SLAVE LAKE PULP BIOMETHANATION WITH POWER GENERATION PROJECT

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ABSTRACT

West Fraser Mills has partnered with ADI Systems Inc. to construct and commission an anaerobic effluent pre-treatment facility at the Slave Lake Pulp (SLP) Bleached-Chemi-Thermo-Mechanical Pulp (BCTMP) mill in Slave Lake, Alberta to convert COD to methane-rich biogas and generate up to 8 MW of green energy. The reduced load to the activated sludge system results in reductions in nutrient use, sludge generation, and electricity consumption. Hydrogen sulfide present in the biogas is removed using biological scrubbers. Cleaned biogas is transferred to dual-fuel reciprocating engine generators (Gensets) for the production of up to 9 MW for internal mill use. This paper examines the new and novel application of the ADI-BVF® low-rate anaerobic digestion and biological scrubber technologies for green energy production in the North-American forestry industry.

INTRODUCTION

Anaerobic digestion of pulp and paper mill effluent can prove to be advantageous, as biogas generated from the digestion process can be recovered and utilized as a green energy source, while operating costs associated with traditional aerobic treatment systems can be greatly reduced. Tighter discharge regulations, global competition, increased water restrictions, energy-reduction measures, and greater consumer demand for products generated from environmentally-friendly processes are some of the challenges that the pulp and paper industry faces. Anaerobic digestion of mill effluent with biogas utilization presents an attractive alternative to address these challenges.

In general, anaerobic digestion involves a series of steps in which microorganisms break down organic matter in the absence of oxygen. When examining why anaerobic digestion results in an attractive return on investment for the pulp and paper industry, one can begin by comparing the fundamental redox reactions that occur in an anaerobic environment versus a conventional activated sludge system (or some variation thereof), which is typically used by pulp and paper mills to treat their wastewater.

At the molecular level, oxygen serves as the electron acceptor in an activated sludge system, whereas carbon dioxide serves as the electron acceptor in an anaerobic environment. For a given unit mass of substrate (electron donor), the free energy release when carbon dioxide acts as the electron acceptor is much lower compared to when oxygen is the electron acceptor, resulting in less energy available for cell synthesis (1). Fundamentally, the sludge yield in an anaerobic environment is lower when compared to an aerobic environment, which results in lower nutrient (i.e., nitrogen and phosphorus) requirements and lower sludge wasting requirements per unit mass of substrate digested.

Additionally, the carbon dioxide electron acceptor half-reaction results in methane as a by-product, which is not the case with the oxygen half-reaction (1). Thus, in an anaerobic environment, the majority of energy available via substrate stabilization is used for methane generation. Methane is poorly soluble in water and evolves from the liquid phase, resulting in the production of biogas, a mixture primarily consisting of methane and carbon dioxide (with trace amounts of hydrogen sulfide and other gases). The high heating value of methane allows for the biogas energy to be recovered and offset fossil fuel consumption.

Biogas utilization can result in significant long-term operating cost savings; however, operating cost savings through anaerobic pre-treatment are not limited to biogas utilization. Power required for mixing and aeration is significantly reduced, as the majority of the available substrate is digested in the absence of oxygen (and potentially with minimal mixing) in the anaerobic system, resulting in the downstream aerobic polishing system having a much lower oxygen requirement to stabilize any residual degradable organics. As previously discussed, the lower sludge yield in the anaerobic environment reduces supplemental nutrient addition. The lower sludge yield also reduces the manpower, chemical, electrical, and transportation costs associated with waste sludge thickening and disposal.

Anaerobic digestion of pulp mill effluent is an accepted alternative to traditional treatment methods; chemical oxygen demand (COD) removals ranging from 30 to 90% have been achieved in full-scale reactors, with methane yields up to 0.40 m^3 per kg COD removed (2). However, anaerobic digestion of pulp and paper wastewater does not come without challenges, which vary from mill to mill, and can vary based on raw materials, pulping processes, chemical recovery, bleaching, pulp mill age, etc. (2). Hydrolysis and digestion of complex organic matter, such as lignocellulosic material, can be difficult and requires reactors with long sludge residence times. The presence of anaerobic inhibitors, such as resin acids, wood extractives, sulfur, hydrogen peroxide, chelants, and organochlorine compounds, can reduce the potential organic removals and biogas yields of the anaerobic pre-treatment system (3). The effect that these compounds may individually or collectively have on the anaerobic digestion process is not easy to predict. Oftentimes, conducting a pilot study of the anaerobic technology is required to determine the degree which these factors will influence the performance of the anaerobic digestion system. These factors not only differ from mill to mill, but their effects can vary depending on the selected anaerobic technology.

Despite these potential challenges, the financial and environmental benefits of anaerobic digestion proved to be very attractive for Slave Lake Pulp.

Slave Lake Pulp, a subsidiary of West Fraser Mills Ltd., is a 240,000 MTPY BCTMP mill located in northern Alberta. The mill primarily processes aspen through refiners and subsequent bleaching stages to produce market pulp for the global market. The mill generates a high-strength wastewater stream which, prior to the Biomethanation project, was treated in a conventional activated sludge (CAS) system.

In the existing CAS system, pulp mill effluent is pre-screened using side hill screens, with filtrate being discharged to the Krofta and/or Poseidon DAF clarifiers. Clarified effluent is dosed with aqueous ammonia and ammonium polyphosphate (for supplemental nutrient addition) and sent to the activated sludge system, consisting of four aeration basins and two secondary clarifiers. The activated sludge system removes the biologically degradable organic load, and CAS effluent is discharged to the reaeration chamber prior to direct discharge to the Lesser Slave River. Waste solids from the side hill screens, DAF clarifiers, and activated sludge system are sent to the sludge storage chest, and a sludge press is used for sludge thickening. Final effluent is monitored for BOD_5 (max monthly average of 1,750 kg/d), TSS (max monthly average of 2,800 kg/d), pH (6.0 – 9.5), and acute lethality using rainbow trout and daphnia magna (50% or greater survival in 100% treated effluent sample).

West Fraser is committed to environmentally responsible management. With assistance from the Climate Change and Emissions Management Corporation (CCEMC) and the EcoTrust Fund, West Fraser has invested significant capital towards the Biomethanation with Power Generation Project, with the objective of anaerobically digesting pulp mill effluent to generate biogas, which would subsequently be treated and utilized (along with natural gas) in a set of three 3 MW generators for the production of up to 9 MW of power for mill use.

The objective of the Biomethanation and Power Generation Project was not limited to green energy production, as the following benefits would be achieved by installing an anaerobic digestion system to pre-treat the pulp mill effluent:

- Responds to consumer demand for products produced through environmentally-friendly processes
- Reduces and stabilizes the organic load to be treated in the activated sludge system
- Decreases energy (mixing and aeration) requirements in the CAS system
- Allows for the retirement of existing aeration basins and the Krofta DAF clarifier, reducing the number of tanks to be operated and maintained in the long-term
- Reduces chemical usage (aqueous ammonia and ammonium polyphosphate) due to lower nutrient requirements for overall wastewater treatment system
- Decreases sludge generation for the overall wastewater treatment system, which subsequently results in lower chemical requirements for sludge dewatering and lower sludge transportation costs
- Improves consistency of final effluent quality

In short, significant electrical and operating cost savings are realized by installing green-energy generating and recovering technologies.

Tenders for design, supply, and installation of the anaerobic digestion and biogas treatment systems were submitted in July 2012. Technologies considered included low-rate, mid-rate hybrid, and multiple high-rate technologies. Low-rate technology was selected because of the low manpower requirements, buffering capacity for COD variability, and availability of land required for a large-footprint digester. SLP selected ADI Systems to perform this work.

As part of the tendering process, several anaerobic pilots were commissioned including an onsite high-rate pilot using granular sludge and several bench-scale pilots utilizing floccular sludge (mid- to low-rate). A lab-scale low-rate anaerobic pilot followed by an aerobic pilot stage was performed by Alberta Innovates - Technology Futures (AITF) to simulate the final effluent quality of an anaerobic pre-treatment stage followed by conventional aerobic treatment. The purpose of the pilot studies was to evaluate soluble COD (sCOD) conversion rates, operational issues with the various technologies (toxicity, solids sensitivity, COD variability, etc.), and the colour impact on final treated effluent.

ADI Systems, headquartered in Fredericton, NB, specializes in supplying biological wastewater treatment technologies to industrial customers. For the SLP Biomethanation and Power Generation Project, ADI Systems proposed to install a 120,000 m^3 low-rate, anaerobic, ADI-BVF® reactor system for digesting the SLP mill effluent as well as a BioGasclean biological scrubber system to reduce the hydrogen sulfide (H_2S) content in the biogas generated from the BVF® reactor.

The ADI-BVF® reactor is a proven technology for anaerobic treatment of industrial wastewater, with over 125 full-scale installations worldwide in a wide variety of industries, including food and beverage, dairy, brewery, distillery, chemical, and biofuels. BVF® technology has achieved BOD removals of 70 to 90% when treating various pulp and paper waste streams at the bench and pilot-scale (4). However, ADI Systems had not installed a full-scale BVF® reactor treating pulp and paper wastewater prior to the Slave Lake Pulp Biomethanation project.

Globally, 390 anaerobic digestion systems have been installed in the pulp and paper industry, with the majority of these installations being high-rate expanded/fluidized bed reactor systems, such as the BIOPAQ® Internal Circulation (IC) reactor marketed by Paques, the Biobed® Expanded Granular Sludge Bed (EGSB) reactor offered by Veolia, and the R2S reactor offered by Voith (5).

The BVF® reactor installed at Slave Lake Pup is not only ADI Systems' first full-scale BVF® reactor in the pulp and paper industry, but represents a shift in the traditional approach to anaerobic digestion of pulp mill wastewater from high-rate to low-rate. Furthermore, the biological biogas scrubber system to treat the biogas prior to utilization is among the world's largest biological scrubbers installed in terms of hydrogen sulfide load treated.

ADI-BVF® REACTOR AND BIOGAS SCRUBBER TECHNOLOGY DESCRIPTIONS

The BVF® reactor is effective at consistently achieving a high organic removal efficiency and biogas production rate, yet the technology is relatively simple and has few moving parts. The anaerobic reactor itself is an earthen basin with a concrete perimeter wall lined with a geotextile underlay and geomembrane liner. Specially-designed influent piping evenly distributes incoming wastewater throughout the front-end of the reactor, where the majority of the biologically degradable organics are digested. A supernatant recycle (SREC) pump is used to mix clarified liquid from near the top of the reactor through the influent distribution system, and a return anaerobic sludge (RANS) pump is used to periodically return settled sludge from the back-end (sedimentation zone) of the reactor to the front-end.

The reactor is covered with a multi-layered, flexible, geomembrane cover which allows for the reactor to operate at a slight vacuum pressure. The geomembrane cover is insulated to reduce heat loss, and sampling ports on the cover allow for the reactor contents to be accessed.

Biogas generated in the system migrates to the BVF® reactor cover perimeter, and variable frequency drive (VFD) controlled blowers ramp up or down (based on the actual biogas production rate) to remove biogas from underneath the BVF® cover in order to maintain the target cover pressure range. The blowers pull gas through the biogas scrubbing system, boost the biogas pressure, and transmit the scrubbed biogas to the generators for utilization. Any biogas not utilized is combusted in a waste gas incinerator.

The process schematic of the BVF® reactor system is shown in Figure 1. In addition to the standard components previously outlined, the BVF® reactor installed at Slave Lake Pulp includes the following customized components:

- Automatic valves to alternate influent and RANS header lines.
- Sump pumps in the control building's pump and blower rooms to discharge liquid (i.e. collected condensate from the gas/liquid separator trap and blower drip traps) to the BVF® reactor recycle line.
- Sump and pump to suppress groundwater from beneath the BVF® reactor and discharge back to the BVF® reactor.
- VFD-controlled waste anaerobic sludge (WANS) pump with downstream flow meter to discharge waste sludge to the existing sludge storage chest.

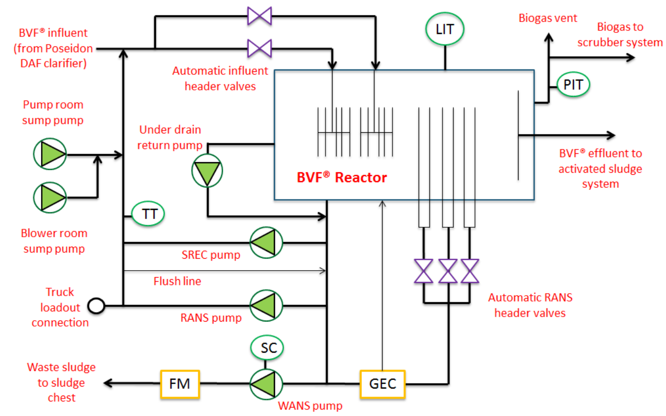

Figure 1 – Process schematic of ADI-BVF® reactor system at Slave Lake Pulp

BVF® technology is classified as a low-rate anaerobic technology, implying that the reactor treats a low organic load per unit volume (typically 0.5 to 2.0 kg COD·m^{-3}·d^{-1}). For large organic loads, this results in a relatively large reactor, meaning that footprint available for wastewater treatment can be a potential obstacle for the technology. However, the large reactive volume, as well as the long hydraulic retention time and large anaerobic biomass inventory with exceptionally long solids residence time, are the keys to the technology's success.

The significant inventory of biomass in the BVF® reactor results in a low food-to-microorganism (F:M) ratio. When the low F:M is paired with the long hydraulic retention time, very long solids residence time, and adequate recycle arrangement, the result is enhanced process stability, robustness, and an inherent ability to handle swings and peaks in hydraulic and organic loads. This factor is important for Slave Lake Pulp, as the mill frequently alternates pulp brightness grades, resulting in swings in wastewater sCOD concentrations from 5,000 to 19,000 mg/l.

The large physical size of the BVF® reactor results in a relatively low ratio of biogas produced to reactor surface area. Consequently, the BVF® reactor does not require granular anaerobic sludge to operate effectively. Compact, dense granules have much better settleability than flocculent biomass; thus, it is critical that high-rate anaerobic systems maintain a bed of granular sludge due to the high biogas production rate per unit surface area. Failure to maintain the granular sludge bed in a high-rate anaerobic system (potentially due to changes in organic loading rates, transient occurrences in toxic and inhibitory substances, high inputs of oxygen, etc.) can result in granule degradation, decreased biological performance, biomass washout, and possible re-seeding. Since there are few high-rate anaerobic reactors with available granular sludge in the area surrounding Slave Lake, AB, acquiring a sufficient amount of granular seed sludge for reactor seeding would be logistically difficult and costly.

The ability of the BVF® reactor to operate with a large inventory of flocculent sludge simplifies the process, reduces seeding cost and complexity during the start-up phase, and increases the resistance to inhibitory compounds and changes in wastewater characteristics. Additionally, the long solids retention time associated with the BVF® reactor allows for waste solids from an activated sludge system to partially contribute to the initial seed sludge mass, further simplifying the seeding process.

The large reactive volume of the BVF® reactor also provides the benefit of sludge storage for extended periods of time before sludge wasting is required. With a proper sludge management strategy, anaerobic sludge can be wasted from the BVF® reactor during campaigns as infrequently as twice per year.

Furthermore, a portion of the waste activated sludge (WAS) generated in a downstream aerobic polishing system can be wasted to the BVF® reactor for solids digestion. This process reduces the sludge volume delivered to the sludge dewatering system, reduces hauling of thickened sludge off-site (of particular importance during spring/fall road weight restrictions) and recaptures nutrients, which contributes to further cost savings.

Prior to the full-scale Biomethanation project, a four-month pilot study was conducted by SLP and an anaerobic digestion vendor using a high-rate anaerobic technology to treat mill influent. The pilot was exposed to significant variations in anaerobic effluent quality on a day-to-day basis (i.e., effluent sCOD concentration ranging from 5,000 to 10,000 mg/l). Based on ADI Systems' analysis of this pilot data, a design BVF® reactor soluble COD removal efficiency of 70% was projected.

Additionally, SLP conducted an anaerobic continuously-stirred tank reactor (CSTR) pilot study with Alberta Innovates – Technology Futures (AITF). The pilot studies demonstrated that the SLP wastewater was amenable to anaerobic treatment and that the anaerobic systems could achieve a maximum weekly average COD removal efficiency of 60%. This study was done on a single representative influent sample and was coupled with an aerobic post-treatment stage to evaluate the effects of anaerobic pre-treatment on effluent qualities including colour. It was found that colour is not directly increased by anaerobic treatment of COD; rather, colour increases by nearly double after aeration of anaerobically treated effluent. The study suggests that the colour increase is a result of humic compounds contained in the recalcitrant COD passing through the anaerobic digester, which are oxidized to fulvic acids during aeration. It is also suggested that final effluent colour is a function of influent COD concentration (7), which is discussed later in this article.

Table 1 shows the design characteristics of the SLP wastewater (Poseidon DAF clarifier effluent) and anaerobic BVF® reactor effluent.

Table 1 – Design Characteristics of SLP Wastewater and Anaerobic BVF® Reactor Effluent

PARAMETER	POSEIDON DAF CLARIFIER EFFLUENT (ADI-BVF® INFLUENT)	ADI-BVF® EFFLUENT
Flow, avg (m^3/d)	9,040	9,040
Flow, max (m^3/d)	11,445	11,445
tCOD, avg (mg/l)	17,000	5,000
tCOD, max (mg/l)	20,500	6,000
sCOD, avg (mg/l)*	15,900	4,800
sCOD, max (mg/l)	19,200	5,800
sCOD, avg (kg/d)	143,500	43,000
sCOD, max (kg/d)	173,000	52,000
sBOD, avg (mg/l)	4,400	450
TSS, avg (mg/l)	750	400
TN (mg/l)	40**	10
TP (mg/l)	10**	4
SO_4 (mg/l)	1,200	---
pH	6.7-8.4	6.6-8.0
Temp (°C)	38-40	32-35

*Soluble COD used for design basis (and described in this paper) is analyzed on samples centrifuged using an IEC clinical centrifuge (samples are not filtered after centrifuge)

**Existing aqueous ammonia and ammonium polyphosphate metering systems used to increase biologically available nitrogen and phosphorus in the Poseidon DAF clarifier effluent

Figure 2 shows the components of the biogas treatment and transmission system. Biogas from the BVF® reactor is conveyed through the BioGasclean scrubbing system on the suction side of the biogas blowers. The BioGasclean system consists of two parallel 750 m^3 scrubbing tanks filled with packed media and *Thiobacillus* bacteria which biochemically convert the sulfide in the biogas to sulfate. Sufficient air (oxygen), scrubbing liquid, nutrients (aqueous ammonia and ammonium polyphosphate), and heat are supplied to the scrubbing tanks to promote the biochemical reactions. Hydrogen sulfide is oxidized and transferred from the gas phase to the liquid phase; the scrubbing liquid, high in sulfate, is discharged to the activated sludge system. The biogas blowers transmit the scrubbed biogas through two speed-controlled biogas coolers (gas-to-air heat exchangers) prior to utilization in the three 3 MW generators. Any biogas that cannot be utilized in the generators is released to the enclosed biogas incinerator.

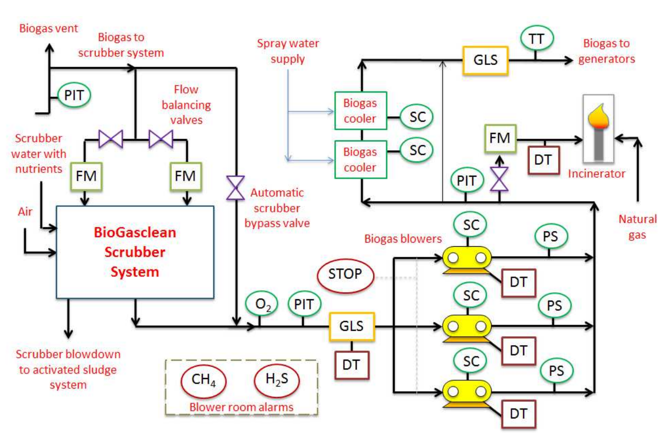

Figure 2 – Process schematic of biogas scrubbing and transmission system at Slave Lake Pulp

Table 2 summarizes the design characteristics of the raw and treated biogas from the anaerobic digestion and biogas scrubbing systems.

Table 2 – Design Characteristics of Raw and Treated Biogas

PARAMETER	RAW BIOGAS	TREATED BIOGAS
Flow, avg (m^3/d @ STP)	39,300	48,700
Flow, max (m^3/d @ STP)	48,200	59,700
Temp (°C)	25-35	< 36
Methane, CH_4 (%)	75 (expected) 60-85 (range)	60.5
Carbon dioxide, CO_2 (%)	23 (expected) 15-40 (range)	18.6
Hydrogen sulfide, H_2S (ppm)	20,300	< 100
Nitrogen, N_2 (%)	---	19.4
Oxygen, O_2 (%)	---	1.5
Water vapour	Saturated	---

PROJECT TIMELINE AND CHALLENGES

Detailed design of the anaerobic digestion and biogas scrubbing systems began in February 2013. At the onset of the project, the decision was made to split the plant construction into two phases due to the large physical size of the ADI-BVF® reactor and the harsh northern Alberta winter conditions.

The first construction phase was conducted from June to December 2013. The primary objectives for the anaerobic digester at the conclusion of the first phase of construction were to have the basin, liner, and internals installed and to fill the reactor with water before the beginning of winter.

To construct the anaerobic digester, an approximate area of 95 m by 185 m had to be stripped and excavated. During excavation and construction of the berms and perimeter wall, heavy rainfalls would result in short-term construction delays. Concrete pipe support pads were laid for the internal piping network, and the BVF® reactor liner and internals were installed by Geomembrane Technologies, Inc. (GTI).

In November 2013, the BVF® reactor was filled with effluent from the SLP CAS system. Once the reactor had been filled, the warm CAS effluent continued to be circulated to the BVF® reactor prior to discharge in order to prevent the liquid in the BVF® reactor from freezing during the winter. The BVF® reactor was maintained in this condition until the second phase of construction.

In addition to meeting the target objectives for the first phase of the BVF® reactor construction, the new pre-engineered metal frame control building was erected during this period. The control building includes an electrical room (housing MCC, PLC, VFDs, and transformer), blower room (housing the three biogas blowers, CH_4 and H_2S detection for the atmosphere, gas-liquid separator, biogas oxygen content monitor, and sump pump) and pump room (housing the SREC and RANS pumps, heating system for the building and biogas scrubber system, and sump pump).

The second phase of construction began in April 2014. This involved the installation of the BVF® geomembrane reactor cover, completion of the biogas piping, and construction of the biogas scrubber system. During this period, the recirculated CAS effluent increased the BVF® temperature up to the minimum operating temperature of 25 +/- 2°C.

When the reactor was sufficiently warm, a satisfactory quantity of seed sludge was added to the reactor. As previously discussed, the low-rate BVF® reactor does not require granular sludge to operate, which reduces the cost and complexity of sourcing anaerobic seed sludge. Sludge from the anaerobic reactors at the City of Edmonton Capital Region Wastewater Treatment Plant (WWTP) was used to seed the BVF® reactor. Furthermore, as a result of the long solids retention time in the BVF® reactor, WAS from the SLP CAS system was used to supply a portion of the dry sludge mass required for seeding. This approach is acceptable for the low-rate BVF® reactor, as the biological WAS solids convert to anaerobic solids in the weeks between seeding and the beginning of wastewater feeding.

By September 2014, the BVF® reactor was ready to accept SLP wastewater.

ADI-BVF® REACTOR PERFORMANCE

During the start-up phase, wastewater flow to the BVF® reactor was progressively increased over a period of several weeks; this approach gradually increases the food-to-microorganism ratio and gives the anaerobic biomass time to acclimate to the new substrate source.

As seen in Figure 3, wastewater flow to the BVF® reactor was gradually increased over the first few weeks of operation. From November 2014 to April 2015, the BVF® reactor treated an average of 5,850 m^3/d of SLP wastewater, corresponding to approximately 60% of the total wastewater produced from SLP. Beginning on March 11, the BVF® reactor began accepting 85% of SLP wastewater (average of 8,600 m^3/d)

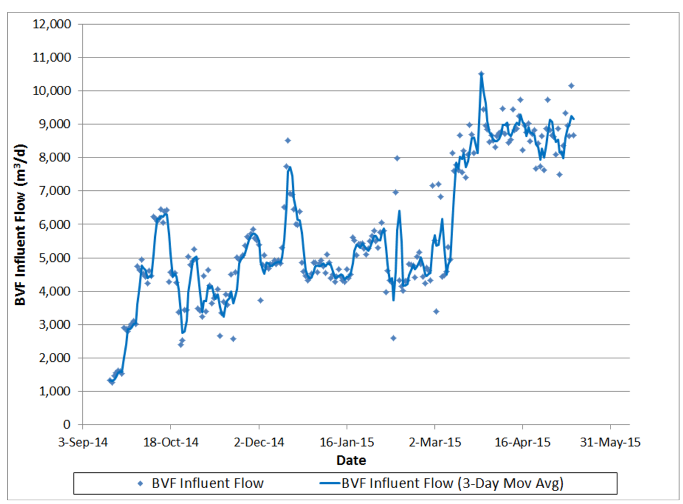

Figure 3 – BVF® reactor influent flow

While the BVF® influent flow has been relatively constant during these periods, the BVF® saw regular peaks and troughs in influent sCOD load, as shown in Figure 4, due to SLP's varying pulp brightness grades. Influent sCOD loads ranged from 12,000 to 165,000 kg sCOD/d, with an average sCOD load of 71,500 kg COD/d during the first eight months of reactor operation.

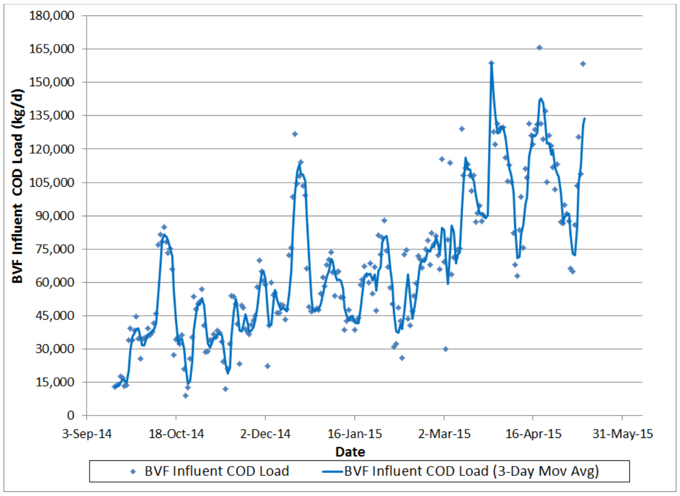

Figure 4 – BVF® reactor influent COD load

During the initial stage of increasing the flow to the BVF® reactor, signs of reactor stress were occurring, including a decrease in reactor pH, increase in effluent sCOD concentrations, and accumulation of short-chain volatile acids in the anaerobic reactor. The upset conditions may have been attributed to a number of factors, including a rapid increase in reactor organic loading resulting from a pulp grade change (as seen in Figure 4) and a high ratio of sulfur to biodegradable COD in the BVF® reactor (due to initially filling the reactor with a high-sulfate/low-COD effluent stream). The corrective action taken was to gradually add caustic solution into the BVF® influent line in order to increase the reactor pH and provide supplemental buffering capacity. A total of 23,000 kg of caustic solution was dosed into the BVF® reactor from October 23 to November 11, improving the health of the BVF® reactor. As seen in Figure 5, the caustic addition during this time resulted in a period where the anaerobic biomass digested the accumulated sCOD in the reactor, returning the reactor to steady-state conditions. Since this time, the BVF® reactor has not required supplemental alkalinity (caustic) to maintain high organic removal efficiency.

Figure 5 shows that after the initial upset conditions had been corrected, the BVF® reactor maintained a consistent sCOD removal efficiency. Despite the variations in influent sCOD load (due to influent sCOD concentrations ranging from 6,000 to 18,500 mg/l), the BVF® reactor generated a consistent quality anaerobic effluent, with an average sCOD removal efficiency of 72%. The trend of sCOD removals demonstrates how the long hydraulic retention time and significant biomass inventory work together to handle variations in organic loading conditions while maintaining a high level of anaerobic treatment. These factors simplify the operation of the downstream aerobic polishing system (as the CAS influent characteristics are much more consistent and predictable) and improve biogas production.

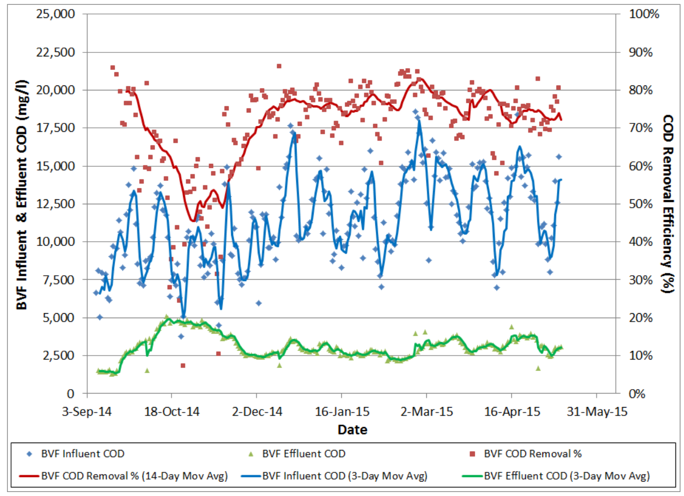

Figure 5 – BVF® reactor influent and effluent sCOD concentrations and sCOD removal efficiency

The sCOD present in the anaerobic effluent (average of 3,100 mg/l) is primarily composed of long-chain fatty acids and complex, non-biodegradable compounds. However, a portion of the effluent sCOD is biologically degradable. The biochemical oxygen demand (BOD) test provides an indication of the oxygen demand exerted by a wastewater sample over a 5-day period; the BOD removal across the BVF® reactor indicates how well the reactor is able to remove this material.

Figure 6 reaffirms the strong organic removal efficiency of the BVF® reactor. Since the BVF® reactor start-up, the wastewater BOD concentrations have ranged from 2,700 to 7,500 mg/l (average of 5,100 mg/l). BVF® effluent BOD concentrations have averaged 720 mg/l, corresponding to a BOD removal efficiency of 86%. Furthermore, since commissioning of the BVF® reactor, the average BOD load of SLP's final effluent to the river decreased to an average of 310 kg/d, corresponding to an 8.2% decrease compared to average results prior to commissioning the BVF® reactor.

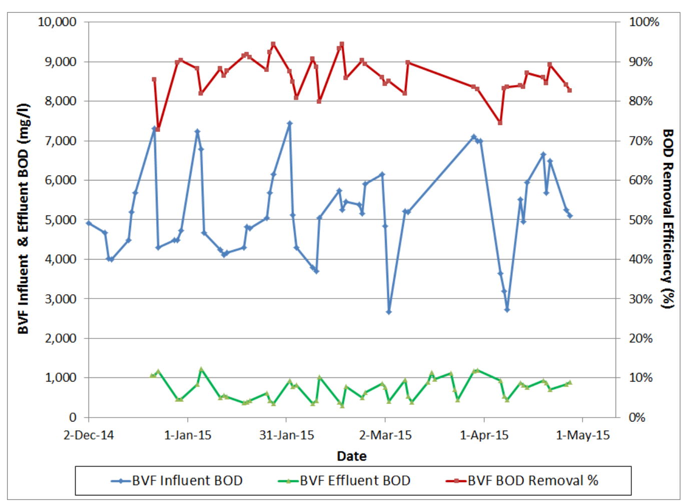

Figure 6 – BVF® reactor influent and effluent BOD concentrations and BOD removal efficiency

The BVF® reactor environmental conditions (pH and temperature) are shown in Figure 7. As previously discussed, a drop in reactor pH was observed during the first few weeks of reactor operation, signifying that the anaerobic biomass was experiencing stress. Sufficient volume of caustic was added over a period of three weeks to bring the reactor pH up to 7.3, and since this period the BVF® reactor has maintained an average pH of 7.45 without supplemental alkalinity addition.

SLP wastewater is sufficiently warm such that temperature control in the BVF® reactor is not required. The ideal temperature for mesophilic anaerobic bacteria is 37°C (6); however, the design of the low-rate BVF® reactor allows for operation at sub-optimal temperatures. Thus, reactor heating or cooling does not contribute to SLP's overall energy balance. During the start-up phase, the BVF® began to accept wastewater at a reactor temperature of 25°C, and the wastewater heat gradually increased the reactor temperature to 35°C by the end of 2014. During the winter months, the reactor temperature dropped to as low as 31°C; however, no change in performance was observed as a result of the lower operating temperature.

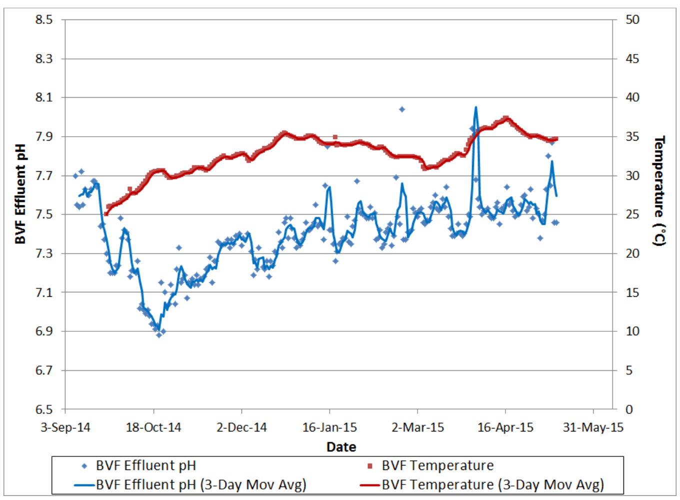

Figure 7 – BVF® reactor operating pH and temperature

Final effluent colour is indirectly affected by the amount of sCOD anaerobically treated in the BVF® reactor. Colour in final effluent increases linearly as the rate of influent to the BVF® reactor increases as shown in Figure 8. Colour has increased by a factor of three times, which is higher than the AITF study estimated. This may be caused by the higher than expected sCOD reduction in the full-scale BVF® reactor (72%) compared to sCOD reduction obtained during the AITF study (60%).

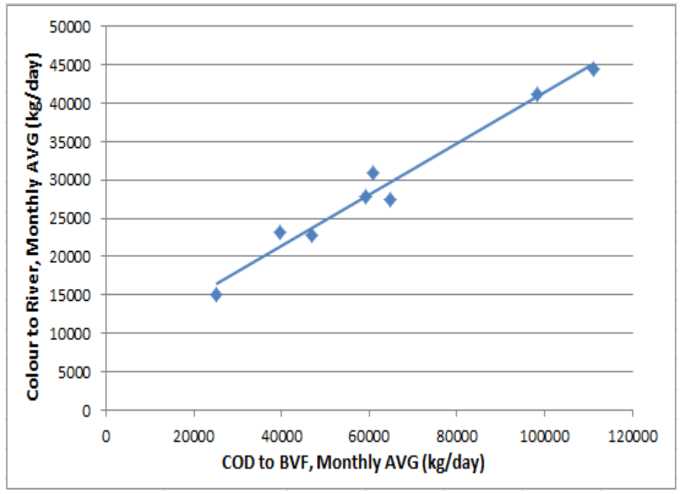

Figure 8 – Final effluent colour vs. influent sCOD load to BVF® reactor

SLP tracks many different parameters in its effluent treatment system, some of which are inhibitors to anaerobic digestion such as DTPA and resin acids, along with various biological health parameters analyzed by Dr. Clifford Lange out of Auburn State University (8). In the anaerobic digestion process there are three fundamental steps: hydrolysis, fermentation, and methanogenesis (9). In the methanogenesis step, volatile acids (VA) that were produced from the breakdown of long-chain organic compounds are converted to methane. Since short-chain volatile acids (such as acetic, butyric, and propionic acids) are a precursor to methane production, these key components to anaerobic digestion are being tracked to develop a baseline for VA production and accumulation (partitioning to the biomass) in the sludge bed of the BVF® reactor. As seen in Figure 9, VA concentrations in the biomass have slightly increased as influent sCOD load (and subsequently biogas production) increases throughout the commissioning phase. It is expected that the VA concentration trend will stabilize once all influent flow is directed to the BVF® reactor. Any changes in VA concentration trends can be compared to the baseline in order to assist in understanding BVF® performance with regard to biological activity and stability.

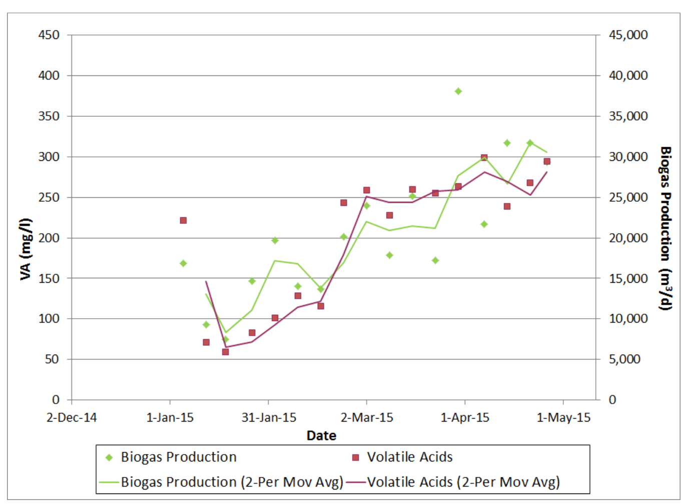

Figure 9 – Volatile acid bioaccumulation and biogas production

To further understand the biological health of the anaerobic bacteria, ATP production is also being tracked in order to develop a baseline during steady-state conditions and aid in troubleshooting any changes in biological activity. As seen in Figure 10, there is a direct correlation between ATP production and biogas production.

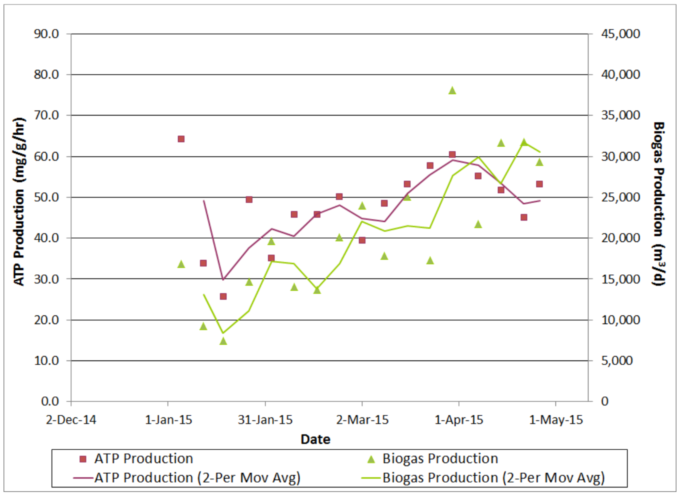

Figure 10 – Anaerobic ATP production and biogas production

When comparing CAS effluent data before and after BVF® reactor commissioning, an increase in average concentrations of several groups of inhibitors has been observed, as shown in Table 3. However, with neither the BVF® nor CAS systems having reached a true final steady state (when BVF® reactor pre-treats all wastewater flow) inhibitory compound thresholds cannot be developed until all influent flow is being anaerobically pre-treated in the BVF® reactor.

Table 3 – CAS System Effluent Inhibitor Averages Before and After Commissioning the BVF® Reactor

INHIBITOR	CAS SYSTEM EFFLUENT		% INCREASE
	BEFORE BVF®	AFTER BVF®	
Long chain fatty acids (mg/l)	155.63	217.56	39.8
Quaternary amines (mg/l)	23.69	37.92	60.1
Anionic surfactants (mg/l)	22.32	24.16	8.2
Terpenes (mg/l)	9.09	14.23	56.5
Resin acids (mg/l)	1.01	2.04	102.0
DTPA (mg/l)	11.11	8.59	-22.7

The high organic removals due to positive biological activity have translated to an exceptional biogas production rate. While the biogas scrubber system is being constructed, all biogas generated in the BVF® reactor is sent to the waste gas incinerator. The flow meter on the biogas incinerator line has provided an indication of the volume of biogas generated in the BVF® reactor; since the BVF® reactor began accepting 85% of SLP wastewater (corresponding to an average influent sCOD load of 110,000 kg/d) the BVF® reactor has generated an average of 28,500 Nm^3/d of biogas (in this paper, biogas production rates are expressed at normal conditions of 0°C and 1 atm).

Additionally, the biogas composition has been monitored to evaluate the quality of biogas generated from the BVF® reactor. As seen in Figure 11, during the steady-state period the biogas has been composed of 85% methane, 13.8% carbon dioxide, and 1.2% hydrogen sulfide. The biogas composition results are important, as scrubbed biogas must have a minimum threshold methane content in order to be utilized by the generators. Air is supplied to the BioGasclean scrubber system in order to provide the oxygen required for the biochemical sulfur oxidation reactions to take place. The nitrogen and residual oxygen dilute the biogas; however, the raw biogas methane and hydrogen sulfide content results obtained during the first eight months of BVF® reactor operation indicate that the composition of the scrubbed biogas will be acceptable for utilization.

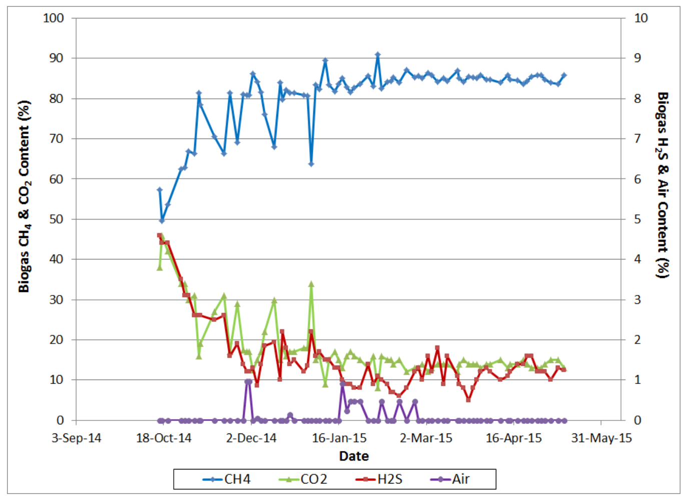

Figure 11 – BVF® reactor biogas composition

The biogas composition data can be used to calculate the observed methane yield for the BVF® reactor. At STP conditions, anaerobic biomass will theoretically generate 0.35 L of methane per gram of COD removed (1). In practice, the observed methane yield will be lower than the theoretical methane yield, particularly for systems treating wastewater with high concentrations of sulfur. In an anaerobic environment, sulfate is reduced to the sulfide form by sulfide reducing bacteria (SRB), which compete with methane producing bacteria (MPB) for substrate. In terms of redox reactions, sulfate is the preferred electron acceptor to carbon dioxide (1); thus, for the BVF® reactor with a long HRT and exceptionally long SRT, sulfate is fully reduced to sulfide (either the unionized [H_2S] or ionized [HS^-] forms). Sulfur reduction results in a decrease in observed methane yield of 0.23 m^3 methane per kilogram of sulfate reduced.

Data accumulated during steady-state conditions indicates that the BVF® reactor generates 0.29 Nm^3 methane per kilogram of COD removed. Considering the lower heating value of methane (35.8 MJ/Nm^3), this methane yield results in **10.4 GJ of biogas energy per tonne of COD anaerobically removed**.

As seen in Table 1, the BVF® reactor is designed to anaerobically remove an average COD load of 100 tonnes per day. At design loading conditions, assuming all biogas is utilized and the generators achieve 38% electrical efficiency and 45% thermal efficiency, **4.7 MW of electrical power and 5.6 MW of thermal energy can be generated through biogas utilization**. On average design loading days, 50% of the electrical energy produced by the three generators will come from biogas, with natural gas supplementing the generator fuel. At the current COD removal rate and methane yield, the **BVF® reactor will generate enough biogas to generate 8 MW of electrical power on peak loading days**.

SLP WWTP PROCESS IMPROVEMENTS AND OPERATING COST SAVINGS

Construction of the biological biogas scrubber is being completed at the time of writing. Commissioning of the scrubber system will occur during summer of 2015, at which point SLP will realize the full green-power-generating potential of the anaerobic digester. However, SLP have already observed significant benefits by anaerobically pre-treating the mill wastewater:

Increased Overall WWTP Process Stability – Variations in organic load discharged to the CAS system have been greatly mitigated since the start-up of the BVF® reactor. As shown in Figures 4-6, regular changes in pulp brightness grades had previously resulted in swings in wastewater strength, which would increase the operational difficulty of the CAS system (i.e., aeration basin foaming, variations in solids settleability in the secondary clarifiers resulting in biological solids washout, highly variable nutrient chemical dosage and solids wasting regimens, etc.). The BVF® reactor has generated an anaerobic effluent with consistent sCOD, BOD, suspended solids, pH, temperature, and residual nitrogen and phosphorus concentrations, which has simplified the operation of the downstream CAS system. Figure 12 shows the stabilizing effect of the BVF® on cumulative depth to sludge bed in the clarifier. In Figure 12, bed depth represents the clarified effluent above the settled sludge bed; thus, higher numbers indicate better settleability.

Decommissioned Aeration Basins – As a result of the significantly reduced organic load sent to the CAS system, two of the four existing aeration basins have been decommissioned during the first eight months of BVF® reactor operation. Anaerobically removing 86% of the influent BOD load results in the remaining two aeration basing operating at a very conservative organic loading rate and F:M ratio, which ensures that the BOD and TSS discharge limits can be consistently met.

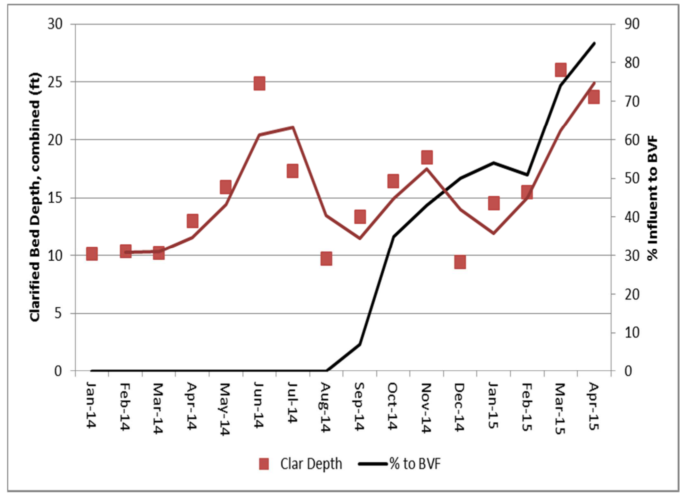

Figure 12 – CAS settleability (combined clarifier depth to bed)

Reduced Electrical Costs – The existing CAS system was an energy-intensive process, with three large aeration blowers needed to supply the mixing-intensity and oxygen required in the four aeration basins for BOD stabilization. Prior to installing the anaerobic digester, aeration of the CAS system consumed an average of 1500 MW-h of energy per month. The BVF® digester removes approximately 90% of the BOD load anaerobically, with no aeration and minimal mixing. Power usage for the BVF® reactor itself has been primarily limited to operating the SREC and RANS pumps (each rated for 15 kW, no more than one pump operates at a time) and the three biogas blowers (each rated for 60 kW, variable frequency drives used to adjust speed of blowers to maintain target cover pressure range, one or two blowers operate at a time). Since influent flow to the BVF® reactor was increased to 85% of the total wastewater flow, CAS aeration and new WWTP equipment has consumed an average of 850 MW-h of energy per month, resulting in 43% savings in energy usage. Figure 13 shows the combined electrical load of the CAS blowers, the largest load in the WWTP. In Figure 13, one blower operating at its full rated capacity corresponds to 100%, resulting in a maximum combined blower load of 300%.

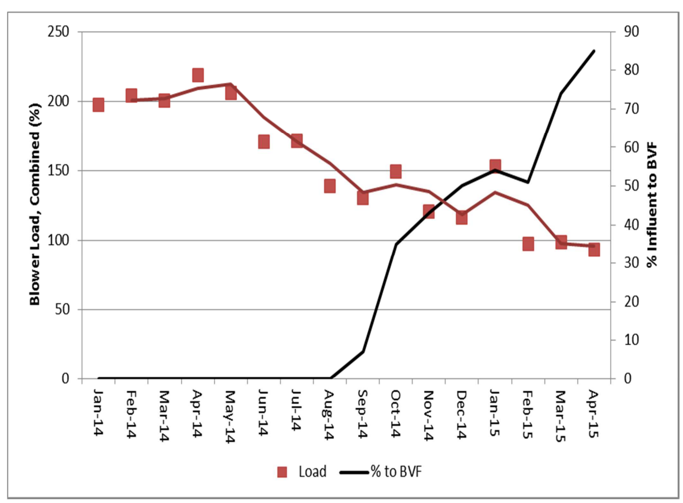

Figure 13 – Cumulative CAS blower load

Reduced Nutrient Chemical Usage – As outlined earlier, the lower sludge growth rate in an anaerobic environment results in lower nutrient (nitrogen and phosphorus) requirements per unit mass of BOD stabilized compared to removing the BOD aerobically. Prior to operating the anaerobic reactor, an average of 5.6 m^3/d of aqueous ammonia and 0.6 m^3/d of ammonium polyphosphate were used to satisfy the nutrient requirements for the activated sludge in the CAS system. Additionally, the dosage rates were prone to significant week-to-week variations due to the swings in wastewater organic strength. When treating 85% of the total influent flow, the BVF® reactor has required minimal ammonium polyphosphate for supplemental phosphorus addition, and an average of 1.4 m^3/d of aqueous ammonia for supplemental nitrogen addition. Nutrient chemical requirements for the CAS system have been minimized, resulting in a 75% net decrease in aqueous ammonia and 50% net decrease in ammonium polyphosphate. Figure 14 tracks monthly ammonia and fertilizer deliveries to SLP.

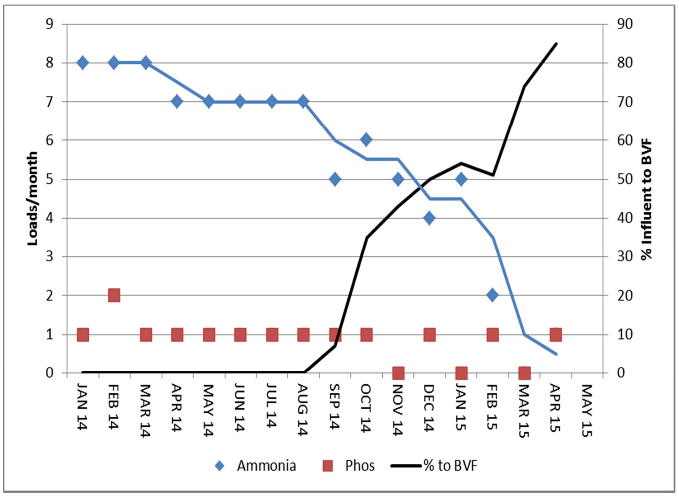

Figure 14 – Chemical deliveries by month

Reduced Waste Sludge Generation – During the first eight months of BVF® reactor operation, the anaerobic digester pre-treated approximately 60% of the SLP mill wastewater. In this time, no anaerobic sludge has been intentionally wasted from the BVF® reactor. In contrast, prior to installing the anaerobic digester the SLP WWTP would waste an average of 1450 m^3/d of waste sludge to the sludge chest, which is subsequently thickened into sludge cake and trucked off-site for land application. Since the BVF® has treated 85% of the total influent flow, an average of 1150 m^3/d of thickened sludge has been generated, resulting in a net decrease in secondary effluent dry waste solids of 20 - 25%. Figure 15 shows how WAS rates have stabilized and decreased over time. The reduced runtime of the sludge dewatering press has contributed to lower polymer usage for solids coagulation and lower power consumption.

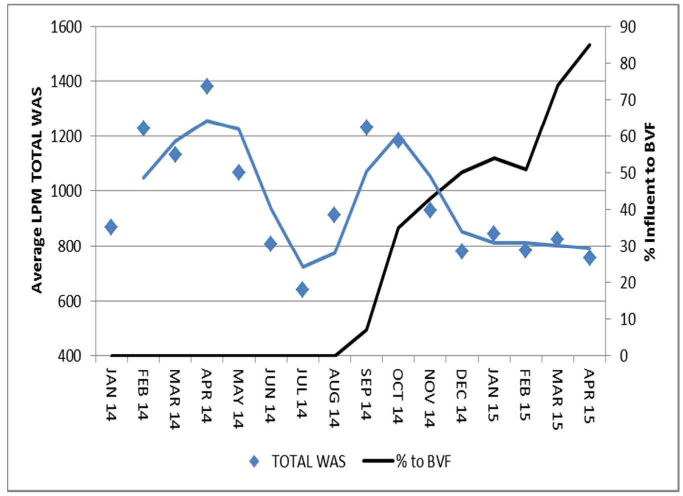

Figure 15 – CAS WAS rates, monthly average

CONCLUSIONS

Canada's first low-rate anaerobic BVF® reactor treating pulp and paper wastewater has achieved the target objectives for improving the performance and efficiency of the SLP WWTP, including increased process stability, reduced electrical costs by 43%, lower chemical usage by 50-75%, and reduced waste sludge generation and disposal requirements by 20-25%. Anaerobic pre-treatment has allowed SLP to decommission two of the four existing aeration basins, which has further simplified the overall treatment system.

Additionally, the low-rate anaerobic digester has provided benefits that would not otherwise be attained using high-rate reactors typically used for anaerobic digestion of pulp and paper mill wastewater. Anaerobic effluent quality has been consistent during the regular variations in influent wastewater strength as a result of the long hydraulic retention time and large biomass inventory (in contrast, the short HRT associated with high-rate reactors typically results in greater susceptibility to changes in organic removal efficiency and biogas production due to changes in wastewater strength). sCOD and BOD removals of 72% and 86%, respectively, have been achieved in the BVF® reactor using the flocculent anaerobic biomass; the reactor has been designed such that expensive granular sludge needed for high-rate anaerobic digesters is not required for operation.

Final effluent colour is increased when anaerobic pre-treatment is conducted prior to the CAS system. Final effluent colour loads have increased with increasing sCOD loads digested in the BVF® reactor.

SLP is actively tracking parameters (including inhibitor compound concentrations and ATP production) to better understand the overall biological health of the anaerobic and aerobic systems and develop baselines for these parameters during steady-state conditions. Despite observing increases in concentrations of inhibitory compounds in the aerobic system, overall biological health does not appear to be inhibited. In addition to the strong organic removals in the BVF® reactor, improved settleability has been observed in the CAS clarifier.

Biogas generated during anaerobic digestion has provided SLP with a green energy source; 10.4 GJ of biogas energy is generated per tonne of COD anaerobically removed, which corresponds to 4.7 MW and 8.0 MW of electrical power on design average and peak organic loading days, respectively.

The biological biogas scrubber system will be commissioned during summer 2015 and will be used to remove the hydrogen sulfide in the raw biogas. When commissioned, the treated biogas stream (as well as supplemental natural gas) will be utilized in the three 3 MW generators to generate up to 8 MW of electrical power.

The SLP Biomethanation with Power Generation Project has simplified and improved the performance of the WWTP, generated a reliable, green energy source, and greatly improved the mill's long-term economic sustainability.

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