	89.7	0.28	95.8	0.07	53.5

[a] Flow proportioned daily 24-hour composite samples.
[b] Grab samples (4 to 5 days/week).

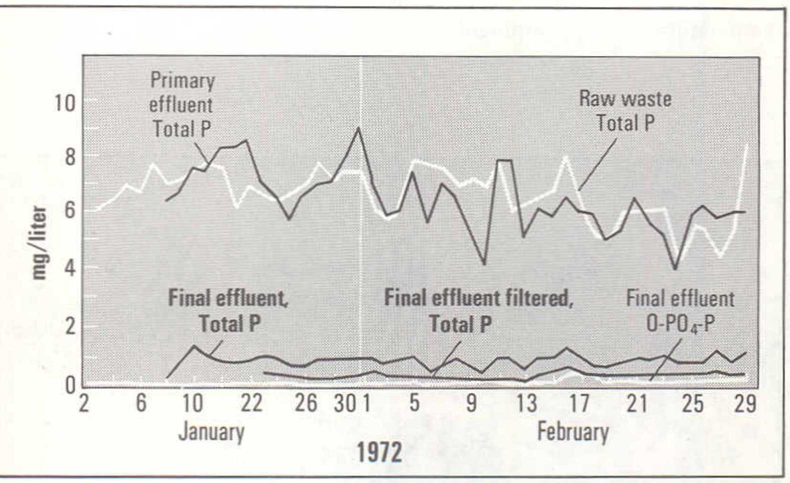

Figure 6. Phosphorus removal results of pilot plant test

Table 3. Phosphorus profile through aerating section

		Total phosphorus, mg/liter
Primary effluent:		5.9
		Remaining total dissolved phosphorus, mg/liter
Aerating cylinder:	A1	2.56
	A2	0.86
	A3	0.22
	A4	0.15
	A5	0.11
	A6	0.11

Each cylinder provides one hour aeration.

values achieved are also given. The original laboratory work reported that very high rates of aeration were necessary to achieve phosphorus uptake. The first pilot plant studies showed, however, that this was attributable to poor oxygen transfer rates achieved in the laboratory flasks. To compensate for the low oxygen transfer efficiency in the shallow depth of the aeration cylinders and to sustain mixing, a rate of 3 cu ft/gal of wastewater was selected as approximating the average 1 cu ft/gal used in full-scale plants.

Results

Weekly averages of the key data are presented for the seven weeks of the test period. The pilot plant consistently produced effluent with very low residual phosphorus concentrations regardless of variations in influent phosphorus as shown in Figure 6.

Averages of 90 percent of the total phosphorus in the raw wastewater and 96 percent of dissolved phosphorus in the raw wastewater were removed from the influent. Thus, the latter removal would be expected in a plant in which the effluent were filtered to remove suspended solids. The average total phosphorus was reduced to 0.69 mg/liter and orthophosphate to 0.07 mg/liter. With filtration, the total phosphorus content of the effluent was reduced to 0.28 mg/liter. The average concentration of stripper supernatant was 53.5 mg/liter P. The weekly and overall phosphorus averages are given in Table 2.

A dissolved phosphorus profile through the aeration section shown in Table 3 describes phosphorus removal as a function of aeration time. The major portion of dissolved phosphorus was removed after only two hours of aeration, indicating the possibility of operating with a shorter aeration period.

A mass balance of phosphorus for the test period was made and showed that approximately two-thirds of the phosphorus removed by the process was transferred into the stripper supernatant with the remaining one-third being removed with the sludge wasted from the anaerobic stripper.

In addition to its excellent phosphorus removal, the process performed well in removing BOD and SS (suspended solids), as shown in Table 4. Removal of BOD averaged 88 percent and increased to 96 percent with filtration of the effluent. This resulted in effluent BOD's of 14.2 and 3.7 mg/liter, respectively.

As shown in Table 4, an average of 80 percent of the influent solids was removed during the seven-week period. Table 4 also gives the average concentrations of MLSS maintained in the sludge and the sludge settleability expressed as sludge density index (SDI). It is interesting that the SDI increased, suggesting a beneficial effect of anaerobic exposure on sludge settling.

Precipitation of phosphorus

The primary purpose of the pilot plant operation was to test the ability of the process to remove

Table 4. Biochemical oxygen demand and suspended solids data

	BOD					Suspended solids				
		Final effluent					Final effluent		Activated sludge	
		Unfiltered		Filtered						
Time period, 1972	Primary effluent (mg/liter)	(mg/liter)	Removal (%)	(mg/liter)	Removal (%)	Primary effluent (mg/liter)	(mg/liter)	Removal (%)	Mixed liquor (mg/liter)	Sludge density index
Jan. 12–18	110.0	15.0	86.4	...	...	88.0	16.0	82.0	1079.0	1.17
Jan. 19–25	140.0	18.3	86.9	...	...	100.6	26.1	74.0	1048.0	1.06
Jan. 26–Feb. 1	120.0	15.0	87.5	4.0	96.7	81.7	20.3	75.2	1175.0	1.15
Feb. 2–8	110.0	13.0	88.2	3.0	97.3	94.3	18.3	80.6	1286.0	1.26
Feb. 9–15	110.0	15.0	86.4	2.0	98.2	99.0	17.5	82.4	1620.0	1.44
Feb. 16–22	110.0	12.0	89.1	4.0	95.5	96.6	16.4	83.0	1306.0	1.55
Feb. 23–29	94.5	11.5	87.8	5.5	94.2	97.3	16.0	83.6	1307.0	1.50
Overall average:	**113.5**	**14.2**	**87.5**	**3.7**	**96.4**	**94.0**	**18.6**	**80.2**	**1260.0**	**1.30**

Table 5. Lime precipitation of stripper supernatant phosphorus

	Phosphorus remaining after precipitation and filtration		Suspended solids generated	
Lime dosage CaO (mg/liter)	Total dissolved phosphorus (mg/liter)	Orthophosphate (mg/liter as P)	In supernatant (mg/liter)	Based on total wastewater flow[a] (mg/liter)
0	56.0	51.0	25.0	2.0
100	37.5	32.3	125.0	10.0
200	26.8	20.3	227.0	18.2
300	3.0	2.3	321.0	25.7

[a] The supernatant flow was eight percent of the total sewage flow.

phosphorus from the influent wastewater and to transfer it into a small volume of supernatant from the anaerobic tank. Final disposal of this phosphorus-rich liquid could readily be accomplished by existing technology and, hence, continuous precipitation of the phosphorus was not part of the test program. However, laboratory tests were conducted with samples of pilot plant stripper supernatant to confirm the efficiency of standard chemical procedures for phosphorus precipitation. After some calculations and preliminary tests, lime precipitation was selected as most effective and economical for this purpose.

Results of precipitation experiments with different lime dosages, followed by filtration to simulate final settling, are shown in Table 5. A 200 mg/liter dose of CaO precipitated more than 50 percent of the total phosphorus, and 300 mg/liter precipitated 95 percent of the total phosphorus, leaving a residual of 3 mg/liter.

With the supernatant flow volume being only eight percent of the wastewater flow, the dosage of 300 mg/liter CaO is equivalent to a dosage of 24 mg/liter based on total wastewater flow. This compares to the 300 or more mg/liter required by direct chemical treatment of the total flow. The SS generated by the precipitation of the phosphorus stripper supernatant with 300 mg/liter CaO were only 321.0 mg/liter which corresponds to 25.7 mg/liter based on the total wastewater flow. This extrapolates to 214 lb of

Under the provisions of the Federal Water Pollution Control Act Amendments of 1972, every municipality in the United States is required to collect and treat its sewage. By the middle of 1977, that treatment must be as effective as "secondary treatment"; by 1983, it must be "the best practicable waste treatment technology" available, or some combination of treatments at least as effective as "the best practicable" technology.

In addition, treatment plant effluents destined for discharge into lakes must be treated to remove phosphates, which are not removed by conventional biological treatment processes.

Until now, all methods available for wastewater phosphorus removal have required chemical treatment of the entire wastewater flow. Treatment costs are unbearably high for all but the most seriously threatened water bodies, with the principal cost components being the expense of buying the chemicals and for disposing of the sludge.

The pilot-plant data reported here for Blue Plains, the District of Columbia's sewage treatment plant, have been confirmed by a separate set of tests at Seneca Falls, N.Y. In the Seneca Falls tryout, PhoStrip removed 91% of the phosphates at a bulk chemicals cost of about $2.10 per million gallons of sewage.

dry chemical sludge generated/mil gal of wastewater treated. This is approximately seven percent of the lime treatment of the entire wastewater flow.

Discussion

The PhoStrip process has been tested at the pilot scale on synthetic wastewater and on municipal wastewater. The results demonstrated that it can achieve consistently high removals of phosphorus when exposed to wide fluctuations of wastewater composition as encountered in an operating plant. During the pilot plant tests no attempt was made to adjust the operational parameters to achieve maximum operating economy. Full-scale operation may show that the process can be further refined in the direction of reduced costs. Aeration and anaerobic detention times may be shortened and the lime dosage may be further decreased.

The two main advantages are a direct result of the biological nature of the process. First, the microorganisms can scavenge variable concentrations of wastewater phosphorus to produce uniformly low residuals and, second, the microorganisms can release the phosphorus in concentrated form in a small volume of liquid.

The first factor, to a large degree, insulates the process from fluctuations in influent phosphorus concentration. Direct chemical treatment requires precise control of chemical feed or maintenance of a substantial overdose to assure good removal during influent phosphorus concentration peaks.

The ability to concentrate phosphorus into a small volume of liquid simplifies chemical precipitation. Substantial savings in chemical costs result directly from this concentration. Further savings can be obtained because it is not necessary to reduce the stripper supernatant to low phosphorus concentrations when the liquid is returned to the aeration tanks. Additional savings are realized by reduction in the amount of chemical sludge and associated disposal costs.

Ancillary benefits may accrue to the process. The cycling of the sludge through an anaerobic phase may assist in the control of bulking by killing off the filamentous organisms to which bulking is generally attributed and, therefore, may aid those plants generally having difficulty in this area of operation. The reservoir of sludge provided by the anaerobic tank may be useful in controlling MLSS to maintain an optimum food:microorganism ratio. This reservoir capability might provide an important asset in the automation of MLSS control under diurnal variations of flow and strength of wastewater.

Conclusions

Analysis of the data and review of the operating experience presented permit the following conclusions:

1. The PhoStrip process removed approximately 90 percent of the total phosphorus present in domestic wastewater and produced an effluent containing 0.69 mg/liter total P. Orthophosphate was reduced to 0.07 mg/liter as P.
2. The addition of a filtration step may increase total phosphorus removal to approximately 96 percent, producing an effluent containing 0.28 mg/liter total P.

al activated sludge process and appears to be compatible with modifications of it.

4. The process produces less chemical sludge than phosphorus removal processes treating the entire wastewater flow.
5. Tendencies to reduce bulking, improve settling and improve shock resilience are indicated for the process.
6. The method provides a sludge reservoir to control MLSS.
7. Principally through drastic reductions in chemical dosage, the method promises to offer a high degree of phosphorus removal considerably cheaper than other available methods.
8. Sufficient data have now been obtained in the field and the laboratory to warrant full-scale application of the PhoStrip process for phosphorus removal.

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