# BIOLOGICAL PHOSPHOROUS REMOVAL

## AN OPERATOR'S GUIDE

**ABSTRACT**

If you have ever faced a rising effluent phosphorous concentration and you are relying on biological phosphorous removal, the information offered in this guide will help you identify the steps you should take to regain effective treatment performance.

Enhanced biological phosphorous removal (EBPR) relies on a healthy population of phosphorous accumulating organisms. Creating and maintaining the right environment for these organisms is the key to effective biological phosphorous removal.

Keeping an eye on the signs that lead to an unhealthy environment is the best tool available to the operator. While the process may appear as a "brown box", the steps to control the process are relatively straight forward.

Management of the environment involves creating anaerobic, anoxic, and aerobic conditions in the proper sequence for the raw sewage, return sludge, and mixed liquor recycle flows. Managing the food source involves ensuring proper nutrient ratios and sufficient volatile fatty acids to promote enhanced phosphorous uptake by the organisms.

Increasing phosphorous concentration is a sure sign that the environment or food source conditions are discouraging a predominance of phosphorous accumulating organisms. Check the organic and nutrient loading conditions preceding the event. Check the oxygen and nitrate concentrations in the anaerobic and anoxic zones of the biological selector. Check to see if recycle flows are returning any significant biomass to the process.

Take time to consider all of the facts before determining a course of action. Corrective action steps should be taken one at a time to narrow the primary cause for the reduced performance. Start with managing the environment. The introduction of volatile fatty acids prior to the anaerobic zone is sometimes needed with weaker raw sewage characteristics with marginal nutrient ratios.

Remember that the effect of any change will take time because of the long solids residence time in most activated sludge systems. A decreasing phosphorous concentration should be observed within one to two weeks.

## BIOLOGICAL PHOSPHOROUS REMOVAL THEORY

Conventional activated sludge treatment biologically removes phosphorous at the rate of 1 percent of the biochemical oxygen demand removed. In the early 1970's, researchers found that greater phosphorous removal rates were possible through biological selection. Today enhanced biological phosphorus removal (EBPR) can increase the biological phosphorus removal rate to 5 percent or more with proper process design and operation.

EBPR is a two-step process. In the first step, phosphorous is converted to a soluble form. In the second step, the phosphorous is assimilated by Phosphorous Accumulating Organisms (PAOs).

Acinetobacter and Proteobacteria are the predominant PAOs thought to enable enhanced phosphorous uptake in municipal facilities. It is important to note that there remain a number of unanswered questions regarding the microbiology of the EBPR process.

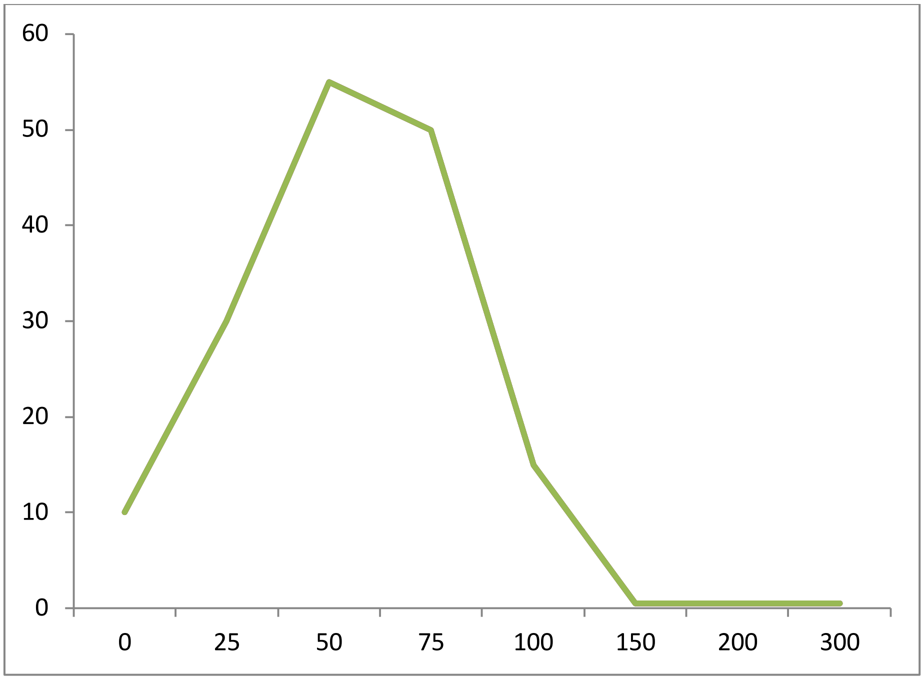
The first step involves several complex biochemical processes occurring under anaerobic conditions. Organic matter present in the waste is converted to volatile fatty acids (VFAs). VFAs, in the form of acetate, are converted to polyhydroxybutyrate (PHB) while Glycogen intercellular matter is converted to polyhydroxyvalerate (PHV). These intercellular products are essential to support the luxury phosphorous uptake that takes place during the second step of the process. In this assimilation process, polyphosphates are also converted to adenosine triphosphate (ATP) making all forms of phosphorous in the waste stream soluble. A visual summary of this process step is shown in Figure 1.

Figure 1 – EBPR Anaerobic Process

| | | | | |
|---|---|---|---|---|
| Glycogen | | | | |
| ↓ | | | | |
| Pyruvate | → | Acetate | | |
| | | ↓ | | |
| ↓ | | Acetyl-CoA | → | |
| | | ↓ | | |
| Oxaloacetate | → | Citrate | | |
| ↓ | | ↓ | | |
| Malate | | Oxoglutarate | | |
| ↓ | | | | |
| Fumarate | | ↓ | | ↓ |
| ↓ | | | | |
| Succinate | → | Succinyl-CoA | | |
| ↓ | | ↓ | | |
| ATP | | Methylmalonyl-CoA | | |
| | | ↓ | | |
| | | Propionyl-CoA | | |
| | | ↓ | | |
| | | PHV | | PHB |

Figure 2 illustrates the increase in phosphorous that occurs during the first step of the EBPR process and the subsequent uptake of soluble phosphorous during the second step of the process.

Figure 2 – Soluble Phosphorous




The second step is less complex and involves assimilation of the soluble phosphorous formed during the first step by PAO's under aerobic conditions utilizing the PHB and PHV intercellular products as the energy source.

The success of EBPR depends on the competition between phosphorous accumulating organisms (PAOs) and glycogen accumulating organisms (GAOs). Potential causes of GAO dominance include long solids retention time (SRT), a high ratio of anaerobic–aerobic hydraulic residence time, high glucose content in the waste, low phosphorus-to-carbon ratio in the feed and excessive aeration. The pH in the anaerobic zone can also affect the competition between PAOs and GAOs.

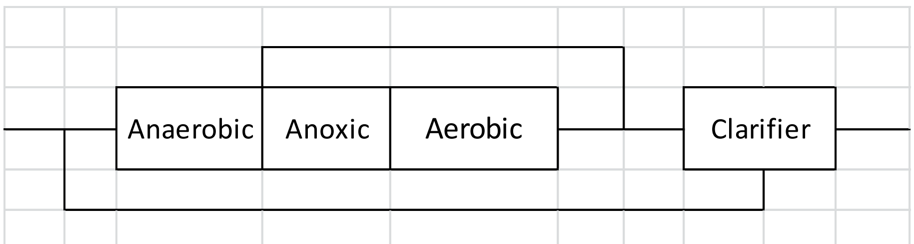
It is important to note that phosphorous contained within the cellular structure of the waste sludge will be released under anaerobic conditions.

**PROCESS OPTIONS**

The conventional activated sludge process has been arranged in four different configurations to offer the capability for EBPR. EBPR application to the conventional activated sludge process is capable of producing effluent with a phosphorous concentration of 0.5 to 1.0 mg/l provided that the solids concentration in the clarifier effluent is less than 10 mg/l.

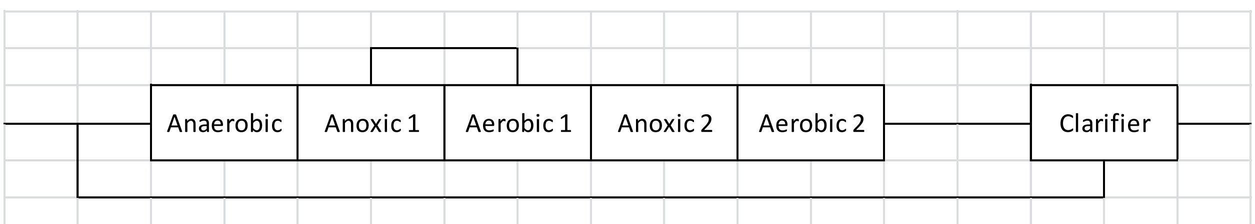
The A/O process includes anaerobic, anoxic, and aerobic reactors in series with aerobic mixed liquor recycle to the anoxic reactor and return sludge recycle to the anaerobic reactor. This process option is the most widely used today. Figure 3 illustrates the A/O process.

Figure 3 – A/O Process



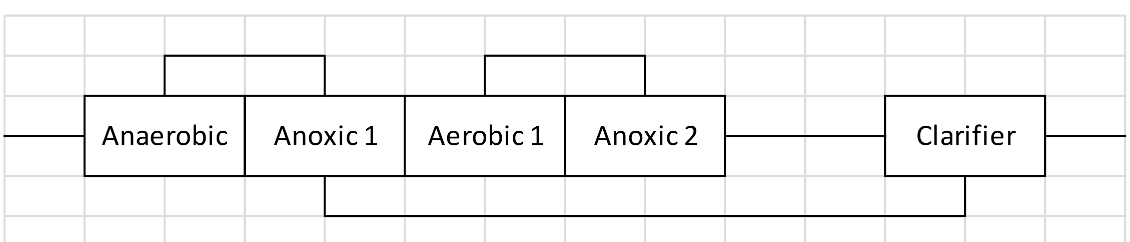

The Bardenpho process includes anaerobic, anoxic, aerobic, anoxic, and aerobic reactors in series with first stage aerobic mixed liquor recycle to the first stage anoxic reactor and return sludge recycle to the anaerobic reactor. Figure 4 illustrates the Bardenpho process.

Figure 4 – Bardenpho Process




The University of Cape Town (UCT) process includes anaerobic, anoxic, aerobic, and anoxic reactors in series with aerobic mixed liquor recycle to the second stage anoxic reactor, first stage anoxic mixed liquor recycle to the anaerobic reactor, and return sludge recycle to the first stage anoxic reactor. Figure 5 illustrates the UCT process.

Figure 5 – UCT Process



The Virginia Initiative Plant (VIP) process includes anaerobic, anoxic and aerobic reactors in series with aerobic mixed liquor recycle to the anoxic reactor, anoxic reactor mixed liquor recycle to the anaerobic reactor, and return sludge recycle to the anoxic reactor. Figure 6 illustrates the VIP process.

Figure 6 – VIP Process

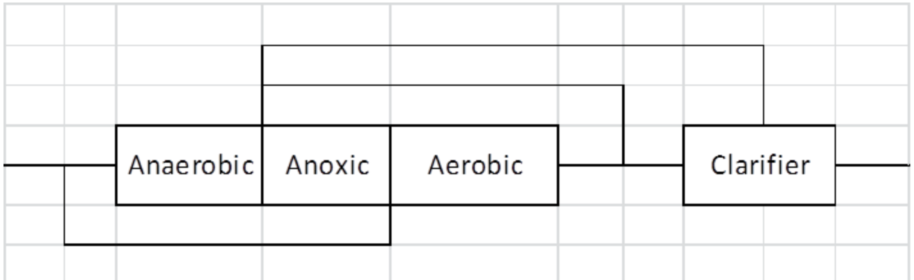



Table 1 provides a summary of typical process design criteria for each conventional EBPR process described.

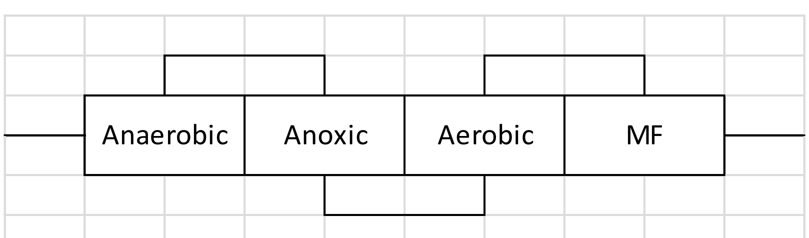
Table 1 – Conventional EBPR Typical Design Criteria

| | A/O | Bardenpho | UCT | VIP |
|---|---|---|---|---|
| FM ratio | 0.15-0.25 | 0.1-0.2 | 0.1-0.2 | 0.1-0.2 |
| Solids Retention | 4-27 | 10-40 | 10-30 | 5-10 |
| Detention Time | | | | |
| Anaerobic | 0.5-1.5 | 1-2 | 1-2 | 1-2 |
| Anoxic 1 | 0.5-1.0 | 2-4 | 2-4 | 1-2 |
| Aerobic 1 | 3.5-6.0 | 4-12 | 4-12 | 2.5-4 |
| Anoxic 2 | | 2-4 | 2-4 | |
| Aerobic 2 | | 0.5-1 | | |
| Mixed Liquor | 3000-5000 | 2000-4000 | 2000-4000 | 1500-3000 |
| Recycle | 100-300 | 400 | 100-600 | 200-400 |
| Return Sludge | 20-50 | 50-100 | 50-100 | 50-100 |

Membrane bioreactors (MBR) also offer EBPR opportunity utilizing either a pre or post denitrification arrangement of the process reactors. Both process arrangements are capable of producing an effluent phosphorous concentration of 0.05 to 0.10 mg/l.

The pre-denitrification MBR includes anaerobic, anoxic, aerobic and membrane reactors in series with membrane mixed liquor recycle to the aerobic reactor, anoxic mixed liquor recycle to the anaerobic reactor and aerobic mixed liquor recycle to the anoxic reactor. Figure 7 illustrates the pre-denitrification MBR process.

Figure 7 – Pre-denitrification MBR Process



The post-denitrification MBR includes anaerobic, aerobic, anoxic, and membrane reactors in series with membrane mixed liquor recycle to the aerobic reactor and anoxic mixed liquor recycle to the anaerobic reactor. Figure 8 illustrates the post-denitrification MBR process.

Figure 8 – Post-denitrification MBR Process

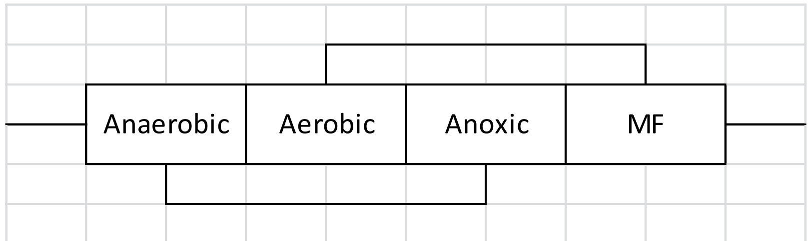



Table 2 provides a summary of typical process design criteria for the MBR EBPR process options.

Table 2 – MBR EBPR Typical Design Criteria

| | Pre-denitrification | Post-denitrification |
|---|---|---|
| FM Ratio | 0.1-0.15 | 0.1-0.15 |
| Mixed Liquor Solids | 12,000-13,000 | 12,000-13,000 |
| Solids Retention Time | 10-30 | 10-30 |
| Detention Time | | |
| Anaerobic | 0.5-1 | 0.5-1 |
| Anoxic | 7-10 | 8-10 |
| Aerobic | 7-10 | 6-8 |
| Recycle | | |
| Anoxic-Anaerobic | 100% | 100% |
| MF-Aerobic | 400% | 400% |
| Aerobic-Anoxic | 400% | |

**PARAMETERS TO CONSIDER**

A proper carbon to phosphorous ratio is necessary to consider EBPR treatment. Sufficient concentrations of other elements given in Table 3 (given as a percentage of total cell mass) are also necessary for effective EBPR.

Table 3 – Biological Nutrient requirements

| | |
|---|---|
| Potassium | 1.50 |
| Calcium | 1.40 |
| Sodium | 1.30 |
| Magnesium | 0.54 |
| Chloride | 0.41 |
| Iron | 0.20 |
| Manganese | 0.01 |
| Copper | 0.01 |
| Aluminum | 0.01 |
| Zinc | 0.01 |

Proper sludge age ensures optimum biochemical reactions that need to take place and for the biomass to uptake excess phosphates in the aerobic basins. Too short a sludge age will result in insufficient treatment with resulting poor effluent quality. As sludge age increases in an activated sludge system, nitrification becomes a factor and the need for anoxic zones becomes critical for denitrification and the removal of nitrates. Long sludge ages such as in extended aeration systems, can lead to secondary release of phosphorus through biomass decay. Long sludge ages can also result in biochemical reaction problems for PAOs. Sludge ages of 10-30 days are likely to be observed in successful EBPR plants.

Hydraulic residence time (HRT) is a very important operational parameter to ensure enough time for EBPR reactions to take place. The amount of VFAs in the incoming wastewater will determine the optimum HRT for the anaerobic selector. Higher VFAs in the influent require less HRT while low VFAs in the influent require a longer HRT. An HRT of 0.5 to 2 hours in the anaerobic zone is all that is usually needed for the biochemical reactions to occur for successful EBPR in municipal wastewater treatment plants. The hydraulic residence time of an anaerobic selector can be affected by influent flows during wet weather and return activated sludge (RAS) rates.

The pH in the anaerobic and aerobic zones has an influence on the type of organisms that will predominate. A more alkaline condition is necessary in the anaerobic zone in order to promote the dominance of PAOs. A more neutral condition is necessary in the aerobic zone to promote luxury uptake of the soluble phosphorous formed during the anaerobic treatment stage.

The recycle of nitrates to the anaerobic selector can interfere with the biological phosphorus removal process just as oxygen would. Anoxic zones are provided to denitrify ($NO2 + NO3 \rightarrow N2$) recycle streams. When mixed liquor or return sludge streams contain nitrates, recycle rates need to be adjusted to minimize their impact on treatment performance.

The sludge phosphorus content of an EBPR process should be 5.0-6.0 percent or higher. More efficient EBPR processes will have higher phosphorus content in the waste sludge. A waste sludge phosphorous concentration less than 5.0 percent warrants a more detailed process review.

Because the activated sludge phosphorus content is high in an EBPR plant, effluent TSS must be kept low. A small amount of total suspended solids with high phosphorus content could contribute to a high total phosphorus concentration in the effluent.

Sludge age in the final clarifier or the recycle of decant from an anaerobic digestion process can cause release of stored phosphorous in the waste sludge.

The following is a summary of criteria to monitor and typical operating ranges to guide the operator.

- The ratio of COD to phosphorous should be greater than 45 for effective EBPR.
- The ratio of VFAs to phosphorous should be greater than 7 for effective EBPR.
- The anaerobic and aerobic zone pH should be in the range of 8.0 to 8.5 and 7.0 to 7.5, respectively, for effective EBPR.
- ORP in the anaerobic zone should be in the range of-100 to -200mV). ORP in the anoxic zone should be in the range of -50 to +50 mV. ORP in the aerobic zone should be in the range of +100 to +300 mV.
- The HRT of the anaerobic zone should be in the range of 0.5 to 2.0 hours.
- Phosphorous content of the sludge should be greater than 5%.
- Nitrate loading to the anaerobic reactor must be less than the oxygen demand of the wastewater.
- The solids retention time should be in the range of 15 to 25 days depending on wastewater temperature.

**TROUBLESHOOTING**

The following scenarios are presented to assist the operator in diagnosing potential causes and presenting actions that should be considered. This troubleshooting guide assumes that the SRT and HRT are within the values presented in Table 1 or 2. It is important to limit the number of process changes made at one time and to recognize the response time will be affected by the solids retention time.

Phosphorous gradually increasing with normal effluent nitrogen and suspended solids

1. Phosphorous uptake could be reduced due to low VFA production in the anaerobic reactor. Check VFA to phosphorous ratio. If less than 7, increase the HRT of the anaerobic reactor.
2. ATP production could be affected by pH in the anaerobic reactor. Check pH. If less than 8.0, add caustic soda to adjust pH.
3. Nitrates could be affecting anaerobic conditions. Check the ORP of anaerobic reactor. If the ORP is greater than -100 mV, reduce the return sludge recycle rate so that the oxygen in the nitrates is less than the oxygen demand of the wastewater.

Higher effluent phosphorous with higher than normal effluent suspended solids

1. Phosphorous increase could be associated with effluent suspended solids. Check the ORP in the anoxic reactor. If the ORP is greater than +50 mV, reduce the mixed liquor recycle so that the oxygen from the nitrates is less than the demand. Polymer addition to the final clarifier could be considered to reduce the effluent suspended solids for an interim period.

A rapid phosphorous increase with normal effluent nitrogen and suspended solids

1. A side stream with high phosphorous content is being recycled. Check phosphorous concentration to the anaerobic reactor. If higher than normal, a side stream recycle is the likely cause. Regulate the side stream flow to limit the phosphorous loading to the process capability.
2. A secondary release of phosphorous is occurring from the clarifier sludge blanket. Check ORP of the clarifier sludge blanket. If the ORP is less than 0 mV, reduce the sludge blanket detention time by reducing the blanket level.
3. A secondary release is occurring in the mixed liquor recycle. Check the soluble phosphorous concentration in the mixed liquor recycle. If the soluble phosphorous is greater than 0.5 mg/l, reduce the HRT in the aerobic reactor.