SHIFTING THE ENERGY BALANCE WITH BIOLOGICALLY ENHANCED PRIMARY TREATMENT- HOW CARBON DIVERSION MAKES SENSE

Christopher Waul, Michael Doyle, George Smith, Sergio Pino-Jelcic, and Argun Erdogan

Evoqua Water Technologies LLC, 2607 N. Grandview Blvd., Suite 130, Waukesha, WI 53188, USA

ABSTRACT

A novel biologically enhanced primary treatment (BEPT) has gained rapid acceptance among carbon diversion technologies. The Captivator® System works based on the principles of biosorption to divert more organics to anaerobic digestion in lieu of aerobic oxidation. This diversion is capable of increasing biogas production by more than 40% while simultaneously reducing the amount of carbon oxidized in the mainstream activated sludge process by 40%. This BEPT system has been shown to be a unique and cost-effective alternate to other carbon diversion systems, such as chemically-enhanced primary treatment or mechanically-enhanced primary treatment, being able to extract not just higher levels of particulate BOD but also extracting a substantial amount of soluble BOD by biological means. The Captivator System has been validated though piloting and full-scale tests, proving the following performance: 50-60% BOD and 70-80% TSS removals without chemicals. It has also shown the ability to generate 4-6% thickened sludge without the need for polymers. This BEPT technology includes the use of well-established equipment in the wastewater industry arranged in an innovative configuration to achieve carbon diversion. The world's first full scale Captivator System came online at the Agua Nueva Water Reclamation Facility, AZ in January 2014. Additional full-scale tests will be conducted in 2016 to keep developing the modelling of biosorption kinetics of this BEPT technology.

KEYWORDS: Captivator® System, energy-neutral, Folded Flow® dissolved air flotation, contact tank

INTRODUCTION

During the last decade, the wastewater treatment industry has rapidly advanced in the development of technologies to enhance conventional primary treatment. The term carbon diversion has been adopted by the industry and researchers. Carbon diversion technologies have the ability to capture more organics from the inlet wastewater stream, resulting in more raw biochemical oxygen demand (BOD) load diverted to the biosolids line in lieu of aerobic oxidation. Carbon diversion shifts the typical energy balance in a wastewater treatment plant (WWTP) by: i) reducing the aeration energy demand in the activated sludge process, and ii) diverting more organics to anaerobic digestion to capitalize on renewable energy opportunities by generating more biogas.

The development of the enhanced primary treatment technologies has been approached from three different angles: i) chemically, ii) mechanically, and iii) biologically. This paper presents the progression and current status of a novel biologically enhanced primary treatment (BEPT) developed by Evoqua Water Technologies. The Captivator® System works under the principles of biosorption and carbon diversion. It blends waste activated sludge (WAS) - from the downstream secondary process - with raw wastewater in a mildly-aerated contact tank to activate rapid biosorption of soluble organics (Ding et al., 2015). Likewise, colloidal BOD is adsorbed onto larger flocs in the contact tank. Following this tank, the stream flows to a high-rate dissolved air flotation (DAF) unit that functions as a solids-liquid separation unit as well as a sludge thickening step. In the DAF unit, the biologically-occurring extracellular polymeric substance (EPS) in the WAS works as a bioflocculant to enhance the capture of particulate and colloidal solids (organic and inert) as well as to co-thicken primary and secondary sludge without the need for polymers. Floated solids from the DAF unit are soaked with organic material and can be sent to digestion without the need for intermediate thickeners. The effluent liquid stream from the DAF unit is directed to the activated sludge (AS) process which can now operate with less organic load, resulting in less aeration energy demand and potentially smaller treatment volumes. Figure 1 depicts a concept flow diagram of the Captivator System. The novelty that makes this BEPT system a unique solution is that it incorporates well-established equipment in an innovative configuration to achieve carbon diversion with a reliable, simple, and sustainable approach. The Captivator System is gaining acceptance in the wastewater treatment industry due to its simplicity and versatility to be applied in upgrades, expansions, and retrofits.

The initial studies on biosorption that led to the development of the Captivator System were conducted by Envirex in the 1990s. This BEPT technology has gone through a rapid progression in the past years, achieving a key milestone with the first full-scale installation in January 2014 at the 121,000 m^3/d (32 mgd) Agua Nueva Water Reclamation Facility, AZ (Johnson et al., 2014). This BEPT system has been validated, proving the following performance: 50-60% BOD and 70-80% TSS removals without chemicals. It has also shown the ability to generate 4-6% thickened sludge without the need for polymers (Ding et al., 2015). Empirical results also show that the performance of anaerobic digestion can be greatly improved, enabling facilities to produce 40% more biogas (Ding et al., 2015). In simple terms, more readily biodegradable organics are diverted to the digesters. Likewise, since the organic load to the AS process is significantly reduced with this BEPT technology, less WAS is generated, and thus complex organics (cell walls and EPS) entering the digesters are reduced, improving the overall VSS destruction.

This paper summarizes the pilot study at the Bethlehem, PA WWTP and the research conducted at Evoqua's R&D facility in Singapore. In addition, a comparative example with a conventional alternative is presented based on the performance of this BEPT technology validated through extensive piloting and the full-scale installation. The industry has now a cost–effective alternative of a biologically enhanced carbon diversion system that can transform the economics of a WWTP with an innovative and simple approach.

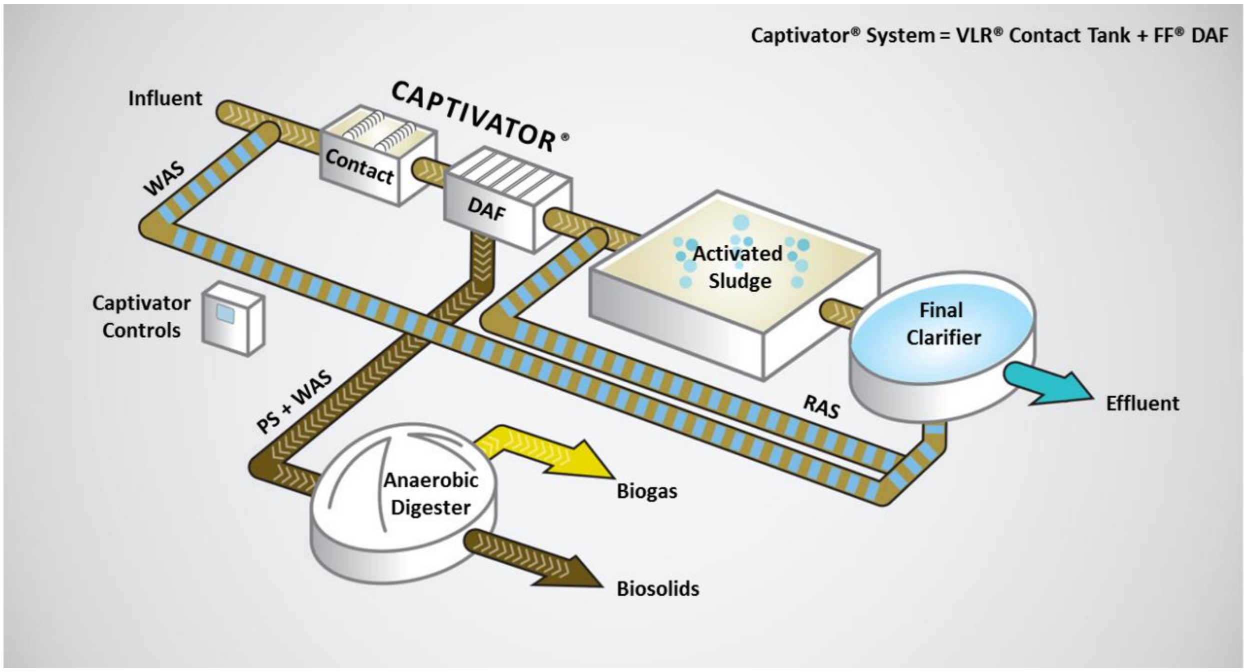


Figure 1. Captivator® System process configuration

Influence of Contact Tank - Bethlehem, PA

PROCESS DESCRIPTION-BETHLEHEM

The following shows results of pilot tests conducted with an earlier version of the Captivator System at the Bethlehem WWTP in 1996. This version of the Captivator is very similar to that shown in Figure 1, however, there was no air added to the contact tank. Furthermore, the retention time in the contact tank was not optimized. These experiments represent earlier development of the Captivator System. This BEPT pilot study had an influent flow rate of 84 m^3/h (370 gpm) and the surface overflow rate of the FFDAF (Figure 5) used was about 5 times that of a primary clarifier.

Bench scale floatation tests were also conducted to investigate the TSS removal potential of raw wastewater using either WAS or polymer or a combination of both. A 1 mg/L polymer addition was used while WAS addition on a solids basis represented 100% of the theoretical production rate (0.9 TSS/BOD) of the BOD added.

RESULTS AND DISCUSSION-BETHLEHEM

Experiments conducted on a pilot scale of an earlier version of the Captivator System showed that with insufficient or no contact time the performance of the system would not be maximized. In these experiments the TSS removal efficiency of the system was 66% (without chemicals) and the soluble BOD (sBOD) removal was 25%. In these tests the biosorption mechanism was not yet fully understood. Therefore, factors such as contact-time between WAS and raw wastewater as well as the aeration requirement to activate biosorption were not yet optimized.

The results of a bench scale batch flotation unit using WAS and/or polymer as a flotation aid are shown (Figure 2). The data show that a quick proof of effectiveness of the Captivator System can be achieved through these studies. It was observed that 66% TSS removal was obtained from using WAS only as the flotation aid. No improvement in TSS removal was achieved by using the higher addition of WAS.

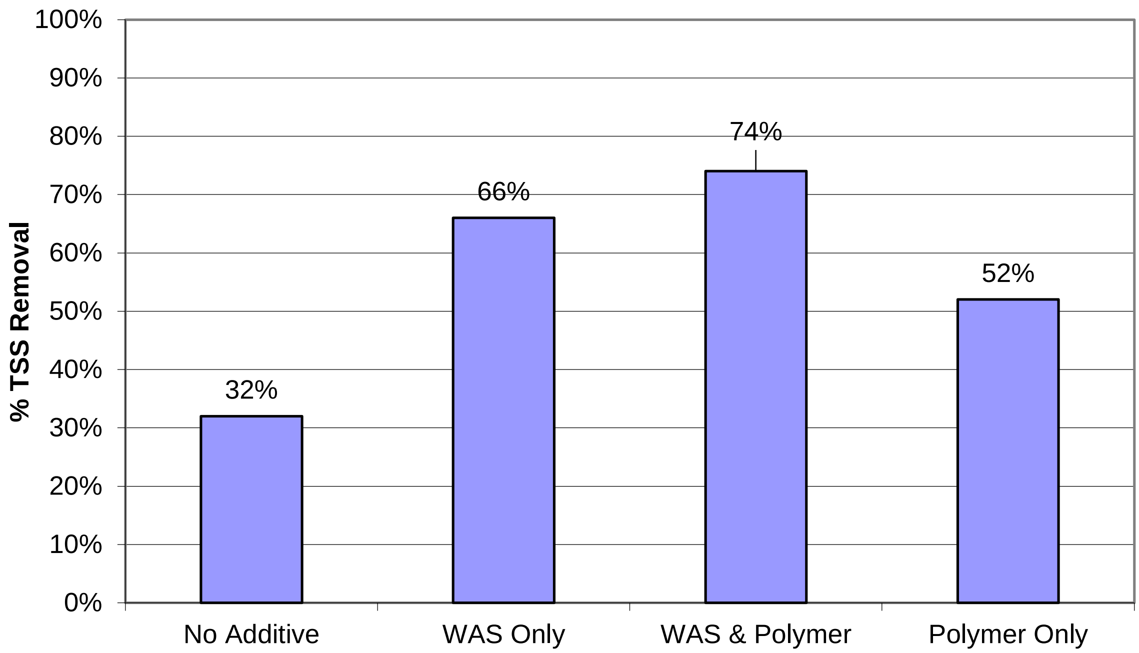


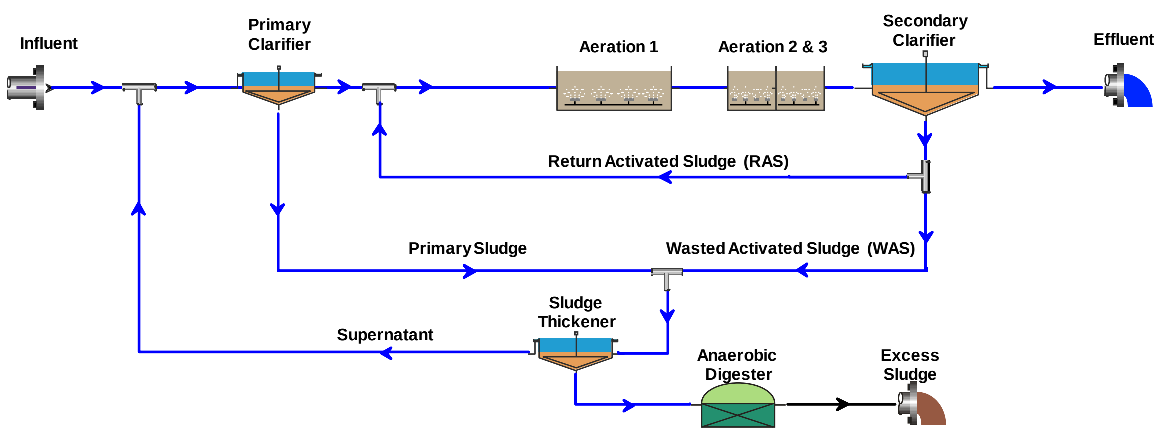
Figure 2. Bench scale testing with polymer and waste activated sludge on TSS removal in a flotation cell at Bethlehem WWTP

Captivator System and Conventional Plant Comparison – Pilot Testing in Singapore

PROCESS DESCRIPTION-SINGAPORE

A 200 m^3/d (37 gpm) pilot test was conducted at the Ulu Pandan Water Reclamation Plant, Singapore (Figure 3) in 2012-2013. The test plant could be configured as an activated sludge plant with conventional primary clarification, or with the Captivator System as a BEPT unit operation. A baseline conventional activated sludge (CAS) process and the Captivator System process were evaluated by using the same aeration tanks but different primary treatment configurations. Figure 4 shows the process outline of both configurations. The DAF used was a prototype Folded Flow® (FF) which has an innovative design of “folding” the flow by removing effluent from the same end of the tank as the influent is introduced, resulting in better utilization of tank volume and flotation area with less short circuiting (Figure 5). This unique DAF configuration was pioneered by Evoqua Water technologies in the 1990s and allows higher hydraulic loads compared to conventional DAF units. For the Captivator System testing, the primary clarifier of the CAS process was replaced with a contact tank and the DAF unit. The thickened sludge (by either a centrifugal decanter or DAF itself) was sent to a digester with a SRT of 25 days for biogas production.

Figure 3. Pilot Plant in Ulu Pandan WRP shown under tarpaulin cover



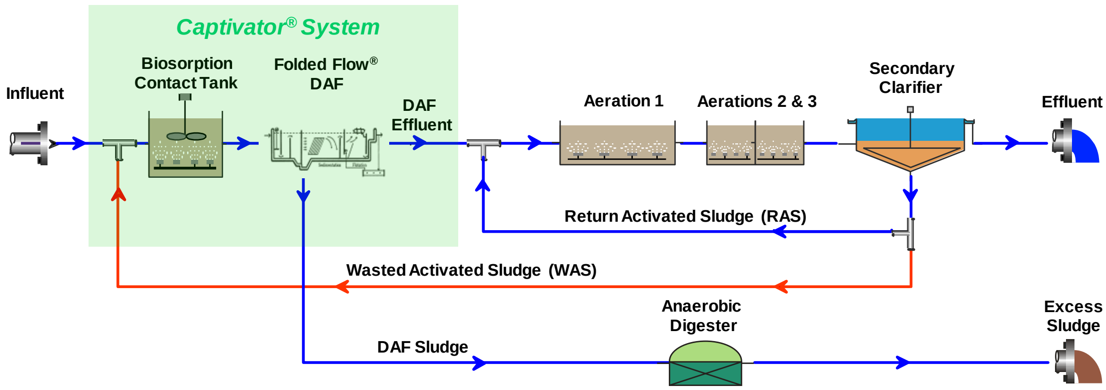


Figure 4. A baseline conventional activated sludge (CAS) process (top diagram) and the Captivator System configuration (bottom diagram) were piloted

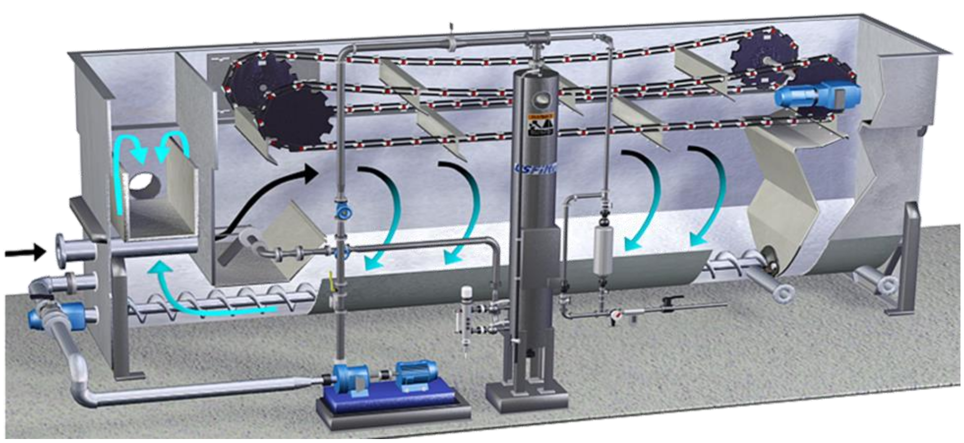


Figure 5. Conceptual diagram of a Folded Flow® DAF unit developed by Evoqua Water Technologies

The pilot plant received wastewater from the nearby plant headworks. The wastewater was first fine screened by a drum screen before entering primary treatment. The screened influent characteristics are shown in Table 1. The influent and effluent samples were composite samples while other samples such as primary effluent, primary sludge, contact effluent, mixed liquors in all aeration tanks, thickened sludge, WAS, and digested sludge were daily grab samples. The CAS process was first examined in the pilot plant to collect a baseline data for comparison purposes. Then the process was converted into the Captivator System. The overall plant performance was evaluated mainly on liquid treatment efficiency, biogas production and final excess sludge generation.

Table 1. Average characteristics of fine screened influent, effluent and plant treatment efficiencies

Parameters		**CAS**			**Captivator System**		
mg/l		*Influent*	*Effluent*	*Removal*	*Influent*	*Effluent*	*Removal*
$tBOD_5$		316	21	93%	324	13	96%
$sBOD_5$		82	6	93%	101	5	95%
$cBOD_5$		37	3	92%	61	3	95%
tCOD		666	43	94%	704	66	91%
sCOD		124	34	73%	140	47	66%
cCOD		119	5	96%	96	14	85%
TSS		406	13	97%	416	25	94%
VSS		346	11	97%	352	20	94%
TN		40	24	40%	47	27	43%
TP		9.1	3.8	58%	9.8	4.0	41%
pH	-	6.7	7.0	-	7.1	7.3	-
Alkalinity		180	155	-	170	156	-

Note: t – total; s – soluble; and c – colloidal.

RESULTS AND DISCUSSION-SINGAPORE

Liquid Treatment Efficiencies

Table 1 shows that overall BOD and COD removals for the conventional and Captivator System applications were satisfactory and over 90%. The nitrogen removals were low for all processes since the pilot plant configuration and operation were not designed for biological nitrogen removal (sludge age was controlled at 3 to 4 days). Nitrification was limited as indicated by small decrease in alkalinity level. Therefore, it was assumed that most of the oxygen consumed was utilized for COD oxidation.

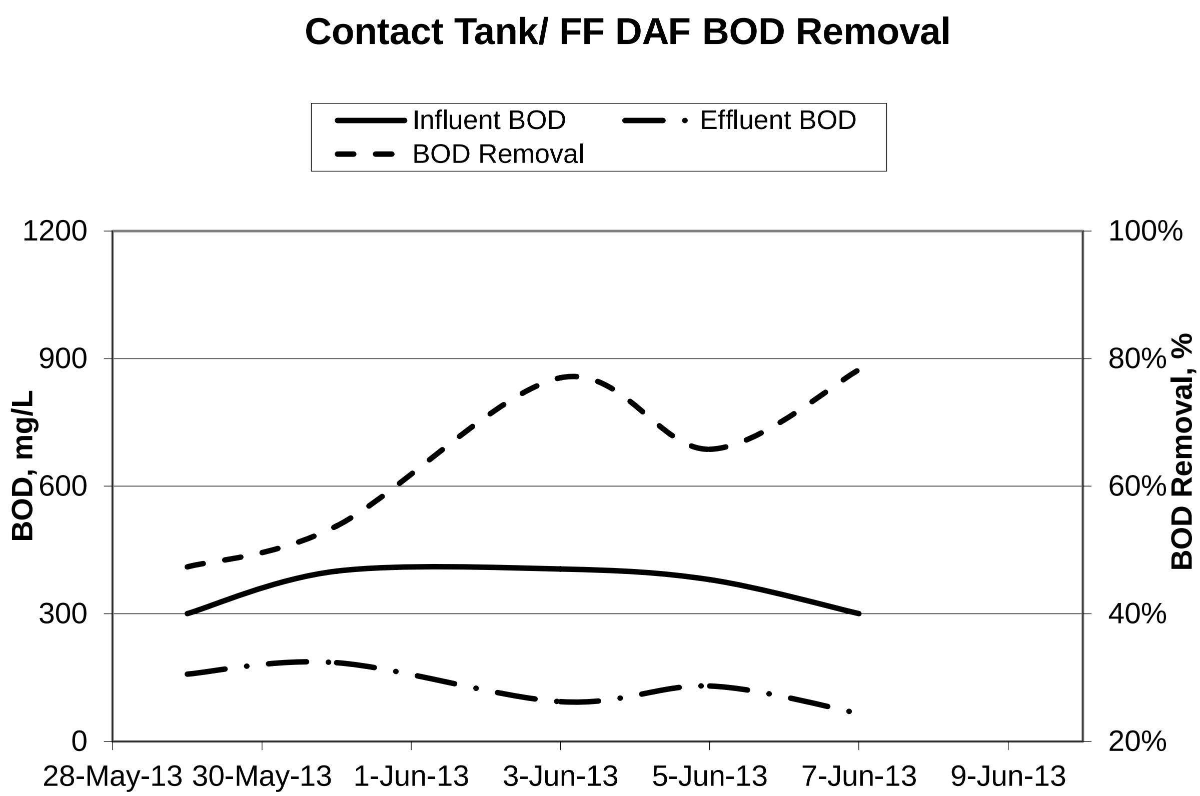
Folded Flow (FF) DAF Treatment Efficiencies

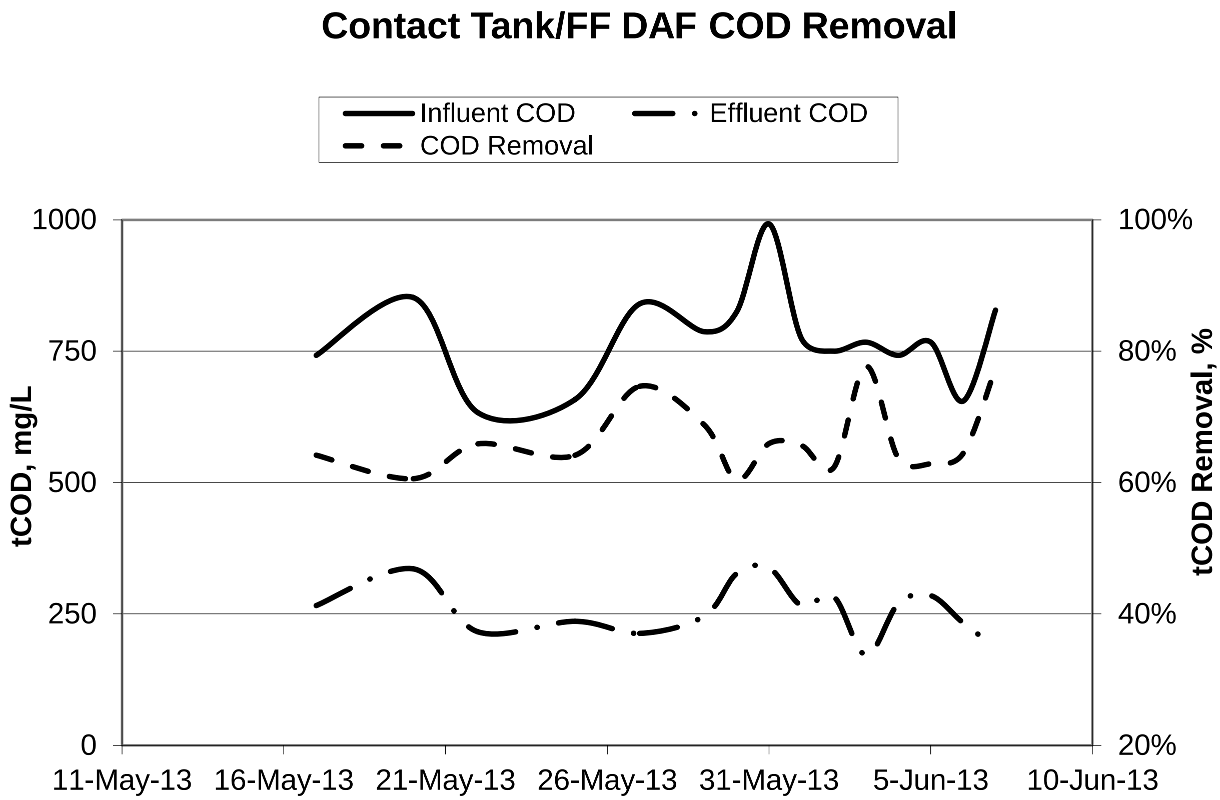
Preliminary studies. Preliminary studies were conducted to collect design parameters before the full pilot plant operation. The first study evaluated the FF DAF performance in a Captivator System simulation. When 100% WAS from downstream aeration process was used for biosorption, the FF DAF was able to accomplish very good removal of TSS/BOD/COD (Table 2), superior to conventional primary clarifiers which typically generate BOD/COD removals in the 25 to 40%, range. It was also observed that chemical coagulation by 5 ppm $FeCl_3$ increased the FF DAF performance.

Table 2. Preliminary studies on FF DAF performance in types 1 and 2 applications

FF DAF Applications	WAS or Bio-adsorbent Loading Conditions	DAF Removal Efficiencies, %		
		TSS	*BOD*	*COD*
Captivator System	100% WAS	73	62	61
	100% WAS + 5 ppm $FeCl_3$	86	79	76

FF DAF performance in the full pilot plant operation. FF DAF performance was evaluated during steady state operation (Figure 6).The average BOD, COD, and TSS removals were 64%, 67% and 81%, respectively. BOD/COD removals were similar to those achieved in the preliminary study and TSS was even much better.




Contact Tank/FF DAF COD Removal
Influent COD
Effluent COD
COD Removal
tCOD, mg/L
tCOD Removal, %
1000
750
500
250
0
100%
80%
60%
40%
20%
11-May-13
16-May-13
21-May-13
26-May-13
31-May-13
5-Jun-13
10-Jun-13

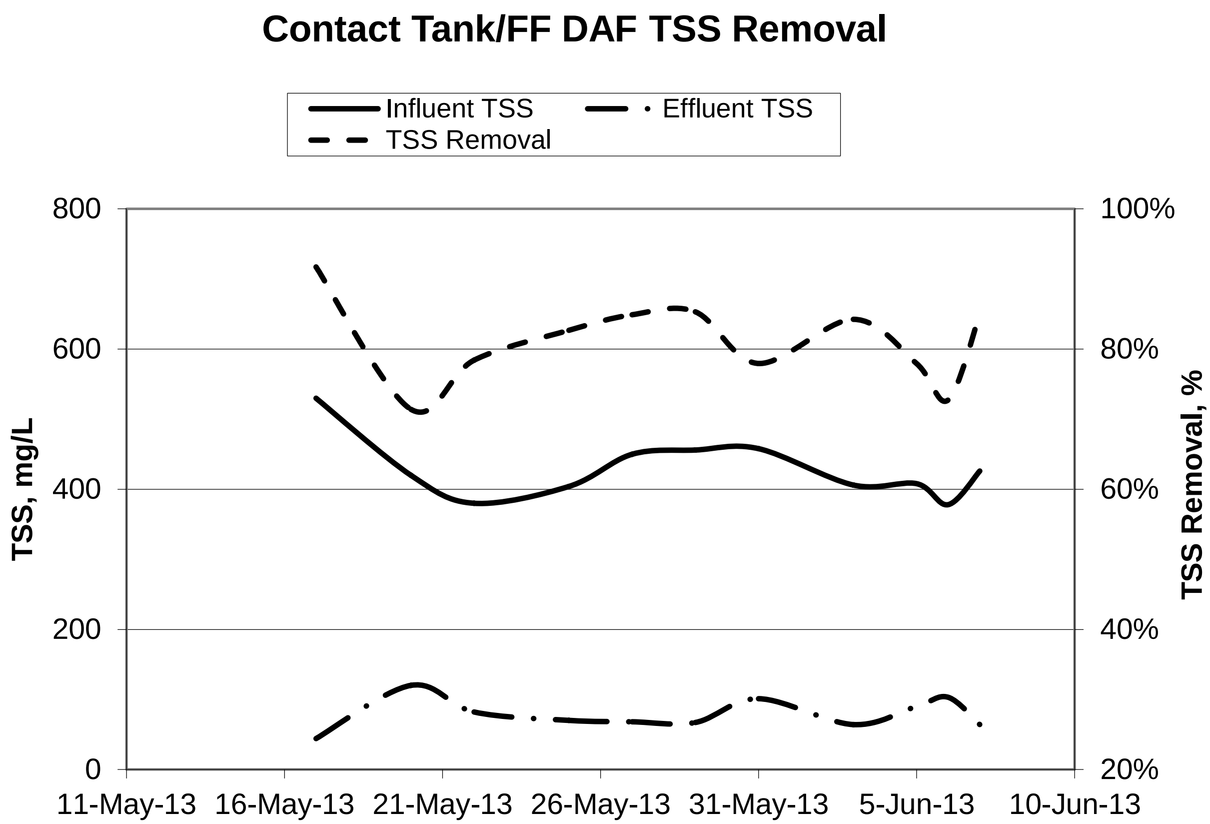
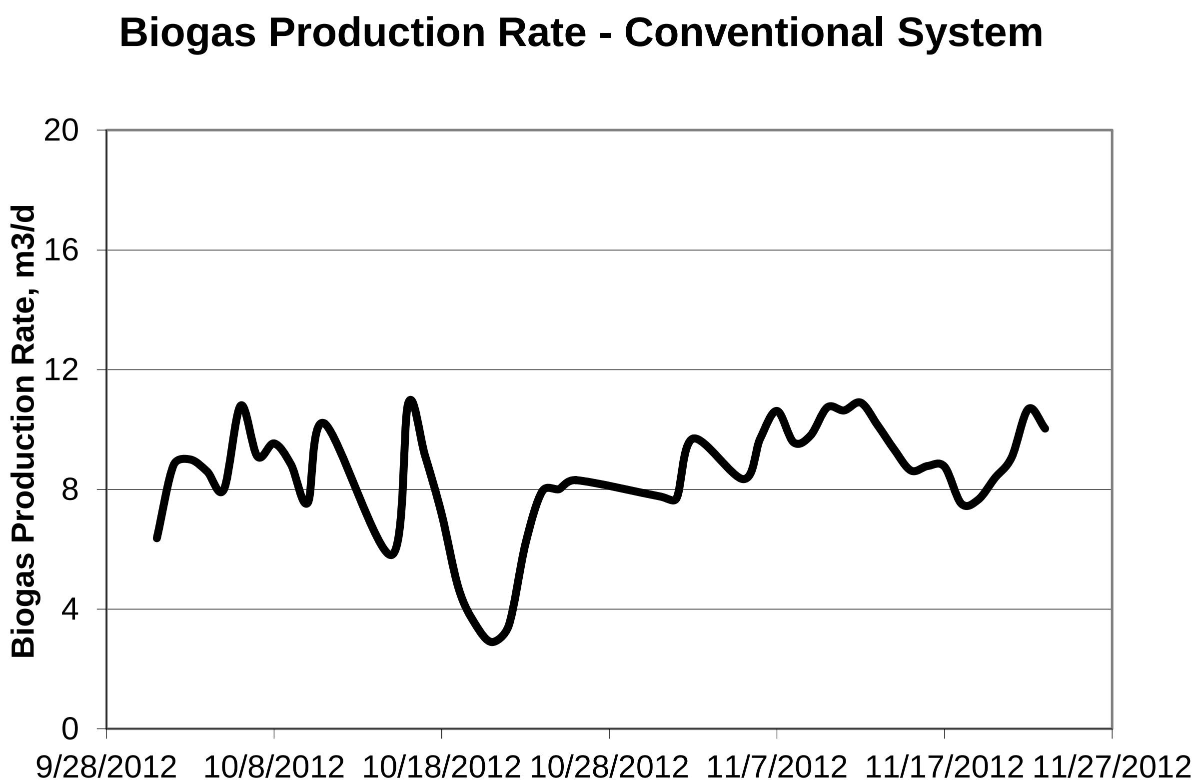


Figure 6. DAF performance in Captivator System

Biogas Production

The daily biogas production is shown in Figure 7. The average biogas production was 15.0 m^3/d for the Captivator System compared to 8.3 m^3/d observed in the CAS process. This data showed the effect of capturing raw wastewater biodegradable organics that would normally escape primary clarification, and diverting it to the anaerobic digester where it can be converted to biogas. The analysis showed that the Captivator System was able to capture over 70% of the primary wastewater VSS while in the CAS process primary VSS removal was only 43%. The greater capture of readily biodegradable VSS in the Captivator System resulted in a greater VS destruction efficiency in the anaerobic digester. The digester VS destruction efficiency was 55% in the Captivator System compared to 42% VS destruction in CAS process. This shows that the FF DAF quickly captured the readily biodegradable organics for more biogas production.


Biogas Production Rate - Conventional System
Biogas Production Rate, m3/d
20
16
12
8
4
0
9/28/2012
10/8/2012
10/18/2012
10/28/2012
11/7/2012
11/17/2012
11/27/2012

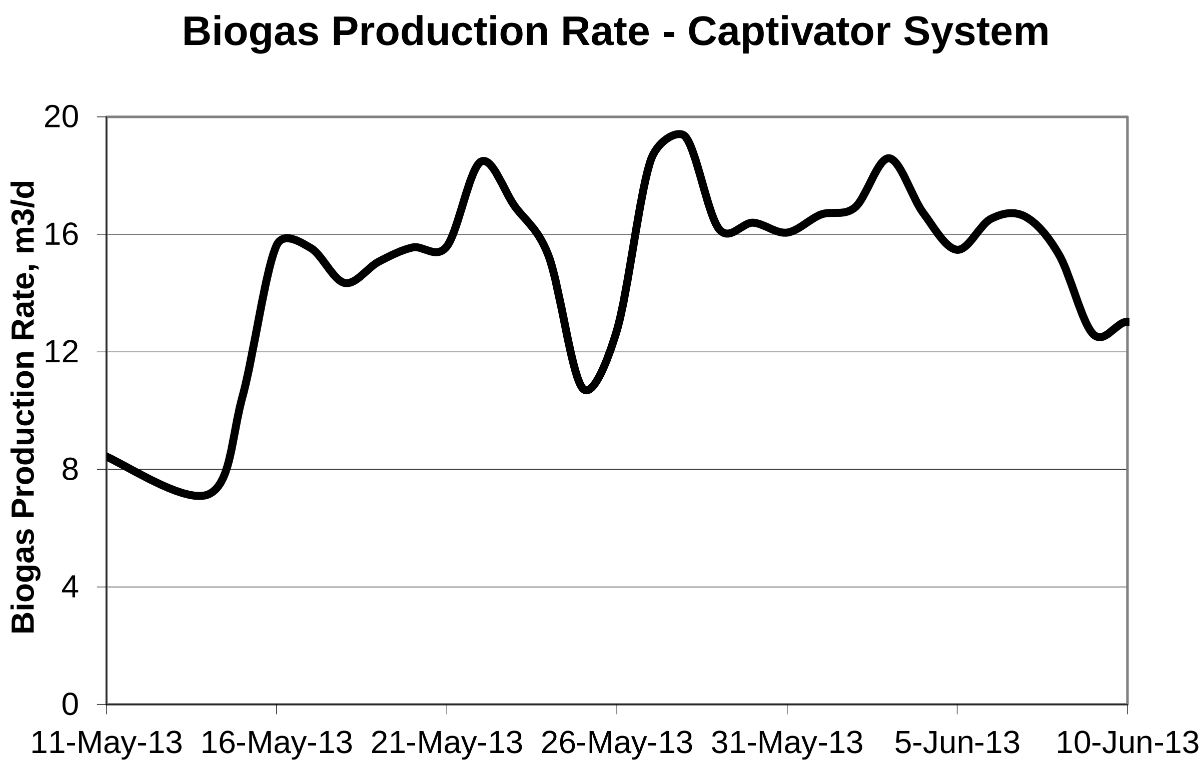


Figure 7. Biogas production in CAS (Top) and Captivator System (Bottom)

COD Balance

The daily analytical results were collected and used to perform COD balance to understand the impact of Captivator System on the whole treatment train. Figure 8 shows the COD balance of CAS process. The primary sludge captured 30% of influent COD. The centrifugal decanter delivered 55.1% of influent COD in the thickened sludge for biogas production. From this 55.1% COD, 22.9% was converted into methane and 32.2% was discharged as excess sludge. This indicates a VS destruction efficiency of 42% in the digester. 38.9% of influent COD was oxidized in the aeration tank. The overall COD balance of this CAS is very close to the simulated result by BioWin.

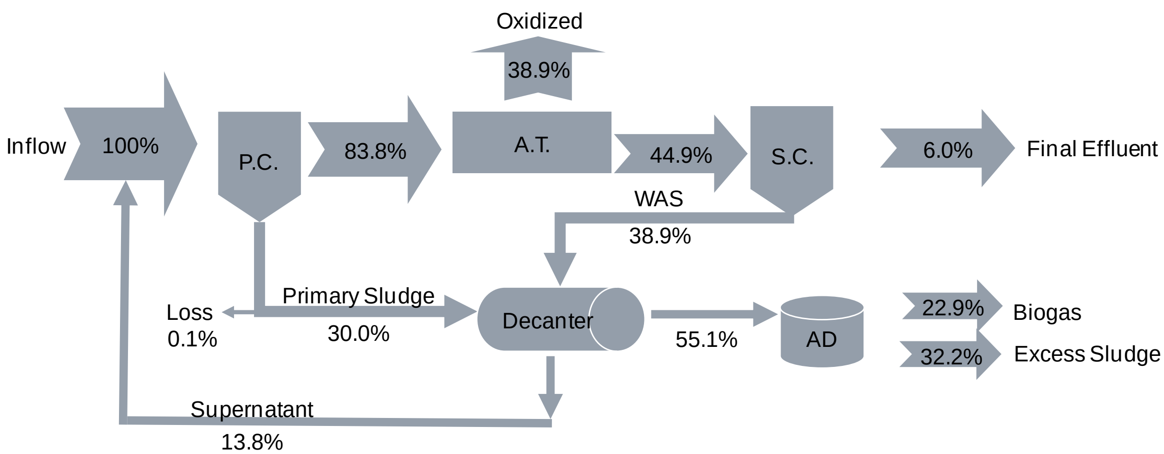


Figure 8. COD balance of the baseline conventional activated sludge (CAS) process

Note: P.C. – Primary Clarifier; A.T. – Aeration Tanks; S.C. – Secondary Clarifier; AD – Anaerobic Digester.

Figure 9 shows the COD balance of the BEPT application in the treatment train. The FF DAF in this application captured and sent 71.2% of influent COD for biogas production. Around 78% of VS mass in the FF DAF sludge came from primary solids. In the digester, 38.0% of influent COD was converted into methane and 33.2% was discharged as excess sludge. This corresponds to a high VS destruction efficiency of 53%. There was some COD oxidation loss (1.9 % of influent COD) in contact tank in which coarse bubble aeration was provided to keep WAS activated for biosorption. The main aeration tank oxidized 15.2% of influent COD into carbon dioxide. The final effluent contained quite high COD which was caused by mechanical issues with the small clarifier of the pilot unit.

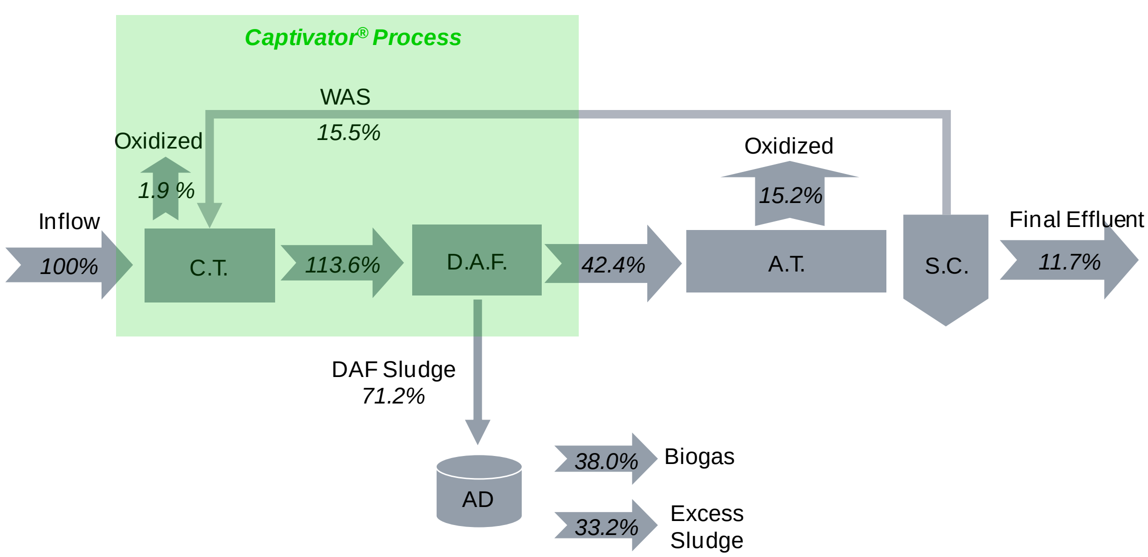


Figure 9. COD balance of Captivator System

Note: C.T. – Contact Tank; D.A.F – Dissolved Air Flotation; A.T. – Aeration Tanks; S.C. – Secondary Clarifier; AD – Anaerobic Digester.

COD distribution in final effluent, oxidation, biogas, and excess sludge is summarized for comparison in Table 3. The BEPT Captivator System produced 65% more biogas than CAS and only required 44% of CAS aeration energy for COD oxidation.

Table 3. Summary COD balance of CAS Process vs. Captivator System

	CAS	Captivator System
Final Effluent	6%	12%
Oxidized	39%	17%
Biogas	23%	38%
Excess Sludge	32%	33%

FULL-SCALE OPERATION-AGUA NUEVA

The first full-scale plant using the Captivator System came online in January 2014 at the 121,000 m^3/d (32 mgd) Agua Nueva Water Reclamation Facility in Pima County, Arizona. The Agua Nueva plant uses six FF DAF tanks, each 18 m x 6 m (60ft x 20ft) with a design overflow rate of 7.5 m/h (4,444 gpd/ft^2). Under full-load operating conditions, it has achieved 75% TSS removal and up to 35% sCOD removal. Little drop-off in performance was noticed during peak stormflow (2Q) events. Additional information on the design and operation of the Agua Nueva WRF is provided in Johnson et al., 2014.

FULL-SCALE DESIGN EXAMPLE

A better understanding of the actual benefits possible with the Captivator carbon-diversion technology can be provided by looking at the comparison of biogas production and aeration tank BOD reduction in a full-scale design example (Table 4). In this example, a plant handling a design flow of 400,000 m^3/d (106 mgd) with influent BOD and TSS concentrations of 315 mg/l. Typical WW characteristics, as accepted in BioWin and GPS-X modeling, were selected with the BOD broken down into particulate, colloidal, and truly soluble fractions. The Captivator System performance was based upon a 75% TSS removal rate in the DAF and a 35% sBOD bio-adsorbed in the aerated contact tank. The anaerobic digestion performance is based upon a steady-state model which results in biodegradable VS destruction and gas production based upon equal mesophilic digestion HRT for both systems.

Table 4. Design example comparison of Captivator System vs. CAS process

Parameter	Captivator System	Conventional Plant
BOD, kg/d	126,000	126,000
TSS, kg/d	126,000	126,000
COD, kg/d	244,700	244,700
biodegradable COD, kg/d	200,000	200,000
Raw BOD removed in Primary/DAF - % removal	55.3	29.3
Activated sludge oxygen demand, kg/d	57,600	90,500
Raw BOD to digester, kg/d	68,200	37,400
TSS to digester, kg/d	136,000	120,300
VSS to digester, kg/d	104,500	88,800
VSS removal in digester, %	62.3	52.3
Biogas production, m3/day	65,800	45,500
Solids hauled from plant, dry kg/d	70,960	73,900

In this example, the biogas production increase with Captivator is 44.6% while the amount of BOD to be oxidized in aeration has been reduced by 36.3%. The design example even shows a slight reduction in the solids hauled from the plant (4%); this reduction possible due to less complex VSS being creating in the activated sludge process with Captivator. The complete analysis was based on data obtained from Dold, (2007); Sotemann et al., (2005) and; Nopens et al., (2009).

SUMMARY AND CONCLUSIONS

The Captivator System offers a biologically-enhanced primary treatment system in which a higher degree of carbon can be diverted directly to anaerobic digestion, the diversion capable of increasing biogas production by more than 40% while simultaneously reducing the amount of carbon oxidized in the mainstream activated sludge process by 40%. A prominent feature of this unique carbon-diversion system is the removal of sBOD from the incoming wastewater stream, piloting and full-scale operation both showing up to 35% removal capabilities. The Folded-Flow DAFT used with the Captivator System, operating at hydraulic load levels several times higher than conventional primary clarifiers, has shown TSS removal capability of 75% while still achieving floated solids concentrations above 5% without chemical addition. The combination of

35% sBOD removal and 75% particulate BOD (pBOD) removal results in a net BOD removal performance of 55%.

This BEPT system has been shown to be a unique and cost-effective alternate to other carbon diversion systems, such as chemically-enhanced primary treatment or mechanically-enhanced primary treatment, being able to extract not just higher levels of pBOD but also extracting a substantial amount of sBOD. Diverting more of the organic load away from the mainstream activated sludge process not only reduces aeration energy demands and bioreactor tankage requirements, but, with decreased waste activated sludge production, lessens the amount of complex cellular material sent to anaerobic digesters. With a higher degree of 'less-complex' easier-to-degrade organic material going to anaerobic digestion, a lower amount of biological solids will also exit from the digesters, resulting in a reduction of dewatering and hauling costs.

Further, in spring 2016 a larger scale pilot work will be conducted to gain additional verification of performance under an assortment of varying load and operating conditions. During this pilot study, some tests will run with a floated solids internal recycle (to establish an independent biomass inventory) to determine if even higher levels of carbon diversion can be achieved.

REFERENCES

Ding H-H., Doyle M., Erdogan A., Wikramanayake R., and Gallagher P (2015). Innovative Use of Dissolved Air Flotation with Biosorption as Primary Treatment to Approach Energy Neutrality in WWTPs. *Water Practice and Technology*, **10**(1) 133

Dold, P (2007). Quantifying Sludge Production in Municipal Treatment Plants. *Proceedings Water Environment Federation*. 1522 – 1549.

Johnson, B. R., Phillips, J., Bauer, T., Smith, G., and Sherlock J., (2014) Startup and Performance of Worlds's first Large Scale Primary Dissolved Air Flotation Clarifier. *Proceedings of the Water Environment Federation*, **6** 712-721

Nopens, I, Batstone, DJ, Copp, JB, Jepsson, U, Volcke, E, Alex, J, Vanrolleghem, PA. (2009). An ASM/ADM Model Interface for Dynamic Plant-Wide Simulation. *Water Research*. 1913-1923.

Sotemann, SW, Ristow, NE, Wentzel, MG, and Ekama, GA. (2005). A Steady State Model for Anaerobic Digestion of Sewage Sludge. *Water SA*. **31**(4) 511-527. FFFDAF