A review of characterisation requirements for in-line prefermenters
Paper 2: Process characterisation

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Abstract

The operational factors having a significant effect on in-line prefermentation efficiency include the sludge recycle rate and the subsequent sludge elutriation rate, solids concentrations and retention times. The prefermenter configuration employed is a determining factor, which allows for some degree of operational flexibility. Side-stream and multiple tank systems are superior in this regard and outnumber the use of in-line single tank prefermenters, which are mainly employed due to lower space and capital cost requirements. This paper reviews the basic design and monitoring requirements for in-line prefermenters, to establish simple strategies on which prefermenter evaluations could be based.

Nomenclature

ADWF = average dry weather flow
APT = activated primary tank
BEPR = biological excess phosphorus removal
BNRAS = biological nutrient removal activated sludge
C = carbon
COD = chemical oxygen demand
DO = dissolved oxygen
DR = downflow velocity rate (stilling chamber)
DWAF = Department of Water Affairs and Forestry
HRT = hydraulic retention time
HRT_{eff} = effective hydraulic retention time
N = nitrogen
NH_3 = ammonia
NH_3+NH_4-N = total ammonia nitrogen
NO_3 = nitrate
MUCT = modified University of Cape Town
o-PO_4 = orthophosphate
P = phosphorus
PST = primary settling tank
r_{VFA} = rate of VFA production
RAS = return activated sludge
SER = sludge elutriation rate
SetS = settleable solids
SO_4 = sulphate
SRR = sludge recycle rate
SRT = sludge retention time
SS = suspended solids
T = ambient temperature
TDS = total dissolved solids
TKN = total Kjeldahl nitrogen
TOD = total oxygen demand
TP = total phosphorus
TS = total solids
UCT = University of Cape Town
UR = upflow velocity rate (tank)
VFA = volatile fatty acid
WCW = water care works

Introduction

The significance of prefermentation

Approximately 98% of the potable water supply in South Africa is drawn from closed surface water sources such as dams and lakes (Lötter and Pitman, 1992). The primary nutrients that cause eutrophication in surface water are C, N and P, with P usually considered to be the limiting nutrient (major contributor) (Lilley et al., 1997). The current review of legislative standards by DWAF, which includes the reduction of WCW effluent P and N concentrations discharged into surface water, emphasises the necessity to optimise contemporary nutrient removal processes. Pitman (1999) reports that the proposed constituent limits for the northern catchment of Johannesburg includes a 2.0 mg N/ℓ (NH_3+NH_4-N), a 6.0 mg N/ℓ NO_3 and a 0.6 mg P/ℓ *o*-PO_4 standard. Complete compliance with stricter regulations should ideally be met at existing WCW without the need for additional capital expenditure, or at a higher operational cost due to chemical dosing.

Research must therefore be directed on enhancing the biologically mediated prefermentation processes, to enrich settled sewage with biodegradable organic matter for BNRAS performance improvement (Lötter and Pitman, 1997). A controlled anaerobic environment, devoid of molecular or chemically bound oxygen, is required for prefermentation. Adequate wastewater characterisation and prefermenter performance guidelines are essential for operational control to ensure that the prefermented settled sewage is suitable for the downstream BNRAS process.

The factors governing prefermentation

The full-scale prefermentation of primary sludge was implemented successfully at WCW in the early 1980s as a primary treatment process to enhance BNRAS (Pitman et al., 1992). PSTs and thickeners were retrofitted or constructed from this stage as in-line or side-stream prefermenter configurations to enrich the settled sewage with soluble fermentation products. In a single (in-line)

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primary tank configuration, formulated as an APT (Barnard, 1984), the settled sludge is recycled to combine with the raw sewage inflow. The solids resettle to maintain a sludge blanket and to elutriate the generated soluble organic matter from the "active" sludge blanket.

The solids thickening and solids removal objectives of a PST must be counterbalanced with the organic matter fermentation requirements of an APT. Major operational factors influencing the fermentation process in an APT include the SetS, SS and TS loading, the sludge age or SRT, and the SER, which is obtained from the SRR. At a higher solids loading, more material is available in the tank that can be transformed to VFAs, although inhibition, solids overloading and solids carry-over can occur. The generated VFA concentration can be used as a guideline to quantify the changes in organic matter due to prefermentation. At lower sludge ages less VFA is produced, but better solids settling can be achieved due to the lower solids concentration in the tank. The amount of VFA elutriated out of an APT should be directly related to the SER. The expected solids carry-over in the settled sewage at a high SER will, however, place a practical limit on the SRR. It has been reported that excessive solids carry-over in the settled sewage during sludge elutriation is unpredictable and difficult to control (Pitman, 1999).

Prefermenter fundamentals

Terminology

A variety of names represent the prefermentation process, due to emphasis placed on different reference mechanisms (Münch, 1998). The terminology used includes biological sludge hydrolysis (Brinch et al., 1994), hydrolysis-acidogenesis (Perot et al., 1988), primary sludge fermentation, acidogenic digestion, acid-phase anaerobic digestion, activated PST (Randall et al., 1992), acid (high rate) fermentation (Pitman, 1999) and APT settling (Barnard, 1984). The term prefermentation is widely used, and the following general definition is adapted from Münch (1998): "Prefermentation is the intentional anaerobic production of VFA in primary treatment tank(s), from the suspended or settled organic matter present in domestic and industrial wastewater, with the aim of transferring and using these VFAs to improve the biological nutrient removal performance of a WCW".

Biological mechanisms

The anaerobic digestion process, traditionally used to prepare WCW sludges for ultimate disposal, has been extensively researched during the last 20 to 30 years (Münch, 1998). Prefermentation is the first phase of this digestion process, and a multiple series of successive and concurrent biological degradation reactions can be tabulated to illustrate the general digestion process terminology. The reactions are listed in Table 1, based on pathways described in detail by others (Perot et al., 1988; Elefsiniotis, 1993; Münch, 1998).

The Phase I reactions of hydrolysis (or liquefaction, Gujer and Zehnder, 1983) and acidogenesis are required at prefermenters, with the emergence of the Phase II reactions of acetogenesis and methanogenesis leading to prefermentation failure. The suppression of Phase II reactions is achieved in practice by maintaining a low SRT, which ensures that methanogenic bacteria are washed out of the prefermenter (Münch, 1998). The additional Phase III VFA consumption reactions, as listed in Table 1, must be considered when evaluating prefermenter performances. Limited VFA generation can be related to the presence of, amongst others, DO, NO_3 or SO_4, which results in concurrent VFA consumption during the Phase I VFA generation processes.

Equipment configurations

The main prefermenter process configurations are classified according to the number of tanks used, flow configurations and sludge retention time control modes (Münch, 1998). An in-line prefermenter, fed with raw sewage, consists of a gravity thickener equipped with a settled sludge recirculation capacity. A side-stream prefermenter, fed with primary sludge from an upstream PST, consists of a mixing tank, a thickener or both. The most

TABLE 1
Biological pathways in anaerobic degradation processes

Phase I: Prefermentation (VFA generation processes)	
Hydrolysis	Extracellular enzyme-mediated transformations, where complex soluble and particulate (insoluble) organic material is transformed into simple soluble substrate, by incorporation into water molecules.
Acidogenesis	Acidogenic bacteria (faster growing when compared to methanogenic bacteria) ferment the hydrolysis products into long- and short-chain volatile acids, other acids, alcohols, etc.
Phase II: Methane generation (VFA consumption processes)	
Acetogenesis	High molecular fatty acids, as well as volatile acids (except for acetate), are decomposed into reaction intermediates: simple acids such as acetate, propionate and butyrate.
Methanogenesis	Methanogenic bacteria (slower growing) metabolise the VFA (decarboxylation of acetate), methane formation.
Phase III: Additional VFA consumption processes	
Aerobic respiration	DO present: bacteria (aerobic) consume VFA
Sulphate reduction	SO_4 present: bacteria (sulphate reducing) consume VFA
Denitrification	NO_3 present: bacteria (heterotrophic) consume VFA

TABLE 2
Basic process configurations for prefermenters

Configuration	Equipment	Feed inlet	Sludge outlet	Supernatant outlet
In-line prefermenters				
APT	Gravity thickener	Raw wastewater	Recycle to inlet and waste, or to BNRAS reactor	BNRAS reactor
Side-stream single-stage prefermenters				
Static	Gravity thickener	Primary sludge from up-stream PST	Waste, no recycle	BNRAS reactor
Complete-mix	Mixing tank	Primary sludge from up-stream PST	None	BNRAS reactor or optional return to PST
Side-stream two-stage prefermenters				
Complete-mix static thickener	Mixing tank and gravity thickener	Primary sludge from up-stream PST to mixing tank	Thickener sludge re-cycle to mixing tank, or waste	Thickener overflow to BNRAS reactor

prevalent configurations are tabulated in Table 2 (adapted from Münch, 1998). The listed configurations can be operated as batch or continuous processes. A schematic representation in **Appendix A** (Fig. 1) illustrates the basic prefermenter configurations.

The major advantage of an in-line configuration is the lower capital construction cost (Hartley et al., 1999) and a compact civil design due to lower space requirements. The major advantage of a side-stream configuration is the larger operational flexibility and control allowed (Banister, 1996), which can be even more beneficial in the absence of raw sewage hydraulic equalisation or flow balancing facilities at a WCW. In a side-stream prefermenter the sludge blanket level control, and therefore, the sludge age in the secondary tank, are simply controlled by adjusting the waste sludge from the secondary tank (Barnard, 1984), together with the prefermenter inlet primary sludge flow from the PST (Rabinowitz et al., 1997). The reported secondary thickener on-line sludge level monitoring and control instrumentation employed successfully at existing side-stream two-stage prefermenters ensures fully automated sludge inventory management (Wilson and Keller, 1995).

The agitation of primary sludge in a complete-mix tank enhances fermentation due to better contact between suspended organic material and organisms (Perot et al., 1988). In a side-stream prefermenter the supernatant flow rate is only about 2 to 3 % of the raw sewage inflow to the upstream PST, and the VFA in the total BNRAS feed is only increased moderately (4 to 5 mg/ℓ, Rabinowitz et al., 1997) when reintroduced into the mainstream process (BNRAS feed). The VFA generation rate is, however, higher for a side-stream system and the VFA addition to the BNRAS reactor can be controlled (Brinch et al., 1994). The BNRAS reactor feed characteristics are also more controllable at dedicated PSTs, when compared to in-line prefermenters, as most of the raw sewage in a side-stream system bypasses the prefermenters, to be treated exclusively in the PSTs.

Prefermenter process unit interaction

Prefermentation and BNRAS configurations

Unintentional wastewater prefermentation has taken place ever since wastewater has been transported in sewers with long retention times, at high temperatures and with minimal air ingress, and whenever anaerobic conditions existed in a WCW (Münch, 1998). The removal of C was, however, the primary purpose of aerobic secondary treatment units until the 1960s. With the use of anoxic zones the ammonia (nitrification) and nitrate (denitrification) removal processes were developed and implemented for N removal. The P removal mechanisms were finally formulated in the early 1970s, when it was observed that anaerobic conditions were beneficial for BEPR (Barnard, 1974a and b).

In the early 1980s researchers realised the full impact of prefermentation. The Canadian Kelowna WCW was the first BNRAS WCW to be retrofitted in 1982 for side-stream prefermentation by retaining primary sludge from a PST for 6 d in an over-sized thickener (Barnard et al., 1995; Münch, 1998). The VFA-enriched supernatant from the dedicated static prefermenter (the thickener) was directed to the anaerobic zone of the BNRAS reactor, leading to an improved overall P removal. The preferred process sequence for a mainstream 3-stage BNRAS process was thus established as prefermentation, followed by anaerobic, anoxic and aerobic reactor stages (Barnard, 1984), to ensure that biologically mediated C, N and P removal took place.

Appropriate BNRAS aeration management systems can reduce the presence of oxygen in anaerobic reactor zones, but not the impact of high TKN/COD ratios. High TKN/COD ratios in the prefermented settled sewage and oxidised nitrogen compounds (e.g. nitrate) or molecular oxygen in the RAS recycle stream to the anaerobic zone makes BEPR in the mainstream single sludge denitrification processes (Phoredox or Bardenpho) difficult to control (Osborn et al., 1979; Wentzel et al., 1985). As one alternative, the UCT and MUCT process configurations allow the RAS to pass through a separate anoxic zone before entering the anaerobic zone. This ensures an optimal anaerobic condition and prevents VFA

TABLE 3
Common BNRAS configurations and suitable TKN/COD ratios for settled sewage

BNRAS process	Implementation	TKN/COD Limit
Wuhrman	1962	-
Modified Ludzack-Ettinger or MLE	1973	> 0.1
Bardenpho	1973	< 0.1
Phoredox (also named Anaerobic/Oxic or A/O)	1974	< 0.07 to 0.08
3-stage Phoredox (also named Anaerobic/Anoxic/Oxic or A^2/O)	1974	< 0.07 to 0.08
5-stage Modified Bardenpho or Phoredox (also named Modified Bardenpho)	1978	< 0.08
UCT (also named Virginia Initiative Project or VIP)	*ca.* 1983	> 0.11
MUCT	*ca.* 1983	0.9 to 0.11

TABLE 4
PST and prefermenter functions, performances and objectives or impacts

Function	Performance level	WCW Impact or objectives
Removal of SetS	Average 90 to 95%	Reduce solids load and energy requirements in BNRAS reactor.
Removal of SS	Average 50 to 80%	Reduce the solids load (and TOD) in BNRAS reactor.
Removal of COD	Average 30 to 50%	Reduce the organic load (and TOD) in BNRAS reactor.
Removal of TKN and TP	Average 15 to 25%	Reduce the nutrient load (and TOD) in BNRAS reactor.
Removal of floatable material and scum	Depending on local operation and facilities	Prevent equipment damage and blockages. Reduce odours.
Thickening of settled solids	Maximum of 6% TS, 1% TS required if additional thickeners available	Waste sludge treatment processes or disposal handling capacity optimisation.
Reduction in secondary (activated) sludge yield	Average 50 to 70%	Smaller BNRAS reactor, less secondary sludge. Secondary sludge is voluminous and difficult to dewater.
Equalisation of the inflow	Depending on local operation and facilities	Reduce shock loads (hydraulic and constituent).
Fermentation of primary sludge for VFA generation	Maximum 0.2 mg VFA/mg COD (side-stream) or 1 to 70 mg VFA/ℓ·h	Convert and degrade complex organics as carbon and energy source in BNRAS. Smaller anaerobic zone.
Elutriation of fermentation products via sludge recycle	Depending on local operation and facilities	Release generated VFA from sludge to water for transfer to BNRAS reactor anaerobic zone.
Eliminate need for chemical precipitation of P	Complete elimination of chemical addition possible	Lower operational cost. Lower sludge yield (average 25%). No salinity increase and no alkalinity decrease.

consumption (instead of nitrate) by denitrifying bacteria, where VFA is available as the external energy source (Barnard and Fothergill, 1998). The most prevalent conventional full-stream BNRAS process configurations in South Africa (Randall et al., 1992; Lilley et al., 1997) are summarised in Table 3. Available design TKN/COD ratios are also supplied in Table 3 as a simple assessment of the suitability of a BNRAS process configuration for a specified settled sewage.

From the 1980s, WCW started incorporating full-scale prefermenters in existing or at new primary treatment units, not waiting for all the aspects of prefermentation to be fully researched (Münch, 1998). More than 30 % of BNRAS WCW in Australia employed prefermentation by 1998 (Hartley et al., 1999), and it is often considered as a standard design practice at a new WCW (Randall et al., 1992). When an existing WCW is retrofitted to include prefermentation, the suitability of the nutrient ratios from the prefermenter for the existing BNRAS process must be taken into account, as listed in Table 3.

Prefermentation and primary settling

Primary settling, or sedimentation, is the oldest and one of the most widely used wastewater process units (Christoulas et al., 1998). Theoretical mathematical sedimentation models are, however, not yet fully representative, due to the complexity of phenomena such as particle composition, flocculation effects, fluid characteristics, flow regimes, environmental factors (sun, temperature and wind) and structural tank details. The conventional uniform overflow theory, which assumes one-dimensional flow (to calculate the settled sewage upflow rate), is still widely used (Van der Walt, 1998). Column-settling tests frequently fail to predict average settling velocities reliably under full-scale operational conditions (Christoulas et al., 1998). The reported high scale-up design factors (1.25 to 1.75) used are a reflection of the uncertainty involved in the sizing and optimisation of a PST.

The primary settling process consists of a thickening and clarification function, and the raw sewage is thus separated into a concentrated settled sludge and a clarified settled sewage component (Bergh, 1996). A PST employs energy dissipating devices and gravity-settling principles at reduced flow conditions to induce this water-solids separation (Lilley et al., 1997). The four types of settling occurring in a PST are quantified as discrete, flocculent, zone and compressive settling (Anderson, 1981), and similar settling modes occur in an APT.

Prefermentation comprises four distinct stages for which a minimum of two tanks are usually required. These stages consist of the separation of the particulate organic matter (primary settling), the fermentation (prolonged thickening or mixing) and transfer of the soluble organic products (sludge recycle and elutriation), and the clarification of the fermented effluent (settled sewage transfer) (Gonçalves et al., 1994). An APT fulfils several functions in a single tank, with the four settling modes and the four prefermentation stages occurring simultaneously during continuous operation. The major functions, performance levels and impacts of a PST and a prefermenter are summarised in Table 4 (based on Randall et al., 1992; Park et al., 1997).

The principle objectives from the primary treatment unit are to modify the solids and organic loads to lower the required TOD and BNRAS reactor volume, ideally at an increased nutrient removal capacity.

Prefermenter operational factors

It has been reported that prefermenter operational guidelines are still full of contradictions, with conflicting opinions and experimental data available on prefermenter performances (Randall et al., 1992; Münch, 1998). A principal measure of prefermenter efficiency is the VFA production rate (r_{VFA}), which is affected by a range of design and operating parameters (Münch, 1998). The most important operational parameters reported are the hydraulic and solids residence times (HRT and SRT) and the influent solids concentration, expressed as TS for a side-stream prefermenter and as SS for an in-line APT.

Other significant factors reported, which are usually not controlled at prefermenters, include ambient temperature, settled sewage and sludge pH, mixing intensity and mass transfer, type and concentration of substrate, solids particle size, chemical inhibitors and trace metals (Banister, 1996; Münch, 1998). Sludge blanket level stability, odour generation and visual indicators can be included as basic monitoring factors. The major omissions from the reported factors are, however, the SRR and the SER. These rates represent the potential transfer of soluble fermentation products from the fermented sludge to the settled sewage, and unsuitable rates can have a detrimental impact on the downstream BNRAS process. General prefermenter performance guidelines reported are summarised in Table 5.

The differences between laboratory-scale experimental results and full-scale prefermenter performance results must be kept in mind, as noted by some researchers (Skalsky and Daigger, 1995; Münch, 1998). Performance variations in excess of 100 % are reported between bench- and full-scale prefermenter tests, with the maximum r_{VFA} of 30 mg VFA/ℓ.h observed as 70 mg VFA/ℓ.h in bench-scale side-stream prefermenters. Laboratory and even pilot-plant performances usually represent ideal testing environments (Randall et al., 1992), and guidelines based on full-scale prefermenter operation are preferred.

Another important aspect of prefermenter evaluation concerns the prefermenter feed used to compare prefermenter performance. The fermentation potential yield of 0.06 to 0.26 mg VFA (as COD)/ mg influent sludge VSS (as COD) is widely used (Wentzel et al., 1991; Skalsky and Daigger, 1995). This benchmark can only be used for side-stream prefermenters with primary sludge feed, and not for in-line prefermenters with raw sewage feed.

Sludge recycle and elutriation rates

A portion of the settled sludge is recycled to the inlet of an APT, where it is usually mixed hydraulically with the raw sewage before re-entering the APT. The water-soluble fermentation products (represented as VFA), which are adsorbed to the sludge, are elutriated from the sludge and transferred to the settled sewage (Osborn et al., 1986; Randall et al., 1992) and the solids resettle in the APT. The SER refers to the ratio of the mass of fermented solids recycled to the volumetric inflow rate of raw sewage to the APT, whereas the SRR refers to the ratio of the volume of sludge recycled to the volumetric inflow rate of raw sewage to the APT. The SER must be high enough to ensure adequate elutriation contact between the sludge particles and the raw sewage. A SRR that is too high can lead to sludge blanket disintegration, when the top water layer is drawn through the sludge blanket into the recycle stream. A SRR that is too low or a discontinuous (cyclic) SRR pumping interval can lead to sludge draw-off pipe blockages and travelling sludge bridge failures due to excessive sludge thickening.

Limited published data are available about SER or SRR and potential correlations with r_{VFA}. A recent full-scale evaluation (Hartley et al., 1999) indicated that a high SRR (0.5 m^3 sludge/m^3 raw sewage) increased the VFA outflow concentration in an APT. It was further reported that only 50% of the VFA production occurred in the sludge blanket. This can be contributed to the high SRR, leading to a high SS inventory in the settled sewage layer above the sludge blanket. Another full-scale APT evaluation (Rössle, 1999) indicated that a higher SRR (from 0.01 to 0.09 m^3 sludge/m^3 raw sewage) and a resulting higher SER (from 0.7 to 3.7 kg sludge/m^3 raw sewage) increased the VFA production rate (1.4 to 5.7 mg VFA/ℓ·h) in an APT. It was also confirmed during this evaluation that the SS concentration increased (together with nutrient ratios) in the settled sewage at the elevated SRR.

Hydraulic retention time

The HRT is the average length of time that water remains in the tank (Münch, 1998). The benefits of flow equalisation at in-line and side-stream preliminary storage basins, to dampen the diurnal variation of hydraulic, solids and organic loads and nutrient ratios entering the BNRAS reactor, have been reported (Armiger et al., 1993). The side-stream prefermenter configuration facilitates HRT (and load) equalisation into the prefermenter, which is not possible for an in-line APT configuration. The HRT is an important design parameter for prefermenters, as it is directly related to required tank sizes and, thus, to the capital construction cost. The upflow velocity

TABLE 5
Design, operational and monitoring guidelines for prefermenters

Variable	Level	Associated detail	Reference
SER	0.7 to 3.7 kg/m^3	Low VFA transfer and high TKN/COD increase at low SER	Rössle, 1999
SRR	0.5 m^3/m^3 0.01 to 0.09 m^3/m^3	High SS in settled sewage, additional primary clarifiers required High SS carry-over at high SRR	Hartley et al., 1999 Rössle, 1999
HRT	15 h 6 to 42 h, average 18 h 2 to 4 h	General guide for side-stream prefermenter (not complete-mix) r_{VFA} varies to according prefermenter type in survey of 8 WCW General guideline for single in-line APT	Dawson et al., 1995 Münch and Koch, 1998 Rössle, 1999
HRT_{eff}	80% of HRT	Sludge volume < 20% of total tank volume (only hopper volume)	Rössle, 1999
DR	45 to 60 m/h	Sludge scouring and resuspension problems at high DR	Rössle, 1999
UR	1.5 to 2.0 m/h	Deep tanks (> 3 m depth) required to ensure settling at a high UR	WRC, 1984
SRT	6 d 4 to 6 d	Maximum SRT for 75% VFA yield, guide to prevent methanogenesis 2% of ADWF as primary sludge feed to side-stream prefermenter	Banister, 1996; Lilley et al., 1997 Rabinowitz et al., 1997
SS_{INFLOW}	Raw sewage load	No control at in-line APT	Rössle, 1999
TS_{SLUDGE}	< 1% 0.5 to 1% solids 0.5 to 2%	r_{VFA} double at 0.43% TS compared against 2.6% TS (at SRT of 2 d) Side-stream prefermenter feed Maximum TS to prevent VFA inhibition at side-stream prefermenter	Skalsky and Daigger, 1995 Münch, 1998 Banister and Pretorius, 1998
pH_{SLUDGE}	4.3 to 7.0	Limited range (guideline 5-6) to prevent VFA generation inhibition	Skalsky and Daigger, 1995
T	21 to 24°C 22 to 28°C	50% reduction in VFA yield at lower 14-16°C 45% reduction in VFA yield at lower 12 °C	Skalsky and Daigger, 1995 Banister, 1996
r_{VFA}	1 to 10 mg VFA/ℓ·h 15 to 30 mg VFA/ℓ·h	Raw wastewater as prefermenter feed (in-line) Primary sludge as prefermenter feed (side-stream)	Münch, 1998 Münch, 1998
Sludge blanket	Variations > 1m	Hydraulic load too large or HRT_{eff} insufficient	Rössle, 1999
Inhibitors	Oxidised compounds	VFA consumption and r_{VFA} reduction if inhibitors present	Rössle, 1999
Visual indicators	Black settled sewage, bubbles, solids floating	Prefermentation failure (methanogenesis) or floor sludge scraper failure	Rössle, 1999

TABLE 6
Minimum data required for a basic in-line prefermenter evaluation

Item	Inflow (raw sewage)	Outflow (settled sewage)	Settled sludge	Sludge recycle
Wastewater characteristics				
Solids	SS, SetS	SS, SetS	*	TS
C	COD, VFA,	COD, VFA	*	COD, VFA
N	TKN, (NH_3+NH_4–N)	TKN, (NH_3+NH_4–N)	*	TKN, (NH_3+NH_4–N)
P	TP, *o*-PO_4	TP, *o*-PO_4	*	TP, *o*-PO_4
Operational & monitoring factors				
Hydraulic	Volumetric flow	Volumetric flow	Volume	Volumetric flow
Environmental	pH, T, DO	pH	*	pH
Calculated guidelines				
Parameter	HRT, HRT_{eff}, UR, DR	Removal of COD, N, P	SRT	SRR, SER
Nutrient ratios	TKN/COD, TP/COD	TKN/COD, TP/COD	*	TKN/COD, TP/COD
VFA generation	r_{VFA}			

* similar to sludge recycle

rate (UR), which is the average upward vertical velocity of liquid in the tank, can be used as a substitute for HRT. The UR should be low enough (< 2.0 m/hr, WRC, 1984) to ensure that settleable particles are able to gravitate out of suspension. The stilling chamber DR, which is the average downward vertical velocity of the raw sewage inflow into the tank stilling chamber (central inlet port), can be used as an indicator of potential sludge scouring and settled solids resuspension.

It is proposed that an effective HRT_{eff} parameter be introduced for an APT, which is the average length of time that water remains in the available tank contact volume (volume occupied by water alone). In an APT with a high sludge content (i.e. a high sludge blanket) the solids removal is restricted by the loss of available clear water settling space. This loss limits the settling capacity, or detention efficiency, of the tank. The thickening and storage of sludge should take place within the sloped hopper section of the tank PST (Randall et al., 1992), which should not be larger than 20% of the total tank volume. Accurate (preferably continuous) sludge blanket level measurements are required at an APT to determine this sludge inventory (Busch, 1991), and to identify excessive blanket height variations (larger than 1 m). These variations can occur during peak inflow conditions and can lead to the resuspension and excessive carry-over of solids from the tank (Rössle, 1999).

Solids retention time

The SRT, also called the sludge age, is higher than the HRT in most prefermenter types (except for a completely mixed tank without recycle), by some mechanism of water and solids separation. The SRT is the average length of time that solids remain in the prefermenter tank (Münch, 1998). A too short SRT leads to the washout of organisms, an unstable process, a diluted sludge and excessive sludge production. A too long SRT leads to the loss of fermentation products due to methanogenesis. The acidogenic bacteria are faster growing than the methanogenic bacteria, and process control through SRT management is thus guided to ensure that the desired bacteria content stays in the reactor. The SRT influences the required tank size and sludge handling facilities (Skalsky and Daigger, 1995).

The accepted SRT determination method is based on the ratio of settled solids volume in the prefermenter to the rate of solids removal from the prefermenter by means of sludge wasting and settled sewage solids carry-over (Münch, 1998). A portion of the biodegradable matter (volatile solids) in the settled sludge will, however, hydrolyse to soluble matter due to the prefermentation reactions. A more representative prefermentation SRT, a "prefermentation retention time", should be based on COD changes in the prefermenter. A COD mass balance, with sludge blanket and liquid COD determinations, and equivalent COD changes based on VFA production, is thus required. Such a COD balance appraisal for an APT is not documented in the available references (Rössle, 1999).

The literature is contradicting regarding an ideal SRT (Randall et al., 1992). Some references cite that solids must be removed completely (Osborn et al., 1989) on a scheduled basis, while practical results indicate that total solids inventory removal from a prefermenter at regular intervals is not necessary. There is no universal SRT suitable for all prefermenters, due to variable local conditions, but the general guideline is 4 to 6 d (Banister, 1996; Rabinowitz et al., 1997).

Solids concentration

Solids management strategies can be implemented easily in a side-stream prefermenter, as solids thickening and removal, and organic matter fermentation, take place separately in two tanks. The PST primary sludge solids content should be thickened to about 0.5 to 1% TS (Münch, 1998), and transferred to the secondary tank(s) for fermentation. One study indicated that a solids concentration decrease from 2.6 to 0.43% TS (at a 2 d SRT) resulted in a twofold

VFA generation rate increase (at the lower TS) (Skalsky and Daigger, 1995). A maximum of 2 to 3% TS is allowed in a prefermenter to prevent solids inhibition effects (Bannister, 1996). Sludge settleability improvement has also been reported at lower solids concentrations (Skalsky and Daigger, 1995).

The dual physical and biological functions of settling and fermentation in a single APT require appropriate management strategies. The raw sewage inflow solids concentration to an in-line APT cannot be controlled. The introduction of the recycled sludge solids into the raw sewage at a SER of 3.7 kg/m^3 increases the solids surface load on the APT from about 10 to 70 kg/m^2·d, or 600% (Rössle, 1999). Solids overloading and solids carry-over have been reported at such high SER levels, due to solids not resettling. The settled solids removal efficiency will further decrease at an increasing UR (Akca et al., 1993), as experienced during peak inflow conditions in the absence of upstream flow equalisation. The complex relationships between SS and SetS concentrations, retention times, overflow rates, throughflow and settling velocities, tank shape and surge and scour actions (Anderson, 1981), which are found in a PST, are complicated in an APT by the additional SRT and SRR required. It has been established that the solids and nutrient removal in an APT show an inverse relationship with the r_{VFA} (Rössle, 1999).

VFA generation rate

The r_{VFA} is the best measure of general prefermenter efficiency (Münch, 1998). The required r_{VFA} also determines the required design tank volume. The r_{VFA} reported for side-stream prefermenters ranges between 15 to 70 mg VFA/ℓ·h, and it is usually less than 10 mg VFA/ℓ·h for an APT. The large difference is contributed to the respective primary sludge or raw wastewater feed to the prefermenter (Münch, 1998). By comparing the inflow, accumulated sludge and outflow VFA concentrations, the prefermentation efficiency and r_{VFA} can be monitored. A settled sewage VFA content of at least 50 to 100 mg VFA/ℓ is considered as adequate for BEPR (Pitman, 1991).

Prefermenter evaluation

From a summary of hydraulic and composition characteristics, a basic review of the performance of an in-line prefermenter is possible. The information required for such an APT evaluation is listed in Table 6, and it can be adjusted for side-stream prefermenter evaluations.

Conclusions

The importance of counterbalancing the fermentation requirements with solids removal and thickening requirements at an APT has been highlighted. This is essential when the downstream waste sludge handling capacity is limited, due to the absence of additional thickeners or limited digester capacity. The increased solids loading on the prefermenter due to the internal sludge recycle places a limit on the level of thickening and the solids removal that can be achieved in an APT. This aspect is not considered in detail in the available literature and a solids mass balance calculation across the APT should be performed to determine the extent of resettling or resuspension of solids under variable hydraulic loads.

A prefermenter operational efficiency evaluation must be based on proper wastewater characterisation, including solids and nutrients fractions and the identification of inhibitory substances, on-line sludge blanket level management and co-ordinated sludge wastage for proper SRT control. These steps should minimise and justify the degree of odour generation, which causes resistance for prefermentation implementation, specifically in circumstances where uncovered prefermenters are used.

The operational complexity at a single in-line prefermenter is created due to the multiple goals of solids removal and thickening, managed concurrently with the fermentation of organic matter. The benefits of an APT, mainly initial savings in construction cost and reduced space requirements, need to be evaluated over the projected lifespan of the WCW. Multiple tank systems are predominately implemented due to the operational flexibility offered. The prefermentation of a portion of the raw sewage (as settled primary sludge) in a side-stream configuration, with upstream primary settling available for the total raw sewage inflow, should reduce the increase in nutrient ratios which is common with in-line prefermenters. BNRAS process performance variations should therefore always be related to the potential changes in nutrient ratios and solids loads occurring at upstream prefermenters.

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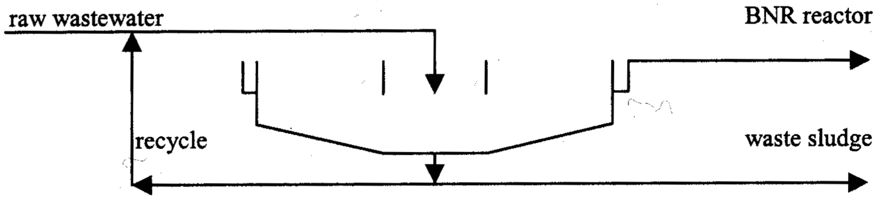
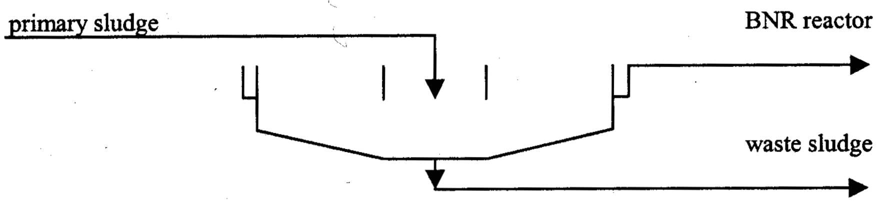
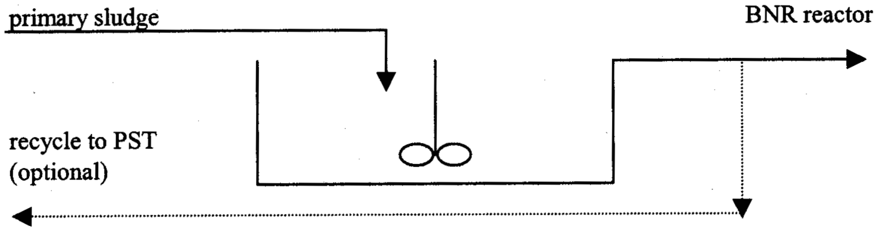
Appendix A



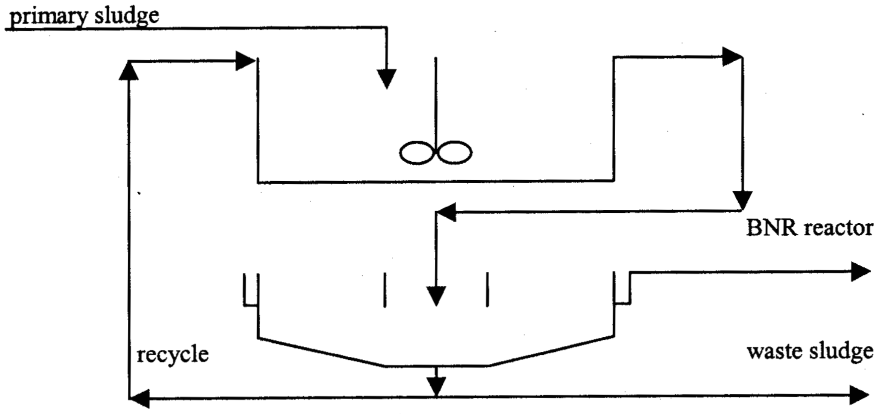
1.1. Activated Primary Tank (in-line)



1.2. Static prefermenter (side-stream)



1.3. Completely mixed prefermenter (side-stream)



1.4. Two-stage prefermenter (side-stream)

Figure 1
Schematic representation of typical prefermenter configurations