

# Fermenters for Biological Phosphorus Removal Carbon Augmentation



MARCH 2019

The 2011 *Fermenters for Biological Phosphorus Removal Carbon Augmentation Compendium* was written to identify knowledge gaps to be addressed by the Nutrient Removal Challenge. That document contains the state of the art and the knowledge to achieve reliable, cost-effective nutrient removal. The 2011 compendium included a number of questions and challenges to reduce nutrients in advanced treated wastewater. This 2019 compendium revision contains a summary of the findings presented in reports and documents generated by the Nutrient Removal Challenge researchers and contributors.

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## ●●●● FERMENTERS IN WASTEWATER TREATMENT

### What Is a Fermenter?

A fermenter is a reactor or unit process found on site at a wastewater treatment plant in which complex particulate and soluble substrates present in the sludge and wastewater are anaerobically broken down to form volatile fatty acids (VFAs) through acid fermentation. The VFAs can be used to develop stable populations of phosphate accumulating organisms (PAOs) and denitrifying bacteria in the biological nutrient removal (BNR) process, thus helping the process achieve low total phosphorus and total nitrogen concentrations biologically.

### How Are Fermenters Used for Biological Phosphorus Removal?

VFAs play a crucial role in the enhanced biological phosphorus removal (EBPR) biochemistry in the BNR process. Stable EBPR occurs when the PAOs are sequentially subjected to anaerobic and aerobic conditions in the BNR process train. Under anaerobic conditions, PAOs take up and intracellularly store VFAs as poly-hydroxyalkanoates (PHAs) while releasing stored polyphosphates into the bulk liquid. The polyphosphates are hydrolyzed to orthophosphate, which is subsequently taken up in the aerobic zone of the process, where the PAOs utilize the stored PHA to restore their polyphosphate reserves. Orthophosphate may also be taken up similarly in anoxic zones where nitrate or nitrite rather than oxygen is the electron acceptor; here the PAOs are referred to as denitrifying PAOs (dPAOs). The ionized forms of the VFAs generated in fermenters, primarily acetate and propionate, play an important role in maintaining effective EBPR in BNR processes, particularly those that treat wastewaters that do not have sufficient influent VFAs to sustain reliable and efficient EBPR. Fermenters are most effective in promoting EBPR when the VFAs generated are readily available to the PAOs in the anaerobic zone of the BNR process (Barnard 1984; Oldham and Stevens 1984; Barnard 1994).

### How Are Fermenters Used for Denitrification?

Denitrification is carried out in the anoxic zones of the BNR process by heterotrophic organisms that have the necessary enzyme systems to utilize nitrate-nitrogen and nitrite-nitrogen, or NO<sub>x</sub> (to indicate total nitrate plus nitrite) instead of dissolved oxygen as the terminal electron acceptor. Denitrification reduces oxidized nitrogen to nitrogen gas, which is released to the atmosphere. In addition to promoting EBPR, VFAs are also highly effective carbon sources for denitrification because of their soluble and readily biodegradable nature. The availability of VFAs produced through fermentation results in significantly higher denitrification rates in the anoxic zones of the BNR process than would be achieved with the use of primary effluent only.

### Describe the Principal Biochemical Pathways Involved in Acid Fermentation.

Acid fermentation is made up of the first three stages of anaerobic digestion—hydrolysis, acidogenesis, and acetogenesis. The fourth stage of anaerobic digestion, methanogenesis, involves the conversion of the principal products of acid fermentation (primarily acetate and

hydrogen) into methane gas (Gujer and Zehnder 1983; van Haandel and Lettinga 1994). Methanogenesis should be avoided in a fermenter that is used for carbon augmentation as it consumes the VFAs needed for EBPR and denitrification. This is best done through optimizing the fermenter solids retention time (SRT) for a given temperature and pH.

Hydrolysis involves the conversion of complex organic matter into lower molecular weight dissolved compounds. The process is mediated by exoenzymes (extrocellular enzymes) that are excreted by fermentative bacteria. Proteins are degraded to amino acids, carbohydrates are broken down into soluble sugars, and lipids are converted into long-chain fatty acids and glycerine through beta oxidation coupled with hydrolysis.

In acidogenesis, dissolved organic compounds generated by hydrolysis are taken up by a diverse group of fermentative bacteria (most of which are obligate anaerobes) and converted to simple organic compounds such as VFAs, alcohols and lactic acids; and mineral compounds, such as carbon dioxide, hydrogen, ammonia, and hydrogen sulfide gas.

In acetogenesis, the products of acidogenesis are converted into acetate, propionate, hydrogen and carbon dioxide. Approximately 70 percent of the COD originally present in the sludge can be converted into acetic and propionic acids and the remainder of the electron donor capacity is concentrated in the formed hydrogen (Gujer and Zehnder 1983; van Haandel and Lettinga 1994).

### **What Are the Principal Feedstocks Used for On-site Sludge Fermentation at WWTPs?**

Primary sludge, mixed liquor, and return activated sludge are commonly used in fermenters to produce VFAs. Imported organics (food waste, fats, oils, and grease, etc.) could also be used as feedstock for a fermenter, but operator attention is required in the handling of the additional load to the fermentation system. In one instance, molasses was used to increase a fermenter VFA yield (Thomas et al. 2003).

### **What Are the Principal Products of On-site Sludge Fermentation?**

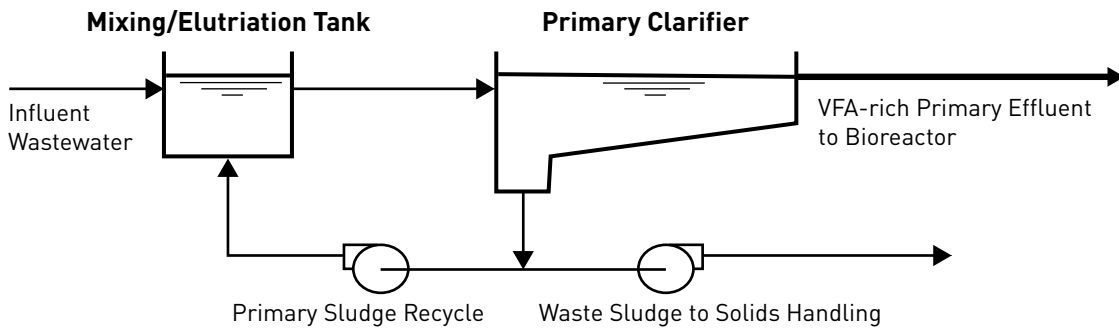
VFAs, or their ionized forms, acetate, propionate, valerate, and butyrate can be beneficially used as supplementary carbon sources for EBPR and denitrification.

Rabinowitz (1985) operated pilot-scale primary sludge fermenters at ambient temperatures of 18 to 22°C and solids retention times between 2 and 10 days and found that acetic and propionic acids made up more than 90 percent of the VFAs produced. The ratio of acetic:propionic acid was approximately 55:45. Elefsiniotis and Oldham (1994) found that acetic, propionic and butyric acids accounted for 45, 31 and 9 percent, respectively, of the VFAs produced through primary sludge fermentation. Aside from VFAs, small quantities of formic acid, ethanol, and lactic acid were detected in both the laboratory-scale completely mixed and upflow anaerobic sludge blanket (UASB) fermenters.

# PRIMARY SLUDGE FERMENTERS

## What Are the Principal Sludge Fermenters Configurations?

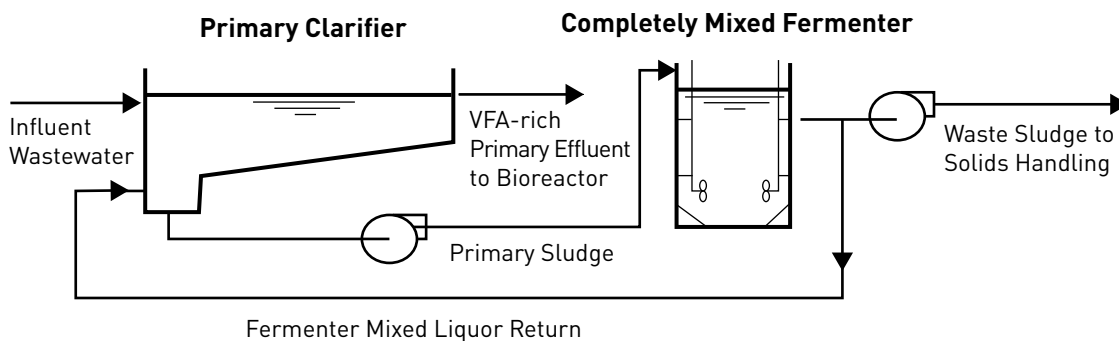
### Activated Primary Sedimentation Tanks



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Primary sludge is continuously recycled to the primary clarifier inlet, either directly or through an elutriation tank, so that a fermenting sludge blanket is allowed to build up on the clarifier floor. Generally speaking, activated primary tanks require purpose-designed primary clarifiers that allow sufficient sludge blanket depth to be maintained. The VFAs generated in the sludge mass are elutriated through mixing with the influent wastewater, and conveyed to the BNR process together with the primary effluent. The sludge inventory and blanket height are controlled by wasting a fraction of the primary sludge to the sludge handling system. This fermentation concept was first proposed by Barnard (1984). One mode of operating this type of fermenter is known as alternating activated primaries, in which primary sludge is retained and fermented in one primary sedimentation tank and then pumped to another for VFA elutriation. Raw wastewater is settled in both tanks at the same time. This design was used at the Baviaanspoort plant in South Africa and the operation allowed for the process to be reversed (Randall et al. 1992).

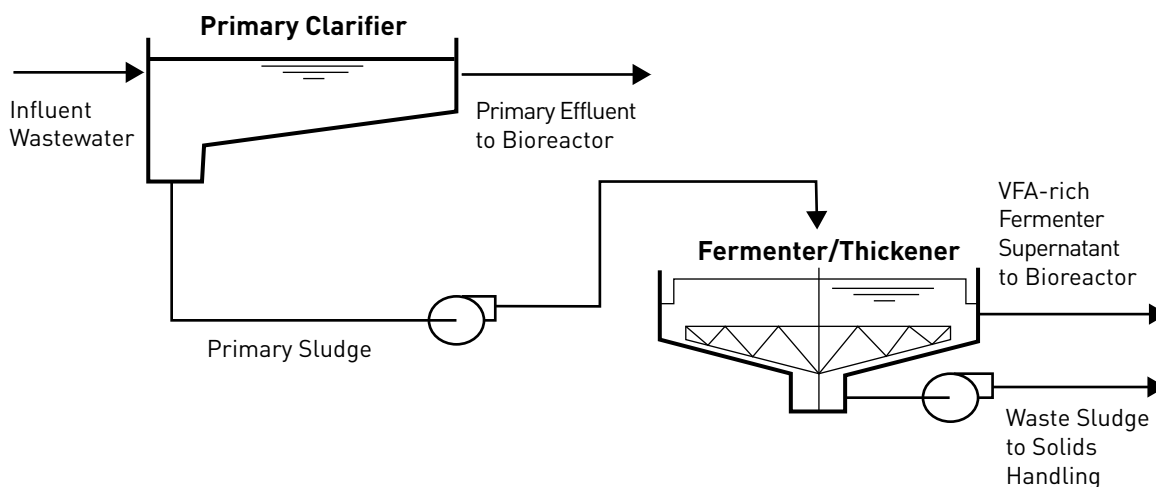
### Complete Mix Fermenter



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Primary sludge is continuously pumped to a mechanically mixed tank where acid fermentation occurs. The complete mix fermenter tank overflow is returned to the primary clarifier inlet. The VFAs generated in the fermenter are elutriated through mixing with the influent wastewater, and conveyed to the BNR process together with the primary effluent. The fermenter SRT is controlled by wasting a fraction of the fermented sludge to the sludge handling system. The fermenter HRT is controlled either by adjusting the complete mix tank volume or by adjusting the primary sludge pumping rate. The VFAs elutriated in the primary clarifier are conveyed to the BNR process together with the primary effluent. This fermenter configuration was first proposed by Rabinowitz et al. (1987).

### Single-Stage Static Fermenter/Thickener

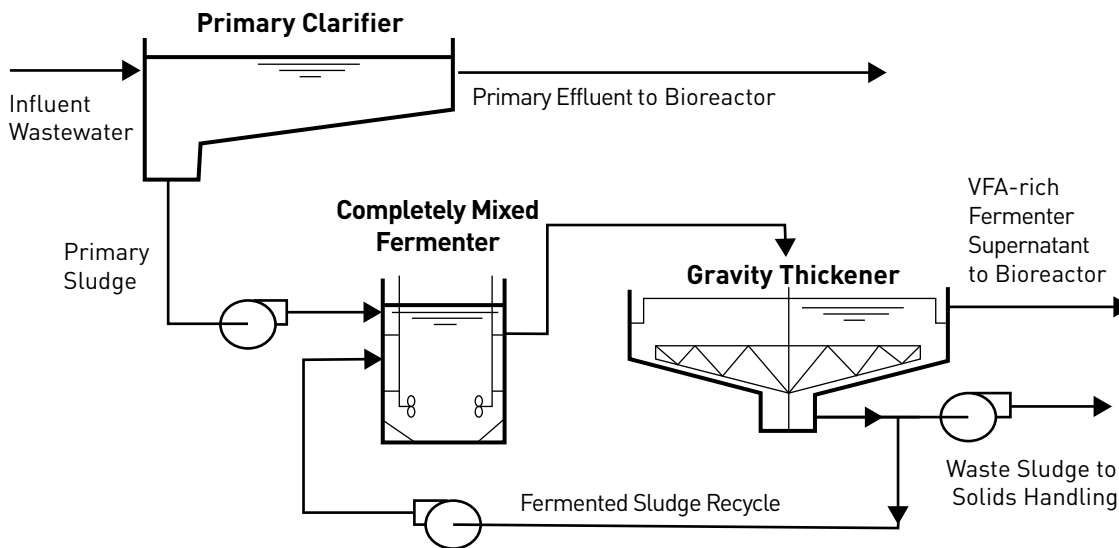


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This fermenter is essentially a lowly loaded gravity thickener with an increased side water depth (SWD) to allow a fermenting sludge inventory to accumulate on the thickener bottom. Primary sludge is continuously pumped into a center well and allowed to settle and thicken in the fermenter/thickener. The VFA-rich supernatant is conveyed directly to the BNR bioreactor, where it can be optimally used for EBPR and/or denitrification. A source of elutriation water is normally added to the incoming primary sludge or directly to the thickener to minimize sulfide and methane formation in the sludge blanket, and help convey the VFAs to the BNR bioreactor. The fermenter SRT and sludge inventory are controlled by wasting the thickened sludge to the sludge handling system to maintain a target sludge blanket height. This fermentation concept was first applied at the Kelowna WPC in British Columbia in the early 1980s (Oldham and Stevens 1984).



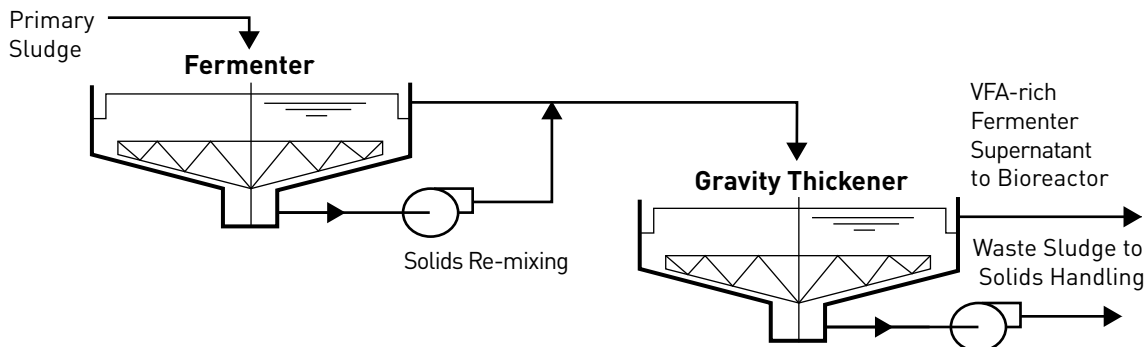
## Two-Stage Mixed Fermenter/Thickener



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This fermenter configuration consists of a complete mix tank followed by a gravity thickener. Primary sludge is continuously pumped to a mechanically mixed tank where acid fermentation occurs. The complete mix tank overflows to the gravity thickener for liquid-solids separation. Thickened sludge is continuously recycled from the bottom of the thickener to the complete mix tank inlet. The VFA-rich thickener supernatant is conveyed directly to the BNR bioreactor, where it can be directed to an anaerobic or anoxic zone to optimally use for EBPR and/or denitrification. A source of elutriation water is normally added to the gravity thickener inlet or into the thickener blanket to minimize sulfide and methane formation in the sludge blanket, and help convey the VFAs to the BNR bioreactor. The fermenter SRT and sludge inventory are controlled by wasting a portion of the thickened sludge to the sludge handling system and maintain a target sludge blanket height. This fermentation concept was first applied at the Kalispell WWTP in Montana in the early 1990s (Oldham and Abraham 1994).

## Unified Fermentation and Thickening (UFAT) Fermenter



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This fermenter configuration consists of two gravity thickeners in series, and was patented by Baur [2002]. The first thickener is operated as a fermenter, and the settled solids and supernatant are recombined and directed to the second thickener, where liquid-solids separation occurs. The fermenter SRT is controlled by varying the thickened sludge pumping rate from the bottom of the fermenter. The VFA-rich thickener supernatant from the second thickener is conveyed directly to the BNR bioreactor, while the solids are conveyed to the sludge handling system. Elutriation water can be added to the thickener to condition the solids to improve sludge settling and thickening, and help convey the VFAs to the BNR bioreactor.

### What Are the Advantages, Disadvantages, and Control Features of the Fermenter Configurations?

Advantages, disadvantages, and control features are summarized below by fermenter configuration:

#### Activated Primary Sedimentation Tanks

##### Advantages:

- Simple operation
- No additional unit processes are required
- Easy to retrofit to existing facilities

##### Disadvantages:

- High solids loading rate to the primary clarifiers can result in solids loss over weirs.
- Difficult to control the SRT of the fermenting sludge mass
- High potential for methane and sulfide formation in clarifiers could cause sludge rising and odors.
- VFAs produced cannot be discharged directly to a specific zone in the BNR process but must be conveyed in the primary effluent, thus restricting the BNR process configuration used.
- VFAs generated may be partially stripped in the passage through the primary clarifiers.
- Recycling the primary sludge can lead to a build-up of fibrous material and plastics in the sludge mass, which can cause blockages in the primary sludge pumps and pipework.

##### Control Features:

- Primary sludge recirculation rate
- Sludge blanket height
- Primary sludge wastage rate

#### Complete Mix Fermenter

##### Advantages:

- Simple operation
- Relatively easy to control the SRT and HRT of the fermenting sludge mass

##### Disadvantages:

- VFAs produced cannot be discharged directly to a specific zone in the BNR process but must be conveyed in the primary effluent, thus restricting the BNR process configuration used.
- VFAs generated may be stripped in passage through primary clarifiers.

- Recycling the primary sludge can lead to a build-up of fibrous material and plastics, and “roping” as a result of the vortexing action of the mixers, which can cause blockages in the primary sludge pumps and recycle pipework.
- Potential formation of a stable scum layer, which is difficult to remove

**Control Features:**

- Primary sludge pumping rate
- Fermenter volume
- Fermenter MLSS concentration
- Primary sludge wastage rate

**Single-stage Static Fermenter**

**Advantages:**

- VFAs produced can be directed to the anaerobic or anoxic zones of the BNR process.
- No increase in solids loading rate to primary clarifiers
- Allows primary sludge to be withdrawn at low concentrations, thus allowing higher primary clarifier overflow rates.
- Fermented primary sludge is thickened to 5 to 8 percent (as dry solids).
- Single unit process required.

**Disadvantages:**

- Deep sludge blankets in thickener require high torque mechanism.
- Grit not removed upstream accumulates on thickener bottom.
- Elutriation water is required to improve thickening, inhibit sulfide/methane generation and flush out VFAs.
- Control of separation and VFA production in one process complicates operation.

**Control Features:**

- Primary sludge pumping rate
- Elutriation water flow rate, usually controlled by ORP measurement in the overflow
- Sludge blanket height
- Thickened sludge wastage rate
- Thickened sludge solids content

**Two-stage Fermenter/Thickener**

**Advantages:**

- VFAs produced can be directed to the anaerobic or anoxic zones of the BNR process.
- No increase in solids loading rate to primary clarifiers
- Accurate independent control of fermenter SRT is possible.
- Fermented primary sludge is thickened to 5 to 8 percent (as dry solids).

**Disadvantages:**

- Potential formation of a stable scum layer in complete mix tank, which is difficult to remove
- Deep sludge blankets require high torque mechanism.

- Recycling of thickened sludge can lead to a build-up of fibrous material and plastics in the complete mix tank, and “roping” as a result of the vortexing action of the mixers, which can cause blockages in the interconnecting pipework
- Thickener solids loading rate depends on complete mix tank MLSS concentration and the primary sludge and thickened sludge recycle pumping rates.
- Elutriation water is required to improve thickening, inhibit sulfide/methane generation and flush out VFAs.
- High primary sludge pumping rate and fermented sludge recycle to complete mix tank results in high solids loading rates to thickener.

**Control Features:**

- Primary sludge pumping rate
- Complete mix tank MLSS concentration
- Elutriation water flow rate, usually controlled by ORP measurement in the overflow
- Sludge blanket height
- Thickened sludge recycle rate
- Thickened sludge wastage rate
- Thickened sludge solids content

**Unified Fermentation and Thickening (UFAT) Fermenter**

**Advantages:**

- Sludge in first thickener is stratified with deeper layers having a longer SRT.
- Recombining sludge and supernatant from first thickener elutriates VFAs before sludge enters second thickener.
- VFAs produced can be directed to the anaerobic or anoxic zones of the BNR process.
- No increase in solids loading rate to primary clarifiers
- Accurate control of fermenter SRT is possible.
- Allows primary sludge to be withdrawn at low concentrations from primary clarifier, thus allowing higher primary clarifier overflow rates
- Fermented primary sludge is thickened to 5 to 8 percent (as dry solids).

**Disadvantages:**

- Deep sludge blankets require high torque mechanisms in both the fermenter and thickener tanks.

**Control Features:**

- Primary sludge pumping rate from first thickener
- Elutriation water flow rate
- Sludge blanket height in both thickeners

**What Are the Key Design and Control Parameters for Fermenters?**

**Solids Retention Time**

Solids retention time (SRT) is a key design parameter for primary sludge fermentation systems

because it defines the groups of fermentative organisms that will grow in the system. If the SRT is too short, many of the fermentative bacteria will be washed out of the system, and a stable population of acid-formers will not develop. Conversely, if the SRT is too long, a population of methane-formers will develop which will consume the VFAs generated and produce highly combustible methane gas. The growth rate of fermentative bacteria is highly temperature dependent. For this reason, primary sludge fermenters are generally designed to operate at an SRT of 3 to 5 days during the summer months when operating temperatures are above 16°C, and at an SRT of 4 to 8 days during the winter months, when operating temperatures are below 15°C (WEF 2006).

### Hydraulic Retention Time

The fermenter hydraulic retention time (HRT) is a function of the tank volume and the primary sludge pumping rate. In general, the HRT is not a critical parameter used in the design of primary sludge fermenters, but is often used to fine-tune fermenter operation. Complete mix fermenters are generally sized with an HRT of between 6 and 12 hours while treating between 4 and 8 percent of the incoming plant flow. The primary sludge pumping rate to 2-stage complete mix/gravity thickener fermenters is generally lower, about 2 to 4 percent of the incoming plant flow, so that the HRT of the complete mix tank is normally between 12 and 24 hours. Other fermenters are designed to maintain a specific sludge inventory and SRT in the system. In these cases, the fermenter HRT can be also controlled by varying the primary sludge pumping rate, and the elutriation water flow rate when added directly to a gravity thickener (WEF 2006).

### Effect of pH

In anaerobic digestion, the bulk liquid pH is extremely important because methanogenesis proceeds at a high rate when the pH is maintained in the neutral range, with most methane formers known to be inhibited at pH values below 6.3 and above 7.8. However, acid-formers are significantly less sensitive to high or low pH values and hence acid fermentation usually prevails over methane formation at pH values around 6.5 and lower. Primary sludge fermenters tend to operate at ambient pH values between 4.8 and 6.0 due to the acid formation reactions that are part of fermentation, and raising the fermenter pH value to around 7.0 does not result in improved VFA production. The lower pH is beneficial since it inhibits growth of methane-forming bacteria.

### Elutriation Water

It is important to note that, in addition to VFA generation through the conversion of the particulate primary solids to soluble VFAs, these VFAs must be separated from the fermenting solids and conveyed to the BNR process through elutriation. The discharge of a source of external elutriation water into the fermenter helps ensure that most of the VFAs generated in the fermenter do not end up in the sludge handling stream but are available to augment the readily biodegradable carbon source to the BNR process.

## Control of Primary Sludge Fermentation

The key parameter used to control the operation of primary sludge fermenters is the system SRT. VFA production tends to be low at short SRTs due to the difficulty in establishing a stable population of acid-formers as well as completion of the hydrolysis, acidogenesis and acetogenesis reactions. However, at long fermenter SRTs, methanogenic bacteria will grow and the VFAs formed will be consumed by methanogenic activity that produces methane gas. For this reason, the most effective way of preventing the establishment of a methane forming population is by introducing trace amounts of dissolved or combined oxygen into the fermenter bulk liquid. For example, the use of primary effluent with small concentrations of dissolved oxygen, or a nitrified secondary effluent, as a source of elutriation water will control the onset of methanogenic activity in the fermenter. Other process benefits are that the elutriation water will also inhibit sulfide formation, thus helping control odors and corrosion in the fermenter (WEF 2006). Oxidation-reduction potential (ORP) measurement of the fermenter overflow has been used to optimize and control the elutriation water flow rate.

## What VFA Yields Can Be Expected from Primary Sludge Fermenters?

The ratio of VFA produced per unit mass of volatile suspended solids (VSS) added to a primary sludge fermenter has a fairly broad range from 0.05 to 0.3 g VFA/g VSS added (WEF 2006). Lilley et al. (1990) found that VFA production from primary sludge followed first order reaction kinetics in a laboratory-scale investigation. The maximum potential VFA yield at 20°C was reported to be 0.17 mg VFA (as COD) per mg of primary sludge (as COD) applied. It is generally believed that a well operated fermenter should have a VFA yield of 0.15 kg VFA (measured as acetic acid, HAc) per kg of TSS added to the fermenter (Oldham 1994). Oldham and Abraham (1994) reported on the VFA yield from the complete mix fermenter at Penticton, the single-stage static fermenter at Kelowna, and the 2-stage complete mix-fermenter/thickener at Kalispell. These fermenters added the equivalent of 17 mg/L, 21 mg/L, and 58 mg/L of VFA, respectively, to the wastewater entering the BNR processes. Practical experience suggests that higher VFA yields are observed in fermenters receiving primary sludge generated from “fresh” wastewaters collected sewerage systems in which relatively little natural fermentation takes place.

## Do Current Process Models Accurately Predict Sludge Fermentation?

The current generation of process models includes biological processes for hydrolysis, acid formation, and methane formation. The key to accurately predicting primary sludge fermentation is to accurately model the hydrolysis of the primary sludge. Other modeling challenges include quantifying the mass of heterotrophs entering the fermenter with the incoming sludge, and modeling the elutriation of the formed VFAs from the sludge mass into the bulk liquid. In general, complete mixed fermenters can be accurately modeled, while partially mixed fermenters cannot be accurately modeled. This is because current process models use simple point clarifier or one-dimensional flux models, which imperfectly capture the mass transfer behavior in liquid-solids

separation and elutriation processes. Computational fluid dynamic (CFD) modeling is a more powerful tool to capture the non-ideal behavior in partially mixed fermenters.

### What Control and Monitoring Parameters Can Be Used to Optimize the Performance of Fermenters?

#### The key fermenter control parameters include:

- Primary sludge pumping rate
- Solids retention time (SRT)
- Elutriation water flow source and rate
- Hydraulic retention time (HRT)
- Mixing intensity in complete mix tanks

#### The key fermenter monitoring parameters include:

- Supernatant VFA concentrations and yield
- Supernatant COD, soluble COD (sCOD), soluble BOD (sBOD), readily biodegradable COD (rbCOD), etc.
- Supernatant VFA fractionation (acetic, propionic, butyric, etc.)
- Complete mixed tank TSS concentration
- Thickened fermented sludge concentration
- Gravity thickener sludge blanket height
- Gravity thickener mechanism torque
- Sludge blanket and supernatant pH
- ORP (difficult to measure in fermenter contents; best measured in fermentate)
- Headspace H<sub>2</sub>S

### What Are Some Examples of EBPR Performance with Primary Sludge Fermentation?

The Nutrient Challenge evaluated statistical treatment performance and reliability for various WRRFs with nitrogen and phosphorus removal (Bott and Parker 2011). Two facilities included in the study relied nearly completely on EBPR with primary sludge fermentation and minimal or no chemical phosphorus removal. Both plants also have tertiary media filters. Effluent TP statistics for these plants in Kelowna, BC and Kalispell, MT are presented in Table 1. Additional details and plant descriptions can be found in the study cited above.

**Table 1 - Effluent Total P Concentrations at Sample WRRFs with Primary Sludge Fermentation**

Parameter	Kelowna, BC	Kalispell, MT
Annual Average, 50th Percentile, mg/L	0.16	0.12
Annual Average, 90th Percentile, mg/L	0.22	0.13
Monthly Average, 95th Percentile, mg/L	0.22	0.17
Daily, 99th Percentile, mg/L	0.85	0.36

Source: Bott and Parker, 2011

## ●●●● SECONDARY SLUDGE FERMENTERS

### What Is the Difference Between Secondary Sludge Fermentation and Sidestream EBPR?

The term sidestream EBPR (or S2EBPR) is used for processes that include a dedicated fermentation zone in the EBPR to ferment the mixed liquor or RAS. A related WRF study (Gu et al. 2019) presents process options and configurations for S2EBPR. Secondary sludge fermentation and S2EBPR both refer to an EBPR process that includes fermentation of the biomass in the process; S2EBPR also use the fermentation zone as a selector for PAOs. The two terms are considered to be synonymous; RAS fermentation or mixed liquor fermentation may also be used to refer to the fermented biomass more specifically.

### What Is Secondary Sludge Fermentation and How Is It Applied to EBPR?

Effective EBPR can be achieved in processes in which mixed liquor or RAS is fermented to form rbCOD or VFAs, provided that only a portion of the secondary sludge is fermented and that the rbCOD or VFA formed is made available to the PAOs in the mainstream BNR process. In practice, secondary sludge fermenters usually consist of completely mixed or intermittently mixed reactors that are incorporated into the BNR process train. These reactors can either be in the main process stream, or a sidestream of the process (e.g. on the RAS line), or on a recycle loop that is withdrawn from and returned to the anaerobic zone. Secondary sludge fermentation has been successfully implemented in several unconventional BNR plants where the manipulation of the aeration and mixing systems has created mixed liquor or RAS fermentation zones within the BNR process train (Barnard et al. 2011, 2017).

Clarke (2009) switched off the mixer in one out of two anaerobic zones of a plant with insufficient VFA in the incoming wastewater and successfully removed phosphorus from about 8 mg/L in the influent to less than 0.5 mg/L through in-basin fermentation. A similar strategy at the Henderson, NV, plant, where nitrates added to the sewerage system destroyed the natural VFA, resulted in effluent orthophosphate concentrations well below 0.1 mg/L (Barnard et al. 2011).

Fermentation of a portion of the RAS has been used for VFA generation in BNR processes (WEF 2006). Although this fermentation option could be employed at any BNR process, it particularly applies to plants that operate secondary treatment processes without primary clarifiers. There are several variations on the configuration in operation in North Carolina. In a patented sidestream EBPR process with RAS fermentation, a portion of RAS from the secondary clarifier is first directed to a sidestream anaerobic zone. A portion of the RAS from the anaerobic zone is then directed to a sidestream fermentation zone (Lamb 1994). Effluent from the sidestream fermentation zone is sent back to the anaerobic zone as a VFA source. The sidestream RAS fermentation zone is similar in operation to any anaerobic or anoxic zone in the mainstream BNR process. As an alternative to the sidestream biological phosphorus removal configuration, the fermentation zone effluent could be sent directly to the anaerobic zone of the mainstream BNR process.



Although the concept of secondary sludge fermentation is newer than primary sludge fermentation, it has been used at numerous WRRFs. While the biological consortia and biochemical mechanisms in secondary sludge fermentation are not completely understood, fundamental knowledge has improved in recent years and points to the role of *Tetrasphaera* PAOs in secondary sludge fermentation EBPR processes (Barnard et al. 2017) as opposed to other PAOs including those related to *Candidatus Accumulibacter*, which have been associated with “traditional” EBPR process without secondary sludge fermentation. *Tetrasphaera* PAOs appear to be more metabolically diverse than other PAOs and can take up amino acids, glucose, and possibly acetate under anaerobic conditions (Nguyen et al. 2011). Therefore, it is possible that not only VFA but other substrates generated in secondary sludge fermenters are utilized by *Tetrasphaera* PAOs.

Overall, secondary sludge fermentation is considered a viable alternative to primary sludge fermentation based on its EBPR performance track record using different configurations in numerous WRRFs, and because it has very few of the operating problems associated with primary sludge fermenters, e.g. odors, corrosion, blockages, abrasion, etc. (Barnard et al. 2011, 2017).

### **What Are the Practical Limitations Associated with Secondary Sludge Fermenters?**

The major disadvantage of fermenting secondary sludge is the high concentrations of ammonia and phosphorus that are released into the fermentate. Ammonia release is the result of the anaerobic metabolism of the protein material in the sludge, while phosphorus is released by the PAOs under anaerobic conditions though the secondary release mechanism (phosphorus released by the PAOs in the absence of dissolved oxygen, nitrate and VFA). However, practice has shown that the overall benefits of the additional VFA provided through secondary sludge fermentation can outweigh the negative effect of these additional nutrient loads. The key to successful application of secondary sludge fermentation is to ferment a relatively small portion of the mixed liquor or RAS, i.e. to ferment enough secondary sludge to generate the VFAs needed to drive EBPR, but not so much that the released masses of nitrogen and phosphorus overwhelm the process (Andreasen et al. 1997; Vollertsen et al. 2006; Vale et al. 2008; Barnard et al. 2011).

Care must be taken that the VFA-rich fermentate does not come into contact with nitrate-rich mixed liquor as the VFAs generated will be preferentially utilized for denitrification, thus rendering them unavailable to drive the EBPR mechanism. A key benefit of intermittently mixed or unmixed in-line fermenters (UMIFs) is that these reactors allow the mixed liquor to settle, thus increasing the SRT of the fermenting sludge while physically separating it from the nitrate in the supernatant. It has been postulated that the most effective secondary sludge fermentation is achieved by pumping mixed liquor from the anaerobic zone of a BNR process through an upflow sludge blanket (USB) fermenter in which the fermenting sludge is thickened, and a long SRT can be maintained in a relatively small tank volume (Tremblay 2005).

### **What Are the Optimum Ranges for Solids Retention Time (SRT) to Be Used in the Design of Secondary Sludge Fermenters?**

Demonstration-scale testing of a sidestream USB fermenter treating mixed liquor from the anaerobic zone of a BNR process showed that the VFA yield from mixed liquor is strongly related to the fermenter SRT. The observed VFA production was 67, 94 and 43 kg/d, respectively, at SRTs of 2.5, 7 and 12 days (Tremblay 2005). This suggests that the optimal SRT for secondary sludge fermentation is around 5 to 7 days, and that some of the VFA produced is lost to methanogenic activity at longer SRTs. However, the study also found that P release increased with increasing SRT in the mixed liquor fermenter. To minimize this release, it was suggested that the lowest SRT that yields sufficient VFAs for effective EBPR should be used, and that a 3-4 day fermenter SRT would likely be sufficient in a full-scale application. The SRT of both sidestream and main-stream secondary sludge fermenters is difficult to quantify given that both the fermenting mass inventory and wastage rates are based on operator decisions such as MLSS concentrations, sludge blanket height, mixing duration, wastage rates, etc.

### **What Are the Optimum Ranges for Hydraulic Retention Time (HRT) to Be Used in the Design of Secondary Sludge Fermenters?**

HRT is thought to be less significant than SRT in the design and operation of secondary sludge fermenters. The fermentation reactor must have an appropriate volume that allows the required fermenting sludge inventory to be maintained at the target SRT. SRT is a function of the sludge inventory and wastage rate, whereas HRT is a function of the reactor volume and flow rate through the reactor. Both the USB and UMIF reactors allow for a fermenter SRT that is significantly longer than the HRT (Barnard et al. 2011). In cases where only a relatively small fraction of the RAS is fermented in a dedicated sidestream complete mix anaerobic reactor (typically between 5 and 10 percent of the RAS flow), fermenter HRTs between 35 and 50 hours have been reported in the literature (Vollertsen et al. 2006; Vale et al. 2008).

### **What Percentage of the RAS Flow is Typically Directed to a Fermenter in RAS Fermentation?**

The Phostrip Process makes use of RAS fermentation by passing RAS through an anaerobic “stripper” tank. The underflow from the stripper tank is returned and mixed with the influent and passed through an aerobic zone. Initially, it was hypothesized that phosphorus is stripped from the RAS solids in the stripper under anaerobic conditions lasting up to 30 hours, solubilized, and then decanted in a lime precipitation process. These same bacteria would then restore their phosphorus reserves by taking up phosphorus in the aerobic zone. Later, Fuhs and Chen (1975) proposed that fermentation in the stripper provided a source of VFAs to drive EBPR in the mainstream process. In early versions of the process, 100 percent of the RAS was fermented in the stripper tank, causing a high degree of secondary P release, which required lime treatment of the supernatant. In current versions of the process, between 20 and 45 percent of the RAS flow is passed through through the pre-stripper and stripper tanks. The RAS

is first denitrified in the anoxic pre-stripper tank, and then thickened, fermented and stripped of its phosphorus in the anaerobic thickener/stripper tank. The P-rich supernatant from the stripper tank is chemically treated to remove the released P, while the thickened RAS is either wasted or returned to mainstream process.

The Phostrip plant in Truckee Meadows, NV was converted to a high-rate Phoredox process with side-stream fermentation of the RAS. About 15 percent of the RAS flow was fermented in the stripper, but both the supernatant and the underflow were returned to the anaerobic zone of the non-nitrifying EBPR process. Thickening in the stripper/fermenter resulted in a longer SRT in this reactor. The high active mass fraction and absence of nitrate in the RAS created conditions that were favorable to fermentation, and the secondary effluent soluble phosphorus concentration was reduced to less than 0.1 mg/L (Narayanan et al. 2002).

Researchers in Denmark reported that efficient phosphorus removal was achieved at a number of plants in which about 7 percent of the RAS flow was directed to a dedicated sidestream anaerobic zone for fermentation. The HRT of the fermenter was between 35 and 45 hours (Vollertsen et al. 2006). Researchers in the UK directed about 6 percent of the RAS flow to dedicated sidestream fermenter, which had an HRT of approximately 48 hours. In summary, it has been suggested that if 7 to 10 percent of the RAS flow is fermented at an HRT of more than 2 days, fermentation of the mixed liquor solids will produce sufficient VFA to sustain EBPR in the mainstream process.

### **What VFA Yield Is Expected in Secondary Sludge Fermenters?**

Recent research shows that the theoretical VFA yield achievable in secondary sludge fermentation is significantly lower than those in primary sludge fermentation. In fermenting raw wastewater solids, the maximum theoretical VFA yield is between 0.55 and 0.9 kg VFA per kg of biodegradable COD (bCOD) applied. However, when fermenting secondary sludge, the maximum theoretical VFA yield is between 0.09 and 0.14 kg VFA per kg bCOD applied (Houweling et al. 2011). Therefore, the VFA yield from secondary sludge fermentation is expected to vary based on how much of the biodegradable COD in the sludge is influent particulate material, and how much is biomass. The biodegradable COD content, in turn, depends on the SRT of the mainstream BNR process and the source of the secondary sludge being fermented. Fermenting mixed liquor or RAS from a BNR process with a longer SRT is expected to have a lower VFA yield than secondary sludge from a plant with a shorter SRT. Finally, secondary sludge withdrawn from the RAS line would have less biodegradable influent particulate material than mixed liquor withdrawn from an anaerobic cell at the head end of the bioreactor, and, therefore, have a lower VFA yield.

Much of the experimental work on secondary sludge fermentation has been done at laboratory-scale. Batch testing of a RAS fermenter indicated a rapid increase in soluble COD and VFAs during the first 3 days. After that time, the rate of VFA production decreased, presumably

due to the onset of methanogenesis or sulphate reduction. VFA production peaked after about 6 days at a yield of approximately 0.09 mg VFA per mg of VS applied (Jönsson and Jansen 2006).

### **Do Current Process Models Accurately Account for Secondary Sludge Fermentation?**

In conventional EBPR process designs, influent rbCOD is relied upon to drive fermentation and phosphorus release in the anaerobic zone. To simulate this behavior, commonly used process models (UCTPHO, ASM2d, ASDM) include VFA sequestration by PAOs as a fast process which, when simulated for conventional BNR designs, is essentially rate-limited by VFA availability. The amount of VFA available is, in turn, determined by the VFA concentration in the influent and the rate of fermentation in the sludge mass. Like sequestration, fermentation is also a relatively fast process that tends to be rate-limited by the amount of fermentable influent rbCOD. As a result, the models predict the expected behavior that EBPR potential is determined by the availability of influent rbCOD.

The commonly used EBPR process models include generation of rbCOD due to hydrolysis of influent slowly biodegradable COD and biomass decay products. The same biological model is used and switching functions (with DO, nitrate, etc.) will allow fermentation to occur in the anaerobic selectors and fermenter zones, as it occurs everywhere in the activated sludge process when the environment is suitable.

The effect of decay and hydrolysis rates on modeling EBPR potential, however, has been mostly ignored in the past. This has not created a large problem with process simulators because it is a relatively slow process and anaerobic selectors in the EBPR liquid stream process have traditionally been designed with a small sludge mass fraction. Experience at full-scale plants and in pilot studies has demonstrated that EBPR can be induced in systems where VFAs are generated from the decay and hydrolysis of secondary sludge within the activated sludge process by incorporating secondary sludge fermentation zones. Essentially, these systems rely on the use of higher anaerobic mass fractions, whether through installation of RAS fermentation basins or implementation of intermittent mixing in the anaerobic selectors. As a result, increased attention is being paid to the influence of decay and hydrolysis rates on EBPR modeling. Process models are being used to identify the benefits of increasing the anaerobic mass fraction at different locations in the process as well as the costs with respect to increased nutrient from the sludge and lowering the overall aerobic SRT.

New observations and results continue to refine the biological models. Key areas of ongoing model development include modeling the behavior of PAOs during short and long-term anaerobic decay conditions and how to account for the relative processes of cell maintenance and lysis (Houweling 2011).

## ●●●● FERMENTER DESIGN

### What Mechanical Issues Should Be Considered in the Design of a Sludge Fermenter?

#### Primary Sludge Pumping

The primary sludge pumping rates used and percent solids concentration varies significantly with different primary sludge fermenter configurations. In activated primary sedimentation tanks, the primary sludge has relatively high solids content (between 4 and 5 percent) because of the deep sludge blanket being maintained in the clarifiers. In these systems, positive displacement pumps are generally used to handle the high solids concentrations and grit loads. In completely mixed fermenters in which the fermented sludge is returned to a point upstream of the primary clarifiers, the primary sludge percent solids is largely determined by the solids concentration being maintained in the complete mix tanks, typically between 1 and 2 percent. In these cases, solids handling centrifugal pumps have been used.

In single-stage static fermenters, thickening occurs within the fermenter and primary sludge is normally withdrawn from the clarifiers at a relatively dilute concentration, generally less than 1 percent solids. In these systems, solids handling centrifugal pumps are more suitable because of their lower power and maintenance requirements. In 2-stage complete mix/thickener fermenters it is usually desirable to pump the primary sludge at lower flow rates and higher concentrations to reduce the solids loading rate to the gravity thickeners, and positive displacement pumps are more appropriate.

As a general rule, the rheological properties of fermented primary sludge are challenging. Therefore, it is recommended that, where feasible, continuous sludge pumping at lower pumping rates be used rather than the use of fixed speed sludge pumps on a timed ON/OFF cycle. Sludge pipe sizes should be matched to the sludge pumping rates so that adequate velocities are maintained in the piping to prevent solids deposition and pipe blockages.

#### Grit Removal

Plants with primary sludge fermenters should have effective upstream grit removal, either from the main plant flow in the plant headworks or from the primary sludge upstream of the fermenters. Grit tends to settle in all unmixed tanks within a wastewater treatment plant. In plants having primary sludge fermenters, all grit not removed in the upstream unit processes tends to accumulate in the fermenter tankage, where it will occupy reactor volume, cause abrasive wear on the mechanical equipment and pipework, and increase the torque load on thickener sludge collector mechanisms.

#### Sludge Grinding and Screening

Primary sludge at plants without fine screening in the headworks has significant quantities of plastics, hair, rags and other fibrous material that cause blockages in the sludge pumps and

pipework. This problem can be exacerbated in complete mix fermenter tanks where the vortexing action of the mixers causes roping of the fibrous material. In-line grinders or chopper pumps can be used to macerate sludge, thus reducing the propensity for pump and pipe blockages. Alternatively, the sludge flow can be screened to remove debris, thus minimizing operating problems in the fermenters and downstream sludge digestion and dewatering processes, and improving the quality of the final biosolids product.

### Sludge Mixing

In configurations that use a complete mix fermenter tank, sufficient mixing energy should be provided to prevent solids deposition on the tank floor and the formation of a stable scum layer on the surface, but not so great as to cause vortexing and excessive air entrainment in the fermenter. The applied mixing energy should be between 8 and 10 W/m<sup>3</sup> in primary sludge fermenter complete mix tanks. In mixed liquor or RAS fermenter complete mix tanks, lower mixing energy near 2 W/m<sup>3</sup> using slow-speed top entry mixers and mixing chimneys has been suggested to avoid oxygen entrainment and maintain deep anaerobic conditions for growth of *Tetrasphaera* PAOs in these secondary sludge fermentation processes (Barnard et al. 2017).

### Sludge Collector Mechanisms

In activated primary sedimentation tanks, static fermenters and fermenter gravity thickeners, deeper sludge blankets are maintained compared to conventional primary clarifiers or sludge thickeners. The deeper sludge blankets, higher thickened sludge concentrations, and increased grit loads all increase the torque load on the sludge collector mechanisms. Consequently, the mechanisms and drives must be designed and specified to accommodate these higher torque loads. Picket fence style thickener mechanisms are recommended for these fermenters.

### Scum Removal

Radial scum skimming should be provided on static fermenters and fermenter gravity thickeners. The collected scum can be thickened and pumped to the digesters together with scum collected in the primary clarifiers. Scum buildup can also be a problem in complete mix fermenter tanks where the mixing intensity provided is insufficient to entrain the scum with the fermenter bulk liquid. Roof-mounted “scum busters” and pumped mixing systems with discharge nozzles at the fermenter surface have been used to prevent the formation of a stable scum layer, an approach that is incorporated into some anaerobic digester designs.

### Fermented Sludge Pumping

In cases where the fermented sludge concentrations are low and the sludge must be pumped relatively short distances and against a low static head, solids handling centrifugal pumps are commonly used. However, in cases where the fermented sludge is thickened prior to pumping

(single-stage static, 2-stage complete mix/thickener and UFAT fermenters) and/or cases where the sludge must be pumped long distances to the sludge handling system, positive displacement pumps are normally used to overcome the higher head losses.

### **What Are the Key Odor and Corrosion Control Issues to be Considered in the Design of a Sludge Fermenter? What Are Some of the Mitigation Measures Typically Used in Fermenter Design?**

Sludge fermentation creates a highly odorous and corrosive environment in the vicinity of the fermentation units. Hydrogen sulfide (H<sub>2</sub>S), reduced sulfur compounds, and to a lesser extent, ammonia and amines, all play a part in creating odor and corrosion problems typically associated with fermenters. Fermenter headspace gases with sulfide concentrations over 50 ppmv were measured at the Bonnybrook WWTP in Calgary. Fermenter off-gases typically contain less than 20 ppm of H<sub>2</sub>S; however, concentrations as high as 100 ppm have been observed in extreme cases.

Fermentation units should be covered and the headspace foul air withdrawn and treated in an appropriate odor control system. Typical headspace venting rates are between 3 and 6 air changes per hour (AC/h), depending on the interaction between the cover and the exhaust rate, as needed to obtain sufficient negative pressure that air moves from outside the cover into the covered space. Fermenter covers should have a low profile to minimize the headspace and thereby reduce the volume of air to be treated in the odor control system. Two and three-stage systems consisting of chemical scrubbers and/or biofilters are commonly used for foul air treatment. An alternative means of foul air treatment would be to discharge the foul air through a dedicated diffused aeration system in the BNR bioreactor designed to prevent the foul air from damaging the main aeration blowers and diffuser system.

Fermenter structures must be corrosion resistant. CO<sub>2</sub> gas generated during fermentation dissolves in the condensed moisture in the headspace and produces corrosive carbonic acid. In addition, sulfur reduction in the fermenter results in H<sub>2</sub>S formation, which when it evolves to the headspace will be oxidized to sulfuric acid in the high humidity environment, also a common cause of corrosion. Another form of microbially induced corrosion (MIC) occurs when biologically reduced sulfur reacts with ferric to cause ferric migration to the surface and form ferric sulfide. To avoid corrosion problems, all surfaces above the liquid level in the fermenter, and all surfaces to a minimum of 1 m below the minimum liquid level should receive a protective coating, preferably a plastic liner, to withstand low pH conditions to around 1.0. The pH in the fermenter bulk liquid is likely to range from 5.0 to 6.5, so surfaces more than 1 m below the liquid level are less susceptible to corrosion problems. However, it is recommended that sludge collector drives and mechanisms have a corrosion resistant coating or be constructed of stainless steel. The grade of stainless steel and its finishing should be selected considering the chloride content of the wastewater and the likelihood that MIC could attack poorly finished welds and other surface disruptions.

## When Can Sludge Fermentation Be Considered Over Other Forms of Carbon Augmentation?

In general, sludge fermentation adds to the capital cost and operating complexity of BNR processes as additional tankage and equipment are required to serve as fermentation units. These fermentation units may also add to the operating complexity by needing extra operator attention and by creating odor and corrosion issues at the plant. On the other hand, many forms of carbon augmentation (e.g. the addition of external carbon sources such as acetate or methanol) add to the plant operating costs if these must be purchased from a chemical supplier. The use of external carbon sources is considered to be less sustainable than sludge fermentation due to the environmental costs involved in manufacturing and transporting the chemicals. The addition of external carbon sources also adds to the mass of waste sludge generated at a plant when compared with internally generated sources from sludge fermentation. In a limited number of cases, suitable carbon augmentation sources are available as a waste product from a local food processing industry. Some of the newer sludge cell lysis technologies used for the pre-treatment of waste sludge ahead of anaerobic digestion also have the potential for becoming viable alternatives to external carbon addition. Finally, the economics of sludge fermentation are highly site-specific, and the true value should be determined through a detailed life cycle cost analysis.



## ●●●● RESEARCH NEEDS

1. Development of a standardized method of expressing the VFA yield in primary sludge and secondary sludge fermenters, e.g., g VFA (as HAc) per g of TSS or VSS applied; g VFA (as HAc) per g of TSS or VSS hydrolyzed; etc.
2. Development of a primary sludge fermenter module capable of representing several fermenter configurations that can be incorporated into process simulators that accurately predicts the production of VFA through acid fermentation and its impact on the system biological phosphorus removal. Development of methods to model/simulate partial mixed fermentation vessels and solids/liquid separation through elutriation.
3. Further development and calibration of existing plant simulators to accurately model the quantities of VFA that can be generated through the decay and hydrolysis of secondary sludge in the anaerobic zones of the bioreactor, and its impact on the system biological phosphorus removal.
4. Development of a design manual for primary and secondary sludge fermenters and their associated odor and corrosion control systems.
5. Identification of the best method of measuring the location of the top of the sludge blanket in static fermenter/thickeners and gravity thickeners.
6. Standardization of the use of ORP measurement of fermentate to control elutriation water flow rate.
7. Further investigation of kinetic and metabolic characteristics of *Tetrasphaera* PAOs.
8. Research on the microbial ecology of fermentative heterotrophs grown in secondary sludge fermenters and their role in secondary sludge fermenters and conventional anaerobic zones.

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