NEXT GENERATION ANAEROBIC DIGSTION

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ABSTRACT

The state-of-the-art features of the latest generation of anaerobic digestion installations are discussed. High performance processes include pre-treatment hydrolysis (thermal, acid, C. bescii), mesophilic, and thermophilic digestion. Some of the largest installations in the world are given as examples. Examples of co-digestion installations are given including an energy neutral water resource recovery facility that co-digests fats, oils, and grease (FOG) near its maximum organic loading rate. Promising results from research on the biological C. bescii bacteria hydrolysis process for the digestion of cellulose and lignin is presented as an example of the next generation of anaerobic digestion. Digestion of condensate from pyrolysis is given as an example of another process to digest recalcitrant cellulose and lignin.

The latest generation of anaerobic digestion include processes and features for optimizing capacity, performance, and reliable operation. They have state-of-the-art systems such as sludge grit removal, thickening, sludge screening, raw sludge feeding and digested sludge withdrawal and dewatering. Some have systems that harvest nutrients and prevent struvite or vivianite scaling. Ammonia loads to the liquid treatment process are addressed with sidestream treatment. All have a high performance, digestion process such as high rate mesophilic, thermal or biological hydrolysis before mesophilic or thermophilic digestion. The digester structure, cover, heating and mixing systems are state-of-the-art. The latest digester gas collection, treatment, and utilization system are incorporated. These components of state-of-the-art digestion for resource recovery of biosolids, nutrients, energy, and water are discussed.

KEYWORDS

Anaerobic Digestion, Organic Loading Rate, Mesophilic, Thermophilic, Thermal Hydrolysis, Co-digestion, Cogeneration, Digester Gas, Biogas, Gas Treatment, Sludge Thickening, Dewatering, Sidestream, Struvite, Pyrolysis, resource recovery

PRESENTER PROFILE

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1 INTRODUCTION

The objective of this work is to provide guidance to managers of water resource recovery facilities that are planning on upgrading or installing anaerobic digestion facilities. It provides insights from planning, designing, and commissioning the latest generation installations on optimizing anaerobic digestion performance. Anaerobic digestion systems have evolved from stabilizing sludge for disposal to playing a key role in the resource recovery of biosolids, nutrients, energy, and water. The latest generation of anaerobic digestion systems that:

- Incorporate high performance processes that provide the required capacity with less volume
- Produce exceptional quality, Class A biosolids for beneficial use
- Screen and remove grit before digestion
- Operate reliably,
- Have provisions to manage foam and rapid volume expansion
- Accept supplemental organics for co-digestion
- Convert a high percentage of the volatile solids into biogas for beneficial use
- Recover nutrients such as struvite from the dewatering side-streams and manage the nutrients in the sidestream

One facility doesn't have all of these characteristics, but perhaps the next generation of anaerobic digestion installations may. State-of-the-art features of the latest generation of anaerobic digestion facilities are discussed. High performance digestion processes include high rate mesophilic digestion and thermophilic digestion. Pre-treatment processes include acid hydrolysis, thermal hydrolysis, and C. bescii bacteria hydrolysis. Pre-treatment is followed by mesophilic digestion or thermophilic digestion. Co-digestion is discussed and an energy neutral water resource recovery facility (WRRF) that co-digests fats, oils, and grease (FOG) is given as an example. Research for future generations of digestion is discussed.

Features from recent world-class projects are given as examples of the latest generation installations:

- The mesophilic digestion facility at the Atotonilco WWTP serving Mexico City, Mexico
- The mesophilic digestion facility at the Metro Biosolids Center (MBC) in San Diego, CA
- The multi-staged thermophilic digestion facility at the Shafdan WWTP in Tel Aviv, Israel
- The Gold Bar WWTP in Edmonton, Alberta, Canada with plans for biological hydrolysis, thermophilic, and mesophilic digestion
- The thermal hydrolysis and digestion facility at Blue Plains Advanced WWTP in Washington DC
- The co-digestion facility at the Des Moines, Iowa WWTP that is accepting more than 40 percent of its solids from trucked in organic waste
- The co-digestion facility at the Gresham, Oregon WWTP that is achieving energy neutrality accepting fats, oils, and grease (FOG)

Research on promising technologies for the next generation of anaerobic digestion include:

- The pre-digestion C. bescii hydrolysis process (CBHP) for hydrolyzing cellulose and lignin for digestion.
- The post-digestion pyrolysis of dried biosolids and the digestion of the condensate.

2 EXAMPLES

Examples from the latest generation of anaerobic digestion facilities are presented to demonstrate state-of-the art practices. Anaerobic digestion processes and digester components were optimized for performance and capacity. Business case evaluations were conducted for decision making. The selected features were based on meeting multiple objectives of economic, environmental, social, and operational categories. Life cycle cost to benefit ratios were compared for different options to guide selecting the best overall digestion system for a given WRRF.

Digester components were designed in terms of tank and cover configuration, mixing, heating or cooling (temperature control), sludge conditioning (screening and grit removal), sludge feeding, and sludge withdrawal (surface, bottom, and emergency), and biogas management. In some designs, different mixing systems such as draft tubes, bubble gun gas mixing, pumped jet mixing, and linear motion mixers were used. The solids concentration of the feed and the resulting solids concentration in the digesters were considered for mixing limitations. Considerations for handling rapid volume expansion, prevention of precipitate formation (struvite and vivianite), and dewatering performance were part of the designs. Sidestream treatment for managing the ammonia load to the liquid stream was included. The impact of co-digestion on digester loading rates, biogas production, and residual biosolids were considered. Biogas system management, gas transport capacity, condensate removal, and gas treatment for energy recovery with combined heat and power (CHP) or renewable natural gas production were also addressed.

Latest generation examples are discussed below:

2.1 ANTOTONILCO WASTEWATER TREATMENT PLANT

The Atotonilco Wastewater Treatment Plant with a dry weather flow capacity of 1990 ML/day serves the greater Mexico City population of 21 million people. Thirty 13 ML mesophilic digesters handle 790 dry tonnes per day (dtpd) of solids during dry weather and up to 1310 dtpd during wet weather conditions. Twelve 2.8 MW internal combustion engine-driven, combined heat and power (CHP) are fueled by the biogas. The 33.6 MW CHP capacity corresponds to 1.12 MW per digester. The digesters are a modified egg-shape design with a steep cone bottom and top. There was no digested sludge available in the area for seeding the digesters so primary sludge was used for seed. The digesters have a conservative design loading rate of 1.25 kgVS/day/m3 during dry conditions and 2.07 kgVS/day/m3 during wet conditions. Corresponding hydraulic retention times are 25 days for dry weather conditions and 15 days for wet weather conditions. The specific energy loading rates (SELRs) are also conservative at 0.11 kgCOD/day/kgVS and 0.18 kgCOD/day/kgVS for dry and wet conditions, respectively. Digested biosolids are dewatered using high solids centrifuges and either stored in a dedicated monofill adjacent to the plant or loaded on trucks for beneficial use. There are seven membrane gas holders to dampen fluctuations in gas production. Hydrogen sulfide concentrations are relatively low at around 100 ppm and activated carbon is used to remove hydrogen sulfide and siloxane. Figures 1 through 4 are pictures of the digesters, CHP units, gas holders, and activated carbon vessels.

Figure 1 – Thirty Mesophilic Anaerobic Digesters at Atotonilco

Figure 2 – One of Twelve CHP units at Atotonilco

Figure 3 – Membrane Gas Holders at Atotonilco

Figure 4 – Activated Carbon Vessels for Gas Treatment at Atotonilco

2.2 SAN DIEGO METRO BIOSOLIDS CENTER

The San Diego Metropolitan Biosolids Center (MBC) was initially designed and constructed in the 1990s to thicken and digest sludge from the North City Water Reclamation Plant (NCWRP) and dewater digested sludge from the Point Loma Wastewater Treatment Plant (PLWWTP) as well as digested NCWRP sludge. MBC has raw sludge grit removal and three 11 ML mesophilic anaerobic digesters. After 20 years of operation, design of the MBC improvements is underway to handle additional sludge from NCWRP. The design includes increasing the capacity and improvements to the sludge grit removal, centrifuge sludge thickening, digestion, and dewatering systems. Figure 5 is 3D rendering of an option to increase sludge grit removal capacity.

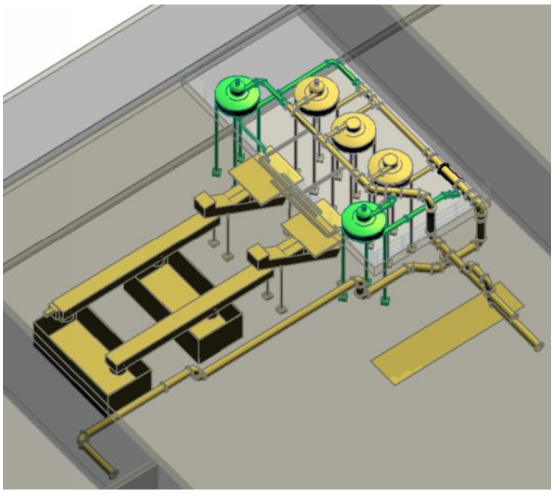

Figure 5 - Sludge grit removal expansion

By increasing the thickened sludge solids concentration, additional capacity can be achieved in the digesters. The pumped mixing system of the digesters are being improved to handle thicker solids. The MBC improvements are being integrated with the other plants in the San Diego wastewater system for solids loadings and nutrient management. Figure 6 is a picture of the existing thickening centrifuges and Figure 7 is a rendering of the new centrifuges.

Figure 6 - Picture of five thickening centrifuges to be replaced

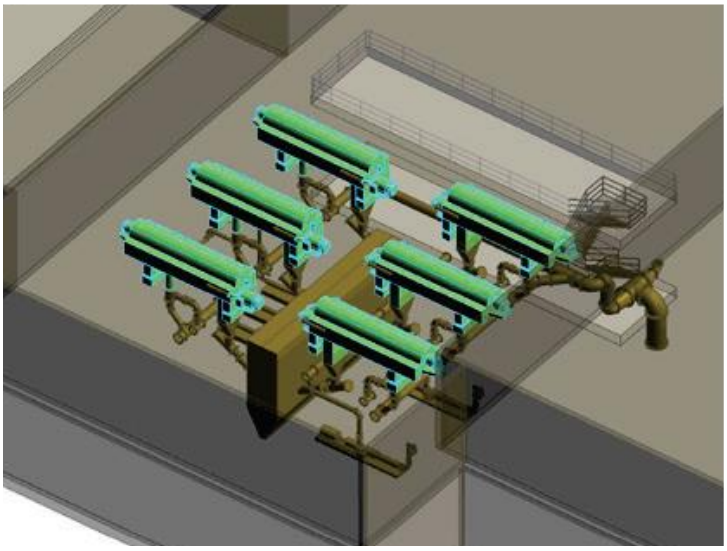

Figure 7. Rendering of six new thickening centrifuges

Improving the sludge thickening system will increase the digestion capacity by feeding higher solids. Five old thickening centrifuges will be replaced with six new centrifuges. Thickened sludge pumps will be replaced and thickened sludge piping will be replaced with larger pipes. The sludge pumping system is being designed to handle 6.5% solids. Improvements to the sludge thickening system will change the limit for digester capacity from sludge thickness to ability of the digester mixing system to mix thicker solids. The digester mixing system is also being improved and designed to mix digested solids at 4% solids.

Volatile solids loading rate (VSLR) increases with sludge thickness fed to the digester. Specific VSLR as high as 0.2 kg VS/day/kg VS are achievable for mesophilic digesters. The specific VSLR is essentially the F:M (food to microorganism) ratio for digesters. It corresponds to the specific energy loading rate (SELR) also referred to as the specific

COD loading rate or simply the organic loading rate of 0.3 kgCOD/day/kgVS. The SELR is used for high strength waste to account for the higher energy content in the feed. The VS or COD per day represents the food fed to the digester and the VS in the digester represent the microorganisms digesting the food. A fraction of the VS in the digesters are the methanogen microorganisms.

As the feed to the digesters increases the solids concentration in the digester increases. As the digester solids concentration increases, the ability to mix the digested sludge in the digesters becomes more difficult. With thickener sludge the potential for gas entrainment and sludge volume expansion also increases. The threshold for most mixers on conventional (non-hydrolyzed) sludge is 3 – 4 percent solids in the digesters where for thermal hydrolyzed sludge the threshold is over 6 percent solids in the digesters.

Improvements to the MBC digesters and associated solids processing system are being made in a business wise fashion. Improvements to the sludge thickening system is incorporated into improvements to the digesters to result in more capacity and all the components (thickening, sludge pumping, digester mixing, and digester gas management) all working together.

2.3 SHAFDAN WASTEWATER TREATMENT PLANT

The Shafdan wastewater treatment plant located south of Tel Aviv is owned by Mey Ezor Dan (MED), an association of 22 cities and towns in central Israel. The plant is operated by Mekorot. The average annual dry weather flow is 410 ML/day producing 104 dry tonnes/day after digestion. Extensive water conservation results in a relatively high solids concentration in the influent and solids production rate. The Shafdan WWTP has an excellent headworks with three sets of screens and grit removal. Primary sludge thickened in the sedimentation tanks and secondary sludge thickened with gravity belt thickeners is sent to sludge screens before being fed to the digesters. The anaerobic digestion and cogeneration facility have been operating since 2015. Figure 8 is an aerial of the Shafdan digestion and cogeneration facility. Figure 9 is a process flow diagram of the multi-stage thermophilic anaerobic digestion system.

Figure 8 – Aerial of Shafdan Anaerobic Digestion and Cogeneration Facility

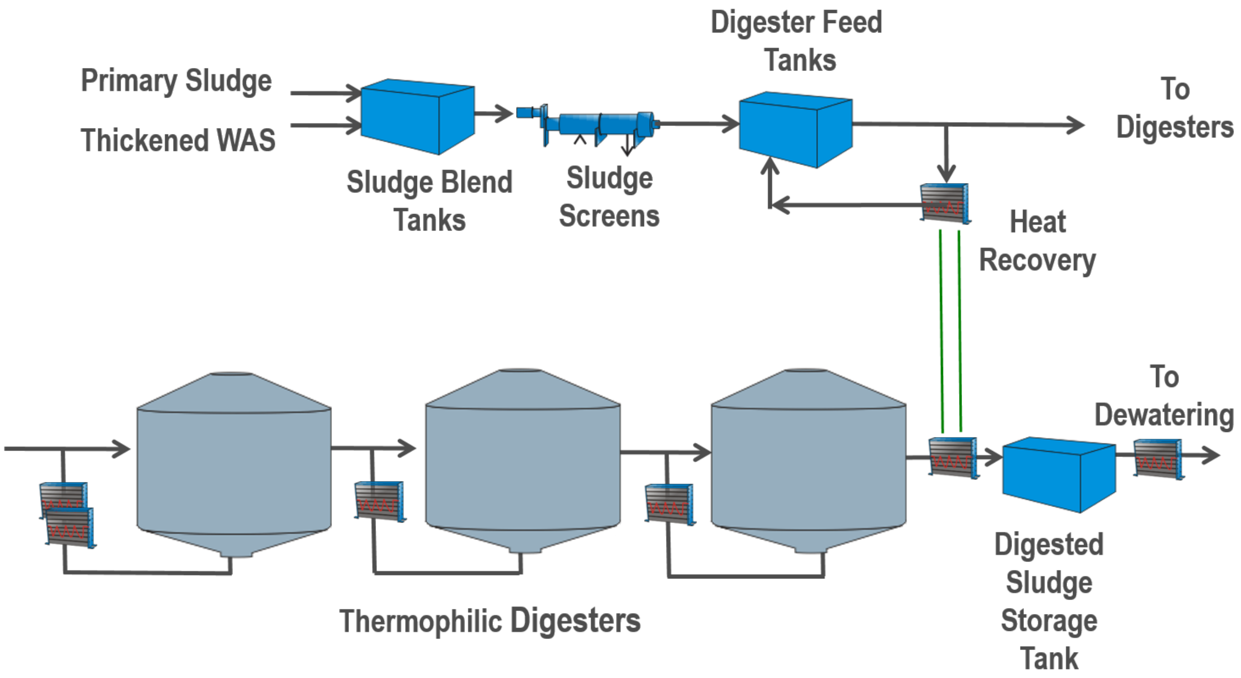

Figure 9 – Process Flow Diagram of Shafdan Multi-Stage Thermophilic System

A three-staged thermophilic process is used to produce Class A biosolids for beneficial use. Primary and secondary sludge is screened with 5 mm screens. Figure 10 is a picture of the sludge screens.

Figure 10 – Shafdan Primary and Secondary Sludge Screens

The primary and secondary sludge is fed to a total of eight 11.4 ML thermophilic digesters. The raw screened sludge is fed to six digesters in parallel followed by two in series. The digesters are a submerged fix cover design with surface sludge withdrawal. The surface withdrawal helps to continually remove any foam from the surface. At design conditions with a 5.5 percent solids concentration feed sludge, the first stage digesters have a 13 day hydraulic retention time and a VS loading rate of 3.1 kgVS/day/m3. The corresponding SELR is 0.26 kgCOD/day/kgVS. An 11.2 MW cogeneration system, consisting of eight 1.4 MW internal combustion engine-driven generators, beneficially uses the biogas to produce heat and power. Figure 11 is a picture of one of the cogeneration units.

Figure 11 – One of the 1.4 MW Cogeneration Units

The facility includes comprehensive biogas treatment including biological hydrogen sulfide removal, dehumidification, and siloxane removal using activated carbon. Figure 12 is a picture of the biological hydrogen sulfide system.

Figure 12 – Biological Hydrogen Sulfide Removal System

A struvite harvesting system is being designed to prevent struvite formation in the digesters and after dewatering. The Class A biosolids are dewatered and the cake is beneficially used as a solid amendment. A biosolids drying facility is planned to increase the flexibility of beneficially using the biosolids throughout the year.

The Shafdan WWTP is an excellent example of the latest generation of anaerobic digestion. It screens its sludge, has multi-stage thermophilic digestion, used a modified egg-shape design, has surface withdrawal for foam control, and is planning on struvite harvesting and biosolids drying.

2.4 GOLD BAR WASTEWATER TREATMENT PLANT

The Gold Bar WWTP is owned and operated by EPCOR and has eight digesters with six 7.5 ML digesters and two newer 9.7 ML digesters. The newer digesters 7 and 8 were added to provide additional capacity to handle wet weather solids loadings. They were structurally designed and lined so they could be operated at thermophilic temperature. They were equipped with concrete submerged fixed covers and a common standpipe for digested sludge surface withdrawal. The surface withdrawal enables foam to be removed with the sludge flow into the standpipe. Gas mixing was chosen to match the bubble gun mixers in the six existing digesters. The six older digesters are now being upgraded to submerged fixed covers and standpipes because of the successful operation of digesters 7 and 8. An evaluation of high performance anaerobic digestion (HPAD) processes was conducted as part of long term planning with key objectives to achieve Class A biosolids through digestion, energy neutrality through codigestion of organic wastes, and to have adequate capacity for future loads including wet weather sludge loadings. Adding pre-pasteurization and a ninth mesophilic digester was compared to a temperature phased anaerobic digestion (TPAD) process, thermal hydrolysis and thermal chemical hydrolysis processes, and an acid gas process. Figure 13 shows the existing mesophilic anaerobic digestion system and Figure 14 shows the recommended improved system. Figure 15 is a picture of digesters 7 and 8 that will be converted to thermophilic operation. The recommended system meets the owner's objectives and takes advantage of existing fermenter and digestion assets. It also benefits with increased digestion capacity from a new sludge thickening system that is planned. The existing fermenters will be heated to increase their capacity and free up other fermenters for acid digesters and biological hydrolysis. The two newest of the eight digesters were designed to operate at higher temperatures and will be converted to thermophilic operation. The recommended system involves feeding the digesters higher solids from the new thickening system, converting some existing fermenters to acid digesters, and converting the two new mesophilic digesters to thermophilic digesters. By making these improvements the additional digestion capacity is achieved without building any new digesters. A cogeneration system is added to beneficially use the biogas to produce heat and power making progress towards energy neutrality. A batch pasteurization system can be installed in the future when Class A biosolids are needed. The biosolids and energy plan meets the multiple objectives of Class A biosolids, adequate digestion capacity, and energy neutrality in a way that makes business sense. Existing assets are used to the maximum extent that doesn't require the addition of another digester. Equipment for producing Class A biosolids can be added in the future when needed.

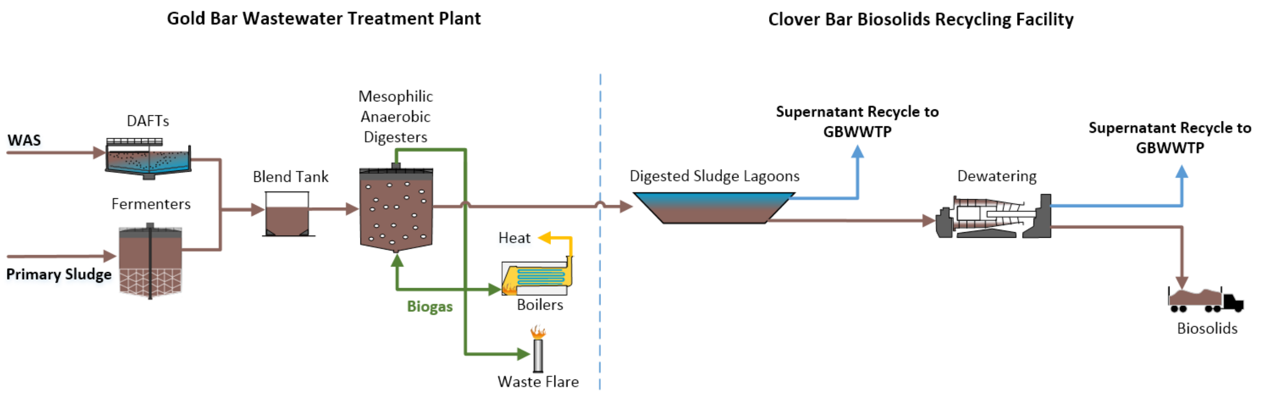

Figure 13 - Existing mesophilic anaerobic digestion system

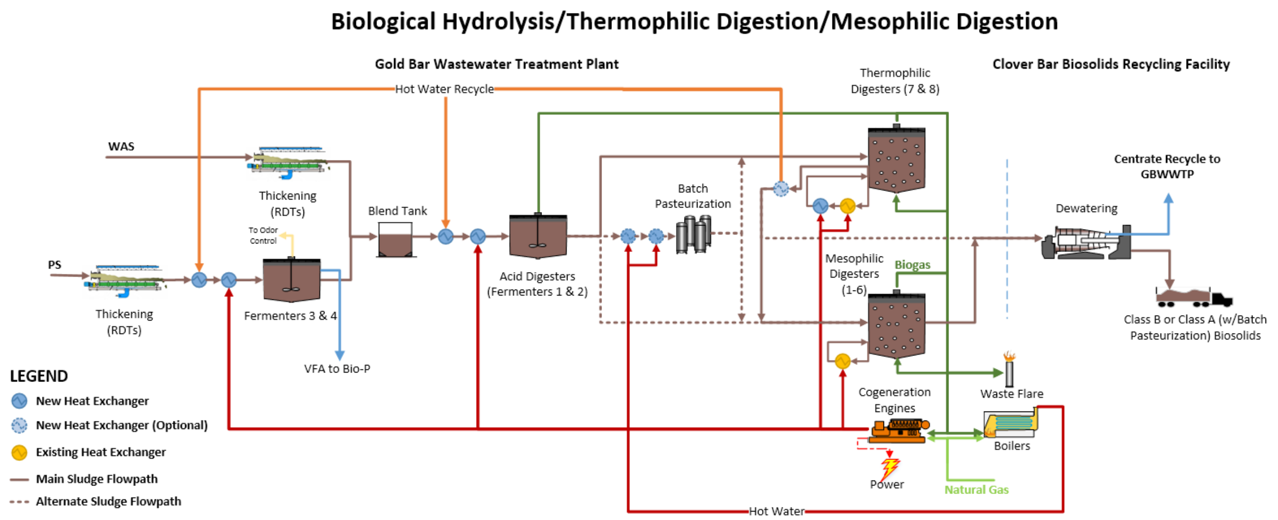

Figure 14 - Customized digestion improvements

Figure 15 - Digesters 7 & 8 that will be converted from mesophilic to thermophilic operation

2.5 BLUE PLAINS ADVANCED WASTEWATER TREATMENT PLANT

DC Water owns and operates the Blue Plains Advanced Wastewater Treatment Plant serving 2.1 million people living in the greater Washington, D.C. area. The thermal hydrolysis process (THP) followed by mesophilic digestion is the largest one of its kind in the world designed to handle 410 dry tonnes per day of solids from the 1020 ML/day average design capacity plant. Figure 16 is an aerial picture of the THP digestion facility.

Figure 16 – Thermal Hydrolysis Process and Anaerobic Digestion Facility

Four 14.4 ML digesters are continuously fed sludge with 10.5 percent solids concentration from the THP units. The digesters are achieving 65 percent VS reduction and a 6 percent digested sludge solids concentration is being mixed with mechanical draft tube mixers (Loomis 2015). There are multiple provisions to handle digested sludge volume expansion including three overflow pipes at the surface of each digester and volume at the top of each digester between the normal overflow and emergency overflow. Figures 17 and 18 are pictures of the sludge withdrawal and emergency overflow provisions.

Figure 17 – Three Sludge Withdrawal Pipes in the Digesters

Figure 18 – Standpipes and Emergency Overflow Piping

The hydraulic retention time at design conditions is 15 days and the VS loading rate is 5.3 kgVS/day/m3. The SELR accounts for the higher solids concentration in the digester and is 0.26 kgCOD/day/kgVS. THP coupled with digestion is resulting in high performance dewatering with 32 percent cake being achieved from belt filter presses.

2.6 DES MOINES WATER RECLAMATION FACILITY

The Des Moines, Iowa Wastewater Reclamation Authority (WRA) is a regional wastewater utility serving the Greater Des Moines area population of 500,000. The WRA owns and operates the Des Moines Water Reclamation Facility (WRF) treating an average daily flow of 230 ML/day with wet weather flows occasionally exceeding 760 ML/day. Six 9.8 ML mesophilic digesters treat the solids from the Des Moines WRF as well as trucked in organic waste. Figure 19 is an aerial picture of the Des Moines mesophilic digesters.

Figure 19 – Digesters at the Des Moines Water Reclamation Facility

The mesophilic digesters are a submerged fixed cover design with draft tube mixers. More than 40 percent of the solids sent to the digesters are hauled in waste. The co-digestion VS loading rate is relatively conservative at 1.6 kgVS/day/m3 and corresponds to a SELR of 0.15 kgCOD/day/kgVS (Parry 2014). A hauled waste receiving station has three truck bays for unloading and two truck scales along with a 640,000 ML below grade tank. Figure 20 is a picture of the truck loading facility.

Figure 20 – Truck Loading Facility for Receiving Organic Waste

The Des Moines WRF has been successfully operating a co-digestion program for more than 20 years. The revenue from tipping fees, selling excess biogas, and generating on-site power from biogas-fueled CHP units covers the costs associated with co-digestion.

Codigestion of organic waste with wastewater solids is a rapidly growing practice. Co-digestion feeds organic waste to the digester along with domestic sludge. With supplemental organics, existing digesters produce more biogas and add more value. A receiving facility to accept trucked in organic waste is required along with pre-processing equipment and storage. Pre-processing equipment removes contaminants such as grit, cardboard, plastics, glass, and metals. Storage is required to equalize the flow and enable control feed of the digesters. Fats, oils, and grease (FOG) are excellent high strength organic waste for co-digestion.

Supplementing the feed to the digester with high strength organic waste requires attention to the organic loading rate. Conventional organic loading rates of hydraulic retention times and volatile solids loading rates are not adequate for high strength wastes. There is also a benefit to accounting for different digester operating parameters from feeding at higher solids concentrations. A food to microorganism (F:M) ratio for anaerobic digesters is needed to account for higher strength food and greater methanogen populations in the digester. The specific energy loading rate (SELR) is proving to be a useful parameter for determining allowable organic loading rates. The development of the SELR is documented in WERF co-digestion research (Parry 2014). The SELR is essential an F:M ratio where the units are kgCOD/day/kgVS. The mass of VS is used as a surrogate for methanogens in the digester. Methanogens are expected to be between 3-5 percent of the mass of the VS in the digester (Speece 2008). The amount of the feed to a digester that can be FOG is also of interest. As part of the co-digestion research for WERF (Water Environment Research Foundation) the upper limit SELR for FOG was determined to be 0.25 kgCOD/day/kgVS and FOG could be as much as 40 percent of feed (in terms of COD) for stable digestion. Research was conducted on 100 percent food waste and supplemental micro-nutrients (especially Cobalt) and feeding at higher solids concentrations (greater than 10 percent solids) were necessary for stable operation (Evans 2015).

Co-digestion impacts the solids processing. It increases both biogas and biosolids production. It can influence the biosolids dewatering and strength of the sidestream requiring treatment in the secondary system. Depending on the characteristics of the organic waste, the Carbon:Nitrogen balance can change as well as the methane content in the biogas.
The economics from the impacts of co-digestion should be considered when determining tipping fees that will cover the cost of solids processing. Depending on the solids processing costs downstream of digestion, the cost of handing the additional residual biosolids from co-digestion can be greater than the savings from producing additional biogas. An appropriate tipping fee can be determined to make up the difference.

2.7 GRESHAM WASTEWATER TREATMENT PLANT

The Gresham WWTP serves the greater City of Gresham, Oregon area about 20 km east of Portland, Oregon. The plant employs primary clarification followed by suspended media activated sludge and secondary clarification. Figure 21 is an aerial of the Gresham plant.

Figure 21 Aerial of Gresham Wastewater Treatment Plant

Thickened primary and waste activated sludge are fed to two 3.8 ML complete mix anaerobic digesters along with FOG. The digesters are heavily loaded at a specific energy loading rate of 0.5 kgCOD/kg VS/day with a high FOG percent of 44 percent of the total COD. Enough biogas is produced and used to fuel a cogeneration system to produce enough heat and power to meet the entire plant demand. The Gresham plan has achieved energy neutrality because of accepting FOG and employing co-digestion.

2.8 RESEARCH ON FUTURE DIGESTION PROCESSES

Research on pre- and post- digestion processes are showing positive results. A C. bescii hydrolysis process is hydrolyzing cellulose and lignin to enable digestion of these recalcitrant substances. Another method to digest cellulose and lignin is by pyrolyzing dried biosolids to convert them into py-gas and condensate and then digesting the condensate.

2.8.1 C. BESCII HYDROLYSIS PROCESS

Research of biological pretreatment of sludge with the thermophilic bacteria Caldicellulosiruptor bescii (C. bescii) is showing promising results. C. bescii pretreatment has the potential to digest the cellulose and similar substances in sludges and greatly increase volatile solids reduction, increase biogas production, and decrease residual biosolids. The chemistry of C. bescii pretreatment is now well understood from both the literature (Kataeva 2013) and lab-scale work at Brigham Young University (BYU). C. bescii produces exozymes that hydrolyze cellulose and lignin to sugars that can then be digested with conventional anaerobic digestion.

Laboratory studies have been completed at BYU using two existing 60 L systems comprised of two tanks each. Pretreatment with C. bescii is done at 75°C in the input waste activated sludge (WAS) solution, which is naturally buffered at pH 7-8. Anaerobic digestion is subsequently accommodated in a secondary tank at mesophilic or thermophilic temperatures. A heat exchange mechanism cools the pretreatment effluent while simultaneously capturing heat for transfer to the feedstock influent pretreatment tank. A process diagram of the CBHP is shown in Figure 22.

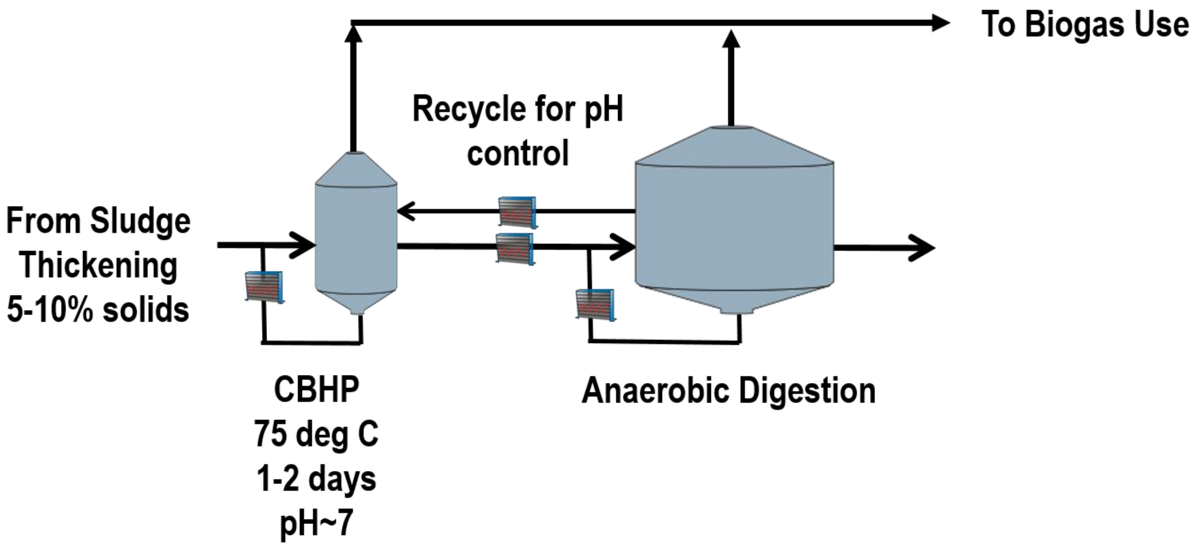

Figure 22 - Process Diagram of C. Bescii Hydrolysis Process (CBHP)

Digestion of waste activated sludge (WAS) was increased nearly three-fold producing 2.9 times the biogas with C. bescii pretreatment than without pretreatment. Figure 23 is a graph of the gas production from the control and test digesters. Other cellulosic material like cow manure and green waste showed similar results. The next research step is to compare digestion with and without pretreatment at a pilot scale.

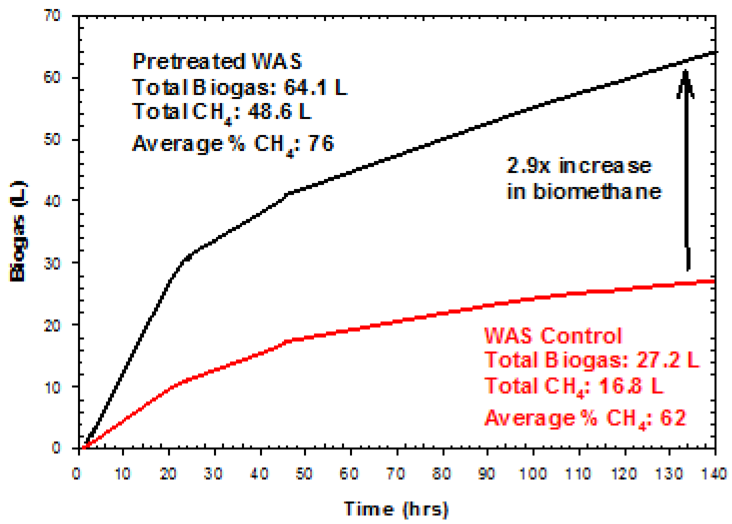

Figure 23 - Biogas Production from the Digestion of Waste Activated Sludge

2.8.2 PYROLYSIS AND DIGESTION OF CONDENSATE

Research was conducted to investigate the feasibility of enhancing anaerobic digestion by feeding the products of pyrolyzed biosolids back to the digester (Parry 2012). Some organic matter such as recalcitrant cellulose and lignin are not biodegradable in anaerobic digestion. The objective of pyrolysis was for converting recalcitrant lignin (lingo-cellulosic material) and other organics remaining after anaerobic digestion into wood vinegar (acetic acid) and wood alcohol (methanol) for subsequent reintroduction into the anaerobic digestion process. A low temperature (200 deg C) pyrolysis step was used on dried biosolids to convert a substantial portion of the ligno-cellulosic matter into organic matter amenable for anaerobic digestion. This process uses a thermal process (pyrolysis) to enhance a biological (anaerobic digestion) process. Figure 24 is a process diagram of the pyrolysis process with py-gas and condensate being returned to the digester.

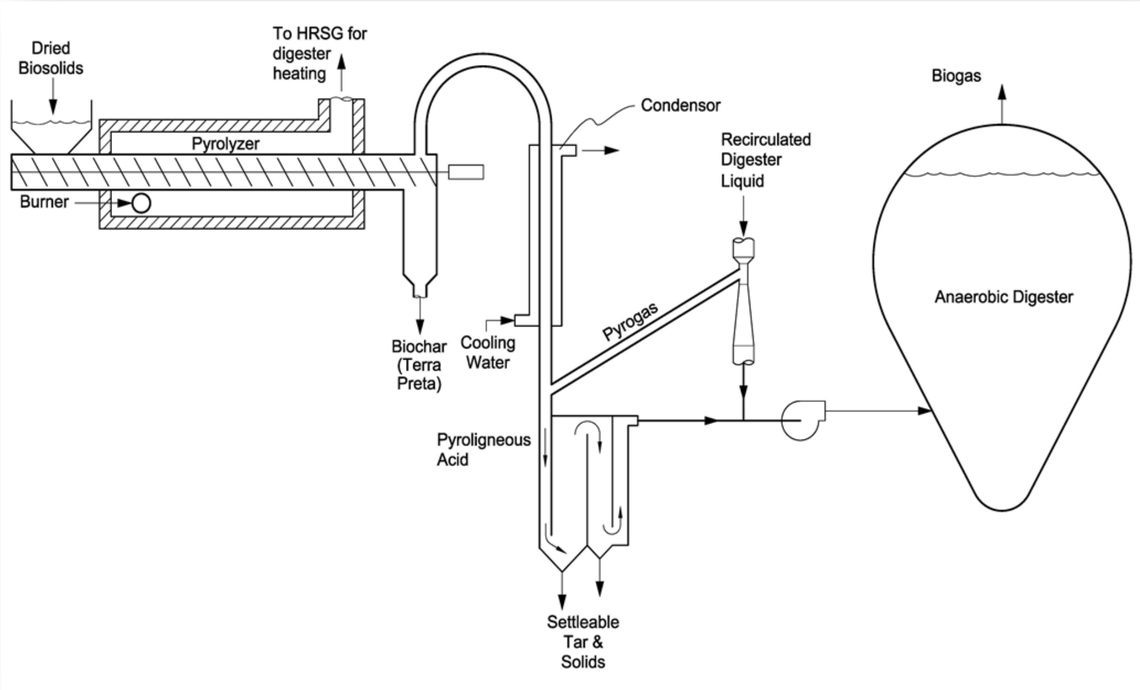

Figure 24 - Process Diagram of Pyrolysis of Dried Biosolids and Condensate Digestion

The results of this research demonstrated that feeding the condensable gaseous products of pyrolyzed biosolids to an anaerobic digester will result in the production of more biogas and significant solids reduction. A 46 percent reduction in the mass of dried biosolids was observed from pyrolysis in this research. The condensate from pyrolysis was observed to be digestible and produce more biogas. Therefore, it appears that digesting the process has the potential to enhance the digestion process to recover more energy in the form of biogas while reducing the amount of the residual biosolids. Research on the digestion of condensate from pyrolysis continues to be researched at Marquette University (Seyedi 2018)

3 CONCLUSIONS

Insights from the examples of state-of-the-art digestion facilities is that the systems include the sludge conditioning, feeding, digester configuration, digester mixing, temperature control, sludge withdrawal, and biogas management. A conventional mesophilic digester can deliver high performance using best practices. Conditioning of the sludge prior to digestion with screenings and grit removal improve the digester performance and quality of the digested biosolids. Feeding a higher solids concentration of thickened sludge to the digester at a continuous rate improves digester stability, increases digester capacity for a given volume, and reduces the sludge heating demand. Digester configuration using egg-shaped or modified egg-shaped tanks improves mixing, reduces deposition with steep sloped bottom cones, and provides for surface withdrawal of scum and foam from a small area.

A greater capacity can be achieved from a given volume by continuously feeding higher solids concentrations of thickened sludge. The limiting factor of higher solids concentration is the ability to mix the higher solids concentration in the digester as well as potential ammonia toxicity from higher ammonia concentrations. The higher solids concentration results in a higher methanogen population that can accept more food. The resulting volatile solids (VS) or chemical oxygen demand (COD) feed rate can be higher based on a given food to microorganism ratio for the digester. Maintaining the temperature of the digested sludge in the digester within a narrow range is fundamental to achieve high performance digestion and conversion of food into biogas. High digester feed rates and solids concentration results in greater gas production and an increase potential for biogas entrainment and digested sludge volume expansion. Provisions for regular sludge withdrawal as well as handling the increased amount of sludge from sludge volume expansion must be included in the digester design.

Provisions for volume expansion can be made by providing volume at the top of the digester and emergency overflow piping with adequate capacity to handle the digested sludge flow. If the emergency piping can handle the predicted flow, then volume doesn’t have to be reserved at the top of the digester. Research on volume expansion is resulting in a greater understanding of its causes and prevention. Biogas entrainment in digested sludge is a cause of volume expansion. The amount of biogas entrained is proportional to the apparent viscosity of the sludge and the amount of biogas produced. As solids concentrations in the digester increase for higher performance, the apparent viscosity increases and the probability of volume expansion increases. Digester mixing lowers the apparent viscosity as it increases the shear rate and creates a “shear thinning behaviour” (Bartek 2015). Thermal hydrolysis lowers the apparent viscosity and enables mixing at higher solids concentrations.

A state-of-the-art digestion installation would not be complete without the treatment and beneficial use of the biogas. Biogas treatment can include hydrogen sulfide removal, moisture removal, and siloxane removal. Biogas can be further treated to remove carbon dioxide and produce pipeline quality biomethane. It can be compressed and used as renewable CNG (compressed natural gas). As a default, biogas can be used as a boiler fuel to produce hot water or steam for digester and space heating with the excess being flared. A high performance biogas utilization system would be a combined heat and power (CHP) or biomethane system to get higher value from the biogas.

Based on the examples, state-of-the-art practices are summarized in Table 1.1 and state-of-the-art components in Table 1.2. Promising results of the C. bescii lab tests at BYU were presented earlier. C. bescii pretreatment has the potential to increase volatile solids reduction by enabling the digestion of cellulose. Applying this pre-treatment to the other state-of-the-art practices discussed in this work would begin the next generation of anaerobic digestion with high volatile solids reduction due to the digestion of cellulose. Applying the post-digestion treatment of pyrolysis and digesting the condensate is another next generation technology that could digest cellulose.

Table 1.1 Examples of State-of-the Art Practices

State-of-the-Art Practice	**Atotonilco**	**San Diego**	**Shafdan**	**Gold Bar**
Digestion Process	Mesophilic	Mesophilic	Thermophilic	Mesophilic
Solids Capacity 1000 kgTS/day	1300	120	200	200
Digesters	Thirty 13 ML	Three 11 ML	Eight 11.4 ML	Six 7.5 ML Two 9.7 ML
Loading Rate, kgVS/day/m3	2.5	3.0	4.0	2.5
Tank Configuration	Modified Egg Shape	Fixed concrete cover	Modified Egg Shape	Modified Egg Shape
Sludge Conditioning	Conventional	Grit Removal	Sludge Screening	Conventional
Sludge Thickening	Primary sedimentation	Co-thickening	High solids thickening	Optimized thickening
Sludge heating and cooling	CHP with backup boilers	CHP with backup boilers	CHP with backup boilers	Boilers
Digester mixing	Draft tube	Pumps with jets	Pumps with jets	Gas bubble guns
Sludge feeding and withdrawal	Conventional	Conventional	Continuous feed, surface and bottom withdrawal	Surface and bottom withdrawal
Digested sludge dewatering and side-stream	High solids dewatering	High solids dewatering	Class A dewatered cake; Sidestream treatment	Struvite harvesting from side-stream
Biogas handling, treatment, and use	Siloxane removal; biogas-fueled CHP	H_2S, H_2O, biogas-fueled CHP	H_2S, H_2O, Siloxane removal; Biogas-fueled CHP	Biogas-fueled boilers

Table 1.1 Examples of State-of-the Art Practices (continued)

State-of-the-Art Practice	**Blue Plains**	**Des Moines**	**Gresham**
Digestion Process	Thermal Hydrolysis	Mesophilic	Mesophilic
Solids Capacity 1000 kgTS/day	450	20	19
Digesters	Four 14 ML	Six 9.8 ML	Two 3.8 ML
Loading Rate, kgVS/day/m3	6.0	1.6	4.0
Tank Configuration	Tall Silo	Submerged Fixed Cover	Conventional
Sludge Conditioning	Sludge Screening	FOG grit removal	FOG grit removal
Sludge Thickening	Pre and Post-dewatering	Conventional	Conventional
Sludge heating and cooling	CHP with backup boilers	CHP with backup boilers	CHP with backup boilers
Digester mixing	Draft tubes	Draft tubes	Linear motion
Sludge feeding and withdrawal	Continuous feed, surface and bottom withdrawal	Surface withdrawal	Co-digestion with FOG
Digested sludge dewatering and side-stream	Class A dewatered cake; Sidestream treatment	Conventional	Conventional
Biogas handling, treatment, and use	H2S, H2O, Siloxane removal; Biogas-fueled CHP	Sell biogas, renewable natural gas, biogas-fueled CHP	H2S, H20, Siloxane removal; Biogas-fueled CHP

Table 1.2 State-of-the-Art Practice for Anaerobic Digestion Components

Component	State-of-the-Art Practice
Anaerobic Digestion Process	Site specific: pre-treatment (hydrolysis), mesophilic digestion, thermophilic digestion
Digester Tank and Cover	Modified egg-shape, tall silo configuration
Debris Removal	Sludge grit removal and sludge screening prior to digestion
Sludge Thickening	Thicken sludge for high solids concentration feed to digesters
Sludge Temperature Control	Reliable heat recovery and supply with compatible temperatures
Digester Mixing	Dependent on owner's objectives
Sludge feeding and withdrawal	Continuous feeding, surface and bottom withdrawal, emergency overflow provisions for volume expansion
Digested sludge dewatering and side-stream management	High solids dewatering and nutrient removal from sidestream treatment
Biogas handling, treatment, and use	Condensate removal, comprehensive biogas treatment including hydrogen sulfide, moisture, and siloxane removal; biogas fueled combined heat and power system; carbon dioxide removal and renewable natural gas to pipeline or vehicles

Examples of the latest generation of anaerobic digestion installations have been discussed and the state-of-the-art practice can be summarized by the following components:

1. Digestion process (mesophilic, thermophilic, pasteurization, thermal, C. bescii, and acid hydrolysis)
2. Digester structure and shape (egg-shape or modified egg-shape)
3. Sludge cleaning (grit removal, screenings)
4. Feeding (continuous, high solids thickening, codigestion feedstock)
5. Withdrawal (surface overflow, emergency overflow, bottom withdrawal)
6. Digester Mixing
7. Digested sludge dewatering
8. Sidestream treatment (ammonia, struvite, vivianite)
9. Digester gas (handling, treatment, use)
10. Temperature management (heating, cooling)
11. Biosolids quality (Class A or B after digestion)
12. Digested biosolids drying and pyrolysis (product characteristics, odor, trace contaminants, thermal and biological connection)

The latest and next generation of anaerobic digestion installations involve considering all these components.

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