Waste Activated Sludge Pretreatment to Boost Volatile Solids Reduction and Digester Gas Production: Market and Technology Assessment

J. Hunter Long and C. Michael Bullard

Stabilized biosolids from the wastewater treatment process have three primary disposal alternatives: land application, landfilling, and incineration. Tightening regulations related to residuals incineration, reduced landfill capacity, and increasingly stringent nutrient management and control requirements for land application have led to increasing costs for biosolids disposal in each of the primary biosolids management avenues. Additionally, lower total nitrogen effluent limits are increasing the required liquid treatment activated sludge age, which leads to a decrease in activated sludge degradability during final stabilization via digestion. In response to the rise in biosolids disposal cost and decreasing sludge degradability during digestion, an increasing number of wastewater treatment plants are evaluating sludge minimization technologies to reduce final poststabilization biosolids mass.

Three biosolids minimization options available are: minimizing activated sludge production by targeting the activated sludge process; increasing the bioavailability and degradability of waste activated sludge (WAS) through anaerobic digestion pretreatment; and enhanced anaerobic digestion, such as temperature-phased, thermophilic, or acid/gas phase digestion. The WAS pretreatment may be the alternative of choice for many wastewater treatment facilities (WWTFs) because WAS pretreatment systems may be retrofitted to an existing anaerobic digestion process with minimal change or interruption to the overall plant process. During the past decade, a number of WAS pretreatment technologies have been developed to increase volatile solids destruction, increase biogas production, decrease the mass of stabilized biosolids, and increase the capacity of the anaerobic treatment process.

Generally, WAS has a much lower volatile solids reduction (VSR) in anaerobic digestion than primary sludge (PS). The WAS pretreatment technologies will improve the volatile solids reduction and have the potential to significantly decrease the amount of residual biosolids and increase biogas production. The reduced disposal cost of biosolids and the potential savings for generating heat or electricity offsets from the additional biogas may exceed the operational cost of WAS pretreatment, resulting in a net economic benefit to the wastewater treatment plant. Additionally, the increased volatile solids destruction may reduce the capacity requirement for anaerobic digestion, allowing plants to avoid or delay costly anaerobic digestion expansion projects. Some WAS pretreatment technologies have led to improved digested sludge dewaterability and reduced polymer demand, resulting in additional economic benefits.

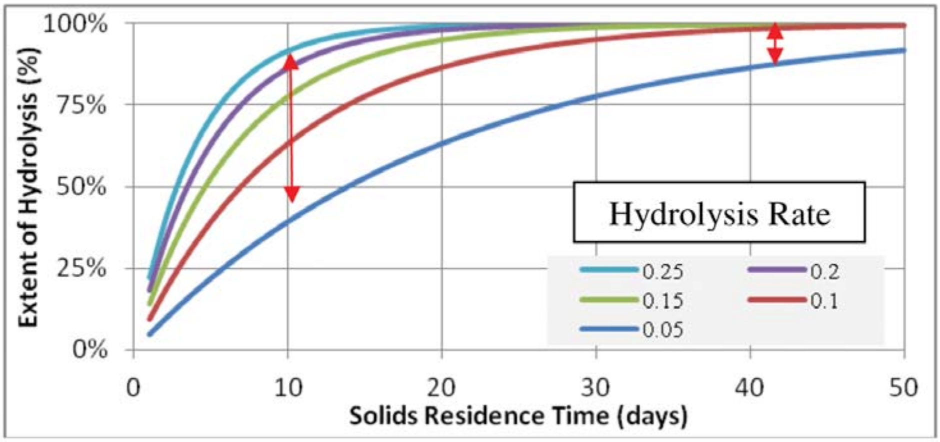

Figure 1. Extent of Hydrolysis

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Anaerobic digestion of WAS is generally hydrolysis-rate-limited and many pretreatment technologies focus on increasing the rate of hydrolysis through floc disintegration and cell lysis. The WAS pretreatment may employ thermal, chemical, mechanical, electrical, or ultrasound, or a combination of these processes to achieve these objectives. It is important to consider multiple treatment technologies and to weigh the relative, and sometimes site-specific, advantages and disadvantages of each technology. Over the past decade, WAS pretreatment technologies have been more widely implemented throughout Europe; however, a number of recent full-scale tests have shown positive results at wastewater treatment plants (WWTPs) within the United States. It is expected that WAS pretreatment will see increased implementation within the U.S. over the next few years.

This study consists of a literature review of peer-reviewed journal articles, as well as conference proceedings, and concludes with two recent case studies, one of which is highlighted here. The purpose of the study is to summarize the qualitative and quantitative results of WAS pretreatment full-, pilot-, and laboratory-scale installations, summarize the mechanism of each technology, and discuss the relative performance of various WAS pretreatment technologies.

Waste Activated Sludge Pretreatment Technologies

Overview

The WAS pretreatment technologies can be divided into two main categories: low-intensity and high-intensity processes. Low-intensity processes increase the anaerobic digestion rate, while high-intensity processes increase both the extent and rate of anaerobic

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digestion. The anaerobic digestion rate may be increased by increasing the rate of hydrolysis (rate limiting step) through floc disintegration and/or cell lysis. The extent of anaerobic digestion may be increased by converting non-biodegradable chemical oxygen demand (COD) to biodegradable COD. This is done by means of significant cell lysis. Figure 1 shows that low-intensity WAS pretreatment processes, which increase the rate of hydrolysis, will have a much more significant effect on anaerobic digesters with low solids retention time (SRT). Figure 2 shows that increasing the extent of anaerobic digestion will cause a similar increase in digestion regardless of the digester SRT.

Thermal Pretreatment Technologies

Thermal hydrolysis has been implemented at over 20 wastewater treatment plants worldwide. The two main thermal hydrolysis technology providers are CAMBI^{TM} and Veolia Water (KRÜGER^{TM}). The CAMBI's thermal hydrolysis process (THP) is a batch process that is comparable to Veolia Water's BIO-THELYS^{TM} process. Both processes use a combination of high pressure and heat to cause cell lysis and increase the rate of hydrolysis prior to mesophilic or thermophilic anaerobic digestion. The CAMBI process consists of three stages:

1. Raw sludge is heated to ~97°C for a retention time of ~1.5 hours (pulper).
2. Heated sludge is fed to the reactor vessel where the temperature is increased to ~ 165°C and the pressure is increased to 6-10 bar (87–145 pounds per sq in. [psi]) for approximately 20 minutes (reactor).
3. The treated sludge passes to another vessel where temperature is reduced to 102°C with ~1.5 hour retention time (flash tank).

The thermally hydrolyzed sludge may then pass through a heat exchanger to provide heat for the influent sludge and reduce the temperature of the effluent sludge for thermophilic (~50°C) or mesophilic (~35°C) anaerobic digestion. The BIO-THELYS process is similar to the CAMBI process with the exception that the BIO-THELYS system has two vessels of the same size and function and does not require a separate pulper and flash tank. Thermal hydrolysis has been reported to increase volatile solids destruction by 10-50 percent and increase biogas production by 10-50 percent, with an average increase of 25 percent compared to mesophilic anaerobic digestion without thermal hydrolysis pretreatment. Additional benefits of thermal hydrolysis include Class A biosolid product, increased digester capacity, improved dewaterability, and elimination of digester foaming. One of the main disadvantages is that the system is very complex and will require a high level of operator training to operate the high temperature and pressure vessels, in addition to requiring regulatory inspections and approved maintenance. Additionally, thermal hydrolysis will increase the soluble inert fraction and may significantly increase the nutrient and soluble inert loading on the dewatering recycle stream. As a rule of thumb, one-third of the COD in the dewatering liquor is refractory COD, meaning that a portion of the COD will show up in COD tests as being chemically oxidizable, but will not be readily biodegradable.

Thermal hydrolysis requires a large amount of energy input and site-specific data would need to be analyzed to determine if the decrease in solids production and increase in digester gas would outweigh the operations cost. Thermal hydrolysis pretreated sludge will have a reduced digester volume requirement, and in some cases, adding thermal hydrolysis to increase digester capacity may be more cost-effective than building additional anaerobic digesters (Wilson et al, 2008; Hunt et al, 2009; Shea 2009; Sandino and Whitlock 2010; Veoliawaterst.com; Cambi.no)

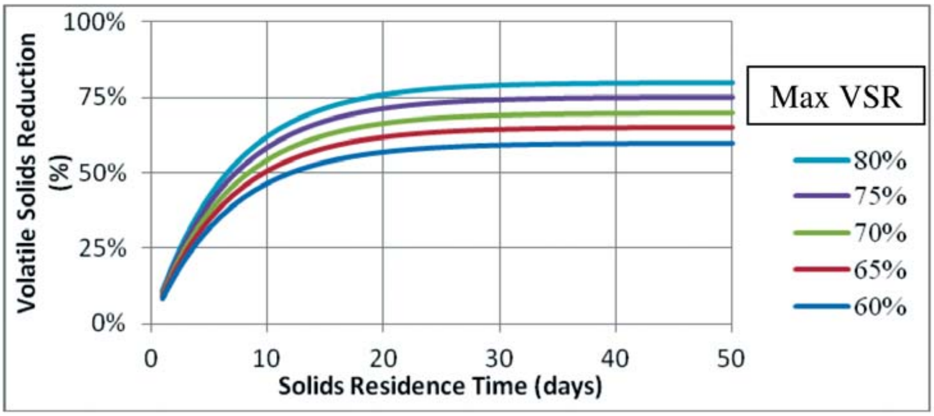

Figure 2. Volatile Solids Reduction

The KRÜGER offers a continuous flow-through thermal hydrolysis treatment process under the trade name EXELYS^{TM}. This process uses the same principles and mechanisms of the batch thermal hydrolysis process, but can be operated at a higher percent (≥ 25 percent) of dry solids (DS) compared with the batch process (16-17 percent), reducing the process heat demand. The EXELYS system may be added upstream of mesophilic or thermophilic digestion, or a Digestion-Lysis-Digestion (DLD^{TM}) configuration may be used in which the EXELYS is located between two digesters operated in series. To date, there has only been one full-scale installation, at a wastewater treatment plant in Denmark, and the DLD configuration has resulted in a 30 percent increase in biogas production and a 25 percent reduction in biosolids (Kline et al, 2011; Krugerusa.com).

Chemical Pretreatment Technologies

Chemical pretreatment can serve one of two main purposes. Chemicals such as ozone or hydrogen peroxide may be added to activated sludge to increase sludge destruction through floc disintegration, solubilization, and the oxidation of the released organics into carbon dioxide (Yeom et al, 2002; Carrére et al, 2010). Chemical oxidation will reduce total sludge mass, but may not provide the added benefit of increased digester gas production in the anaerobic digestion process. Alkali treatment is another chemical pretreatment that is often used as a preliminary step to weaken the cell walls and reduce viscosity before thermal or mechanical treatment. Sodium and potassium hydroxide (NaOH, KOH) are the most common alkali treatment chemicals, but magnesium or calcium hydroxide ($Mg[OH])_2$, $Ca[OH]_2$) may also be used (Carrére et al, 2010).

The MicroSludge^{TM} system combines chemical and mechanical treatment. The process utilizes an alkali (NaOH) conditioning step, followed by a sudden pressure drop from 12,000 to 50 psi to cause cell membranes to tear apart. One of the benefits of the MicroSludge system is that it may be easily retrofitted to an existing anaerobic digestion process and it is not as complex as the thermal hydrolysis process. MicroSludge has also been reported to reduce digester foaming, odor, and sludge viscosity. Some of the disadvantages are that it has not shown large improvements in digesters operated at or above 20-day hydraulic retention time (HRT) and it requires chemicals (NaOH). There have been at least three full-scale tests, including the Joint Water Pollution Control Plant in Carson, Calif.; Chilliwack WWTP near Vancouver, B.C.; and the Des Moines Water Reclamation Facility in Des Moines, Iowa. The results of full- and pilot-scale tests varied by location and are summarized as follows (Stephenson et al, 2005; Roxburgh et al, 2006; Gary et al, 2007; Sandino et al, 2010; microsludge.com):

- Des Moines, Iowa
    - Full-scale digesters did not provide conclusive data because of variation in digester feeding
    - 10-16 percent increase in biogas production in pilot-scale reactors
- Carson, Calif.
    - Increased volatile solids destruction from 54 to 57 percent
    - Increased digester gas by less than 5 percent
    - Determined not to be cost-effective
- Vancouver, B.C.
    - Volatile solids destruction increased from 60 to 70-90 percent

Mechanical Pretreatment Technologies

Mechanical WAS pretreatment technologies rely on mechanical shearing, pressure change, and cavitation to induce activated sludge floc disintegration and cell lysis. Technologies include the CROWN™ Disintegration System, MicroSludge (combination chemical and mechanical), BioCrack™ (combination mechanical and electrical), and Biolysis System (BLS™).

The CROWN system is similar to the MicroSludge system and utilizes a maceration process followed by a 12-bar (174 psi) pressure change to cause cavitation, which leads to cell disintegration. The system can be added on to the sludge influent to the anaerobic digestion process and is typically used as a pretreatment for thickened waste activated sludge. There are over 20 full-scale operating facilities, mostly in Europe. These installations have demonstrated a typical 20 percent increase in solids destruction, 16-40 percent increase in biogas, and a 3-6 percent point increase in total solids after dewatering; for example, dewatered cake percent total solids (TS) increase from 20 to 23-26 percent. The CROWN system is recommended for plants with an influent flow greater than 10 mil gal per day (mgd). Additional advantages are that it is relatively simple to operate, may be installed as a single skid-mounted assembly, does not require additional heating or chemicals, and may reduce polymer dosage and digester foaming. (Froud et al, 2009; Sandino and Whitlock, 2010; sludgedisintegration.com).

The BioCrack product has multiple full-scale installations in Europe, in addition to pilot demonstrations in the U.S. The BioCrack utilizes an inline maceration, followed by an electrical pulse that causes floc disintegration. The full-scale implementations have shown an 8 percent increase in biogas production, 11.2 percent decrease in biosolids, and a 17.8 percent decrease in polymer usage. Additional advantages include its simplicity of operation and small footprint, and that it may be installed on a single skid-mounted unit and does not require the addition of chemicals.

The BLS consists of high-speed "rotary mills" that shear the activated sludge, causing cell lysis. The BLS did not have an effect on the sludge yield in a full-scale demonstration at the Plum Island WWTP near Charleston, S.C.; however, in batch studies, volatile solids destruction increased by 16.6 to 110 percent and gas production increased by 15-46 percent. A full-scale pilot test in Gatlinburg, Tenn., showed positive results similar to those from the batch studies. The variation in test results demonstrates the importance of pilot testing before full-scale installations as the same technology may have a significantly different effectiveness at different wastewater treatment plants. (Fairey et al, 2004; Sandino and Whitlock, 2010).

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Ultrasound Pretreatment Technologies

Ultrasound is a cyclic sound pressure with a frequency greater than 20 kHz. The optimal frequency range for waste activated sludge is 20-40 kHz, and at this frequency, the ultrasound wave generates compression and rarefaction, which in turn creates cavitation bubbles. Cavitation bubbles are formed in the rarefaction regions, and when the bubbles collapse, they produce shock waves, which lead to activated sludge floc disintegration and cell lysis. Multiple manufacturers market ultrasonic products, which may have different configurations, but all rely on the same mechanism for sludge floc disintegration and cell lysis. Two such systems are the Sonolyzer™ and the Sonix™ (Silva, 2005; Carrére et al, 2010; Sandino and Whitlock, 2010, Pilli et al, 2011).

The Ultrawaves ultrasound disintegration system goes by the name Sonolyzer in the U.S. Sonolyzer has at least 20 full-scale and 17 pilot-scale installations, mostly in Germany. These installations have demonstrated that ultrasound pretreatment of WAS may result in a 15-35 percent increase in volatile solids destruction and a 15-35 percent increase in biogas production. Sonix has been tested or installed in full-scale operations in Orange County, Calif.; United Kingdom; Sweden; Singapore; Japan; Australia; New Zealand; and Edmonton, Alberta. Sonix pretreatment of WAS has demonstrated a 20-30 percent increase in volatile solids destruction and a secondary sludge volatile solids increase from 40 percent or below to 60 percent (Kruger et al, 2005; Sandino and Whitlock, 2010; ovivowater.com; sonico.net).

Additional benefits of ultrasound pretreatment are that the units are very compact and simple to operate, reduce digester foaming, are easy to retrofit to existing facilities, and do not require extreme temperatures, pressures, or chemicals. Some of the drawbacks are that the units require a high-energy input, and in some cases, the energy input may outweigh the benefits from sludge reduction and increased biogas production. Data have shown both an increase and a decrease in dewaterability and polymer dosage as a result of ultrasound WAS pretreatment, and pilot studies may be required to determine what effect ultrasound treatment will have on the activated sludge and the optimal ultrasound dosage (Pilli et al, 2011).

Electrical Pretreatment Technologies

The OpenCel™ technology utilizes a focused pulse of electricity to break down the cell membrane, eventually resulting in cell lysis. OpenCel has a full-scale installation at the Northwest Water Reclamation Plant (NWWRP) in Mesa, Ariz., and has demonstrated an increase in soluble COD from 1,285 mg/L to 3,310 mg/L, a 60 percent increase in biogas, and a 40 percent reduction in biosolids. As a result of the energy offsets from the increase in biogas and reduction in biosolids disposal cost, the OpenCel™ provided an overall net positive economic benefit to the NWWRP. Additionally, it was also demonstrated that OpenCel caused an increase in the relative abundance of acetate-utilizing methanogens, indicating that cell lysis increases the availability of simple volatile acids. Additional benefits are that the unit may be retrofitted in an existing facility with minimal interruption to plant operation and does not require any chemical addition (Banaszak et al, 2008; opencel.com).

OpenCel has also been demonstrated to treat WAS for use as an internal electron donor for denitrification and could offset the need for methanol or other external source. In a pilot study, OpenCel increased the semisoluble COD of the treated WAS by 26 to 31 times, compared with nontreated WAS (Lee et al, 2010).

Case Study: BioCrack at Municipal Wastewater Treatment Plant

BioCrack is an electrokinetic disintegration process to increase the efficiency of the anaerobic digestion process in biogas and wastewater treatment plants. The wastewater sludge passes through an inline mechanical macerator and is then exposed to a high-voltage electrical field. The process breaks up the sludge flocs and may even rupture the cell walls, increasing the degradability of the sludge.

A full-scale trailer-mounted BioCrack unit was installed at a 20-mgd WWTP located in the southeastern United States.

Figure 3 shows the solids and liquids trains and the location of the BioCrack pilot unit.

The WWTP operates a four-stage biological nutrient removal (BNR) process to meet a year-round 5.5 mg/L effluent total nitrogen (TN) limit and a 0.5 and 2.0 mg/L total phosphorus (TP) effluent limit during the summer and winter, respectively. Thickened waste activated sludge (TWAS) is combined with raw primary sludge in four anaerobic digesters. Waste activated sludge is prethickened in gravity thickeners before final thickening via gravity belt thickeners. The BioCrack unit was installed on the effluent of the gravity belt thickeners. The TWAS is then fed to two digesters (Nos. 1 and 2), operated in parallel, followed by two digesters (Nos. 3 and 4) in series. Digesters Nos. 1

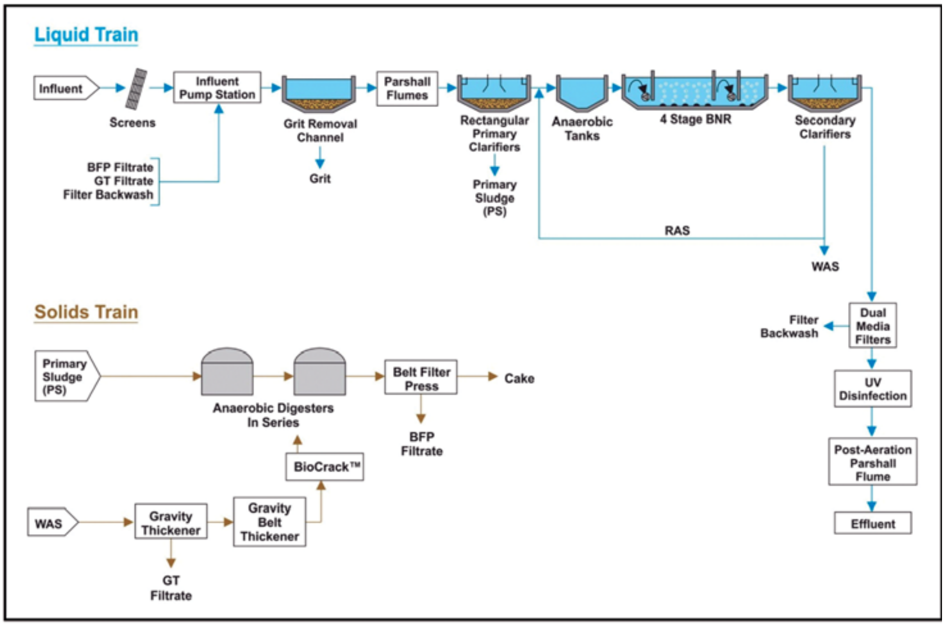

Figure 3. Wastewater Treatment Plant Flow Schematic with BioCrack Pilot Unit

Table 1. BioCrack Operating Parameters

Parameter	Value
Feed Rate	150 gpm
Number of Electrodes	4
Energy Input per Electrode	35 kW
Grinder Power Input	5 hp
Pipe Diameter	6”
Residence time (per Electrode)	~2.9 seconds
Average TWAS TSS	68,820
Net Energy Input (per mass dry solids)	220 kJ/kg TSS
Net Energy Input (per total volume)	1.0 kWH/m^3

and 2 each have a 732,000-gal capacity and Digesters Nos. 3 and 4 each have 1.19-mil-gal (MG) capacity. During the BioCrack pilot the primary digesters had an average 31-day SRT and the secondary digesters had an average 50.4-day SRT for an 81.4-day total-digester SRT.

The BioCrack pilot test ran from the end of September 2011 to the end of December 2011. Table 1 provides a summary of the BioCrack operating parameters. It should be noted that the net energy input (220 kJ/kg TSS, 1.0 kWH/m^3) is on the lower end of the spectrum for WAS pretreatment technologies. As a point of reference, Lee et al, 2010, used a 28 kWh/m^3 energy input with OpenCel to treat WAS for use as a carbon source for denitrification. Figure 4 displays the monthly average gas production from the primary digesters during 2011. The error bars represent ± one standard error of the mean. There appeared to be an increase in gas production during the BioCrack pilot; however, given the inherent variability (daily and seasonal) of digester gas production, it cannot be concluded whether the apparent increase in digester gas was a direct result of the BioCrack pilot.

Table 2 summarizes the impact of the BioCrack unit on TWAS. The total suspended solids (TSS) and volatile suspended solids (VSS) disintegration were calculated using Equation 1 and Equation 2; the COD solubilisation was calculated using Equation 3. The high TSS and VSS disintegration (13.6 and 11.4 percent, respectively) and low COD solubilisation (0.30 percent) indicate that the BioCrack is likely breaking the large-sludge flocs into much smaller particles, but not accomplishing significant cell lysis. It is expected that the COD solubilization would be much higher if the process were achieving a significant amount of cell lysis.

Equation 1: TSS disintegration (percent) =

$$\left(\frac{TSS_{Untreated} - TSS_{Treated}}{TSS_{Untreated}}\right) \times 100$$

Equation 2: VSS disintegration (percent) =

$$\left(\frac{VSS_{Untreated} - VSS_{Treated}}{VSS_{Untreated}}\right) \times 100$$

Equation 3: COD solubilisation (percent) =

$$\frac{SCOD_{Treated} - SCOD_{Untreated}}{TCOD_{Untreated} - SCOD_{Untreated}}$$

The BioCrack process did not have a significant effect on the TWAS or the performance of the anaerobic digesters during this case study. Because the BioCrack appears to achieve floc disintegration, but not cell lysis, it is likely that the process increases the rate of anaerobic digestion, but not the extent of digestion. BioCrack may be more appropriate at WWTPs with lower digester SRT (15-20 days) where an increase in the rate of anaerobic digestion would have a much more significant impact on total gas production.

Conclusion

Multiple WAS pretreatment technologies are available and have been demonstrated to increase volatile solids reduction and biogas production in the anaerobic digestion process. Depending on the technology, there may be a need for additional process heat, electricity, and chemicals, or a combination of these three components. When evaluating WAS pretreatment alternatives, it is important that the plant owner not only considers the volatile solids reduction, biogas production, and improved dewaterability, but also considers the cost and complexity of operation, the ease with which the process may be retrofitted to an existing anaerobic digestion process, the ability to pro-

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Table 2. BioCrack Performance Data

Parameter	Untreated-TWAS	Treated-TWAS
TSS (mg/L)	68,820 (± 9,570)	59,430 (± 10,450)
VSS (mg/L)	43,120 (± 11,890)	38,220 (± 13,850)
Total COD (mg COD/L)	35,720 (± 15,880)	39,200 (± 7,350)
Soluble COD (mg COD/L)	515 (± 65)	620 (± 148)
TSS Disintegration	13.6 percent	
VSS Disintegration	11.4 percent	
COD Solubilisation	0.30 percent	

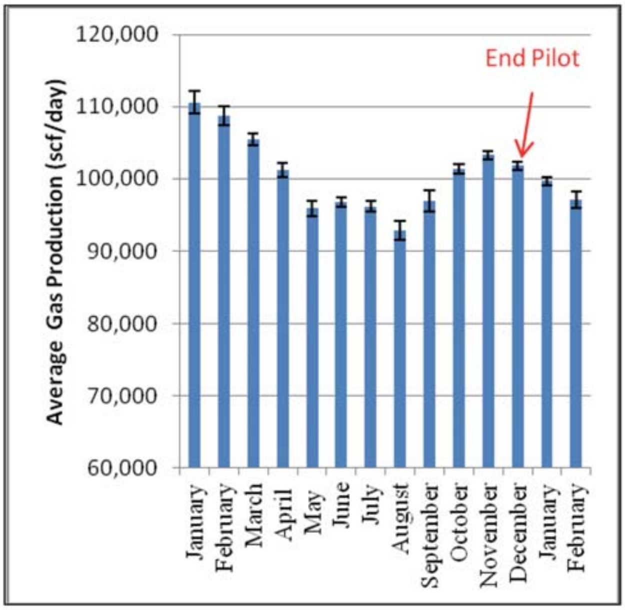

Figure 4. Primary Digester Average Daily Gas Production

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duce Class A biosolids, and additional benefits such as decreased odor from WAS pretreatment processes, as well as the specific operation of the particular wastewater treatment process. Results from laboratory-, pilot-, and full-scale installations have shown that there can be significant variation in performance, depending on the process and sludge characteristics and it is recommended that pilot testing be conducted, when possible, before full-scale installation of any of the WAS pretreatment technologies.

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