BIOLOGICAL PHOSPHORUS REMOVAL:
CURRENT STATUS AND FUTURE PROSPECTS

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INTRODUCTION

The importance of controlling nutrient discharges into watercourses has been recognized for a long time and now is even more apparent because of concerns about premature eutrophication of many lakes, reservoirs and rivers.

The two nutrients of principal interest currently are nitrogen and phosphorus. Either could be the key constituent whose limited availability restricts the amounts of aquatic growths that can be produced in a watercourse. Addition of that "limiting nutrient" to the watercourse could relieve the restriction and allow excessive production of plants. Of the two, phosphorus has attracted the greater attention, for several reasons, and is the nutrient often selected by regulatory agencies for control in wastewater discharges.

Actually, phosphorus compounds enter watercourses from several sources, including land runoff, municipal wastewaters, industrial wastes, and rainfall. The relative amounts from the different sources vary from place to place. Contributions in municipal and industrial wastewaters (referred to as "point sources") often range from 20 to 60% of the total, when point sources are significant, and land runoff ("nonpoint sources") accounts for, perhaps, 40 to 80%. Contributions from nonpoint sources are difficult to control and usually must be approached through improving land management practices of farmers and others -- a slow and difficult process to implement. Reductions in phosphorus discharged in municipal and industrial wastewaters, on the other hand, may be accomplished effectively through end-of-pipeline treatment, which is far easier to regulate under existing pollution control laws.

Imposition of phosphorus standards is becoming more common, although most U.S.A. municipalities still are not required to remove that nutrient from their discharges. Those which do almost always use processes based on adding alum, iron compounds or lime to precipitate phosphorus at some point in the process and remove the precipitate along with other suspended matter by settling. Details of the several available processes and their chemistry will not be discussed here, but some of their good and bad features will be outlined later for comparison with the biological processes to be discussed.

Biological Phosphorus Removal (BPR) is a different approach for removing phosphorus, which has been suggested and studied by several investigators. All wastewater treatment processes remove some phosphorus from the flow because that element is necessary for growth of the organisms that remove organic chemicals from the liquid. Unfortunately, however, the common biological processes usually can remove only a small fraction (typically 10-30%) of the phosphorus in municipal wastewater because it contains far more of that nutrient than the organisms need for their growth during biodegradation of the organics. However, results of several investigations over the past 25 years have indicated that sometimes it is possible to increase the amount of phosphorus removed during biological treatment, even to the point of removing most of it.

During the past ten years, there has been growing interest in biological phosphorus removal and many studies have been conducted to evaluate the possibility for using BPR to meet regulatory requirements for wastewater discharges. The results often have been confusing -- even controversial -- because of difficulties in identifying key process variables and obtaining reproducible results among various experimental facilities, or even from time-to-time in any given one. It is desirable that outstanding questions about BPR should be resolved as soon as feasible because this approach often could offer several advantages over chemical precipitation processes, as will be discussed later.

OBJECTIVES OF THIS REPORT

The overall objective of this report is to review the present state-of-the-art of Biological Phosphorus Removal (BPR). This will be accomplished by summarizing some of the findings in reports and articles by a selected sample of recent investigators. More specifically, the report will address the following subjects:

1. A review of the mechanisms involved in biological removal of phosphorus from wastewaters,

2. A description of the principal BPR processes that have been used or proposed to remove phosphorus from wastewaters in practice,

3. A review of past experience with BPR in experimental systems and full-scale applications,

4. Identification of major areas in which key information about BPR now is missing, and

5. Development of an overall evaluation of the practical potential of BPR.

It is not the intent in this report to compile the details of past work and existing theories into a comprehensive treatment of present knowledge on the subject. Instead, it is intended to serve as a broad compendium of ideas on BPR process concepts, its present status, its prospects for future applications, and a summary of information that will be needed to improve its practical effectiveness.

MECHANISMS FOR BIOLOGICAL PHOSPHORUS REMOVAL

Before discussing the methods by which phosphorus may be removed from wastewaters, we must emphasize that the exact mechanisms remain elusive. What has been presented in the literature so far on this subject is a blend of theory (based largely on empirical observations of experimental and field units) with scientific rationale, conjecture and, frankly, sometimes pure guesswork. There has been little mechanistic study of the processes underway in BPR systems under conditions that typically prevail in wastewater treatment plants. Accordingly, it should not be surprising that there are wide differences in opinions about the mechanisms through which phosphorus removal may be enhanced in wastewater treatment.

In general, two broad groups of BPR mechanisms have been proposed by past investigators. One is based on the concept that enhanced phosphorus removal is accomplished directly through metabolic activities of the wastewater treatment organisms (Nicholls and Osborn, 1979; Harold, 1966). The other assumes that most or all of the removal occurs through chemical precipitation of the phosphorus, which may be accentuated by biochemical and other changes in the process environmental conditions during treatment (Menar and Jenkins, 1969). As might be predicted, there are also some who maintain that both mechanisms are active and important in practical BPR systems (Barnard, 1983).

Biological Mechanisms

Considering the concept of biological removal in more detail, there are three mechanisms that have been proposed to explain the performance observed in treatment plants. The first is the "normal" uptake of phosphorus by organisms as part of their metabolic processes in assimilating carbonaceous chemicals and building cell materials. This is related to their basic requirements for phosphorus, referred to earlier, and can be attributed simply to the fact that growth of cell materials and biochemical processes involved in building them require the availability of some minimum amount of phosphorus as part of the substrate system. That need is reflected, for example, by the presence of phosphorus in the chemical formulas used sometimes to describe bacteria, algae and other organisms, such as $C_{106}H_{180}O_{45}N_{15}P$. Clearly, those biochemical structures cannot be synthesized without having phosphorus available.

When wastewaters are treated biologically, there always is an accumulation of cell materials in the system through multiplication of the organisms. Subsequently, the excess cells are removed for separate treatment and disposal, as a key step in efficient wastewater treatment, and the phosphorus that has been incorporated into them also is removed. This provides a clear and non-controversial biological phosphorus removal mechanism but, unfortunately, the amount of cell material produced in treating a municipal wastewater, using typical biological processes, is enough only to account for a small removal of phosphorus -- perhaps 10-30% of that present in the flow.

A second biological mechanism that has been proposed is "luxury" uptake. Some have described this phenomenon as an excess of phosphorus uptake that occurs when organisms are subjected to stress in the form of a nutrient deficiency, <u>other than phosphorus</u>, and when sufficient energy is available to transfer phosphorus from the water into the cell (Harold, 1966; Nicholls and Osborn, 1979). The extra phosphorus taken up by the cells is converted to polyphosphates and stored as granules in the organisms.

Accordingly, by producing a nutrient deficiency stress in a treatment system, it is possible to increase the phosphorus content of the organisms. Subsequent separation of the cells from the wastewater results in enhanced removal of phosphorus by the biological system. Nicholls and Osborn (1979) suggested that this type of enhanced removal could be expected to occur under endogenous respiration at the ends of aeration tanks in some plants and would produce relatively slow accumulation of polyphosphates in the sludge.

A third biological mechanism is based on rapid uptake of phosphorus by bacteria that have been temporarily deprived of an adequate supply of that element and then are exposed to an abundance of it. It has been demonstrated that when some organisms grown in a phosphate deficient medium are subsequently introduced into a phosphate-rich medium, polyphosphates granules accumulate very rapidly in the cells to levels far higher than needed in their metabolism (Harold, 1966; Nicholls and Osborn, 1979). This has been referred to as "overplus accumulation" by German investigators of the phenomenon, but a better translation might be "overcompensation" by the nutrient-starved organisms. Subsequent removal of the phosphate-enriched organisms enhances the phosphorus removal attainable by the biological treatment system.

Several investigators have noted that exposure of activated sludge to anaerobic conditions can trigger this mechanism. The first effect is release of large amounts of phosphorus from the organisms into the liquid phase. Nicholls and Osborn (1979) speculate that the phosphorus release mechanism probably is triggered in the aerobic organisms by anaerobic conditions that curtail transfer of exogenous phosphorus into the cells, resulting in a metabolic deficiency of phosphorus in spite of its presence in the liquid phase. When the aerobic bacteria are deprived of their oxygen supply and the phosphorus in solution cannot be used by them, high energy polyphosphates stored by the cells may be used to satisfy metabolic needs as long as the supply lasts. In doing so, the cells release orthophosphate to the solution.

Subsequent aeration of the sludge to produce aerobic conditions results in rapid phosphorus uptake by the organisms, which reclaim the phosphorus that had been released by them and take up a substantial additional amount for storage as polyphosphate. This could be viewed as overcompensation by them for the phosphorus deficiency that had existed during the anaerobic phase and can produce a sludge with greatly increased phosphorus content. Of course, removal of that sludge from the system results in enhanced biological phosphorus removal from the wastewater.

Chemical Mechanisms

Other investigators have concluded that most of the phosphorus removal is accomplished through a mechanism of chemical precipitation of orthophosphate, largely by calcium. They view the biological removal as being limited to the "normal" uptake of phosphorus by the cells -- about two to three percent by weight of the sludge mass produced -- and the role of enhanced biological uptake is considered to be negligible or nonexistent.

The calcium phosphate precipitation is described as being controlled by pH, which in turn is controlled by carbon dioxide content of the activated sludge mixed liquor (Menar and Jenkins, 1969; Riding, et al., 1979). The dissolved oxygen concentration is viewed as having no direct influence on the removal of phosphate by activated sludge. The correlation that has been observed between dissolved oxygen and phosphorus uptake or release is attributed to fortuitous circumstances in which minimum DO in mixed liquor occurs simultaneously with maximum carbon dioxide content, both being caused by aeration that is inadequate for the loading applied. The high CO_2 content produces low pH conditions that are favorable to release of phosphate in soluble form. Conversely, with low loadings and high aeration rates the DO increases and CO_2 content decreases, producing higher pH and conditions more favorable for calcium phosphate precipitation.

Studies on which this chemical precipitation theory has been based have certain deficiencies, some of which have been pointed out by Regan and Nesbitt (1980) and Jenkins (1980), making it impossible to reach definitive conclusions about the extent to which chemical precipitation is responsible for enhanced phosphorus removal in practical systems.

Other investigators have concluded that both mechanisms are involved, especially in plants where high levels of phosphorus removal are obtained (Barnard, 1983; Mulbarger, et al., 1971). They attribute the enhanced efficiency of phosphorus removal to a combination of biological uptake and chemical precipitation, their relative importance depending on character of the wastewater and pH in the system.

Summary

In summary, a review of the extensive literature on biological phosphorus removal leads to the conclusion that the exact mechanisms are not known now. Whatever the mechanism, however, it is apparent that enhanced BPR does occur and can be triggered by exposing activated sludge to anaerobic conditions, followed by placing it in an aerobic environment. Under the anaerobic conditions, phosphorus is released from the sludge to the liquid phase. When subsequently aerated, the sludge takes up that phosphorus and more, producing enhanced removal from the wastewater. The precise manner in which this sequence of events occurs is not clear and neither are the parameters that regulate kinetics of the processes and the amounts of phosphorus released and taken up by the sludge.

The role of chemical precipitation in enhanced phosphorus removal under conditions existing in practical activated sludge systems is far from clear. However, it appears entirely reasonable that under some conditions the precipitation of phosphorus by calcium or other metals could represent an important removal mechanism, especially in systems operating at elevated pH.

Because enhanced phosphorus removal can occur in biological treatment systems under appropriate operating conditions, the phenomenon must be recognized and accepted as real, even though its mechanisms remain obscure. For want of better information, it is reasonable to refer to it as biological phosphorus removal because of the situation under which it occurs. That will be done in the rest of this report.

SOME PRACTICAL APPROACHES

Three recognized methods of biological phosphorus removal have received substantial attention in the U.S.A.: the Bardenpho Process, the A/O Process, and the Phostrip Process. As will become apparent shortly, many modifications of those processes have been proposed or used to meet different practical situations.

The Bardenpho Process

The original Bardenpho Process was developed by Dr. James Barnard, in South Africa, for biological removal of nitrogen without the need to resort to the "three sludge" nitrification-denitrification system often proposed for that purpose. As shown in Figure 1, it is a single sludge process, permitting operation with only one final clarifier and return sludge system (Barnard, 1978). The process is proprietary and marketed in the U.S.A. by the Eimco Division of Envirotech Corporation.

The first process step is exposure of recycled nitrified mixed liquor from the first aerobic unit to "anoxic" (no dissolved oxygen) conditions in the first mixed anoxic tank. Biological action in the mixture of return sludge, influent and recycle produces denitrification and accomplishes two benefits: (1) satisfying some of the oxygen demand in influent wastewater by using nitrates in the recycle flow to satisfy biochemical requirements and (2) removing nitrogen from the wastewater through decomposing nitrates and releasing nitrogen gas. The relatively short detention time in the anoxic tank (perhaps 1 to 2 hours) is not long enough to damage activity of the nitrifiers in the return sludge and recycle significantly. Accordingly, nitrification of ammonia in the wastewater occurs subsequently in the first aerobic basin (6 to 20 hours detention).

The second mixed anoxic basin (2 to 5 hours) serves to remove most of the rest of the nitrates, using the remaining BOD and endogenous respiration as sources of oxygen demand. The goal of the second aeration basin (perhaps 0.5 to 1.5

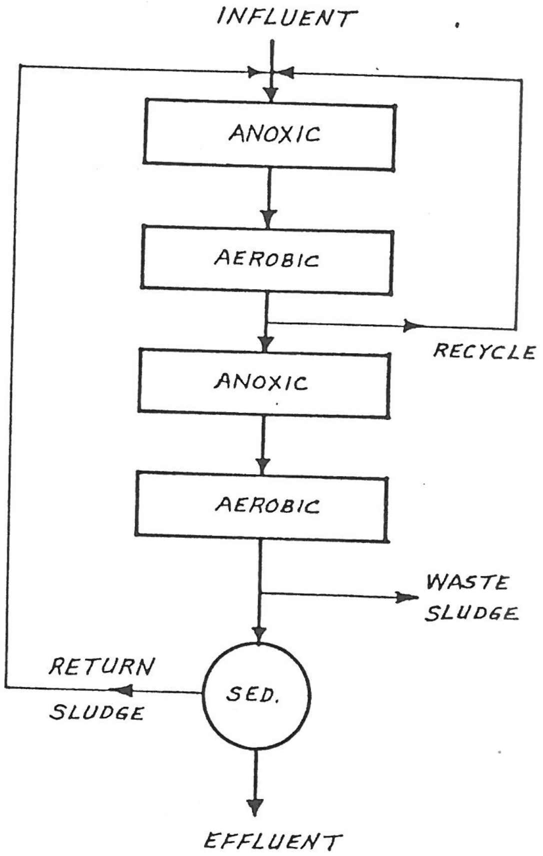

FIGURE 1

THE ORIGINAL BARDENPHO PROCESS, FOR REMOVAL OF NITROGEN

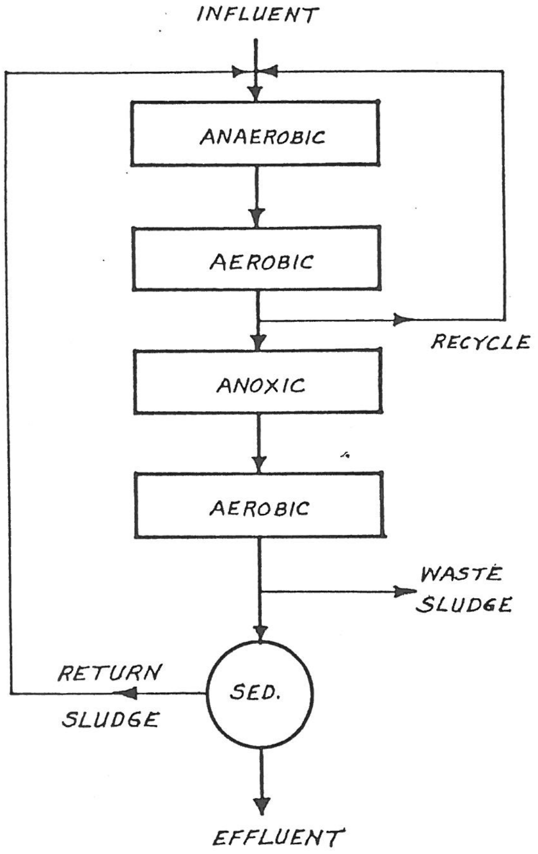

FIGURE 2

THE BARDENPHO PROCESS FOR REMOVAL OF BOTH NITROGEN AND PHOSPHORUS hours detention) is to dissolve oxygen in the wastewater before it passes through the final settling tank and is discharged to the watercourse. The end results of the total process are removal of nitrogen and BOD from the wastewater.

Field observations of early Bardenpho installations revealed that extensive removals of phosphorus also could be attained by the system (Barnard, 1978, 1983). The phosphorus removal can be further enhanced by exposing the organisms to a fully anaerobic environment (neither dissolved oxygen nor nitrates available to them) instead of merely anoxic conditions. That can be accomplished using the same sequence of treatment units as in the original Bardenpho process (Figure 2), provided enough oxygen demanding material is in the influent flow and enough time provided in the first mixed basin to exhaust the supplies of both dissolved oxygen and nitrates in the return sludge and recycle. This can produce the anaerobic conditions needed to release substantial amounts of phosphorus from the sludge into the liquid.

During the subsequent aerobic phase, nitrification occurs and the released phosphorus, as well as other phosphorus in the wastewater, is taken up and stored by the cells, as outlined earlier when discussing mechanisms. Some of the phosphorus may be released again during the anoxic denitrification stage, but it is taken up once more during the final aerobic phase. The net effect of this process is that both nitrogen and phosphorus, as well as BOD, are removed from the wastewater.

As pointed out earlier, anaerobiosis is viewed as essential to efficient biological phosphorus removal. A limitation of the flowsheet in Figure 2 is that often the dissolved oxygen and nitrate concentrations in the return sludge and recycle may be too high to permit attainment of fully anaerobic conditions in the first basin. Accordingly, poor phosphorus removal may result unless the process is modified to correct that situation.

Figure 3 shows the "Modified Bardenpho Process", known in South Africa as the "Phoredox Modification" of the Bardenpho Process or the "5-stage Phoredox process" (Walsh, et al., 1983; Barnard, 1983; Ekama, et al., 1984). In this arrangement, the anaerobic conditions are generated by adding a mixed basin ahead of the four Bardenpho units. Its purpose is to maintain contact between the return sludge and influent wastewater for a period long enough to produce the necessary anaerobic conditions. The mixed liquor recycle is not added until after that step, reducing the nitrate and oxygen supplied to the anaerobic unit. The anoxic step is for denitrification of the mixed liquor and the remainder of the process remains identical with that shown in Figures 1 and 2. The

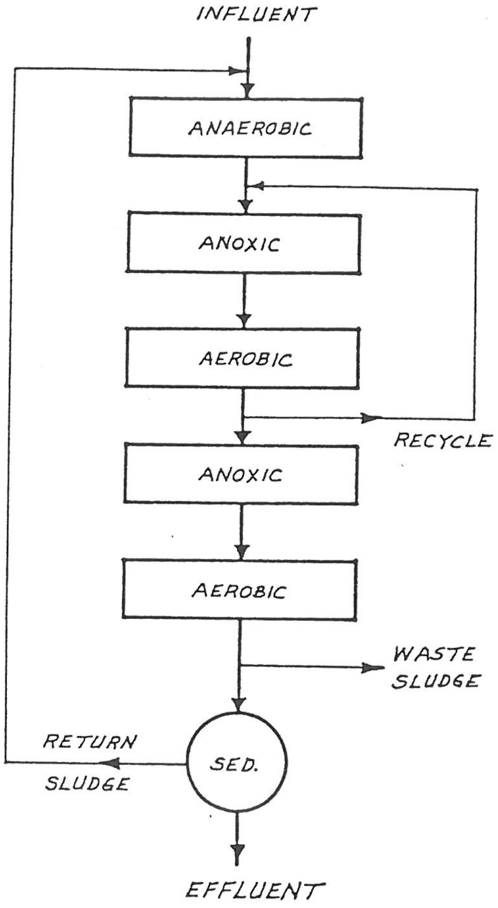

FIGURE 3

THE MODIFIED BARDENPHO PROCESS (OR PHOREDOX MODIFICATION), FOR REMOVAL OF NITROGEN AND PHOSPHORUS

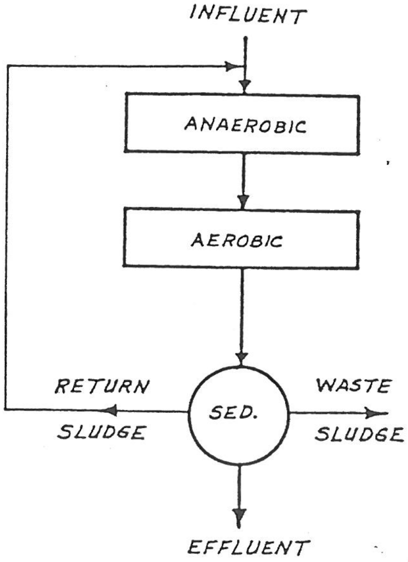

FIGURE 4

THE PHOREDOX PROCESS, FOR REMOVAL OF PHOSPHORUS WITHOUT NITRIFICATION

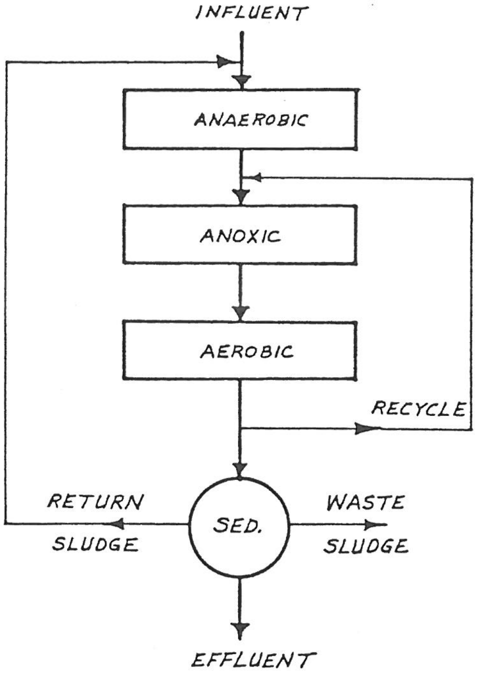

FIGURE 5

THE PHOREDOX PROCESS, FOR REMOVAL OF PHOSPHORUS WITH NITRIFICATION end result of this overall process is removal of BOD and both nitrogen and phosphorus from the wastewater.

The simplest version of BPR is shown in Figure 4 and could be applicable where phosphorus removal is required but nitrogen removal is not. Mixture of the return sludge with influent flow for an adequate period produces the anaerobic conditions required for phosphorus release. The aerobic unit makes possible the subsequent uptake of phosphorus by the cells, as well as removal of BOD from the wastewater by the activated sludge system. This process is referred to as the "Phoredox" process. Its end result is phosphorus removal without nitrogen removal.

In plants where nitrification occurs, even though nitrogen removal may not be required, the oxygen and nitrate content of return sludge may be high enough to interfere with attaining anaerobic conditions adequate for efficient phosphorus removal. In that event, the modification shown in Figure 5 may be necessary to solve the problem. Internal recycle of nitrified mixed liquor from the aerobic stage to a mixed anoxic unit results in denitrification and reduces nitrate content of the plant effluent and return sludge. With enough recycle denitrified in this manner, it is possible to attain the required degree of anaerobiosis in the first basin using only the oxygen demanding materials contained in the influent wastewater as a carbon source.

The principal accomplishments of this process are BOD and phosphorus removal. There is only partial removal of nitrogen, the degree depending on the proportion of flow recycled through the anoxic basin. This type of approach appears to be worthy of consideration for many U.S.A. plants which produce considerable nitrification but are not currently required to remove nitrogen from the wastewater before discharge.

The A/O Process

The A/O Process also is a proprietary system and was developed by Air Products and Chemicals, Inc. (Hong, et al., 1979; Walsh, et al., 1983). It is very similar in many respects to the Bardenpho process and, in fact, the flow sheets for the two principal versions of A/O are identical with Figures 4 and 5.

The exact differences between claims for the A/O and Phoredox processes are not clear presently, although both have been reported to be patented (Hong, et al., 1979; Walsh, et al., 1983). It is possible that the differences might be found in process operating parameters, such as detention times, mixed liquor suspended solids concentrations, sludge ages, unit loadings, use of oxygen instead of air, etc.

Within the context of the basic nature of the processes as described here and the present state of knowledge about them, the two systems could be considered equivalent to each other for the purposes of this discussion.

The Phostrip Process

The Phostrip Process was developed and patented by Dr. Gilbert Levin and is marketed by Biospherics, Inc., and differs basically from the Bardenpho and A/O processes. In Bardenpho and A/O, phosphorus is accumulated in the biological sludge and removed from the process as part of the waste activated sludge. Phostrip, on the other hand, relies on stripping the phosphorus from the sludge, adding chemicals to the supernatant to form a phosphorus precipitate, and removing the precipitate for disposal.

Figure 6 shows one approach by which that may be accomplished. Part of the sludge removed from the final settling tank of the activated sludge plant is passed through a "stripping tank" in which it is exposed to anaerobic conditions for several hours, resulting in release of phosphorus into the liquid, as described earlier. The phosphorus-stripped sludge then is returned to the activated sludge process in which it accumulates more phosphorus to continue the cycle. The phosphorus-enriched supernatant from the stripper is treated with lime to precipitate calcium phosphate and that flow is discharged to the primary clarifier where the precipitate settles and is removed with the primary sludge.

A potentially more efficient system is shown in Figure 7. A feature added to the sludge handling system is a reactor/clarifier to produce more efficient precipitation of the calcium phosphate sludge and its removal by settling before discharge of supernatant to the primary clarifier. Another feature is addition of a return flow of low-phosphate water from the reactor/clarifier to the phosphorus stripper to wash out (elutriate) additional soluble phosphorus from the sludge before its return to the activated sludge process. Other modifications that have been proposed include addition of wastewater to the stripper tank to accelerate phosphorus release and addition of alum to the stripper tank to precipitate the released phosphorus directly.

This process removes phosphorus from the wastewater, but not nitrogen. It has the disadvantages of requiring chemical additions, increasing operating costs and sludge production, and being relatively complex to operate. A potential advan-

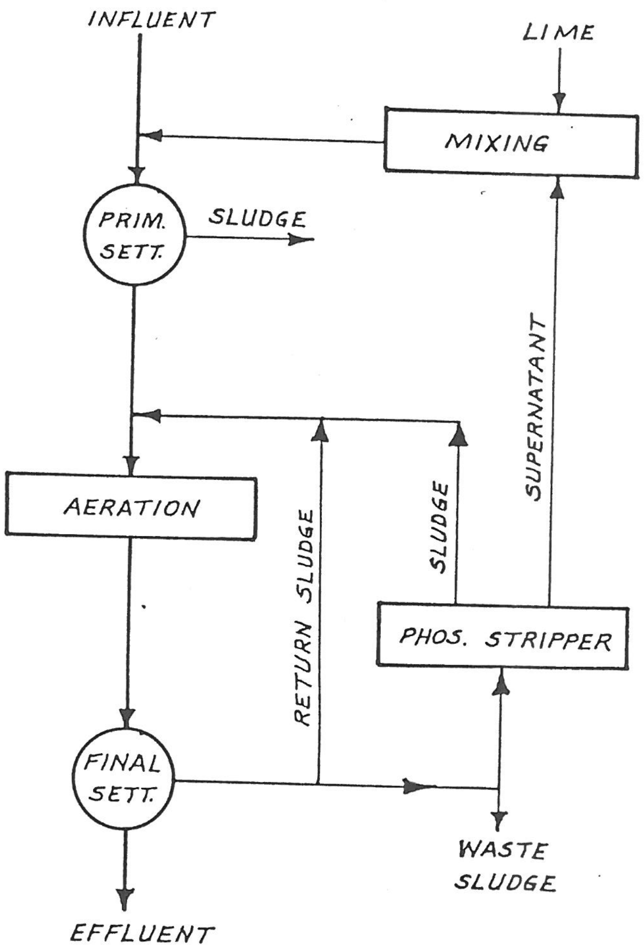

FIGURE 6

THE PHOSTRIP PROCESS

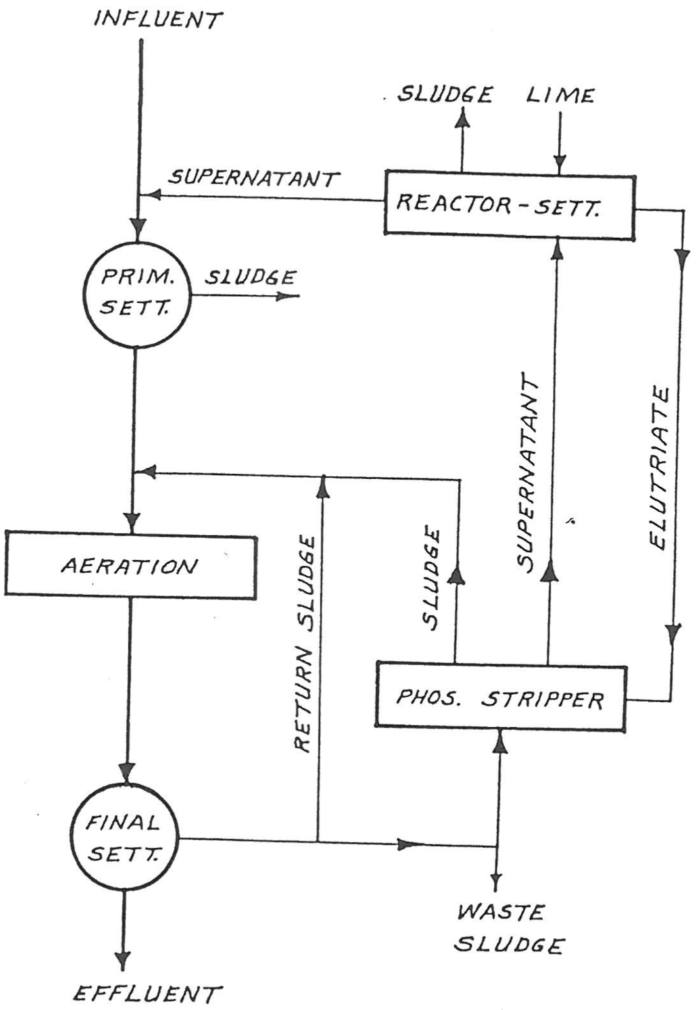

FIGURE 7

THE PHOSTRIP PROCESS, WITH REACTOR-SETTLER FOR REMOVING PRECIPITATED PHOSPHORUS tage is that currently the mechanics of the process are better understood than are those of its competitors. Also, limited experience in the U.S.A. suggests that this process may be capable of attaining lower effluent phosphorus concentrations in plant effluents than are the two processes discussed earlier. However, that does not necessarily include the experience of investigators in South Africa or Canada, where more efficient phosphorus removals have been reported for the Bardenpho process in operating plants than those noted in the few U.S.A. Bardenpho and A/O installations.

PAST EXPERIENCES WITH BIOLOGICAL PHOSPHORUS REMOVAL

South African Experience

South Africa requires nitrification and removal of phosphorus from sewages in many locations. Because of the relatively higher costs there of the chemicals required to precipitate phosphorus, a concerted effort has been made to develop more economical alternatives. This has resulted in special interest in biological phosphorus removal.

A recent South African publication (Anonymous, 1984c) lists 26 plants in that country that use BPR, mostly based on the Bardenpho or Phoredox processes or similar approaches. Because of the desire to avoid chemical processes, no Phostrip installations have been noted.

Paepke (1983) surveyed the performance of eleven BPR plants and concluded that only one of them consistently met its 1.0 mg/l effluent standard for phosphorus and that performances of two or three other plants had improved encouragingly with passage of time. He pointed out that most of the plants surveyed had been started in 1978-79 and that his evaluation was based on their performance in 1980-81. He concluded that most of them were still in the learning phase and suggested that further improvements could be expected in time. The problems encountered most often involved the presence of excess oxygen and nitrates in the anaerobic phase, interfering with the release of phosphorus. This situation usually could be attributed to inadequate denitrification, low COD/N ratios in the wastewater, and pickup of oxygen in the flow as it passed through screw pumps or over cascades in the plants.

Johannesburg has two large (40 mgd) plants that use the Bardenpho process. There are many periods in which effluent phosphorus from one plant is less than 1.0 mg/l, but problems have been encountered with erratic performance (Pitman, et al., 1983). The other plant has produced only minimal removals of phosphorus. Both have suffered problems with inadequate anaerobiosis, which was attributed to low strength wastewater and persistence of oxygen and nitrates throughout the system. Diversion of a high-BOD industrial waste into one system and addition of raw sludge to the biological process in the other improved phosphorus removals by increasing the BOD/N ratio (Pitman, 1983, 1984). The plants also have had difficulties with settling of the activated sludges and with scum formation, apparently because of Nocardia or Microthrix parvicella growths.

Performances of the Johannesburg plants have been improving with time and increased experience of operating personnel. Table 1 shows the improvements in annual average phosphorus removals during the first three years of operation at the more efficient Johannesburg facility (Pitman, 1983).

TABLE 1

PHOSPHORUS IN JOHANNESBURG EFFLUENT

Year	Orthophosphate(P)	Total Phosphorus(P)
1978-79	1.9 mg/l	2.1 mg/l
1979-80	1.1	1.5
1980-81	0.7	1.4

Review of several articles on pilot and full-scale South African plants reveals that effluent phosphorus concentrations of 0.5 to 1.0 mg/l have been produced frequently (Weichers, 1983; Water Research Commission, 1984). However, the plants often have problems, especially in maintaining suitable anaerobic conditions, and effluent phosphorus concentrations then may rise to 2 to 3 mg/l or higher. Currently, it appears that effluent phosphorus concentrations of about 1 to 3 mg/l could be produced with reasonable consistency.

BPR processes are being investigated actively in South Africa, often at full-scale, and most investigators project that the present levels of performance can be improved substantially. If they are correct, it would be reasonable to expect that an effluent standard of 1.0 mg/l could be met reliably in the future. It should be noted, however, that some are beginning to question whether that effluent quality is likely to be attained reliably in plants that are not relatively large and well-operated (Paepke, 1983).

North American Experience

The United States has much less experience with BPR than South Africa, except in use of the Phostrip process. A recent article by Walsh, et al. (1983) summarizes the results of a survey of BPR plants in North America, which included visits to the plants and discussions with operating personnel. As part of the studies leading to this report, the plants were contacted again by phone to update the information reported by Walsh, et al. to mid-1984. All of the findings are summarized in the following paragraphs.

Walsh reported that there were 10 Phostrip plants in the United States, five of which were visited during the survey. The other five either were in early stages of startup or had already been discontinued as Phostrip operations. All of the plants reported operating problems with the relatively complex system, many of which were because of mechanical difficulties and inadequate flexibility provided in the plant designs.

After solving several startup problems, the Lansdale, Pa., plant produced good phosphorus and nitrogen removals during some subsequent four to six month periods. It was not working when visited because mechanical troubles with a clarifier had upset the Phostrip process. However, after repairs the facility consistently produced effluent phosphorus concentrations of 0.5 to 1.0 mg/l. In July, 1983, the Phostrip process was discontinued and experiments initiated to evaluate removals by alum precipitation. In early 1984, Phostrip was resumed and has usually produced 0.5 to 1.0 mg/l effluent phosphorus since then.

The 5 mgd Phostrip process at Adrian, Michigan, was started in 1980 and operated relatively successfully during the summer of 1981. The plant was plagued with many operational problems, but after modifications it has attained consistent effluent phosphorus of less than 1.0 mg/l (often 0.1 to 0.2 mg/l) without chemical additions to the wastewater flow. The plant superintendent is pleased with the process and reports that it is not complex to operate.

The 20 mgd Little Patuxent Plant, in Maryland, was placed in operation in 1981, but major problems have been experienced in obtaining consistent performance. The plant was viewed by the operators as touchy and requiring high operating skills. During the first year, it produced effluent phosphorus concentrations of about 2.0 mg/l and subsequently has improved to 0.5 to 2.0 mg/l. It has consistently failed to attain its effluent phosphorus standard of 0.3 mg/l without adding alum or sodium aluminate and filtering the effluent. Major operating problems with this system have included inadequate instrumentation, lack of reliable operating techniques, inability to maintain anaerobic conditions in the stripper, and need for very careful monitoring of the process.

The 30 mgd Reno-Sparks plant, in Nevada, installed Phostrip as the result of studies conducted in the mid-1970s. It started up in 1981 and during its first year of operation the effluent phosphorus ranged from 0.5 to 1.0 mg/l when the plant was running well, and from 1.0 to 6 mg/l at other times. Subsequent performance has produced fairly consistent effluent phosphorus concentrations of about 1.0 mg/l, which is not adequate to meet the effluent standard of 0.5 mg/l. This has made it necessary to add alum to the wastewater for supplemental removal. Its major problem has been severe foaming and presence of Nocardia filamentous organisms. Reduction of aeration to control those growths has adversely affected phosphorus removals. Other problems have included difficulties with computer control systems, odor production, and control and maintenance of the lime system and stripping operation. It is planned that effluent filtration will be added in the future to improve phosphorus removal.

The 24 mgd Amherst, New York, plant was started up in 1981. During the first several months, it produced effluent phosphorus concentrations ranging from 1.2 to 1.7 mg/l, which was inadequate to meet the standard of 1.0 mg/l. Subsequently, during late 1982 and early 1983, the performance improved to produce 0.7 to 0.8 mg/l effluent phosphorus. Operating difficulties have been encountered with the lime handling system, poor pH control, odor production, a variety of mechanical problems, and high manpower needs for process control and monitoring. In March, 1983, this Phostrip operation was shut down because removal by addition of ferric chloride or ferrous sulfate was found to be more cost effective for the low-phosphorus influent wastewater (3 to 4 mg/l).

Two A/O processes were reviewed by Walsh, et al.(1983). A 3.0 mgd, 3 stage module of a plant in Largo, Florida, was operated on an experimental basis and the facility now has been enlarged to include all three of the modules in the plant. It is the only full-scale facility where this process has been demonstrated, although another plant has been started up in Pontiac, Michigan. Typical effluent phosphorus at Largo is 1.5 to 2.5 mg/l, but there has been no pressure to optimize performance because the proposed effluent standards have not yet gone into effect. The plant is reported to be easy to run.

The Patapsco pilot plant, at Baltimore, was operated for seven months and consisted of a two-stage A/O system (three anaerobic tanks and four pure oxygen tanks). It treated 4.8 gpm of primary effluent and efforts were made to simulate diurnal flow variations. During two months of successful operation, the phosphorus concentration in the plant effluent ranged from 1.4 to 2.2 mg/l (Walsh et al., 1983; Deakyne, et al., 1983).

Walsh, et al. (1983) reported that about 40 Bardenpho installations exist in the world, two of which are in North America. One plant is in Palmetto, Florida, and consists of a five-stage Phoredox process. Filtered plant effluent contained an average of 2.9 mg/l total phosphorus. They report that low influent BOD has made it necessary to feed alum to the plant effluent to reduce its phosphorus concentration to 0.2 to 0.8 mg/l. Various procedures have been adopted to try to improve phosphorus removal efficiency, including: (1) addition of primary sludge to the anaerobic stage, (2) bypassing peak flows around that stage to avoid reductions in anaerobic detention times, and (3) increasing the anaerobic time by returning the activated sludge to the primary clarifiers. However, these practices did not reduce effluent phosphorus concentrations below 1.5 to 2.0 mg/l without adding alum. Operation of the process is not viewed as more complex than a conventional activated sludge plant.

The 6 mgd Kelowna, British Columbia, plant uses the five-stage Bardenpho (Phoredox) process and contains two parallel modules, each having 21 equally-sized cells. The plant was started up in 1982 and the effluent total phosphorus (after filtration in the plant) has averaged about 0.2 mg/l, ranging from 0.15 to 0.31 mg/l during mild weather. During the winter, the effluent phosphorus averaged 0.6 mg/l and ranged from 0.1 to 1.0 mg/l. Overflow from the sludge thickener is used to provide short-chain organics to the process and seems to play a major role in the phosphorus release and uptake mechanism. The plant is operating well, although it has not yet been fine tuned to produce optimum performance. It is operated by a 7-man staff that works only one shift per day and, according to the superintendent, virtually runs itself.

Walsh, et al. concluded that Kelowna was the only BPR plant surveyed that was meeting its design goals without adding chemicals to the wastewater, but Adrian and, maybe, Lansdale now may be added to the list. Based on results of the survey, they concluded that the various processes appear to be capable of attaining the performances summarized in Table 2.

TABLE 2

ESTIMATED EFFLUENT PHOSPHORUS FROM BPR PROCESSES (mg/l)*

Process	Without Filtration	With Filtration
A/O, No nitrification	< 2.0	< 1.0
With nitrification	< 2.0	< 1.5
With nitrification and denitrification	< 3.0	< 1.5
Bardenpho	< 1.0	< 1.0
Phostrip	< 1.5	< 1.0

*Note: Based on conclusion of Walsh, et al. (1983).

They viewed BPR as being in the developmental stage and concluded that all of the plants surveyed lacked tankage and flexibility. All of the responsible operators were reported to believe that the plants could have performed better if they had been designed with more flexibility.

AREAS REQUIRING ADDITIONAL INVESTIGATION

This extensive review of recent literature reveals that the exact mechanisms of biological or chemical phosphorus removal in biological treatment systems remains unclear. In fact, we still do not even know whether biological or chemical processes play the predominant roles. Some specific areas in which knowledge is missing include: (1) identification of the types of organisms that are involved in the processes; (2) biochemical mechanisms for phosphorus removal; (3) types of chemical precipitates formed, if any; (4) optimum conditions for the biological and chemical processes; (5) key parameters in the biological and chemical processes; and (6) reaction kinetics for the processes.

It should be noted, though, that while all of the above information would be helpful and should be sought, the history of wastewater treatment repeatedly has shown that successful application of biological processes can occur long before the mechanisms are fully understood. Accordingly, a substantial amount of applied research and development effort should be directed to empirical investigations of several questions that seem to be especially pertinent to the success or failure of BPR processes. These include areas that have been reported to be problems in observations of past investigators:

1. Methods are needed for defining adequate anaerobic conditions for release of phosphorus.
2. The rates and amounts of phosphorus release during the anaerobic phase in successful plant operation should be known.
3. Optimum flow sheets, detention times, and loadings to insure generation of the anaerobic conditions must be developed.
4. The roles of nitrites and nitrates in the process should be investigated.
5. The conditions needed for rapid and effective uptake of phosphorus during the aerobic phase should be determined.
6. The kinetics and quantities of phosphorus uptake in the aerobic phase should be determined.
7. Flowsheets should be developed for process optimization under various circumstances, including special flowsheets designed to cope with inadequate BOD/N ratios.
8. The feasibility and desirability of chemical additions to cope with process problems, either on a regular basis or intermittently, should be evaluated.
9. Possibilities for process instrumentation and control should be investigated.
10. Means for coping with sludge settling and scum problems should be investigated.

ASSESSMENT OF THE POTENTIAL OF BPR

Past experiences with BPR processes reveal clearly that few existing plants are living up to expectations with respect to phosphorus removal. That rather negative finding is offset in large degree, however, by the worldwide experiences reported by many authors which indicate that BPR processes often are capable of producing effluents with phosphorus concentrations below 1.0 mg/l, and sometimes even below 0.5 mg/l for extended periods. One cannot be sanguine about the number of BPR "failures" that have been reported. However, neither can one ignore the excellent performance for extended periods reported at many plants, such as those at Kelowna and one of the Johannesburg facilities.

Two conclusions appear reasonable in this situation: (1) BPR often is inherently capable of producing excellent removals of phosphorus from municipal wastewaters, and (2) the current state-of-the-art in the design and operation of BPR processes apparently is not yet adequate to insure consistent performance at effluent phosphorus concentrations of 1.0 mg/l or less.

This allows us to progress in our evaluation of BPR beyond the question of whether the approach can produce acceptable phosphorus removals -- it can -- and face the real problem before us; how the processes should be designed and operated to produce consistent performance at levels needed in municipal practice today. As a former skeptic about BPR, I find this evolution in viewpoint to be fundamental, challenging and exciting!

Assuming that the questions remaining about BPR design and operation can be resolved satisfactorily, the approach has many potential advantages. First, BPR processes should reduce drastically, or even eliminate, use of chemicals for phosphorus removal and produce substantial reductions in cost for them. A corollary is that successful application of BPR could result in substantial reductions in quantities of sludge requiring treatment, dewatering and disposal because the chemical precipitates formed during alum or lime treatment would be minimized or eliminated. Further, the reduced chemical content of the sludge would improve its quality for some purposes, such as land disposal, while the additional phosphorus removal from the wastewater would increase usable nutrient content and fertilizer value of the sludge.

There also could be major savings in energy through adoption of BPR technology. These include both indirect energy savings through use of less chemicals for treatment and direct energy savings by recovering some of the oxygen added to the wastewater for nitrification during subsequent denitrification in the anaerobic and anoxic stages of the Bardenpho and A/O processes. The latter could amount to substantial cost reductions in plants required to nitrify before discharge into watercourses. The Bardenpho and A/O processes also provide systems for simultaneous nitrogen removal, if desired or required.

A further advantage that should not be overlooked is that the Bardenpho and A/O processes are fundamentally similar to the biological treatment technology that is familiar in concept to current plant superintendents and operators. In contrast, use of chemical treatment as an add-on to current biological facilities involves addition of another area of technology and process control and could complicate plant operation considerably.

In summary, BPR seems to offer reasonable possibility for solving some of our more difficult and expensive current problems in municipal wastewater treatment. Its potential must be regarded as promising and worthy of careful further study. Those studies should be directed toward filling the many gaps in our understanding of the processes and their operational parameters.

A CAVEAT TO THOSE WHO WOULD USE BPR

This survey of the state-of-the-art of biological phosphorus removal has been made without preconception and with a healthy dose of scientific and engineering skepticism. Some of the findings have been viewed as encouraging because they have shown that under proper conditions BPR can provide efficient removal of phosphorus from municipal wastewaters, with effluents of 1.0 mg/l or less for extended periods. That is the "good news" in this report. On the other hand, the "bad news" is that most of the plants using BPR, both here and abroad, have failed so far to attain their effluent phosphorus concentration goals consistently.

Consultants and municipal officials faced with responsibility for determining whether they should install or recommend BPR processes in facilities for which they have responsibility must consider carefully all of the evidence before them. They must not try to read into this report anything that suggests unqualified approval or disapproval of BPR -- neither is intended.

The record of past experience speaks for itself and indicates that there is substantial potential for rewards to those who plan, design and operate BPR systems successfully. But the pioneers will face an undeniable element of risk and should recognize and embrace the extra care and effort that will be necessary to make their systems work. Also, they would be wise to inform and obtain the cooperation of the responsible regulatory agencies in advance to avoid misunderstandings, frustrations, and bad feelings.

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