# BIOGAS TREATMENT AND UTILIZATION FOR SLAVE LAKE PULP BIOMETHANATION AND POWER GENERATION PROJECT

Shannon Fehr[1], Megan DiJulio[1], Daniel P. Bertoldo[2], Peter J. McCarthy[2]

[1]Slave Lake Pulp, Division of West Fraser Mills Ltd., P.O. Box 1790, Slave Lake, AB T0G 2A0
[2]ADI Systems Inc., 370 Wilsey Rd., Fredericton NB E3B 6E9

## ABSTRACT

West Fraser Mills Ltd. has continued to operate and commission the Biomethanation with Power Generation Project (the Project) at the Slave Lake Pulp Bleached-Chemi-Thermo-Mechanical Pulp (BCTMP) mill in Slave Lake, AB.

The first aspect of the Project was to construct and commission an anaerobic effluent pre-treatment system to convert the biologically degradable compounds in the pulp mill effluent to biogas, a valuable green energy source due to the high methane content in the gas. The pre-treatment system, an anaerobic ADI-BVF® digester, has been in operation for over one year and during this time has continuously generated biogas while reducing the mill's chemical usage, secondary sludge generation rate, and power consumption.

The second aspect of the project was to utilize the biogas in three dual-fuel capable gensets. The raw biogas generated from the anaerobic digester contains hydrogen sulfide; upon combustion, the hydrogen sulfide creates sulfur dioxide and sulfuric acid which corrodes biogas utilization equipment, increases maintenance, and shortens equipment life, resulting in lost revenue. Pre-treating the raw biogas by removing (or "scrubbing") the hydrogen sulfide and removing excess moisture in the biogas allows the biogas to be used for power generation. West Fraser Mills partnered with ADI Systems and BioGasclean to install an innovative biological scrubbing system to significantly reduce the hydrogen sulfide content in the raw biogas. The biological scrubbing system installed at Slave Lake Pulp is among the largest BioGasclean installations in the world, and results in significant long-term operating cost savings compared to alternative biogas scrubbing technologies. Collectively, the anaerobic digester, biogas scrubbing system, and gensets have significantly cut mill operating costs, contributed to increases in mill throughput, and converted organic waste in the Slave Lake Pulp mill effluent, which previously provided no benefit to the mill, into a significant amount of power.

The first five months of scrubber operation have demonstrated that $H_2S$ removal efficiency in SLP's biogas scrubbers can exceed 99.8%, but declines when the scrubbers are overloaded and when packing media becomes fouled. When operating at design conditions, the biological scrubbing system generates a scrubbed gas stream suitable for conditioning and utilization in the gensets. Power generated when utilizing scrubbed biogas is normally between 3.5 and 4.5 MW and can be as high as 5.7 MW.

## INTRODUCTION

Slave Lake Pulp, a subsidiary of West Fraser Mills Ltd., is a 260,000 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.

West Fraser Mills' commitment to sustainable development and responsible environmental management led to the development of the Biomethanation with Power Generation Project. With assistance from the Climate Change and Emissions Management Corporation (CCEMC) and the EcoTrust Fund, West Fraser invested significant capital towards the installation of anaerobic digestion and biogas scrubbing systems with the objective of utilizing the by-product of anaerobic digestion (biogas) in three gensets for the production of up to 6 MW of power for mill use.

The first phase of the project involved constructing and commissioning an anaerobic digestion system designed to pre-treat the mill effluent prior to the existing conventional activated sludge (CAS) system. The anaerobic technology, a low-rate ADI-BVF® reactor installed by ADI Systems, was designed, constructed, and commissioned between February 2013 and September 2014. The ADI-BVF® reactor has provided the expected benefits of anaerobically pre-treating the mill effluent, which included reduced and stabilized organic load to be treated in the CAS system, decreased energy (mixing and aeration) requirements in the CAS system, reduced chemical usage (aqueous ammonia and ammonium polyphosphate) due to lower nutrient requirements for overall wastewater treatment system, and decreased secondary sludge generation for the overall wastewater treatment system, which subsequently results in lower chemical requirements for sludge dewatering and lower sludge transportation costs [1].

In the anaerobic environment, the majority of energy available at the molecular level through consumption of biodegradable organics 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. The relatively high heating value of methane (higher heating value of 37.7 $MJ/Nm^3$ [2]) allows the biogas energy to be recovered to offset fossil fuel consumption.

Sulphite used in the pulping process results in high concentrations (up to 1,500 mg/l) of sulfate in the mill effluent. In the anaerobic environment, sulfate in the mill effluent is reduced to the sulfide form by sulfate 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; thus, for the ADI-BVF® reactor with its characteristic long hydraulic retention time (HRT) and exceptionally long solids retention time (SRT), sulfate is fully reduced to sulfide.

For the typical pH range of an anaerobic treatment system (i.e., 6.5-8.5), sulfide is present in either the un-ionized ($H_2S$) or ionized ($HS^-$) form. The sulfide present in the liquid phase comes to equilibrium between the un-ionized ($H_2S$) and ionized ($HS^-$) forms based on the liquid pH. Figure 1 shows the pH-dependence of the hydrogen sulfide species in the liquid phase. This relationship provides an additional method for operators to control the $H_2S$ loading to the biogas scrubbers, as described in subsequent sections in this paper.

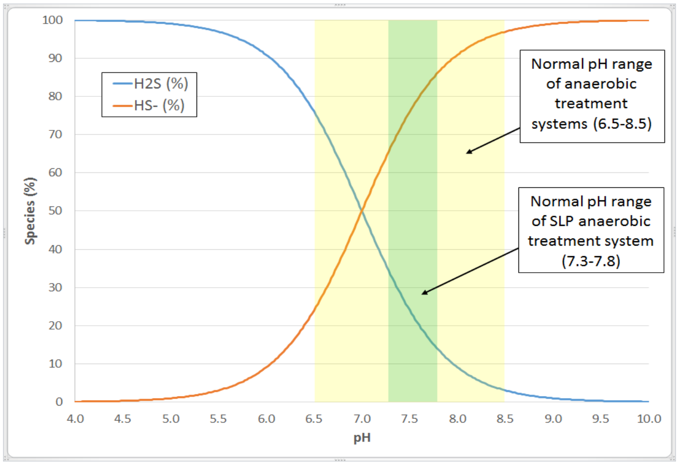


**Figure 1** – Hydrogen sulfide species equilibria versus liquid pH

Furthermore, the hydrogen sulfide present in the system reaches an equilibrium between the liquid and gaseous phases (based on Henry's Law), resulting in approximately 15-40% (temperature and pH-dependent) of the total sulfur in the system being present in the gaseous phase and the remainder present in the liquid phase [3]. The result of these equilibria is the presence of hydrogen sulfide in the biogas.

Hydrogen sulfide in the biogas presents a series of issues. First, health issues can arise when exposed to hydrogen sulfide. At very low concentrations (less than 0.5 ppm), hydrogen sulfide can be detected by its distinct "rotten egg" odour; however, exposure to much higher concentrations of hydrogen sulfide can lead to more sever health risks, including smell paralysis, lung irritation, headaches, dizziness, staggering, sudden collapse, unconsciousness, and death. Second, very high concentrations of un-ionized hydrogen sulfide in the reactor liquid phase can cause toxicity issues with the anaerobic biomass, resulting in decreased reactor performance and reduced biogas production. Finally, and of most importance for this paper, hydrogen sulfide will form sulfur dioxide ($SO_2$) and sulfuric acid ($H_2SO_4$) upon combustion. When combusted in an incinerator, untreated biogas with high concentrations of $H_2S$ can release high sulfur dioxide emissions, while combustion of $H_2S$ in a genset will result in severe corrosion of biogas utilization equipment. This corrosion leads to reduced equipment efficiency, shorter lifetime of utilization ancillary equipment, lost revenue, and increased maintenance requirements. These factors necessitated the installation of a biogas scrubbing system in order to generate a gas stream suitable for utilization in the gensets at Slave Lake Pulp.

Historically, most commercial scrubbing technologies for the removal of hydrogen sulfide have been based on physicochemical principles (e.g., iron oxide adsorbent, activated carbon adsorbent) or solvent-based technologies (e.g., alkaline scrubber) [4]. These technologies can prove to be expensive to operate, thereby negating all financial incentives associated with utilizing the biogas [5]. In the past few decades, increasing attention has been paid to biochemical methods for removal of hydrogen sulfide from gas streams, as biochemical technologies provide a number of significant advantages over traditional technologies [6]:

- Significantly lower operating cost per unit mass of hydrogen sulfide removed
- Same, or even higher, removal efficiency than physicochemical technologies
- Environmentally friendly
- No catalysts, iron, or caustic required
- Do not produce a by-product stream that needs to be specifically treated

After conducting research on commercially available scrubbing technologies, including site visits to existing scrubbing systems, Slave Lake Pulp elected to install a bio-trickling filter system from BioGasclean. This novel approach for scrubbing biogas adhered to West Fraser Mills' principles on environmental responsibility and sustainable development, while also providing a low-cost system to operate and maintain.

## BIOGASCLEAN TRICKLING FILTER DESCRIPTION

In a bio-trickling filter system, biogas is processed through a moist, packed media bed that contains microorganisms which grow on the surface of the media, forming a biofilm [6]. The environmental conditions promote the growth of chemotrophic bacteria, such as *Thiobacillus* bacteria which evoke redox reactions when oxygen is present. Under limited oxygen conditions, hydrogen sulfide is converted to elemental sulfur, as shown in the equations below [4]:

1. $H_2S \leftrightarrow H^+ + HS^-$
2. $HS^- + 0.5\ O_2 \rightarrow S^o + OH^-$

Under excess oxygen conditions, sulfur is oxidized to sulfate, resulting in acidification, as shown in the equations below [4]:

3. $HS^- + 2\ O_2 \rightarrow SO_4^{2-} + H^+$
4. $S^o + 1.5\ O_2 + OH^- \rightarrow SO_4^{2-} + H^+$

Parameters that influence the biochemical reactions include [6]:

- Packed bed surface area
- Oxygen availability
- Contact time
- Nutrient availability
- Humidity
- Temperature
- pH

The design of the BioGasclean scrubbing system addresses all of these parameters. BioGasclean custom-designs each scrubbing system based on hydrogen sulfide load and outlet gas quality requirements. Based on the high hydrogen sulfide load present in the biogas generated at Slave Lake Pulp, the BioGasclean scrubbing system was designed with the following three major components:

1) Process Technique Unit (PTU)
2) Two scrubber tanks
3) Two make-up water (MUW) tanks

The PTU is a fibreglass-lined modular enclosure which houses the system equipment and program logic controls (PLC) with built-in human machine interface (HMI). The MUW tanks (each with dimensions of 3 m Ø x 6 m H) are of fiberglass reinforced plastic (FRP) construction. Piping and wetted equipment in both the MUW and PTU systems is comprised of either PVC or FRP.

The two FRP scrubber tanks (each with dimensions of 6.7 m Ø x 15.7 m H) were constructed in Edmonton and field-erected. Considerable planning was required to transport the scrubber tanks via flatbed truck. This included sizing the tank dimensions for the maximum allowable diameter for road transport. The tanks were delivered and erected in November 2015. In the weeks following the tank erection, mechanical works and tank insulation were completed, polypropylene packing media was randomly added to the two scrubber tanks, and seed liquid (supernatant from the anaerobic reactor) was inoculated into the scrubber tanks. By December 2015, the BioGasclean system was ready to scrub the biogas generated from the anaerobic reactor.

## BIOGASCLEAN SCRUBBING SYSTEM OPERATION

In the anaerobic ADI-BVF® reactor, biodegradable organics are converted to biogas. The anaerobic reactor is covered with a multi-layered, flexible, geomembrane cover which allows for the reactor to operate at a slight vacuum pressure. Biogas generated in the reactor 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 a single point underneath the BVF® cover in order to maintain the target cover pressure range. The BioGasclean scrubbing system is located on the suction side of the biogas blowers; thus, the scrubbing system operates under a slight vacuum. The scrubbed biogas is sent to the gensets for utilization, and any biogas not utilized is combusted in a waste gas incinerator, as shown in the process flow diagram in Figure 2.

One advantage of this design is that all unscrubbed biogas systems (including the anaerobic reactor and biogas scrubbing system) operate under vacuum, minimizing the chance of personnel exposure or fugitive emissions. Continuous system $O_2$ monitoring indicates if air ingress from the BVF® cover, fittings or vacuum breakers is an issue. Another advantage of this design is the minimization of horsepower used in biogas compression. An alternative design would be to install two sets of blowers, one set to withdraw gas from the BVF® reactor and deliver pressurized gas to the scrubbers and incinerator, and a second set of blowers to deliver scrubbed biogas to utilization. The advantage of two sets of blowers is the ability to both scrub and incinerate unscrubbed biogas simultaneously, if a facility's environmental permit allows for it (SLP's does not).

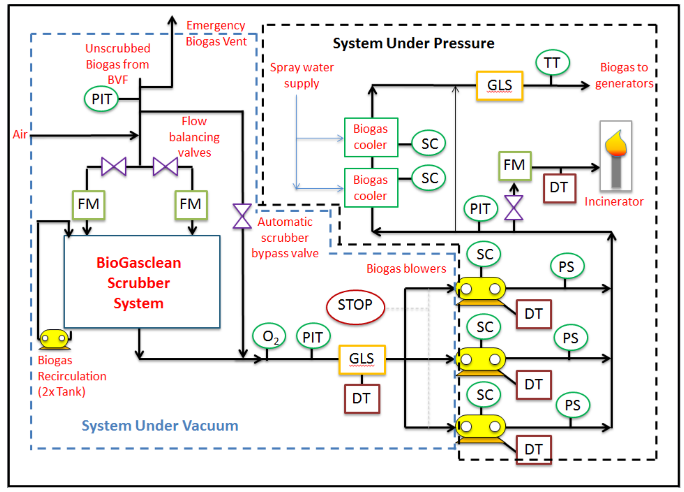


**Figure 2 –** Biogas scrubbing and distribution PFD

Atmospheric air is added to the raw biogas in proportion to the biogas flow rate. Sufficient air is supplied to maintain a target residual oxygen content of 1.5-2.2% in the scrubbed biogas, as measured by an in-line oxygen analyzer. Air is supplied via two VFD-controlled aeration blowers (one duty, one standby) located in the PTU. The required air addition rate must satisfy the biological $O_2$ consumption rate and achieve the scrubbed biogas residual $O_2$ target. Controls are in place to shut down the aeration blowers in the event that the oxygen analyzer measures oxygen content greater than 5% in the scrubbed biogas. This measure is in place to prevent an explosive mixture of oxygen and methane from developing.

The flow of diluted biogas (i.e., raw biogas plus air) to each scrubbing tank is controlled using a flow balancing system consisting of flow meters and flow control valves on the inlets to each scrubbing tank. The positions of the automatic valves are automatically controlled to maintain an equal flow of biogas to each scrubbing tank. Diluted biogas is introduced into the scrubbers through distribution piping located within the top of each scrubbing tank.

Biogas is forced downward through the packing media within each scrubbing tank. The packing media, which occupies well over half of each scrubber tank's volume, is supported on top of a packing support grating located approximately 3 m above the scrubber floor. This quantity of packing media provides a substantial amount of surface area for the bacteria to grow a biofilm and oxidize hydrogen sulfide in the biogas.

Each biogas scrubbing tank is equipped with two biogas recirculation blowers which continuously operate to recycle biogas from the outlet zone of the scrubbers (near the bottom of each tank) to the inlet zone of the scrubbers (top of each tank). This biogas recirculation serves to increase the contact between the biogas and biology, improving scrubbing efficiency. The increased biogas recycle provided by multiple biogas recirculation blowers is a new, novel design modification to the BioGasclean system, and has been implemented due to the high hydrogen sulfide content in the biogas generated at SLP.

The paragraphs above have outlined how the BioGasclean system addresses critical gas-phase parameters for the operation of the scrubbing system, such as packed bed surface area, oxygen availability, and contact time. The critical liquid-phase parameters for the bio-trickling filter system (nutrient availability, humidity, temperature, and pH) are addressed by the addition of make-up water, scrubbing liquid recirculation, and scrubbing liquid blowdown.

As discussed in the previous section, the primary objective of the bio-trickling filter system is to transfer and oxidize hydrogen sulfide in the gas phase into sulfate in the liquid phase. This sulfate is subsequently discharged from the system via the scrubbing liquid blowdown; thus, an equal amount of fresh make-up water must be added to displace this volume. The make-up water addition system also delivers nutrients (nitrogen and phosphorus) to facilitate the biochemical reactions in the scrubbers.

A process schematic of the BioGasclean scrubbing system is shown in Figure 3.

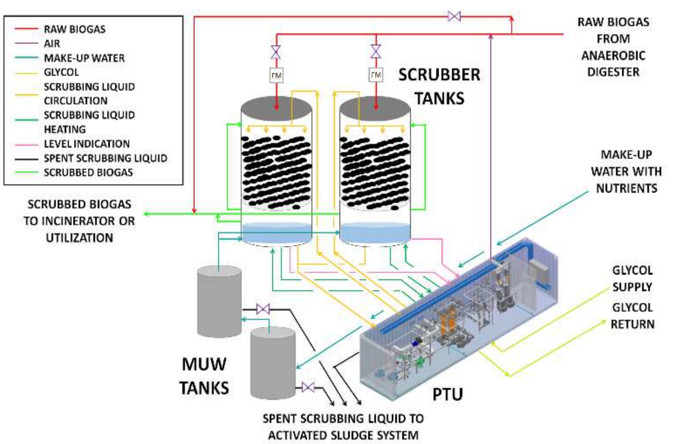


**Figure 3** – Process schematic of BioGasclean scrubbing system at SLP

A scrubbing liquid circulation system is used to spray scrubbing liquid onto the surfaces of the packing media. The circulation system consists of two circulation pumps (one duty, one standby) located in the PTU, automatic open/close valves (one per scrubber tank), and spray nozzles (four per scrubber tank). A small volume of scrubbing liquid is located at the bottom of each scrubber tank, and the scrubbing tanks are hydraulically connected in order to ensure an equal volume of scrubbing liquid is present in each scrubber. The duty circulation pump is used to continuously recirculate scrubbing liquid at the bottom of the scrubbers onto the top of the packing media for alternating scrubbing tanks (only one scrubber tank is sprayed at a time). This scrubbing liquid circulation system not only provides the required humidity for the biomass, but is also used to supply heat and nutrients to the biomass, as described below.

Heat exchangers (one per scrubber) and scrubbing liquid heating pumps (one per scrubber) are located in the PTU and are used to maintain the scrubbing liquid temperature within a range of 30-40°C. Heated glycol is used to transfer heat to the scrubbing liquid within the heat exchangers. Two glycol heaters located in the pump room of the BVF® reactor system are not only used to supply heat to the scrubbing liquid, but are also used to heat the PTU itself.

Treated final effluent serves as the make-up water for the biogas scrubbing system. This stream meets the make-up water requirements in terms of low chemical oxygen demand (COD) and total suspended solids (TSS) concentrations and neutral pH; however, the final effluent has lower concentrations of nutrients (nitrogen and phosphorus) than required by the biology in the scrubbing system. Aqueous ammonia and ammonium polyphosphate, which also serve as nutrient sources for the anaerobic and aerobic wastewater treatment systems, are dosed into the make-up water to satisfy the scrubbing system's nutrient requirements.

The BioGasclean system calls for make-up water to be supplied on a timed schedule (with interlocks in place to control scrubber tank level). Make-up water, as well as a portion of the circulated scrubbing liquid (which is used for acidification in the MUW tanks), are initially discharged to the MUW tanks, which normally operate in series. In the MUW tanks, the circulated scrubbing liquid returned to the MUW tanks decreases the pH of the tank contents. This acidification/water softening process serves to form precipitation (such as calcium sulfate or magnesium sulfate) which subsequently settles to the tank floor, while clarified make-up water is discharged to the scrubber tanks by gravity. The objectives of the acidification and scrubbing liquid blowdown systems are to maintain the MUW tank pH within a range of 5-6 and the scrubbing liquid pH within a range of 2-4.

Draining of scrubbing liquid blowdown from the MUW and scrubber tanks is achieved using automatic open/close valves which operate on an adjustable schedule. Scrubbing liquid blowdown, which is essentially a low-pH, weak sulfuric acid solution, is discharged to a local drain buffer sump and subsequently pumped to the inlet of the activated sludge system.

For each scrubbing tank, level gauges with proximity switches are used to protect the system equipment and ensure the scrubber tanks operate within a target level range. The level gauges are located in the PTU. Level control is required in the scrubbers, as a high level could fill the biogas discharge lines with liquid, whereas low levels could result in gas locking of circulation pumps.

Scrubbed biogas is removed under low levels of vacuum from the base of the scrubber tanks using the reciprocating biogas blowers (two duty, one standby). Differential pressure across the biogas packing media is measured as the difference between the BVF® cover operating pressure (target is -7.5 mm of $H_2O$) and vacuum measured on the suction of the biogas blowers. Vacuum measured at the blower suction increases over time as the packing media fouls with solids. Safety interlocks shut down the blowers if the suction vacuum approaches the scrubber tank vacuum breaker set pressure.

The PTU is divided into equipment and electrical rooms. The equipment room houses the devices required for system operation, and the electrical room houses the PLC with built-in keypad HMI. The equipment and electrical rooms each have gas monitors for detecting $H_2S$ or $CH_4$ in the atmosphere. Distinct visual and sound alarms activate in the event that either $H_2S$ or $CH_4$ are present in high concentrations in the atmosphere. An exhaust fan provides emergency ventilation of the PTU if gas monitors are in alarm state.

Table 1 summarizes the design characteristics of the raw biogas from the anaerobic digester treated biogas on the outlet of the scrubbing system.

**Table 1 – Design Characteristics of Raw and Treated Biogas**

| PARAMETER | RAW BIOGAS | TREATED BIOGAS |
|---|---|---|
| Flow, design ($m^3/d$ @ STP) | 37,000 | 44,500 |
| Temperature (°C) | 25-35 | < 36 |
| Methane, $CH_4$ (%) | 70 (expected)<br>60-75 (range) | 59.1 (expected)<br>55-65 (range) |
| Carbon dioxide, $CO_2$ (%) | 28 (expected)<br>15-40 (range) | 24.0 (expected)<br>20-30 (range) |
| Hydrogen sulfide, $H_2S$ (ppm) | 16,000 | < 100 |
| Nitrogen, $N_2$ (%) | --- | 15.3 (expected)<br>10-20 (range) |
| Oxygen, $O_2$ (%) | --- | 1.5 (target)<br>1.2-2.2 (range) |
| Water vapour | Saturated | --- |

## BIOGAS SCRUBBING SYSTEM TESTING

Biological systems, such as the BioGasclean scrubbing technology, are an integral part of wastewater treatment operations in a pulp mill. In addition to the BioGasclean system, SLP also operates an ADI-BVF® anaerobic digester and a CAS treatment plant. Biological treatment systems are operated on the basis of growth pressures that are targeted to create optimal environments for biological health. These same growth pressures apply to all biological systems; however, their targets will vary with different biological species (aerobic, anaerobic). Management of biological growth pressures, being a familiar concept to the pulp and paper industry, made biological scrubbing technology a good fit for SLP.

In order to maintain an ideal environment in the scrubbing system for biological health, regular process sampling and analysis is critical. System performance is assessed through analysis of both the liquid and gas phases as outlined below.

### Liquid Phase

Samples are collected at various locations throughout the liquid phase (see Figure 4) and analyzed for nutrients (ammonia and phosphorus), pH, conductivity, TSS and COD. These test methods are known to SLP and were easily integrated into regular sampling rounds. The liquid streams tested include $MUW_{in}$, $MUW_{out}$ and $Scrubber_{water}$.

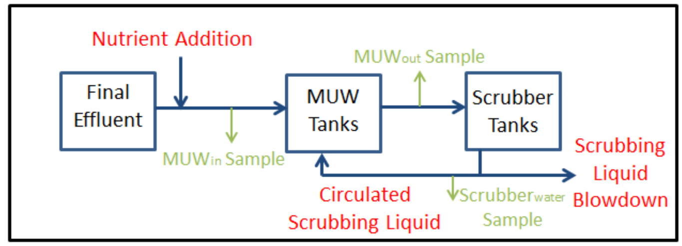


**Figure 4** – Liquid phase sample locations

$Scrubber_{water}$ quality is the most critical in the liquid phase as it has the greatest effect on the system's growth pressures. The sprayed scrubbing liquid influences the growth and health of the biology fixed to the packing media. $Scrubber_{water}$ parameters are controlled by means of MUW flow rates. $MUW_{out}$ parameters, such as nutrient residuals, are adjusted based on $Scrubber_{water}$ requirements. $MUW_{in}$ samples are monitored as a leading indicator for changes made to nutrient addition rates and to ensure other $MUW_{in}$ parameters, feeding the MUW tanks are consistent, such as TSS and COD.

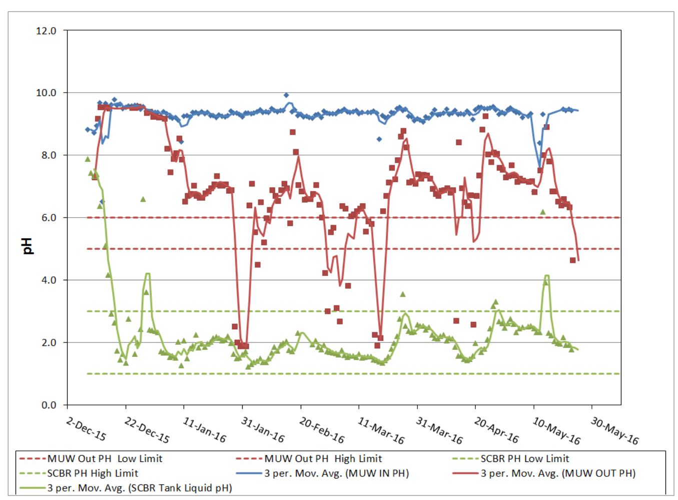


**Figure 5** – Liquid phase pH profile

As previously mentioned, acidification of the MUW tanks is required as a control to reduce fouling in the scrubber tanks by softening the water and removing solids through precipitation. However, due to physical limitations regarding the ability to return scrubbing liquid to the MUW tanks and no current online controls of this loop, acidification of the MUW tanks has been less efficient then desired. As seen in Figure 5, $MUW_{out}$ pH has consistently been outside of the desired pH range (5-6). As a result, the inability to precipitate out solids before utilization of MUW is suspected to be increasing the rate of fouling in the scrubbing system.

**Gas Phase**

More challenging than liquid phase analysis is testing of the gas phase. As gas testing was not previously performed at SLP, greater efforts were required to ensure accurate analysis was being conducted.

Gas sampling is performed at various locations within the biogas system to assess digester and scrubber performance and determine whether biogas is suitable for utilization. The gas streams tested include scrubbed and unscrubbed biogas and monitoring parameters include: $CH_4$, $H_2S$, $O_2$, and $CO_2$ concentrations (by volume or ppm). Due to the corrosive nature of $H_2S$, sample methods vary depending on the expected range of $H_2S$ as described below.

**Raw Biogas**

Raw biogas is collected at sample ports located upstream of the scrubbers (refer to Table 1 for ranges). All raw biogas samples are considered high range $H_2S$ samples, and are under vacuum due to their location on the suction side of the biogas blowers, as shown in Figure 2.

All test methods for raw biogas are manual tests. Kitagawa indicator tubes were selected as the most economical and compatible test method and are used to analyze for $H_2S$ and $CO_2$. For sampling, a one-way valve hand pump is used to pull a biogas sample into a Tedlar bag which can then be transported and analyzed in a fume hood. The Tedlar/Kitagawa method can also be utilized for treated biogas due to the various ranges of $H_2S$ and $CO_2$ indicator tubes available.

**Treated Biogas**

Treated biogas samples are defined as any sample location downstream of the scrubbers (refer to Table 1 for ranges). Treated biogas samples can either be under vacuum or pressurized depending on their physical location, as shown in Figure 2. For manual testing the Tedlar/Kitagawa method is utilized. On a pressurized line, the hand pump is not required and samples can be directly injected into the Tedlar bag from the sample point. As treated biogas contains low concentrations of $H_2S$, the hazards associated with sampling and handling are reduced when compared to sampling raw biogas samples.

For more accurate manual measurements, a Biogas 5000 analyzer by Landtech is used for its precision and portability. This instrument has an $H_2S$ detection range of 0-5,000 ppm $H_2S$ and can be utilized on sample points under pressure or vacuum. The instrument measures $O_2$, $H_2S$, $CO_2$ and $CH_4$ and instantly displays results in the field.

For continuous online measurement, two gas analyzers are utilized: one to monitor and control the $O_2$ content in the scrubbers and one for biogas blending/feeding controls in the gensets. The location of these analysers is shown in Figure 12. Both online instruments utilize electrochemical sensors that display real time values critical to system controls.

**BIOGASCLEAN SCRUBBING SYSTEM PERFORMANCE**

$H_2S$ removal efficiency is the primary performance measure of the biogas scrubbers. If treated biogas $H_2S$ quality is not less than 250 ppm, biogas is not suitable for combustion in the gensets and is incinerated. Review of the following performance factors is then started:

- $H_2S$ Loading
- Flow Stability (Rate of Change of Flow)
- Fouling: Packed Bed Surface Area, Biogas Contact with Biomass, Fouling Rate & Cleaning Frequency
- Biological Growth Pressures; pH, Temperature, Conductivity, Nutrients and Oxygen availability
- MUW Addition Rates

**$H_2S$ Loading Rate**

The scrubbing system was designed for a maximum $H_2S$ loading of 37.5 kg $H_2S$/hr (900 kg $H_2S$/day) through both scrubbing tanks. The actual total $H_2S$ loading rates observed ranged from 400-1,200 kg $H_2S$/day depending on biogas production and $H_2S$ concentration. Biogas production is a function of BVF® reactor COD loading and $H_2S$ concentration is a function of pulp mill grade which affects sulfur utilization in the mill. Pulp mill grades are designated as either high or low loading, where high loading provides more COD and more sulfur to the BVF®. On low loading runs, scrubber $H_2S$ loading is below design, whereas on high loading runs, design $H_2S$ loading is typically exceeded, as shown in Figure 6.

Figure 6 shows each scrubber's $H_2S$ loading and pulp mill grade on a daily basis since start-up on December 9th 2015. The graph depicts the wide range of loading seen by the scrubbing system and clearly displays the periods of overloading. No loading (0 kg $H_2S$) days are indicative of scrubber cleanings. To ensure regulatory compliance, only one tank can be taken off-line to be cleaned at a time while the other tank takes the entirety of the loading during that period.

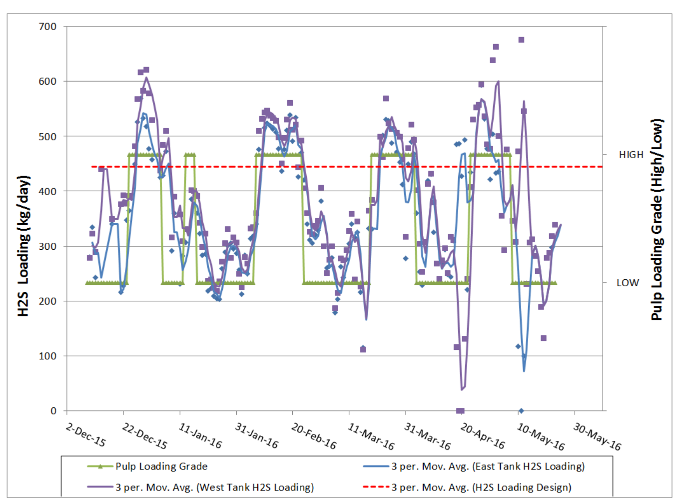


**Figure 6** – Scrubber tank $H_2S$ loading (kg $H_2S$/day) & pulp loading grade

During periods of $H_2S$ overload, supplemental caustic has been added to the ADI-BVF® reactor to increase its operating pH and drive $H_2S$ equilibria towards the ionized form, as indicated in the hydrogen sulfide species equilibria versus liquid pH graph in Figure 1. This effect can be seen in Figure 6 by a brief decrease in $H_2S$ loading observed during the high loading run in February. Caustic was added from February 10th to 22nd where digester $H_2S$ concentration was reduced from 2.2% to 1.5%. Unfortunately, addition of supplemental caustic was not economically feasible as revenue from biogas utilization at the time was less than the cost of caustic addition so pH adjustment was discontinued.

**Flow Stability**

When flow rate varies rapidly through the scrubbing system, the biology, which is slow growing, is unable to adapt. Biology requires 12 – 24 hrs to acclimate to increased loading. Rapid flow increases from grade/loading changes to the BVF®, start-up or shut down of the incinerator and flow imbalance between scrubber tanks negatively affects $H_2S$ scrubbing efficiency. To ensure efficient scrubbing, the rate of change of flow and $H_2S$ loading needs to be minimized through the use of good process control.

**Fouling**

Fouling is expected as part of the $H_2S$ removal process. When $H_2S$ is reduced to sulfuric acid, one of the by-products produced is inert gypsum that accumulates on the packed media. Two other factors will amplify the effects of fouling:

- Inability to acidify the MUW tanks causing precipitation to occur in the scrubber tanks and,
- Insufficient oxygen availability causing the formation of elemental sulfur.

As solids accumulate on the packing over time, channelling begins to occur. As a result, biogas contact time with biomass is reduced, which in turn reduces $H_2S$ removal capabilities. The negative effects of channelling can only be mitigated by scrubber cleaning, the frequency of which is critical in maintaining optimal removal efficiencies for biogas utilization.

Contact time is such a critical parameter for $H_2S$ removals through this system that biogas recirculation blowers were incorporated into the design of the scrubbing system. The recirculation blowers serve two main purposes: to increase contact time and to dilute or buffer inlet $H_2S$ concentration. As the tanks foul, the recirculation blower efficiency reduces as the differential pressure across the scrubbing tanks increase.

Figures 7 and 8 display the relationship between fouling and $H_2S$ removal efficiency. Before the first cleaning took place in mid-April, there were three separate high loading runs, once the system was fully commissioned, where design loading was exceeded, as shown in Figure 6. The second high loading run in February 2016 exceeded design by 9% and the third high loading run in March 2016 exceeded design by 3%. Removal efficiencies on the second and third high loading runs averaged 99%, and 93% respectively. After both tanks were cleaned on May 13th 2016, removal capacities improved and removal efficiency after cleaning averaged greater than 99.9%.

As a result of decreased removal efficiencies, utilization of biogas (defined as the percentage of available biogas generated in the anaerobic reactor that is utilized in the gensets) also decreased over time. Throughout the first three months of operation, until the first cleaning took place, (Jan 21st – Apr 18th) biogas utilization was 77%. Table 2 displays the percent of biogas produced that was utilized on monthly basis. Utilization decreased over time as the tanks fouled. After both tanks were cleaned by May 14th, biogas utilization improved to 93%.

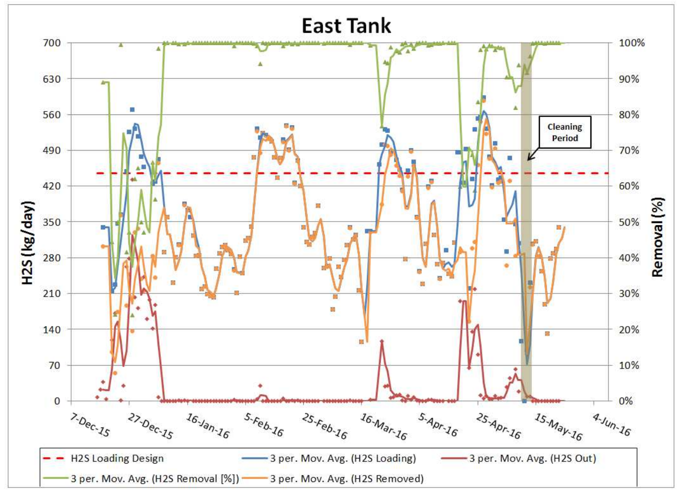


**Figure 7** – East scrubber tank $H_2S$ loading and $H_2S$ removal efficiency

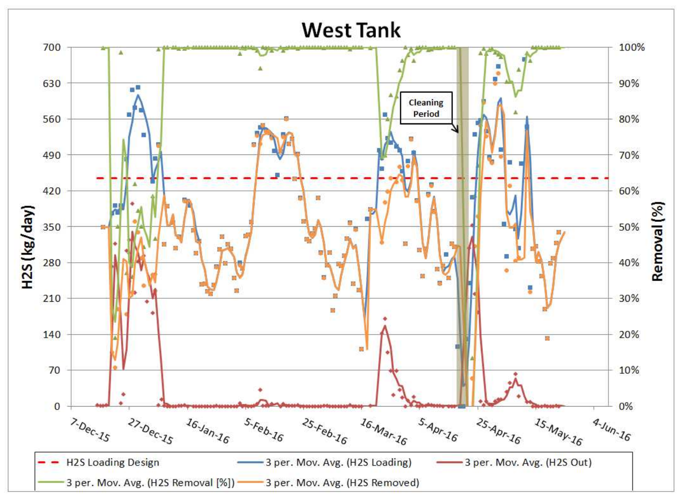


**Figure 8** – West scrubber tank $H_2S$ loading and $H_2S$ removal efficiency

**Table 2 – Biogas Utilization in Gensets**

| MONTH | BIOGAS UTILIZATION (%) | MAX LOADING (kg/day) | AVERAGE LOADING (kg/day) |
|---|---|---|---|
| Jan 20 - 31 | 55 | 632 | 531 |
| February | 89 | 1,099 | 839 |
| March | 66 | 1,099 | 690 |
| April | 59 | 1,187 | 746 |
| May 1 - 23 | 40 | 1,142 | 658 |

In addition to falling $H_2S$ removal efficiencies, another key indicator for fouling is the increased negative pressure (vacuum) on the suction side of the biogas blowers.

Three observations can be made regarding vacuum levels charted in Figure 9. First, a relationship exists between biogas production and vacuum levels; as biogas production increases, vacuum increases as a result of increased pressure differential across the packed media. Second, as the scrubbers foul between cleanings, vacuum increases, which is most apparent during high loading runs. Third, a significant increase in vacuum was observed in the time between tank cleanings. Vacuum continued to increase between cleanings as the effects of fouling were increased by forcing half the raw biogas through a fouled tank. Vacuum was not returned to normal (approximately -30 mm $H_2O$) until the second tank was cleaned. Operation between cleanings created a flow imbalanced system where $H_2S$ removal and biogas utilization was negatively affected. Only 9% of treated biogas was utilized between cleanings.

The first full scrubber cleaning provided evidence that both scrubber cleaning frequency interval and duration between tank cleanings are important factors affecting scrubber performance.

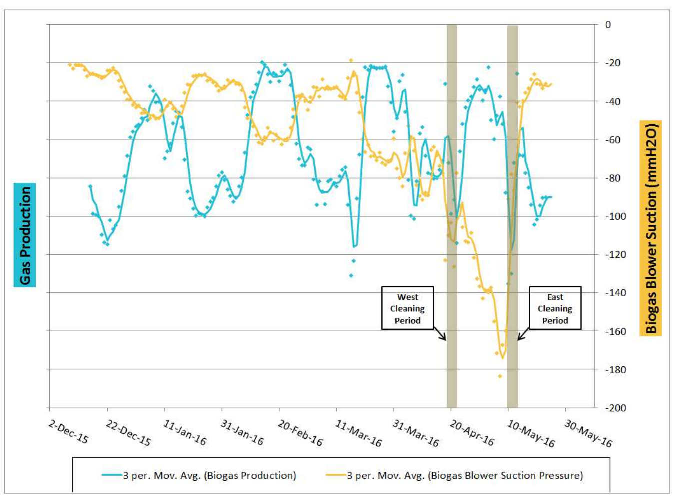


**Figure 9** – Biogas production and biogas blower suction pressure

**Biological Growth Pressures**

The key biological growth pressures for the system include pH, conductivity, nutrients (ammonia and phosphorus) and oxygen availability. Target ranges are established for all these parameters and operating within these ranges is the basis for maintaining biological health.

Oxygen residual in treated biogas is a parameter that is closely monitored due to its potential to affect fouling rates. Oxygen is the limiting factor for complete digestion of $H_2S$ to sulfate; if not readily available, hydrogen sulfide will primarily be oxidized to elemental sulfur which will increase fouling in the scrubbing system, forcing more frequent cleanings. To prevent this, oxygen content in the treated biogas must remain within the normal operating range of 1.5-2.2%. The oxygen content is monitored using manual and online measurements, as previously discussed in this paper.

Conductivity, pH, and nutrient residuals are parameters that are manipulated by adjusting addition rates of MUW. MUW is the carrier water for nutrients and is also used as a means of dilution to increase pH or decrease conductivity, if required.

**MUW Addition Rates**

As the driving factor for biological growth pressures, MUW addition rates are critical to scrubber performance. Insufficient MUW flow will cause performance issues in the scrubbing systems that worsen as growth pressures are driven out of range. For example, MUW rates must increase with $H_2S$ loading to supply sufficient nutrients and prevent the pH from dropping below 1.6 and conductivity from increasing over 30 µS/cm. In Figure 10, MUW flow trends with $H_2S$ loading. In instances where MUW flows are not increased in proportion to loading rates, $H_2S$ removal efficiency drops, as does utilization rate.

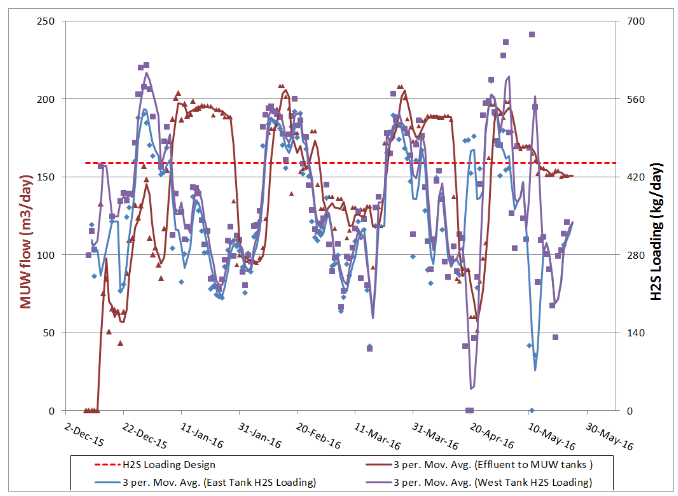


**Figure 10** – $H_2S$ loading (kg $H_2S$/day) and MUW flow rates ($m^3$/day)

**BIOGAS SCRUBBER CLEANING**

Scrubber tanks are cleaned on a regular basis to prevent the differential pressure drop across the packing media to reach excessive levels for two reasons; first to ensure that relief of the vacuum breakers does not result in $O_2$ being drawn into the scrubbed biogas, and second to ensure that fouling of the packing media is not excessive. Excessive fouling makes cleaning of the packing media difficult and in some cases can result in packing media replacement.

Biogas scrubber cleaning is conducted via a process called Quick Sludge Removal (QSR). Since scrubbers are independently operable, cleaning is performed on one tank at a time, which ensures that biogas is scrubbed prior to incineration. The operating scrubber differential pressure is controlled during cleaning to prevent vacuum relief on the operating vessel by both controlling biogas flow during cleaning (plan for low loading, or periods of low biogas production) and cleaning frequently enough to prevent excessive packing media fouling.

The overall cleaning process is as follows:

1. Initiate single-scrubber operation
2. Purge scrubber to be cleaned out of service
3. QSR
4. Purge cleaned scrubber into service
5. Repeat steps 2 – 4 on other scrubber
6. Return to normal service

To change to single-scrubber operation, all biogas is first incinerated to minimize process flow upsets during single scrubber operation. The biogas flow balancing valve to the operating scrubber is then opened 100% and closed on the tank to be cleaned and all biogas is drawn through one scrubber. Biogas blower vacuum, blower loads, scrubbed biogas $O_2$ levels, and digester cover pressure need to be closely monitored to ensure the process is in control before proceeding.

Purging out of service is started by filling the scrubber tank with water while displacing biogas into the operating scrubber until water level reaches the gas inlet lines. The tank must be designed to operate both under vacuum and to bear the full hydrostatic head of the water required for cleaning. Once the tank is full, the biogas lines are isolated, and the top manways are removed in preparation for QSR.

QSR is the process of introducing compressed air through an air grid located at the base of the tank to agitate the packing media and remove the accumulated solids from the packed bed. Figure 11 shows a typical QSR air injection grid layout.

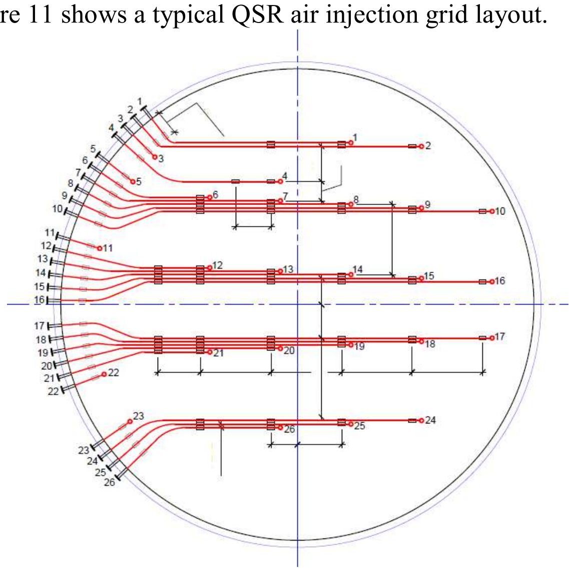

**Figure 11** – QSR air injection grid, typical

Air is injected into 5 separate headers and valves on each header are opened in sequence to allow 30 psi compressed air to lift and agitate the packed bed until a washing-machine type action occurs. Cleaning is complete when a metal testing rod inserted from the top of the tank is able to pass through the packing media without resistance to the packing support grating. Defoamer addition may be required to prevent excessive foaming during air injection.

Air injection is continued during the Quick Sludge Removal, which is the removal of all liquid and solids from the scrubber at a rate of 200 $m^3$/hr (or as fast as is practicable) to prevent solids from settling in the scrubber base. Liquid is discharged directly to the aerobic treatment system and solids are settled out in the settling clarifiers and processed in the sludge dewatering system.

Cleaning efficiency is most affected by the method of injection of compressed air. A sufficient volume at a sufficient pressure in the correct locations is required for good cleaning. If flow, pressure, or location/timing is not optimal, the removal of solids from the packing media at the base of the scrubber (at the packing support grating) will not occur; either elongating the cleaning process or requiring more frequent cleanings.

Finally, solids that settle in the base of the tank (below the packing support grating) are removed using a vacuum truck and processed in the sludge dewatering system. Analysis of scrubber solids indicated 286,000 mg/kg of sulfur present in the solids. The base of the tank and packing media are then inspected for cleanliness before the tank is closed in preparation for the purge into service.

Purge into service is completed by re-filling the tank with clean water, while displacing air out the top of the tank. The design of SLP's tanks allows for filling into the tank dome to displace as much air as possible without requiring the use of inert gases. Alternatively, inert gases may be used to displace oxygen but the volume of the tanks makes this an expensive and infeasible option.

Once the scrubber is full of water, the tank is drained in a controlled fashion while monitoring vacuum in the tank. This is done to ensure that $O_2$ is not pulled into the tank through the vacuum breaker. It is during this phase of cleaning that controls to prevent implosion of the tank must be in place.

When the tank is filled with raw biogas, the operating and cleaned tanks are equalized and scrubber water rich with nutrients and biology are fed to the cleaned tank and recirculated to re-seed the scrubber for operation. The tank is placed back in service and then the process is repeated in the second tank.

Biology in the cleaned tanks takes 24 to 48 hours to reacclimatise and begin to remove enough $H_2S$ to resume biogas utilization. The cleaning process for both tanks takes 7 days from the start to finish including biological acclimation, if cleaning is effective.

Returning a cleaned biogas system to normal operation requires optimal conditions. This process can be negatively affected by various factors including biogas flow variability, high $H_2S$ loading rates, MUW flow, and other suboptimal growth pressure parameters.

**BIOGAS HANDLING AND UTILIZATION**

The biogas handling and utilization system starts at scrubbed biogas compression and extends to the gensets fuel trains, or to the incinerator. Biogas that is incinerated is not conditioned. The conditioning steps required to prepare scrubbed biogas for combustion in reciprocating engine driven generator sets includes condensate removal, compression, cooling, heating, metering, analysis and pressure control.

Biogas quality requirements for combustion in the GE J620 F25 Generator sets and the biogas delivery system PFD are presented in Table 3 and Figure 12 respectively. Parameters requiring control include flow rate, temperature and relative humidity (RH), methane, $O_2$ and $H_2S$ concentrations, biogas pressure and pressure fluctuation. Removal of water droplets are also required to achieve a minimum dew point of biogas. At the genset fuel trains, the mixing rate of natural gas and biogas is an important factor for genset stability, generator output and GHG intensity.

**Table 3 – Design Characteristics of Treated Biogas for Utilization [7]**

| PARAMETER | Target | Allowable Range |
|---|---|---|
| Flow, design ($m^3$/hr @ STP) | 1800 $m^3$/hr | 0 – 2450 $m^3$/hr |
| Temperature (°C) | 30 | 0 - 40 |
| Methane, $CH_4$ (%) | 60 | 40 - 100 |
| Hydrogen sulfide, $H_2S$ (ppm) | 50 | 0 – 250 |
| Oxygen, $O_2$ (%) | 1.5 | 0 - 3 |
| RH (%) | 70 | 0 - 80 |
| Biogas Pressure (kPa) | 22 design<br>30 actual | 19 - 40 |
| Biogas Pressure fluctuation (kPa/sec) | <1 | 0 -1 |

Raw and treated biogas streams are saturated with water, making condensate removal systems an essential part of biogas conditioning prior to utilization. Condensate removal on the raw biogas from the BVF® and treated biogas from the biogas scrubbers is required because of water saturation, especially in the winter months. Effective removal of condensate from biogas lines is essential for ensuring accurate biogas flow metering, and to mitigate the corrosive effects on piping from acidic condensates. Condensate pH is typically the same pH as scrubber water, requiring that biogas piping and equipment be constructed of 316L SS, FRP or PVC. SLP's biogas and condensate handing systems are largely constructed of 316 SS. Continuous drip traps are located on both the biogas blower suction and discharge lines to remove condensed water (see Figure 12). By code, biogas lines must be sloped and have condensate removal points at the low points of piping and equipment.

Water saturation of the biogas coupled with low ambient temperatures in the winter months make heat trace and heating systems important in the reliable all-season operation of the biogas facility. Heat trace and insulation of liquid lines and the MUW tanks, as well as biogas lines and valves is necessary to prevent freezing. In below-freezing temperatures, condensation rates are increased as a result of temperature changes during transmission from above to below ground and indoor to outdoor line locations. Levels are continuously monitored and have high alarms to prevent over-filling of both continuous and manual (periodic) condensate drip traps.

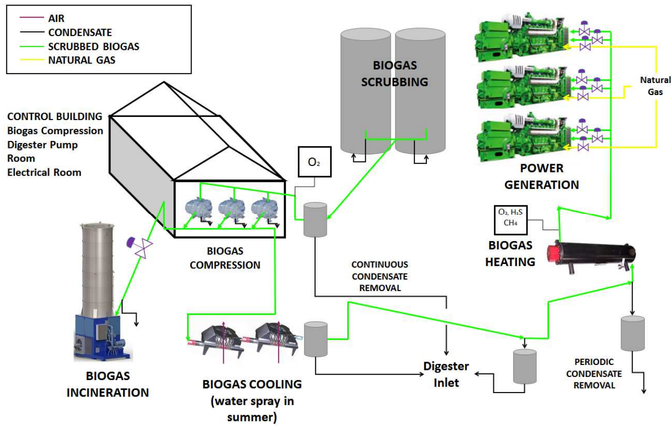


**Figure 12** – Process schematic of biogas compression, conditioning and transmission system

Biogas temperature and humidity control are related parameters, and are an integral part of the design of a biogas delivery system. Compression of biogas for utilization heats the biogas and cooling is required to meet maximum genset temperature targets. Biogas is cooled using two forced air fan coolers arranged in series. Temperature control is critical when ambient day-time highs reach target biogas temperatures of 30°C. To enhance cooling when heat exchange driving force is low, water is sprayed directly on the coolers to induce evaporative cooling. Following the coolers, condensate is removed in continuous drip traps and returned to the BVF® influent line. Condensate is removed in several additional manual condensate traps along the biogas transmission lines.

To ensure a maximum of 80% RH at the gensets, temperature of the biogas is increased by 5°C (on a pressure compensated basis) using an electric immersion heater (one operating, one spare). Biogas is then flow, temperature and pressure metered, analysed for $CH_4$, $O_2$, $H_2S$ content and sent to the gensets biogas trains, where biogas is further pressure reduced and mixed with natural gas (if desired) prior to engine fuel injection.

The power generation plant is supplied by two fuels; 1) high and low pressure natural gas and, 2) biogas. Each genset has a high and low pressure natural gas fuel train and a dual biogas fuel train. A larger volume biogas fuel train is required to accommodate the increased volume of biogas required to supply the same energy as natural gas.

To ensure stable operation of the gensets on biogas, delivered biogas pressure must be tightly controlled in all possible operating modes. Those modes include:

1. Genset ramping, up or down
2. Starting/stopping additional gensets
3. Cycling of the biogas incinerator when there is surplus biogas in the BVF® reactor

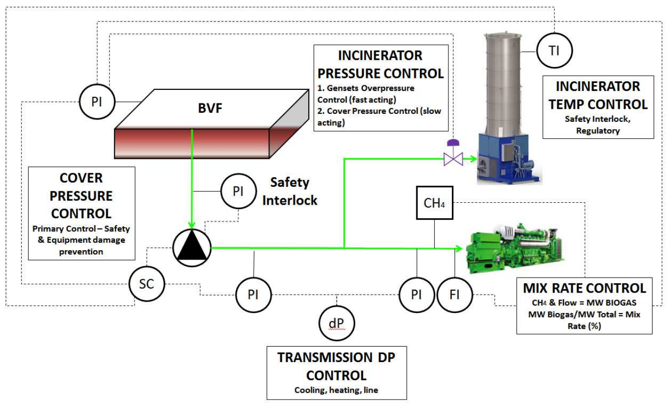


**Figure 13** – Simplified pressure control strategy

Pressure control on a compressed gas system with dead-time, pressure loss and multiple utilization points is very challenging. The genset pressure control strategy depicted in Figure 13, was co-designed by SLP and AMEC Foster Wheeler, and is the most complex control implemented for the Biomethanation with Power Generation project because of the following factors:

- The primary objective of biogas pressure control is to maintain the BVF® cover pressure within an operating dead-band
- Safety factors:
  - Avoidance of overpressure at utilization – fuel trains have rupture disks
  - Cover pressure – BVF® cover pressure must be controlled at all times to prevent cover damage, especially in high winds
- Gensets mix rate and incinerator flow must both control cover pressure, but also satisfy other requirements including:
  - Minimum incinerator top temperature to ensure full conversion of $H_2S$ to $SO_2$ a regulatory requirement
  - Gensets load – gensets are operated at full output to minimize fixed costs
- Control must be slow and fast acting:
  - Slow acting to prevent rapid pressure change causing genset trips
  - Fast acting to act as pressure relief when gensets trip
- System dead-time:
  - Long transmission lines result in biogas dP which varies with flow rate
  - Hot ambient temperatures increase cooling requirements, which increases dP with increasing flow

Stability of genset operation on biogas decreases with increasing biogas, or mixing rate. A mixing rate of over 70% biogas will likely result in a genset trip from pressure variation if biogas is diverted to the incinerator based on quality. It is preferred to continue to run gensets on natural gas and ramp the units down in a controlled fashion as opposed to a hard trip.

Natural gas quality affects the rated output of a genset. For example, high concentrations of ethane in natural gas can cause engine knocking at high loads, which is the case with SLP's gas supply. As a result, genset outputs were limited to 2.8 MW on 100% natural gas. Introduction of biogas, however, pro-rates genset output from 2.8 MW at 0% biogas to 3.0 MW (rated output) at a biogas mix rate of 90% or greater.

Therefore the benefits of gensets stability and output must be weighed along with the cost of generation. Cost of generation is impacted by:

1. Fuel Cost
2. Maintenance Cost
3. GHG Costs

With low or variable fuel costs, the GHG intensity of the power generated and the maintenance costs, which are fixed, when measured against delivered power pool price, determine the profitability of the generation. One benefit of generating electricity using biogas is the reduced GHG intensity per MW, as biogenic $CO_2$ is not taxed.

Best-in-class combined cycle generation in Alberta emits 0.406 MT $CO_2$e/MW and has a heat rate of 7.2 GJ/MW. Figures 14 and 15 show the performance of the GE J620 Jenbacher engines using biogas in April 2016.

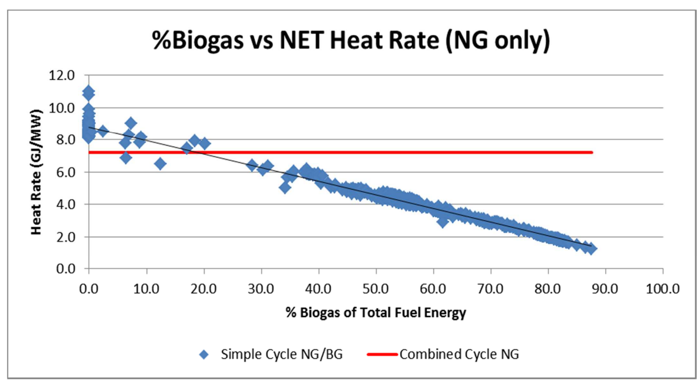


**Figure 14** – Heat rate of simple cycle generation using biogas vs combined cycle natural gas generation

In Figure 14, the y-intercept of 8.8 GJ/MW is the average heat rate of the Jenbacher engines using 100% natural gas as a fuel. The simple cycle curve on biogas intersects the combined cycle curve at approximately 20% biogas mix rate.

The simple cycle GHG emissions rate shown in Figure 15 does not include $NO_X$ or $CH_4$ from biogas combustion, so emissions rates on biogas are slightly understated. This curve would also intersect the combined cycle emissions rate of 0.406 MT $CO_2$e/MW at approximately 20% biogas mix rate, indicating that GHG credits will be generated by generating power with more than 20% biogas under the proposed Carbon Capture Regulation in Alberta.

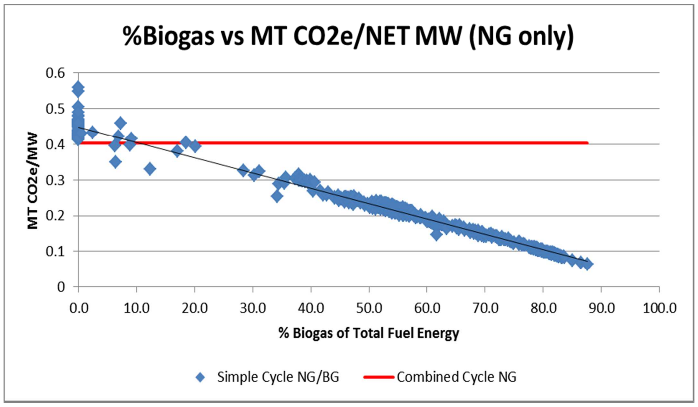


**Figure 15** – GHG of simple cycle generation using biogas vs combined cycle natural gas generation

Generation of power from biogas in April 2016 averaged 3.0 MW, with a maximum output of 5.7 MW. Power from biogas varies with loading; an average of 3.5 MW was produced on low loading and 4.5 MW produced during high loading runs in the month.

## CONCLUSIONS

Biological biogas scrubbing is an effective, low operating cost technology for removing $H_2S$ from biogas and is a good technology fit for facilities familiar with the operation of biological systems.

$H_2S$ removal efficiency in SLP's biogas scrubbers can exceed 99.8%, but declines when scrubbers are overloaded during high loading runs and as packing media becomes fouled.

Biogas scrubbing efficiency is affected by $H_2S$ loading, flow stability, fouling rate, biological growth pressures and MUW addition rates. Quarterly scrubber cleanings are necessary to ensure biogas can be utilized for power generation.

Biogas scrubber differential pressure (biogas blower suction vacuum) and $H_2S$ removal efficiency on high loading are key indicators that scrubber cleanings are required.

As fouling is ultimately a function of the cumulative amount of $H_2S$ removed over time, reducing scrubber $H_2S$ loading will reduce the frequency of cleanings. The two most effective ways to control $H_2S$ loading are by increasing the digester's pH (which is uneconomical) or decreasing the use of sulfur-based bleaching chemicals in the pulp mill.

Scrubbers should be operated similarly ($H_2S$ loading by balancing flow) to ensure the same rate of packed media fouling and be cleaned in sequence to improve operability and $H_2S$ removal efficiency.

Cleaning efficiency is most affected by the sufficient supply and proper application of compressed air used to agitate the packing media.

Quality of the biogas required for utilization drives the design of the biogas handling and transmission systems, and is determined by the genset supplier.

Good pressure control of biogas systems containing multiple appliances (incinerator and generators) is essential to both protect equipment from damage and to ensure safe and stable operation of biogas processes.

Simple-cycle generation of power using biogas in excess of 20% of the fuel energy results in better-than-best combined cycle natural gas generation heat rate (fossil fuel) and GHG emissions.

Power generated using biogas from the anaerobic digestion of pulp mill effluent and scrubbed of $H_2S$ in biological scrubbers is normally between 3.5 and 4.5 MW and as high as 5.7 MW.

## REFERENCES

[1] FEHR, S., DIJULIO, M., BERTOLDO, D. P., MCCARTHY, P.J. "Slave Lake Pulp Biomethanation with Power Generation Project", Pacwest Conference (2015)

[2] DON W. GREEN., ROBERT H. PERRY "Perry's Chemical Engineers' Handbook" Eighth Edition

[3] SPEECE, R.E. "Anaerobic Biotechnology and Odor/Corrosion Control for Municipalities and Industries", Archae Press, Nashville (2008)

[4] ABATZOGLOU, N. & BOIVIN, S. "A review of biogas purification processes". Biofuels, Bioprod. Bioref. 3:42-71 (2009)

[5] SYED, M., SOREANU, G., FALLETTA, P. & BELAND, M. "Removal of hydrogen sulfide from gas streams using biological processes – a review". Canadian Biosystems Engineering. 48: 2.1-2.14 (2006)

[6] ALLEGUE, L.B. & HINGE, J. "Biogas upgrading: Evaluation of methods for $H_2S$ removal". Danish Technological Institute (2014).

[7] FRIEDHELM, HILLEN "Technical Instruction No.:1000-0300 Fuel Gas Quality Natural, Associated Petroleum, bio- and landfill gas". GE Jenbacher (2009).