TECHNICAL, ENVIRONMENTAL, AND ECONOMIC ASSESSMENT OF SLUDGE THICKENING PROCESSES: A COMPARISON OF CONVENTIONAL THICKENING AND ENERGY-EFFICIENT CENTRIFUGAL THICKENING TECHNOLOGIES

by

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ABSTRACT

As of today, several technologies are available for thickening waste activated sludge. Presently gravity belt thickeners (GBTs) tend to be the most commonly installed for waste activated sludge thickening applications (Water Environment Federation, 2012). However, new advancements in thickening centrifuges give reason to believe that the centrifuge may be economically competitive with GBTs and other thickening technologies moving forward, creating a need to compare the economic favorability of each process. In addition, little research has presently been completed in assessing the environmental impact of thickening technologies. Thus, the objective of this study was to compare GBTs with a novel centrifugal thickening technology and compare them on the basis of performance, economy, and environmental impact. GBTs were found to utilize less power than the centrifugal thickener however reduction in the amount of polymer consumed gave a large advantage to the centrifugal thickening technology over the GBT, specifically for larger sized plants.

KEYWORDS

Waste activated sludge, thickening, centrifuge, THK, gravity belt thickeners, biosolids

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1.0 INTRODUCTION

Waste activated sludge (WAS) is characterized by low solids content, ranging from 0.25 to 2% depending on the operational condition. Prior to further stabilization processes, WAS is often thickened to increase total solids (TS) concentration to reduce the volume prior to anaerobic digestion thereby decreasing the amount of energy required to mix and heat the sludge (Metcalf & Eddy, 2003). Several technologies are available for thickening WAS. Gravity belt thickeners (GBTs) utilize a porous belt to separate the free liquid phase from the solid phase. Rotary drum thickeners (RDTs) work similarly by feeding sludge into a porous drum screen where free water can vacate through the drum wall and the remaining solids are transported the length of the drum. Both GBTs and RDTs are reliant on polymers for achieving the required flocculation that frees water from the sludge, enabling separation. Though little technical data has been published to verify this, both technologies are assumed to use relatively low amounts of energy. Dissolved air flotation is a process by which air is blown upward through a blanket of sludge in a designated tank with the objective of attaching and entraining air bubbles to solid particles in a manner such that the solid phase can be decanted off the surface of the tank. Lastly, the decanter centrifuge can be used in the thickening process, though it is most common for sludge dewatering applications. Thickening centrifuges apply forces up to 3000G to the sludge within a rotating bowl oriented horizontally. Thickening centrifuges are also able to perform with reduced quantities of, and sometimes completely without, flocculent polymers but they are believed to use more power than their counterparts.

However, recently a more energy-efficient design of a thickening centrifuge appeared on the market. The modification includes the implementation of a near-centerline discharge which has been shown to significantly reduce power consumption, and an air-assisted cake removal system which enables a higher degree of operational control on the total solids content of the thickened WAS or cake. The novel design has reportedly achieved power use as low as 0.06 kW per gallon per minute (GPM), a new benchmark for any type of decanting centrifuge (Kopper et al., 2012). This novel design has also been shown to work effectively with influent WAS from 0.2 to 2% total solids with and without use of flocculent polymers and demonstrated the ability to control cake solids concentrations in the range of 3.5% to 9% (Kopper et al., 2012).

Presently GBTs tend to be the most commonly installed for new WAS thickening applications. However, with new advancements in the thickening centrifuge, the new, energy-efficient design may be an economically and environmentally competitive option for thickening of WAS. Little research has been completed in assessing the environmental impact of thickening technologies in the past, neither for traditional or novel thickening techniques.

Hence, the objective of this study was to compare conventional gravity belt thickeners and a novel thickening technology (the Centrisys THK thickening centrifuge) in economic and environmental terms. Economic performance was evaluated based on energy consumption, polymer use, annual maintenance, and capital cost. Global warming potential (in kg CO_2 eq.) was used as the main indicator of environmental performance. This study is an attempt to illustrate the importance of unit process selection on overall plant performance.

2.0 LITERATURE REVIEW

A literature review was completed to gain a better understanding of research completed in the area of waste activated sludge thickening technologies. The review first considered the mechanisms at work in conventional thickening technologies such as for gravity belt thickeners. Following this, a review of centrifugal thickening technologies was conducted. Next, a review of several non-conventional technologies was completed to consider what other technologies could be impacting the market in the future and to compare and contrast cost and benefits with conventional technologies such as gravity belt thickeners and the novel centrifugal thickener that is the subject of this document. Finally, two studies regarding life cycle assessment (LCA) as applied to wastewater treatment systems were reviewed for the primary reason that LCA was used in this project to compare technologies on an environmental basis.

2.1 GRAVITY BELT THICKENERS

In the past decade, gravity belt thickeners have been the standard technology for sludge thickening in wastewater treatment. An article from the journal *Water Engineering & Management* describes a gravity belt thickener called the G-25 Gravabelt manufactured by Komeline Sanderson as permitting "reduced construction costs, easy and economical commissioning, ready connections for electricity, sludge feed and polymer addition, quick startup and installation without any special foundation" (Anonymous, 1998). More relevantly, the article describes a unit having 25 square feet of drainage area as having the ability at 120 gallons per minute to save as much as $1000 dollars per day, for a small community plant. Adjusted for inflation using an average inflation rate of 2.36%, this would equate to $1453 in 2014. While the author did not specify what the baseline case was, this was, the claim was likely in comparison with a plant having either no current means of thickening or having only a gravity thickener.

This technology is described as being used to reduce the solids hauling cost and being used to thicken sludge upstream of anaerobic digestion. The mechanism by which this occurs was examined by many parties over the past 4 decades. Focusing on the more recent two decades, an article by Severin et al. (1999) explained that the phenomenon of ponding on gravity belt thickeners can be blamed for much of the ill performance exhibited by gravity belt thickeners in the field. Ponding can be defined as the pooling of sludge atop the belt in the gravity drainage zone of the GBT or belt filter press due to insufficient drainage of the liquid fraction through the belt filter. When ponding occurs, thickened sludge concentrations are reduced and the excess sludge often runs off the side of the belt, thus causing raw sludge to blend in with filtrate. Conditions which create ponding on a gravity belt thickener include increased solids content of feed material to the GBT, excessive throughput to the GBT, insufficient belt speed, and insufficient washing of the belt media. All of these conditions lead to blinding of belt media which in turn causes belt ponding.

The work of Severin et al. also detailed the evaluation of gravity belt thickeners with the use of plows. Severin et al. pointed out that most research completed prior to 1999 focused on settling experiments completed in cylindrical tubes using one or multiple filtration media. However, none of the experiments had attempted to replicate the use of plows at the lab scale to demonstrate the efficacy of plow use for gravity settling despite plows being incorporated into the design of GBTs and belt filter presses since the earliest implementation of such technology for wastewater treatment. A US patent from 1976 speaks of “flow breakers” used to increase flocculation on a continuous belt, and that use of said flow breakers was also found to prevent the formation of a bottom-layer of sludge which could plug the pores of the belt (Wenzel and Kollmar, 1976). Flow breakers-, now known as plows, basically create windrows on the GBT belt surface. This allows for enhanced drainage of liquid out of flocculated solids and then further rolls partially drained solids into additional windrows increasing drainage further yet. See Figure 1 for an image of plows being utilized in the gravity drainage section of belt filter press in a modern wastewater treatment facility.

Figure 1. Plows in the gravity drainage zone on a belt filter press processing anaerobically digested sludge – Photo taken with permission at the Fresno/Clovis Regional Wastewater Treatment Facility in Fresno, CA

Despite being part of the equipment from the earliest days of the inception of GBT, the plow had not been evaluated on the lab scale prior to the work of Severin et al. (1999). This work demonstrated that it is possible to accurately model gravity drainage systems via a modified version of the Darcy equation, referred to as the *General Drainage Equation* (Eq. 1). The work further demonstrated that the effects of ponding and the use of plows to mitigate ponding in gravity drainage could be successfully modeled as well.

$$-(1+\gamma)\,ln\left(1-\frac{V_f}{V_F}\right) = KAt\left(\frac{V_\infty + V_F}{V_F V_\infty} - \frac{1}{V_F}\right) \qquad \text{(Eq. 1)}$$

Where:

γ = Resistance ratio, (unitless)
K = Cake permeability, (m/s)
A = Batch filtration area, (m^2)
t = time, (s)
V_f = Volume of filtrate at time t, (m^3)
V_F = Volume of filtrate at time t = infinity, (m^3)
V_∞ = Volume of cake after a very long drainage time (m^3)

Oliver et al. (2004) considered several modelling techniques previously developed by Severin et al. (1999), one of which was the Darcy-based model described above and the other, an empirical model used to project the dry solids content of sludge generated via gravity drainage processes. Oliver et al. noted that all prior modeling had been based solely on laboratory testing and incorporated no field data for GBTs. After comparing the two models put forth by Severin, Oliver found that the empirical model better matched the lab data collected via experimentation. However, to apply this formula in such a manner to predict performance of industrial GBTs, the assumption that infinite cake volume (defined as the volume of cake after an infinite amount of drainage time) be proportional to the total mass of the initial sludge sample was made. With this assumption, the modified empirical formula can be seen below.

$$C(t) = \frac{DS}{(a_1 \times DS + a_2) + \left(c_1 \times \exp(c_2 \times DS) \times t + \frac{1}{M_0 - (a_1 \times DS + a_2)}\right)^{-1}} \qquad \text{(Eq. 2)}$$

Where:

$C(t)$ = Dry solids content of cake at time t (%)
DS = Dry solids content of initial sludge (%)
M_o = Mass of initial sludge at time zero (g)
a_1, a_2, c_1, and c_2 are all fitting parameters

Using Equation 2 and comparing lab experimentation with field testing of a GBT, two distinct scenarios were found in which different groups of fitting parameters should be used. It was found that for sludge with a dry solids content less than 2%, one set of fitting parameters be used and that for sludges with a dry solids content of 2% or greater, another unique set of fitting parameters be used.

Further research by Christensen et al. (2010) continued on the same track as Severin and Oliver in terms of developing predictive modeling for gravity drainage processes, however it goes further in evaluating the effects of cake compression in the gravity settling and drainage process. In the experimentation detailed by Christensen, a slurry comprised of dextran-MnO_2 was produced and used because the dextran-MnO_2 slurry was said to provide a more consistent product and could be produced in a more repeatable manner than could waste activated sludge. Several interesting findings came out of this research; first it was found that throughout the profile of the settled cake layer, during the filtration step, the solids content increased dramatically from top to bottom. However, it was further found that during the so-called, consolidation step, where solids further drain, a uniform solids content profile was formed. It was also found in this work that due to the compression of solids, the dry solids content of fully drained solids increases with both increased influent solids content and with increased volumetric load. This effect is most dramatic for highly compressible solids where the thickened solids content was found to be proportional to the square of the volumetric load.

In 2011 Domniak et al. published a continuation on the research put forth by Christensen, wherein the compressibility of cake produced from gravity drainage was further investigated. Domniak, however took the findings of Christensen and applied similar logic to waste activated sludge where Christensen had used dextran-MnO_2. Domniak's work validated the methods put forth by Christensen and found the same conclusion to be true: that waste activated sludge cake is compressible, even at low pressures. Because of this, required filtration time increases as volumetric load increases; filtration time $\propto$ volumetric load^2. Domniak also evaluated the effects of floc destabilization on drainability and found that both anaerobic conditions and high speed (~ 800 rpm) shearing reduced drainage speeds with the high speed shearing having the biggest impact. This is believed to happen because as the flocculated solids become destabilized, finer solids are suspended and further blind the filter material, thus slowing the drainage rate.

2.2 CENTRIFUGAL THICKENING TECHNOLOGIES

Research pertaining to centrifuges began with an overview and history of the technology. A detailed review of the different types of centrifuges in existence today and for what types of applications they are used in was provided by Sutherland (2005). The types of centrifuges in use today can be broadly broken down into two groups: batch operation centrifuges and continuous operation centrifuges. Both of these centrifuges are used for separating solids from liquids, for separating lighter liquids from heavier liquids, and for simultaneously doing both of these things at once. In even rarer situations they are used to remove light and heavy solids from a medium density liquid at the same time. Some examples of both batch and continuous operation types of centrifuges include the following: beaker centrifuges, ultra centrifuges, tubular bowl centrifuges, imperforate basket centrifuges, disk stack centrifuges, decanter centrifuges, screen bowl decanter centrifuges, peeler centrifuges, pusher centrifuges, and so on.

In the context of municipal water and wastewater treatment, there are two types of centrifugal devices often used:

1. A hydrocyclone where there exists a stationary body wherein the motion of the fluid generates centrifugal forces enabling heavier material to separate from the lighter liquid. This technology is often used for separation of grit from influent wastewater. This type of centrifugal device is not the subject of this report.
2. A horizontal decanter centrifuge which consists of a bowl that rotates at up to 3000 times the force of gravity and within that bowl, a rotating screw conveyor also known as the scroll, which rotates at a

slightly different speed. This type of machine is used specifically for sludge thickening or dewatering; solids within the sludge are often treated with a flocculent polymer and the flocculated solids under the high g-force readily settle to the bowl wall. The difference in speeds between the bowl and scroll allow for the discharge of solids over what is known as the conical section of the bowl (also known as the beach). A cross-section of a standard decanter centrifuge can be seen in Figure 2.

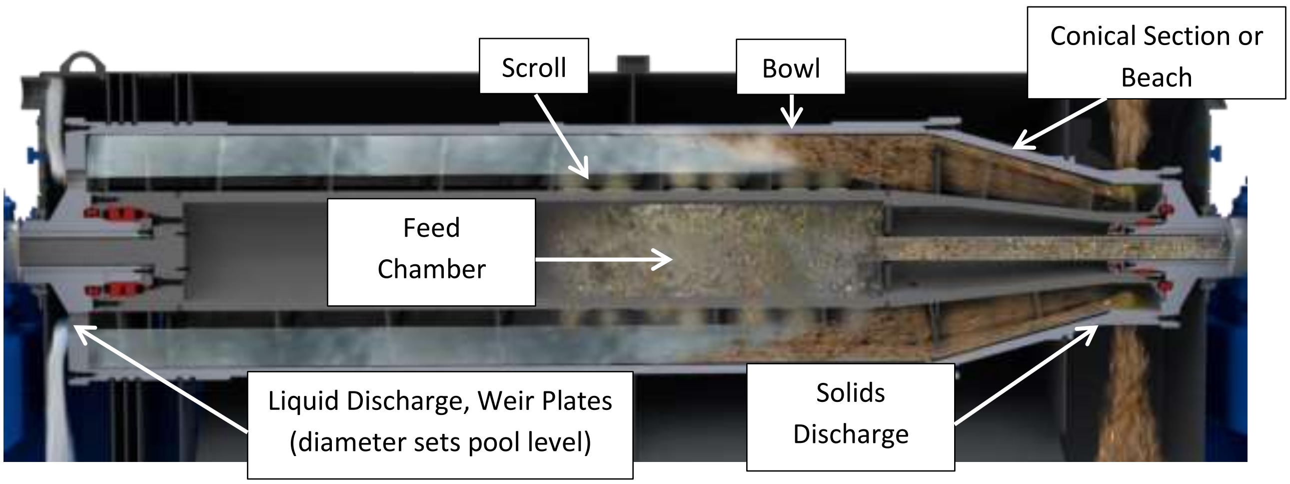

Figure 2. A cross-section of a horizontal decanter centrifuge – courtesy of Centrisys Corporation, Kenosha, WI

Horizontal decanter centrifuges are standard technology for both thickening and dewatering of sludge; however, some innovations are being made on this basic technology which is nearly 70 years old. Pasol, et al. (2010) describes a technology developed by the company Andritz in which the pool level of the machine, and hence the process volume can be altered externally by using what Pasol describes as a “choke plate”. In decanter centrifuges, the free flowing liquid separated from the solids is discharged from the centrifuge over what is known as the weirs or weir plates. For a given flow rate, some cresting height above the weirs exists. The idea of the “choke plate” is thus to distort the natural flow of the liquid away from the bowl in such a way that the cresting height and therefore the pool level, within the bowl is increased. A similar technology has also been put forward by the company GEA (Westfalia). However, in addition to the implementation of variable pond depth technology, GEA boasts of implementing energy recovery nozzles for their liquid discharge (GEA Westfalia, 2014).

The centrifuge business has large conglomerate competition with destruction and absorption of smaller companies by larger ones. The result of this may be viewed as a stifling of technology development for the industry as a whole. Prior to 1978, centrifuges that were used for dewatering varied very little and can be imagined most easily by considering the machine quarter section depicted in Figure 3a (Havrin, 2011).

Following 1978, according to Havrin, the companies Sharples and later Humboldt invested energies into developing a more efficient thickening centrifuge. This began with the Sharples hydraulic assist technology (Figure 3b). The hydraulic assist allowed for the ability to take advantage of the hydraulic head pressure accumulated behind the baffle to drive out solids in the case of thickening and to allow for higher compression of solids in the case of dewatering machines. In both cases, the overall energy efficiency increased because the liquid was now discharged at a lesser distance from the centerline of the centrifuge thereby reducing the amount of energy lost via discharge of the liquid phase.

Humboldt continued further along the same lines, also using a baffle disc, but made a change more drastic to the conical section of the machine, where the bulk solids were also discharged closer to the centerline of the machine, thus increasing energy efficiency even more. Because of the steepness of their cone, however, they also designed an intermittent solids discharge port at a cylinder-cone junction to handle the inorganic solids that would inevitably end up in the solids handling train of a wastewater plant despite the presence of quality preliminary screening and de-gritting technologies.

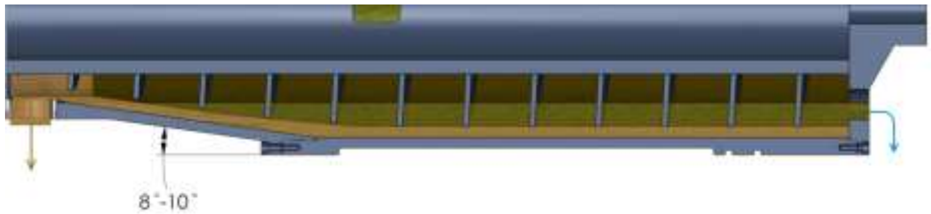

Figure 3a. An example of a pre-1978 thickening centrifuge rotating assembly quarter-section. This design is typical of both dewatering and thickening equipment from the 1940s to 1978. Image courtesy of Centrisys Corporation, Kenosha, WI

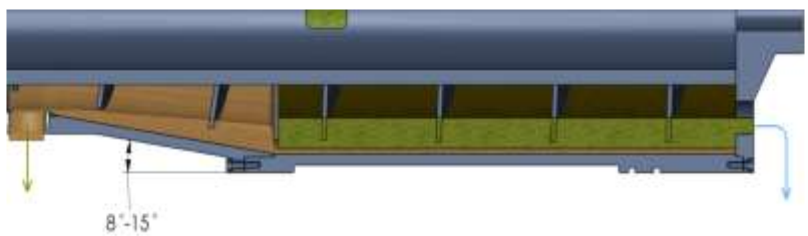

Figure 3b. A quarter-section of a Sharples (company no longer in existence) thickening centrifuge rotating assembly. This design implemented a baffle disc on the solids end of the machine, the first of its kind. In addition, this device used a steeper cone angle than had ever before been implemented. Image courtesy of Centrisys Corporation, Kenosha, WI

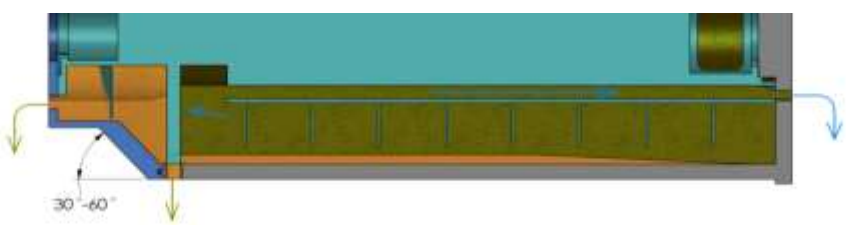

Figure 3c. A quarter section of the Humboldt (an existing company that sold off their centrifuge line) Type B centrifuge rotating assembly. This design implemented a steeper cone angle than had ever before been believed feasible. This design also used a version of the hydraulic assist but also implemented a solids discharge port on the outer wall of the bowl at the cone-baffle interface. Image courtesy of Centrisys Corporation, Kenosha, WI

Despite the progress these two companies made for centrifugal thickening, the continuous improvement of their thickening technologies could not overcome the business politics. In the 1990s, Sharples was bought out by Alfa-Laval and Humboldt was purchased by the Bird Machine Company which was later purchased by the French company Andritz. Unfortunately, when these companies were purchased, the development of innovation for thickening was all but forgotten (Havrin, 2012).

However, a US-based manufacturer (Centrisys Corporation of Kenosha, WI) in 2009 started the development of what they denote as the Centrisys THK series. This design, a rotating assembly pictured in Figure 4 is a continuation of thickening technologies left abandoned by the buyers of Sharples and Humboldt.

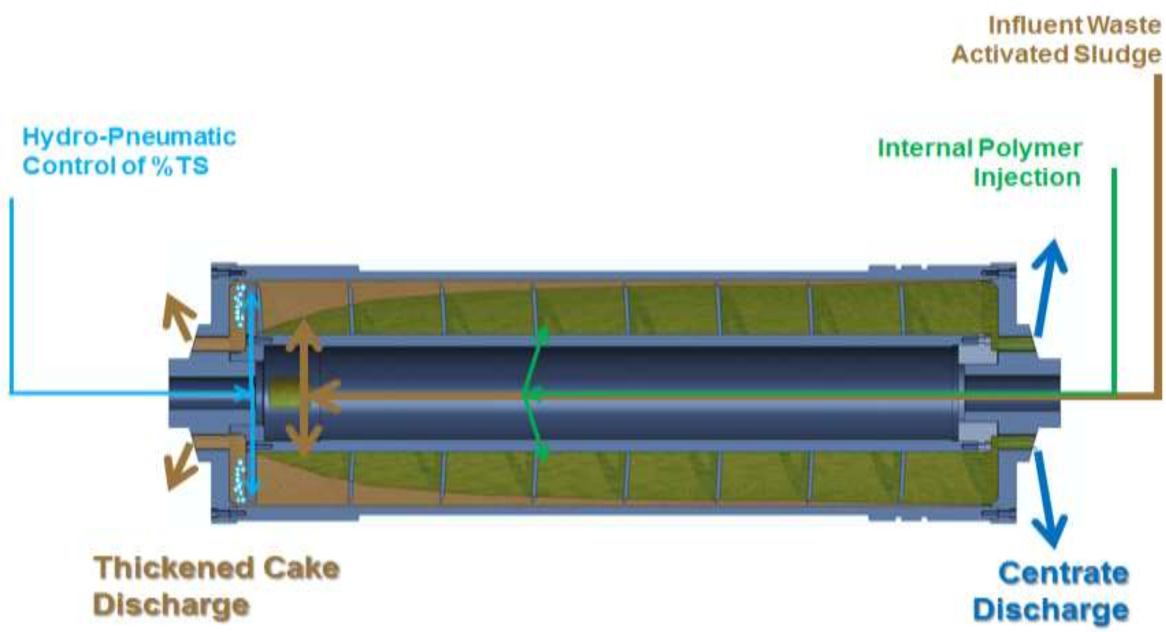

Figure 4. A cross-section of the Centrisys THK series centrifuge, first constructed in 2010. This design abandons the use of a conical section altogether, allowing a discharge of solids nearer to the centerline of the machine than ever-before implemented. Image courtesy of Centrisys Corporation, Kenosha, WI

Figure 4 shows that rather than increasing the steepness of the conical section, the Centrisys Corporation Model THK got rid of the cone altogether. This move marked a complete transition from a process reliant on scrolling to remove solids via drainage, to a process reliant on hydraulic driving forces to remove solids, where the two designs shown in Figures 3b and 3c could be considered intermediates between the two.

In addition to the centrifuge types described above, another type has been created by modifying a traditional style centrifuge to possess and drive an additional mechanical device mounted on the solids discharge end of the centrifuge. This device was used to mechanically apply shear to the thickened sludge. Dohányos et al. (1997) investigated the effects of this device on biogas generation and methane production potential of the sludge in an anaerobic digester. Dohányos reported that the special centrifuge technology increased the sludge methane yield by an average of 31.8%, but with results that varied dramatically from 8.1 to 86.4% depending on the quality of the influent sludge. When considering use of the lysed waste activated sludge with primary sludge for anaerobic digestion, it seems that the net benefit of lysing the WAS was dependent less on the quality of the WAS and more so on the quality of the primary sludge. The more degradable the primary sludge is to begin with, the less increase in yield that can be attained via lysing. It should be noted however, despite the findings of this research, there is no commercial centrifuge manufacturer promoting this technology in the United States. Possible reasons include: increased energy required for centrifugation, operational challenges, and market constraints, among others.

2.3 ALTERNATIVE THICKENING TECHNOLOGIES

There are several technologies for thickening of waste activated sludge that could be considered new and innovative. The first of these technologies, electro-flotation was described by Rahmani et al. (2013). Within this work Rahmani et al. describes a system which in some ways resembles the technology of dissolved air flotation.

The technology consists of a tank having a downward sludge flow with electrodes placed within the reactor. See Figure 5.

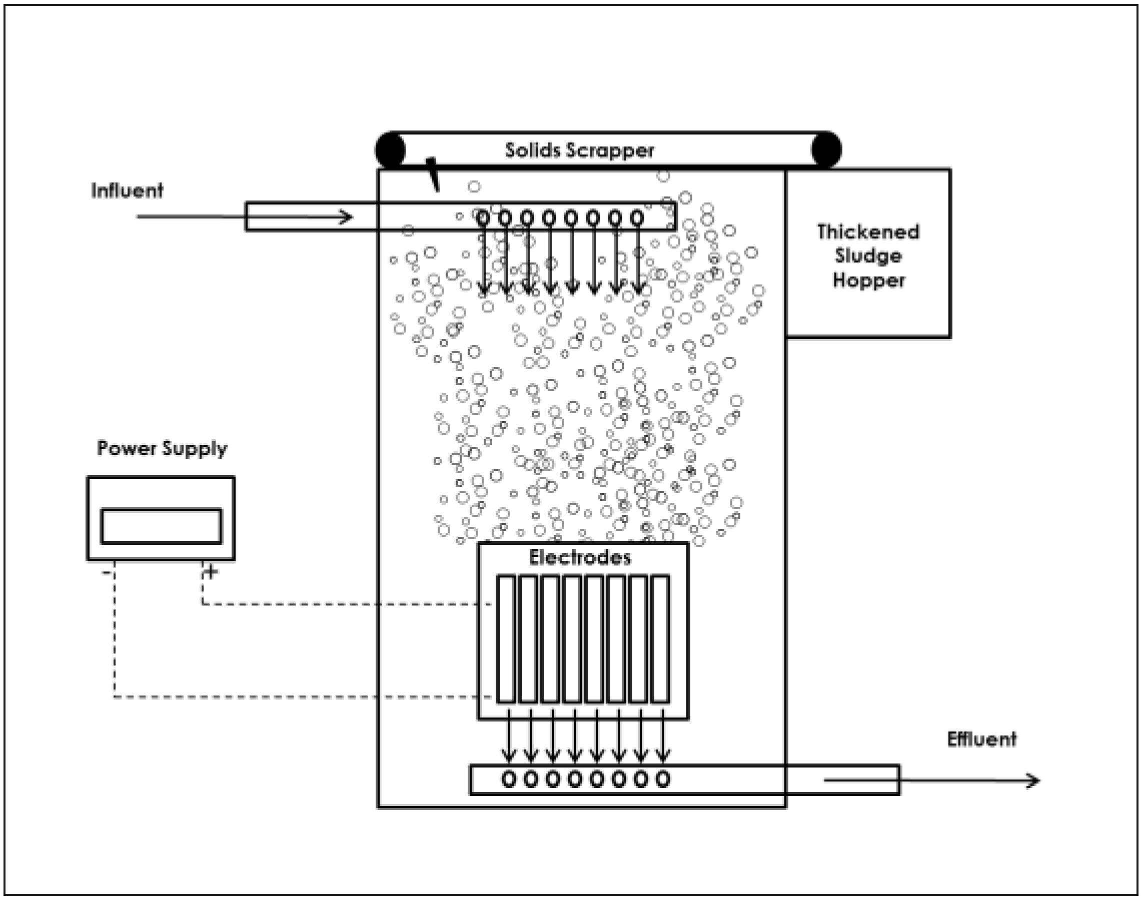

Figure 5. Depiction of electro-flotation system as described by Rahmani et al.

The electrodes themselves can be constructed of many different types of metals but commonly used metals include iron, titanium, aluminum, stainless steel and graphite. Using the electrodes, a low voltage is applied and electrolysis of water within the sludge material takes place. In electrolysis, water molecules are split to emit hydrogen and oxygen gases. These gases are released within the sludge in the form of micro-bubbles. These micro-bubbles then adhere to solids particles in the sludge and transport them upward in the reactor, much in the same way air bubbles are used in dissolved air flotation. According to Rahmani et al., the separation efficiency is improved as higher rates of hydrogen gas micro-bubbles are generated, where the generation rate of hydrogen is said to increase with decreased pH. Rahmani et al. reported that from their own literature review, the optimal pH for treatment of WAS is at a pH = 2. Retention time was also found to play a role however no additional benefit was found above a certain threshold, between 10 – 15 minutes at a current density of 8 mA/cm^2. Likewise, increases in current density played a significant role, but only up to a certain point where increases in performance were no longer seen above 10 mA/cm^2. In the context of comparing this technology to other technologies, Rahmani et al. gave a rather wide range for power consumption for this technology: 0.15 kWh/m^3 to 1 kWh/m^3 or 0.03 kW/gpm to 0.23 kW/gpm. This technology is used without polymers for flocculation but optimization of pH would require the use of acid.

Finally, the technology of forward osmosis in the paper "Feasibility of applying forward osmosis for simultaneous thickening, digestion, and direct dewatering of waste activated sludge" (Zhu et al., 2012) was reviewed. The concept of this technology is to use highly concentrated salt solutions such as those of reject streams from desalination plants or other reverse osmosis plants and use osmotic potential between this and that of a waste activated sludge at a wastewater treatment plant to extract some of the water out of waste activated sludge. To do this a fine pored membrane filter is placed within a reactor where the waste activated sludge is located on one side of the membrane and the brine solution is placed on the other. Because the most balanced state between the two liquids is that in which the liquid would have equal concentrations of total dissolved solids, the excess water from the waste activated sludge is naturally pulled through the membrane surface, lowering the TDS concentration of the brine but also thickening the waste activated sludge. This process can be better understood when viewing Figure 6.

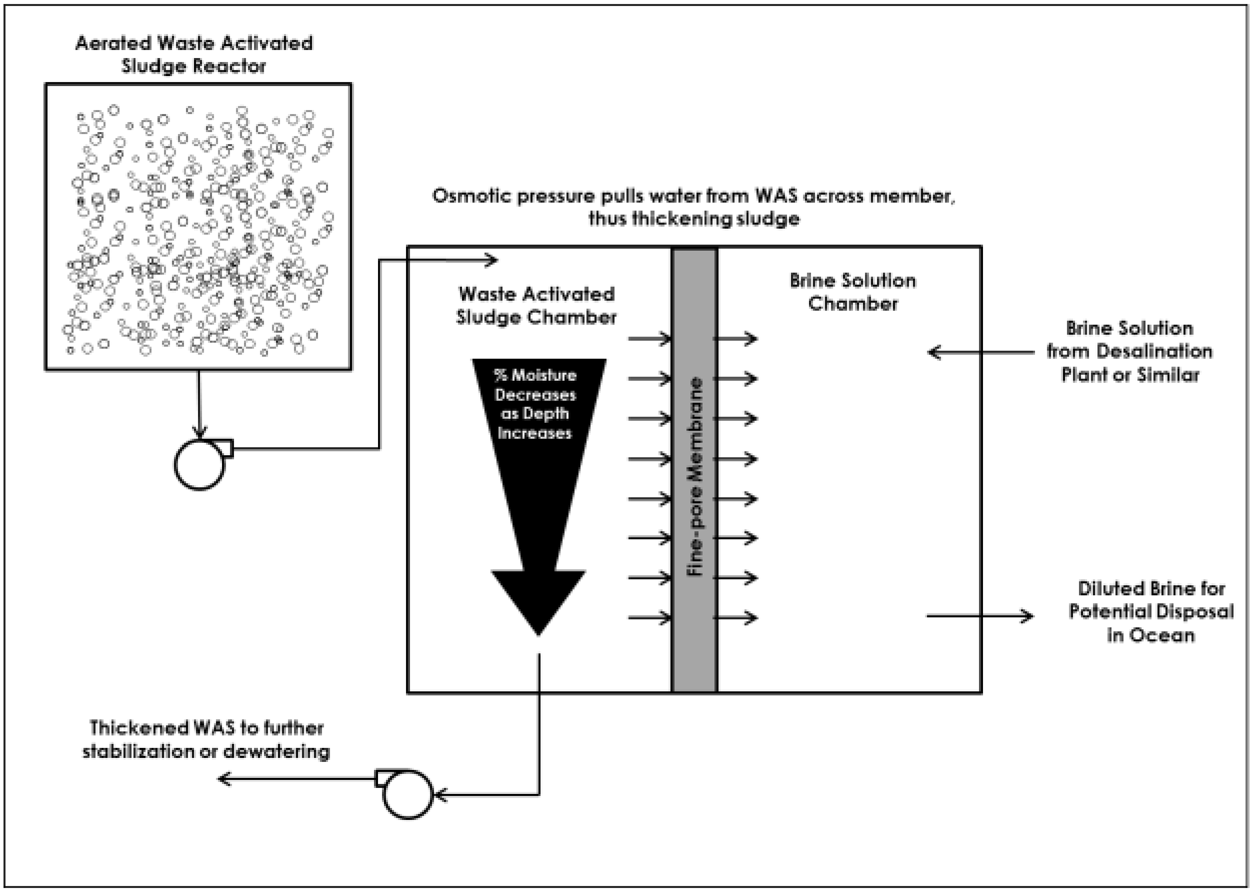

Figure 6. Depiction of forward-osmosis thickening system as described by Zhu et al.

Zhu et al.'s research also evaluated a FO membrane reactor coupled with an aerobic digestion reactor, in which thickened sludge was cycled back into the digester. Although the authors described the technology as being able to simultaneously stabilize, thicken, and dewater, no waste activated sludge was wasted out of the reactor loop during the experiment. However, experimentation showed a mixed liquor volatile solids reduction of 80%. By considering the total solids input into the reactor at the beginning of the experiment, and using the solids destruction rates measured, it was calculated that a thickened sludge concentration of about 10% total solids on average was achieved during the 19 day run.

A separate experiment was conducted and reported within the same article where dewatering of sludge was attempted using a similar membrane configuration. This testing showed that up to 35% total solids content could be obtained using this technology; however the solids content measured was directly related to the depth in the upstream side of the reactor for which the cake sample was taken. Additionally it was found that the dewatering performance was highly dependent on the strength of the draw solution (brine) used on the downstream side of the membrane.

Overall, one key strength of this technology includes that it provides a beneficial use of the brine solutions produced during desalination or other reverse osmosis projects. Additionally, these brine solutions, after extraction of excess water from waste activated sludge, may be suitable for discharge into the ocean whereas strong brine solutions discharged into the ocean have been shown to negatively affect local ecosystems. Additionally, the ability to obtain up to 10% TS content may be of higher value in specific circumstances. However, for most types of conventional wastewater treatment plants, this would be higher than desired if further stabilization was required. Regardless, the idea of dewatering directly may have a significant benefit, specifically if cake as dry as 35% total solids could actually be obtained in real world circumstances for waste activated sludge.

2.4 LIFE CYCLE ASSESSMENT AND GHG EMISSIONS ACCOUNTING FOR WASTEWATER TREATMENT

Life cycle assessment (LCA) was first implemented in the commercial sector in the 1960s and 70s and has been used extensively in the past for solid waste management (Yoshida et al., 2013). Despite this, use of LCA techniques for wastewater treatment applications have been limited in use. To provide better clarity on how LCA has been implemented in the past for wastewater and to aid in forming so-called ‘best practices’ for future implementation, Yoshida, et al. provided a comprehensive review of 35 articles published prior to 2012 on the subject of using LCA in the context of wastewater treatment. Yoshida et al. reported that 18 of 35 studies included thickening and/or dewatering processes in their analysis. Most of these 18 studies considered water content reduction as well as both polymer use and energy consumption in some cases. One peculiarity brought to light was of large discrepancies reported for power consumption of centrifuges between different studies, with the difference being 101 kWh per dry tonne in one study and only 5 kWh per dry tonne in another. Unfortunately Yoshida et al. did not report on the means by which polymer and other chemical use were accounted for or on the emission factors used in the various studies.

Niu et al. (2013) accounted for GHG emissions in the solids handling segment of a generic wastewater treatment system in China where the process included sludge thickening, anaerobic digestion, biogas utilization, and land application of biosolids for beneficial reuse. The method used for estimating the global warming potential (GWP) of each process is called the Fossil CO_2 Output Calculation Method. Using this method, Niu et al. took emission factors from an unnamed source or database and multiplied them with energy use rates to determine the emissions associated with each process. An example of one such calculation can be seen in Equation 3.

$$\mathrm{CO_2Fossil_{generic\ process}} = \left(\mathrm{DM_{influent}} \times \mathrm{EF_{electricity}} + \mathrm{DM_{influent}} \times \mathrm{EF_{diesel}} + \mathrm{DM_{influent}} \times \mathrm{EF_{etc.}}\right) \quad \text{(Eq. 3)}$$

Where:

$\mathrm{CO_2Fossil_{generic\ process}}$ = Total fossil GHG emissions (kg CO_2-eq. per tonne, dry basis)
$DM_{influent}$ = Quantity of dry matter solids tonne (In the case of the Niu et al. study, this equals 1 tonne the functional unit)
$EF_{electricity}$= Rate of GHG emissions per electrical consumption per unit mass processed (kg CO_2-eq. per kWh per tonne DM)
EF_{diesel} = rate of GHG emissions per unit diesel consumed per unit mass processed (kg CO_2-eq. per liter diesel per tonne DM)

Specifically relevant to the topic of this paper, Niu et al. found that conventional centrifugal thickening had the highest global warming potential with approximately 200 kg of CO_2-eq/tonne sludge processed on a dry basis. For gravity belt thickeners, a range of 23 to 94 kg of CO_2-eq/tonne sludge on a dry basis was used. Equally important however, is that for both the thickening and dewatering unit processes, emissions associated with the use of chemicals such as flocculants and coagulants was not taken into account.

3.0 METHODS

This study was carried out in multiple phases. First, operational data for GBT installations was collected from several wastewater treatment plants in the upper Midwest in the United States of America (USA). The process mass balances were assessed by taking the measurements for total solids content, sludge flow rates, process water flow rates and polymer flow rates, of influent WAS, thickened waste activate sludge (TWAS), and reject water. Data for energy consumption of the process and an inventory of the auxiliary process equipment were also collected. Second, the same operational parameters were measured for the novel centrifugal thickening processes at five pilot test sites (different than the GBT sample sites, (4 in USA, 1 in China) in 2012 by Centrisys Corporation of Kenosha, Wisconsin, USA. Lastly, performance, economic, and environmental assessments of thickening technologies were conducted based on the data obtained from the field measurements. A Life Cycle Assessment framework was applied to assess the environmental performance of thickening technology alternatives.

3.1 EXPERIMENTAL METHODS

Wastewater treatment plants utilizing GBTs were found using a number of tools: The Wisconsin Wastewater Operators Association Plant Database, discussions with local engineers, and by making personal inquiries. Once a plant had been identified, the plant was given a survey to complete (see Appendix A), which detailed typical operating conditions for the plant. Subsequently, sampling of the influent WAS, effluent filtrate, and discharge TWAS was completed. Polymer use was confirmed by measurement when possible, and power consumption was measured in two parts using an ammeter and a voltmeter. A clamp-on ammeter (Sperry Digisnap model DSA-540A c) was used to measure amperage and a multi-meter (Sperry model DM-6400) was used to measure voltage. Power data was collected for the following items in the GBT systems: the belt drive, the hydraulic steering unit (where applicable), the washwater pump, and motors associated with the GBT room ventilation system.

Regarding data collection of the novel centrifugal thickening technology, Figure 7 shows a schematic for the pilot testing setup used for the study. This setup was utilized for all centrifuge data collected with the exception of one site, THK Site 1 (THK denotes the thickener centrifuge considered in this study), where data was gathered from an online installation. Note that the five sample sites for the THK were different than the five sample sites with GBTs. In all cases, influent WAS was sampled upstream of the centrifuge; reject water or centrate and thickened WAS were sampled downstream of the centrifuge, prior to entering storage reservoirs. For each pilot test, samples were collected intermittently by varying bowl speeds and sludge throughputs ranging from 900 rpm to 3150 rpm and from 60 gpm to 235 gpm respectively. For two sites use of polymer was not tested however for the other three sites testing with and without polymer addition was completed. Similarly for two of the test sites, the air injection system, which according to Centrisys Corporation is used to fine control of discharge TWAS %TS, was not used. Collected samples for total solids and total suspended solids content were analyzed by plant staff at each of the respective pilot test sites while operational data including polymer use and power consumption was recorded by the Centrisys field engineer or technician. The power consumption for the centrifuge consists of three parts: main drive, scroll drive, and air injection system. The power for the air injection was not measured at the time of pilot testing as it was not feasible due to the cycling nature of the air compressor. However, average power consumption data collected during a power study on the air system completed in 2012 at the Kenosha Wastewater Treatment Plant installation was substituted for the test sites where the air system was used (see Appendix D). From this data we see that the power consumption of the air system only accounted for 2% of the overall power consumption for the centrifugal thickener.

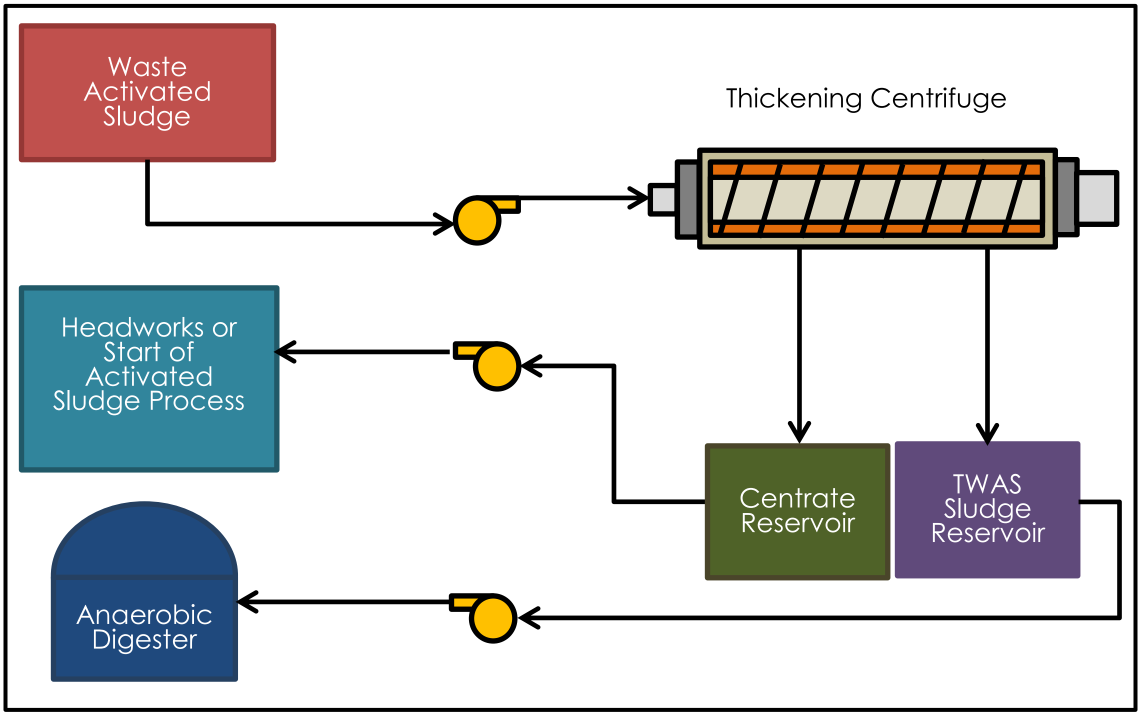

Figure 7. Centrisys Pilot Testing Configuration

3.2 ANALYTICAL METHODS

3.2.1 PERFORMANCE EVALUATION METHODS

After data had been collected both for the GBTs and for the thickening centrifuge, it was compared first in terms of physical performance. The parameters for which performance was compared between the two technologies were the following: increase in % total solids (%TS) of WAS, solids recovery rate, polymer consumption, and power use.

%TS of the influent WAS and TWAS for both technologies was completed on a % weight/weight basis. Total suspended solids (TSS) was measured using vacuum filtration per Standard Method 2540D using a Whatman™ filter (GE 934-AH) with pore size of 1.5 µm. Solids recovery rate was calculated using the following equation:

$$\frac{\%\text{ TS of WAS}}{\%\text{TS of TWAS}} \times \frac{\%\text{TS of TWAS} - \frac{\text{TSS of Supernatant}}{10{,}000}}{\%\text{TS of WAS} - \frac{\text{TSS of Supernatant}}{10{,}000}} \quad \text{(Eq. 4)}$$

Polymer consumption was compared plant to plant on a pound of polymer per ton of dry solids neat basis. It should be noted that all plants in this study used emulsion flocculent polymers. Dosages were compared on a neat basis for several reasons, first the activity for some of the polymer products was unknown, and secondly, pricing for polymer from vendors is typically done on a per pound delivered basis.

Power consumption for each plant was compared on a kW per GPM basis. This was done because influent sludge to thickening equipment is typically relatively dilute (< 1% TS) and equipment capacity is thus limited by hydraulic throughput rather than by solids loading.

3.2.2 LIFE CYCLE ASSESSMENT METHODS

The primary trade-offs among thickening technologies are polymer and electricity usage rates. In order to evaluate these trade-offs, the Life Cycle Assessment (LCA) methodology was adopted. LCA is a framework that translates environmental emissions to its foreseeable impacts on humans and ecosystems. LCA also considers the embedded emissions for energy and chemicals supplied, which provides a more comprehensive view of environmental impacts. In conducting this LCA, global warming potential (GWP) was the only impact category considered. Calculated emissions for all substances were thus converted to kg of CO_2 equivalents (eq.).

-In order to conduct the LCA, EASETECH, a LCA software tool developed by the Technical University of Denmark (DTU) was used. Within the confines of EASETECH, users must define modules, each module having a specific purpose in terms of completing the overall mass balance of the system. Such purposes include specifying emissions to the environment, specifying process energy requirements, or chemical use, and their respective impacts external to the system, specifying mass transfer rates, and specifying the addition of substances, amongst others. The modules are then connected together by arrows directing and splitting the flow. Once all modules are in place and connected, a complete life cycle inventory (LCI) of the system can be viewed. Additionally, both a characteristic and normalized impact assessment can be completed. Alternatively, one module or a group of modules can be selected and an LCI and impacts assessment can be viewed specific only to the module or group of modules, whichever is selected. However, in order for EASETECH to calculate any emissions, emissions rate data must first be imported into the program so that process specific emissions can be tabulated. While there are default emission rates for items such as the emissions related to the production of potable water, some emission rates are very much geographically sensitive, such as those associated with the production of electricity. In such cases, data was imported from the National Renewable Energy Laboratory (NREL) database and data specific to the USA was used.

In completing the LCA, thickening of one metric tonne of WAS, rather than one US ton, was used as the basis of comparison because of the constraints of the EASETECH program which works only in metric units. This study primarily considered the emissions directly related to the operation of the thickening equipment itself, specifically for process water, chemical addition, and energy consumption. This study did not consider emissions downstream of the thickening device for the solids stream (TWAS) because it was assumed that each plant was operating their thickening device as optimized to control solids and hydraulic loading rates to the anaerobic digester. This study did however take into account the energy required to treat the supernatant from the devices as the GBTs and centrifuges do use different amounts of process water which ultimately adds to the hydraulic loading, and thus energy usage, at the treatment plants. The system boundary for the LCA can be seen in Figure 8.

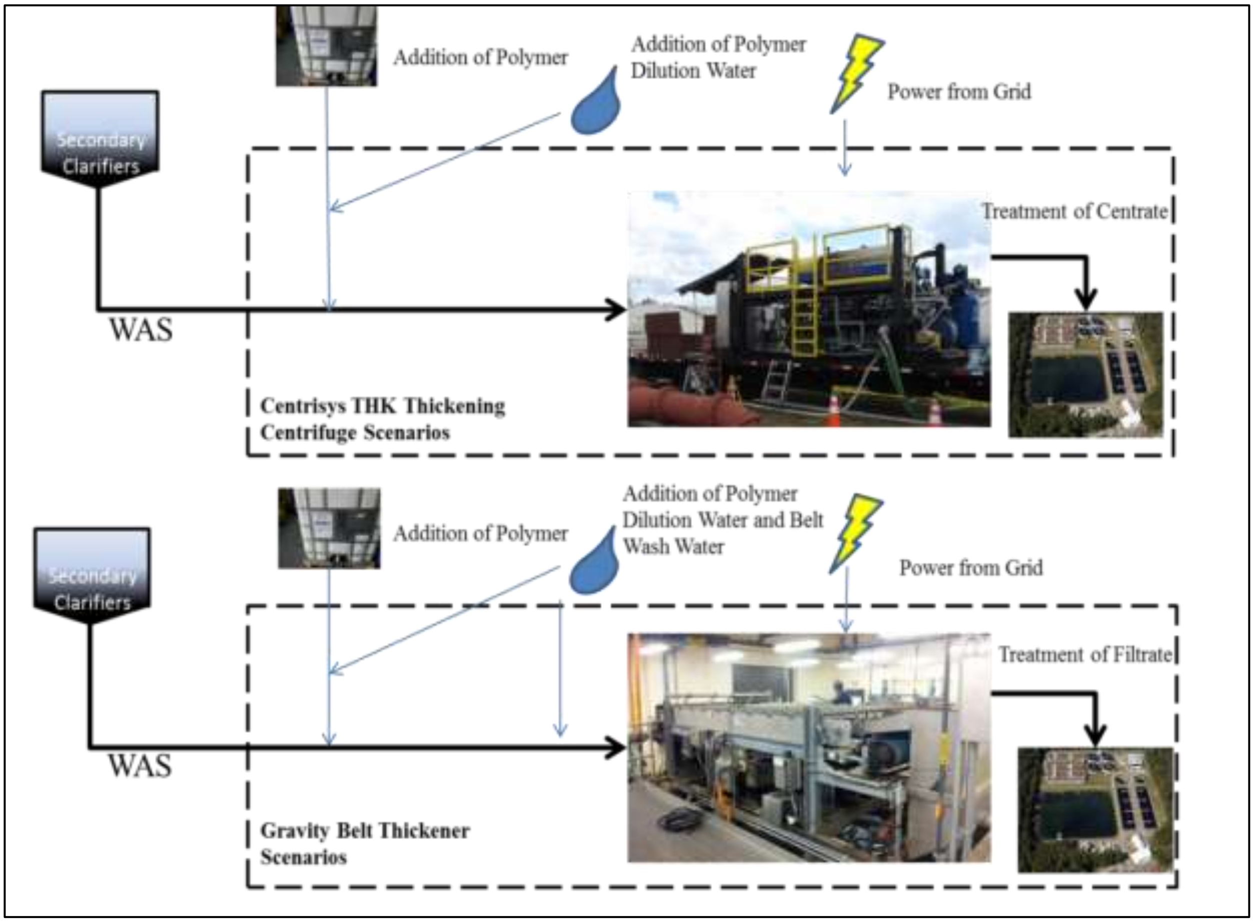

Figure 8. LCA system boundaries used for technology comparison

In constructing the LCI for the use of flocculent polymers, no emissions data was found present in the databases, NREL and others, specific to the production of the flocculent polymers. However, items were found in the NREL database for the major components present in flocculent polymers with the exception of polyacrylamide. Emission data for the production of a similar polymeric substance, polyacrylonitrile, was used. This data was substituted in and then adjusted based on the ratio of the atomic masses of the two substances. The assumed consistency of the polymer was based on the MSDS (Material Safety Data Sheet) for a very common wastewater flocculent, K275FLX manufactured by Ashland Water Technologies (Wilmington, Delaware, USA). From the MSDS, it was assumed for all plants that the polymer used had the following composition:

- Polyacrylamide (46%)
- Ethoxylated Alcohols (0.5%)
- Petroleum Distillates from Naphtha (30%)
- Remainder - water

The geographical boundary was set to be the USA which affects the assumption that needs to be made for energy production. The average energy mix for the USA in 2012 as seen in Figure 9 was used in accounting for the embedded emissions associated with electricity.

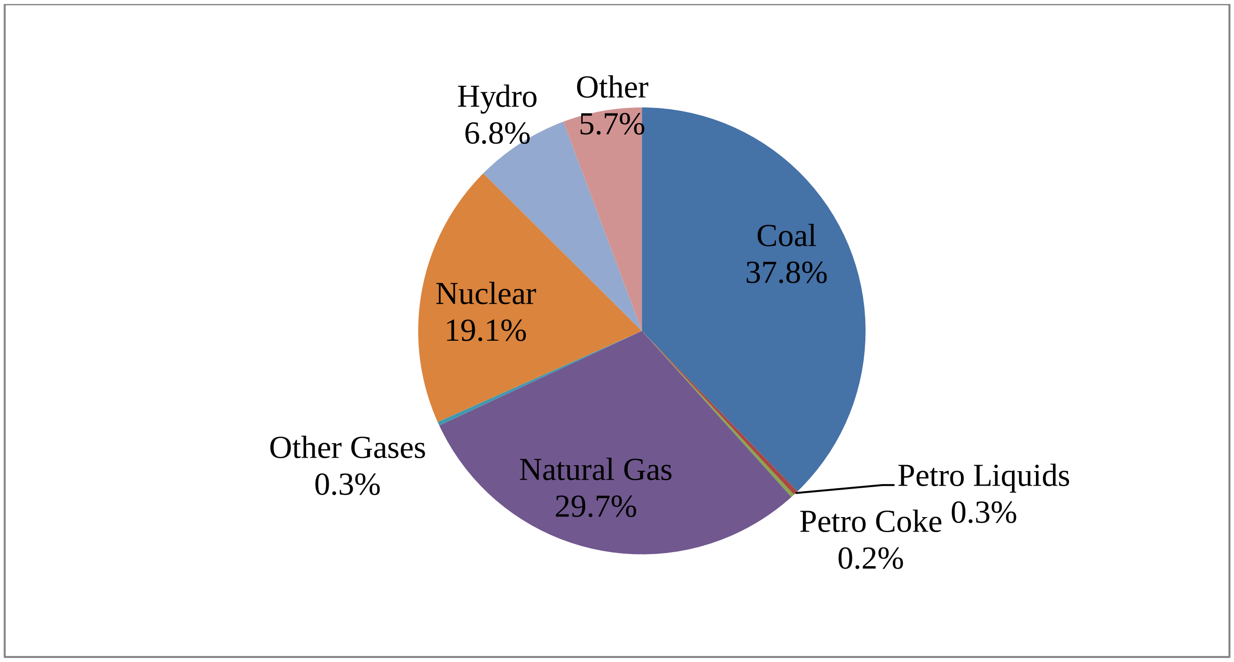

Figure 9. Average energy production for the USA as 2012 according to USA Energy Information Administration

When calculating the emissions associated with the treatment of the supernatant flow, 0.318 kWh of energy per m^3 of additional hydraulic loading to the wastewater treatment was assumed. This rate was based on the findings in the study *Electricity Requirements for Wastewater Treatment by POTWs and Private Facilities* by the

Electrical Power Research Institute (Goldstein, 2002). The value assumes a medium-sized treatment plant which was classified as approximately 10 MGD in the study.

3.2.3 ECONOMIC ASSESSMENT METHODS

The economic assessment was completed in two parts, first considering the operational cash flow, and second, considering the 20-year life-cycle costs. The prior consisted of taking the average operational data that was collected and using it to compare the costs of processing one ton of dry solids. The later likewise uses the average operational data from the centrifugal thickener pilot tests but then considers each GBT test site independently in order to complete a cost-benefit analysis for replacement of the installed GBT with the novel thickening centrifuge. The cost-benefit assessment was completed using five different techniques: Simple Payback, Net Present Value (NPV), Equivalent Uniform Annual Value (EUAV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). While simple payback is by far the easiest to calculate, it suffers from the limitation that its output does not definitively answer whether or not the project should proceed; it is for this reason that the other four analyses were also used. These analyses were carried out based on the guidelines set forth in the 2013WEF Residuals and Biosolids Workshop titled “Using Appropriate Economic Methodologies for Evaluation of Cost-Saving Projects” (Willis, 2013). Following this analysis the process was repeated again for each plant, except for this second round it was assumed that each plant was required to purchase equipment as the existing GBT was at the end of its useable life. In this scenario the cost of a new GBT was subtracted from the capital cost and the economic evaluation was completed only for the marginal cost of the novel thickening centrifuge.

A number of assumptions were required in order to complete a thorough economic assessment including the cost of polymer, the purchasing price of electricity, and so on. The cost of polymer varies year to year and often municipalities negotiate 1~3 year contracts locking in the price of polymer. Because polymer is derived of petroleum based hydrocarbons, the price of polymer is said to be related to the price of oil. In the last two years municipalities negotiating polymer contracts have actually seen the cost of polymer decrease. Additionally, the cost of polymer varies based on the quantity and packaging of the shipped product. The following price information is based on an informal discussion with a representative from the polymer manufacturer, BASF: Average pricing as of April 2013 for bulk shipments, liquid delivered in tanker truck, ranged from $0.90 to $1.00 per lb while polymer shipped by tote (250 gallons each) ranged from $1.10 to $1.20 per lb. For this study, it was assumed that polymer was purchased by the tote and the cost of that polymer was $1.15 per lb delivered in 2013, however an annual escalation factor was also assumed. This factor, 1.19%, was based on the inflation adjusted increase in the cost of crude oil from 1946 to 2012 (Historical Oil Prices, 2013).

The cost of electricity nationwide varies dramatically from $0.045 per kWh in Washington State to $0.299 per kWh in Hawaii as of February 2013. However, the national average industrial rate for electricity is $0.066 per kWh (US Energy Information Administration, 2013). This national average is also representative of the Midwest where the GBT sample sites were located and thus, the rate of $0.066 per kWh was adopted for the baseline scenario in year 2013. Again a cost escalation factor was assumed for the cost of electricity, a rate of 2.22% was used (US Energy Information Administration, 2013).

The discount rate assumed in the analysis was 0.8%. While the discount rate used for such analyses is something that will vary from municipality to municipality, 0.8% was chosen because it is the recommended rate given by the US Office of Management and Budget (US OMB, 2013) for 20-year projects based on the forecasted value of US treasury bonds and because it was necessary to compare all sites on an equal playing field.

The cost of maintenance for GBTs was assumed to be 2.0% annually of the capitol cost of the equipment. This was based on the reported capital of the original GBT surveys and email communication with an operator at GBT Plant B, where details of annual maintenance schedule were detailed. This included 30 minutes daily of cleaning and 1 hour per month for standard maintenance at rate of $21/hr plus $600 every two years for replacement of the belt itself. The reported maintenance schedule can be seen in Table 2 below.

Table 1. GBT maintenance schedule as reported for GBT Plant B

Year	Belt Replacement	Daily Cleaning	Monthly Maintenance	Annual Total
1	$ -	$ 3,833	$ 252	$ 4,085
2	$ 600	$ 3,833	$ 252	$ 4,685
3	$ -	$ 3,833	$ 252	$ 4,085
4	$ 600	$ 3,833	$ 252	$ 4,685
5	$ -	$ 3,833	$ 252	$ 4,085
6	$ 600	$ 3,833	$ 252	$ 4,685
7	$ -	$ 3,833	$ 252	$ 4,085
8	$ 600	$ 3,833	$ 252	$ 4,685
9	$ -	$ 3,833	$ 252	$ 4,085
10	$ 600	$ 3,833	$ 252	$ 4,685
11	$ -	$ 3,833	$ 252	$ 4,085
12	$ 600	$ 3,833	$ 252	$ 4,685
13	$ -	$ 3,833	$ 252	$ 4,085
14	$ 600	$ 3,833	$ 252	$ 4,685
15	$ -	$ 3,833	$ 252	$ 4,085
16	$ 600	$ 3,833	$ 252	$ 4,685
17	$ -	$ 3,833	$ 252	$ 4,085
18	$ 600	$ 3,833	$ 252	$ 4,685
19	$ -	$ 3,833	$ 252	$ 4,085
20	$ 600	$ 3,833	$ 252	$ 4,685

Maintenance costs for the centrifugal thickening technology were similarly based on a maintenance schedule but in this case provided by Centrisys Corporation. This maintenance schedule can be seen in Table 2. $21/hr was again assumed for the cost of labor and here the major capital cost is the rebuilding of the centrifuge rotating assembly (Kopper, 2013). From this schedule and the quoted capital cost of equipment for a THK200 from Centrisys Corporation the annual maintenance was calculated to be 3.2% of the initial capital cost annually.

Table 2. Centrifugal thickener maintenance schedule as reported by Centrisys Corporation

Year	Rebuild of RA	Regular Cleaning	Regular Maintenance	Annual Total
1	$ -	$ 546	$ 549	$ 1,095
2	$ -	$ 546	$ 549	$ 1,095
3	$ -	$ 546	$ 549	$ 1,095
4	$ -	$ 546	$ 549	$ 1,095
5	$ 35,000	$ 546	$ 549	$ 36,095
6	$ -	$ 546	$ 549	$ 1,095
7	$ -	$ 546	$ 549	$ 1,095
8	$ -	$ 546	$ 549	$ 1,095
9	$ -	$ 546	$ 549	$ 1,095
10	$ 35,000	$ 546	$ 549	$ 36,095
11	$ -	$ 546	$ 549	$ 1,095
12	$ -	$ 546	$ 549	$ 1,095
13	$ -	$ 546	$ 549	$ 1,095
14	$ -	$ 546	$ 549	$ 1,095
15	$ 35,000	$ 546	$ 549	$ 36,095
16	$ -	$ 546	$ 549	$ 1,095
17	$ -	$ 546	$ 549	$ 1,095
18	$ -	$ 546	$ 549	$ 1,095
19	$ -	$ 546	$ 549	$ 1,095
20	$ 35,000	$ 546	$ 549	$ 36,095

In calculating the 20 year life-cycle cost of replacing a GBT with the centrifugal thickening equipment, a residual value for the centrifuge was assumed. Because the centrifugal device is constructed of 100% duplex stainless steel, the bowl and scrolls are centrifugally cast, and the headwalls are forged, the equipment is expected to be structurally sound and operable for much longer than 20 years. Currently contractor fire sale prices go for 8% of original capital cost for centrifuges of stainless steel design, while for quality stainless designs that are selectively marketed, 28% of the original sale price can be obtained. Finally, refurbished stainless steel designs can bring as much as 59% of original sale price (Havrin, 2013). Though the re-sale value of the equipment currently varies depending on condition, 10% of the equipment capital cost was conservatively assumed.

4.0 RESULTS

4.1 EQUIPMENT PERFORMANCE RESULTS

Table 3 gives an overview of the data that was collected for the two technologies at their respective sample sites. Considering the first category, increase in TS content, limited meaning can be drawn because wastewater treatment plants generally have a target TWAS output solids content set for optimal anaerobic digester operation. Nonetheless, for the testing completed with the GBT, the average increase in %TS of WAS was 4.3% whereas for the thickening centrifuge, the average was 4.0%.

Considering the solids recovery for the two technologies, the GBT sites had a more consistent and higher capture rate than the thickening centrifuge, 99.0% vs. 94.8% on average. Despite this difference, the novel thickening equipment offered improved recovery rates over traditional thickening centrifuges, where centrifugal thickening specifications in the past have often been written at 85~90% minimum solids recovery without polymer and 95% minimum recovery for use with polymer (Havrin, 2013). This can be seen looking at centrifuge Test Sites 2 and 5 where polymer was not used at all and yet solids recovery averaged 97.2% and 98.5%, respectively. Additionally, when considering the solids capture rate, one must also take into account the flocculent polymer consumed to achieve that level of recovery.

Table 3. Technical data summary

	Sample Site	Increase in %TS	Insoluble Solids Recovery	Polymer Use (lb per ton - neat)	Power Use (kW/GPM)
Gravity Belt Thickeners	Site A	5.8%	99.7%	10.0	0.03
	Site B	2.9%	98.0%	41.5*	0.09
	Site C	3.1%	99.0%	7.6	0.18
	Site D	4.3%	99.1%	13.5	0.03
	Site E	5.5%	99.0%	11.5	0.04
	Average	4.3%	99.0%	10.6	0.07
	Std. Dev.	1.3%	0.6%	2.5	0.06
Novel Thickening Centrifuge (THK)	Site 1	5.8%	92.2%	1.0	0.10
	Site 2	3.0%	97.2%	not used	0.11
	Site 3	3.1%	96.0%	1.2	0.14
	Site 4	4.9%	89.9%	2.8	0.18
	Site 5	3.3%	98.5%	not used	0.12
	Average	4.0%	94.8%	1.0	0.13
	Std. Dev.	1.3%	3.6%	1.2	0.03

*****41.5 lb. per ton – neat, this field verified value was deemed an outlier and was omitted from further calculations pertaining to average values for GBTs.

On that point, the GBTs used more flocculent polymer than the thickening centrifuge in all cases for this study. One GBT plant in particular, Site B, was found to have an unusually high polymer dose, at 41.5 lb per ton neat.

The reason for this high dose is unknown but could possibly be attributed to higher quantities of industrial wastewater being treated and possibly to aged equipment. Regardless, this data point was deemed an outlier and excluded from the average as well as from any further calculations. On average, the GBTs used 10.6 lb per ton neat of polymer whereas the thickening centrifuge on average used 1.0 lb per ton neat and of the five test sites for thickening centrifuge, two were run completely without polymer. This, it seems, is the new thickening centrifuge's largest advantage.

Finally, considering the electrical consumption of the two technologies, power was measured only for system components that were not common to both the GBT and the thickening centrifuge. For example, a sludge pump for the WAS would be required for both a GBT and the centrifugal thickening technology, and was thus omitted from the study. On average, the GBTs consumed about half as much power as the centrifugal thickening technology per gpm of WAS flow, 0.07 kW per gpm vs. 0.13 kW per gpm. Table 4 shows each of equipment components considered and the average power consumption for each. Note that for the air system component for the centrifugal thickener, the value given as mentioned previously was based on a power study completed for the air system at the Kenosha Wastewater Treatment Plant in 2012.

Table 4. Power consumption by system component

	Component	Associated Power Use (kW)	% of Total Power
GBT - Average	Wash water Pump	5.5	41%
	Ventilation System	3.9	30%
	Hydraulic Steering Unit	2.1	16%
	Belt Drive	1.8	13%
THK - Average	Main Drive	16.1	92%
	Scroll Drive	1.2	7%
	Air Injection System	0.3	2%

4.2 ENVIRONMENTAL ASSESSMENT RESULTS

Figure 10 shows the overall results of the LCA. Plants utilizing GBTs had much higher estimated emissions than the centrifugal thickening sites. In particular, GBT - Site B, had much higher estimated emissions than all other plants for either technology at 68.6 kg of CO_2 eq. per tonne of WAS processed. As with the case earlier (regarding the high use of polymer at this site) the plant was deemed an outlier and omitted from the technology average. Omitting Site B, the average estimated emissions for the GBT sites was 14.1 kg of CO_2 per tonne of WAS processed while the average for the centrifugal thickening sites was found to be 1.72 kg of CO_2 per tonne of WAS processed.

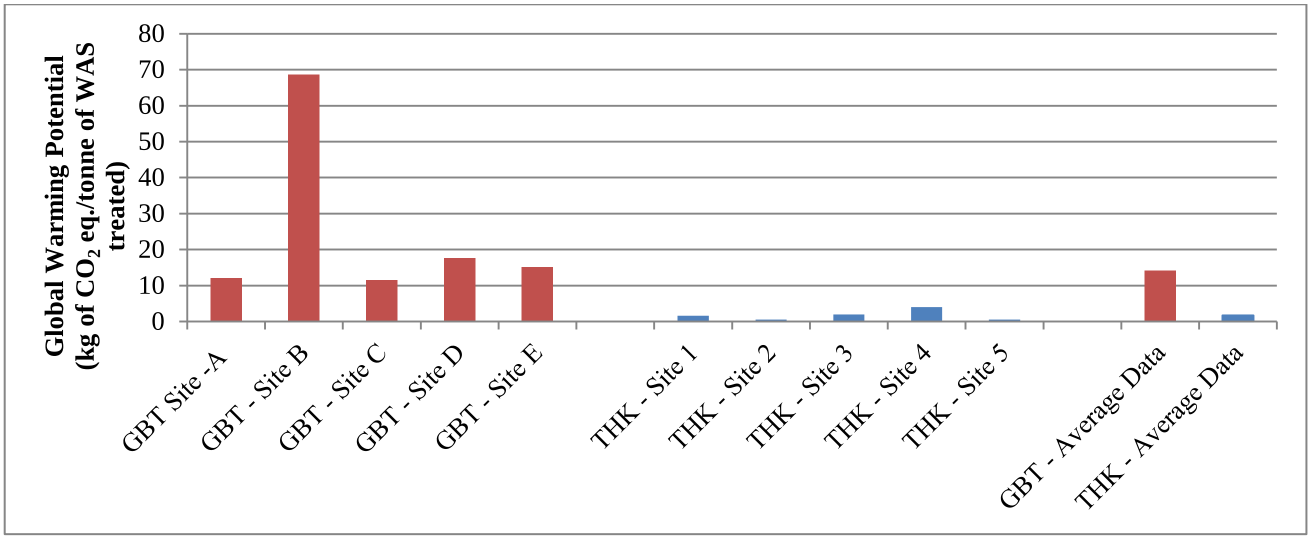

Figure 10. Results of LCA comparing GBTs and the novel centrifugal thickener

Using the process view in EASETECH, emissions were broken out by module allowing for better determination of where the most significant emissions were generated. The emissions associated with the addition of process water and treatment of supernatant were then found to be an order of magnitude smaller than the combined emissions for use of flocculent polymer and electricity. This was found to be the case for both the GBT and the thickening centrifuge. Because of the way the LCA was constructed, testing out which of these two was having the largest impact was slightly more difficult. Thus, a sensitivity analysis to determine which had the most significant influence on overall process emissions was necessary.

To do so, two separate sensitivity analyses were completed for the average scenario for each technology. The first considered the effect on overall emissions by changing polymer usage in increments of 10% and the second was to do likewise by changing energy consumption. This can be seen in Figure 11.

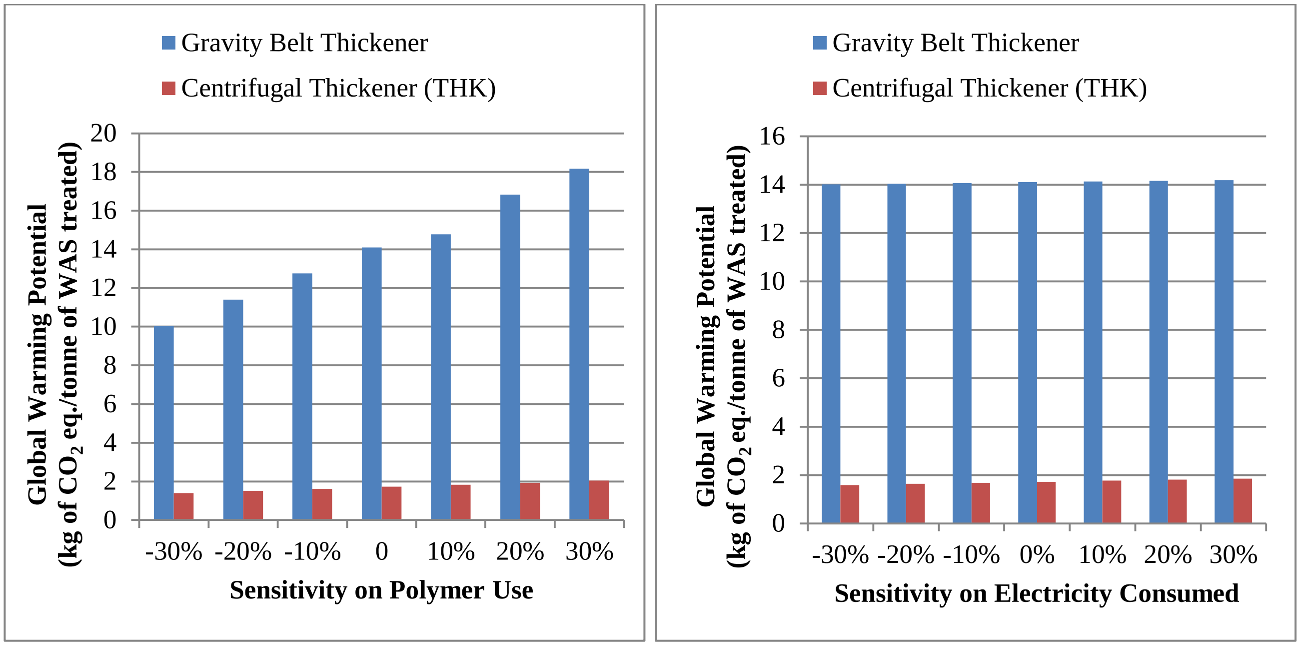

Figure 11. Sensitivity analyses on polymer and electricity consumption

From Figure 11, it can be seen definitively that the parameter having the largest effect on the GWP for the thickening process for both technologies is the polymer use. It also seems that the relationship between polymer use and GWP is relatively linear, where the difference in GWP for a given % increase in usage is much larger for the GBT sites simply because the quantity of polymer used is an order of magnitude larger.

4.3 ECONOMIC ASSESSMENT RESULTS

4.3.1 ANNUAL O&M COST-SAVINGS ANALYSIS RESULTS

Using the average values for the five GBT test sites and the five THK test sites, the average operational costs were calculated on a per dry ton of WAS processed basis. These operational costs were then compared in such a way that the net difference in operational costs per dry ton of solids processed was calculated (operational cost of GBT - operational cost of THK = annual operational savings for GBT replaced by THK). Figure 12 is given to show the effect that changes in the price of polymer and in the price of electricity have on the potential net savings to be had for the average plant sampled at.

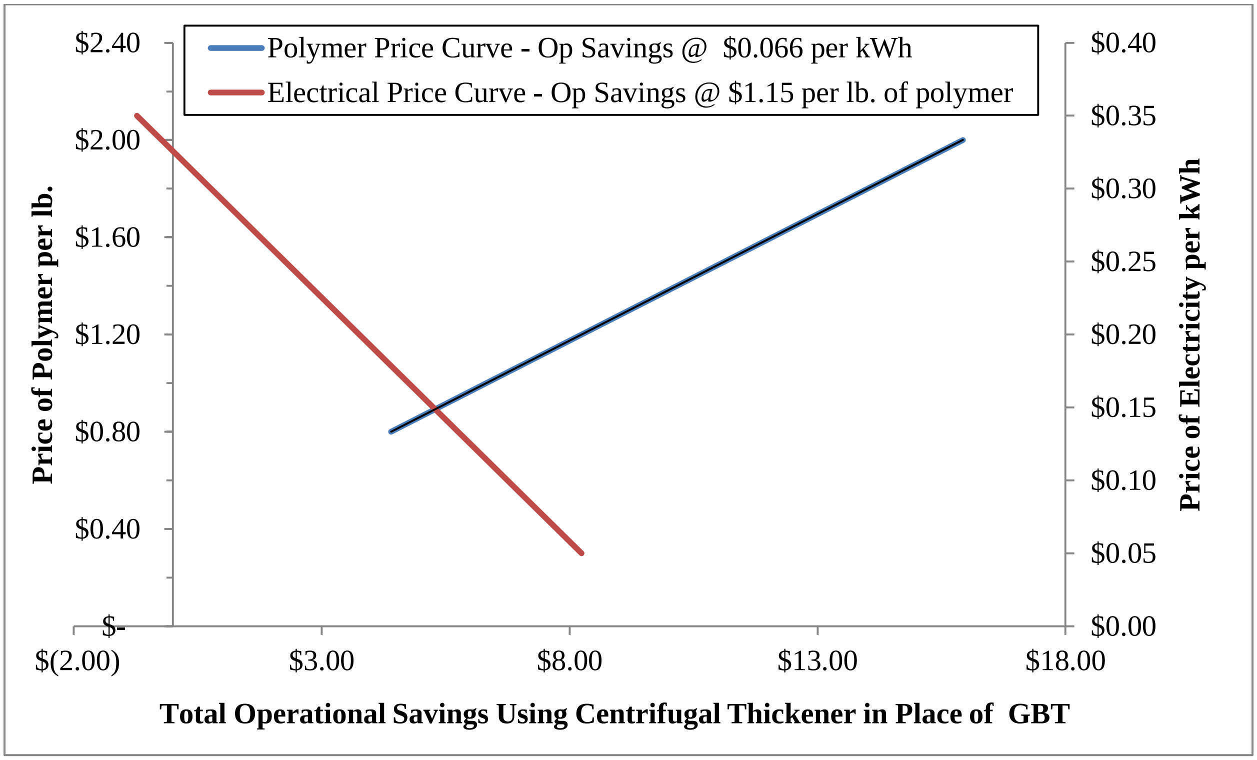

Figure 12. Effect of Polymer and Electric Prices on Total Operational Savings where a GBT is replace with the thickening centrifuge.

Within Figure 12 the blue line shows the effect of the price of polymer on the potential savings when the price of electricity is fixed at $0.066 per kWh and the red line indicates the effect of varying the price of electricity while the polymer cost is fixed at $1.15 per lb. Most important to note here is that increases in the cost of polymer make the replacement of a GBT with the thickening centrifuge more appealing economically because the centrifuge used less polymer than the GBTs for the sampled test sites. Conversely, as the price of electricity is increased, the operational savings to be had when the average GBT is replaced with the average THK, is decreased. This is because on average the centrifugal thickener used more power than the GBTs for the sites where data was collected.

To better convey the impact of changes in the price of these two commodities on the net operational benefit of replacing a GBT with the thickening centrifuge, Figure 13 is given.

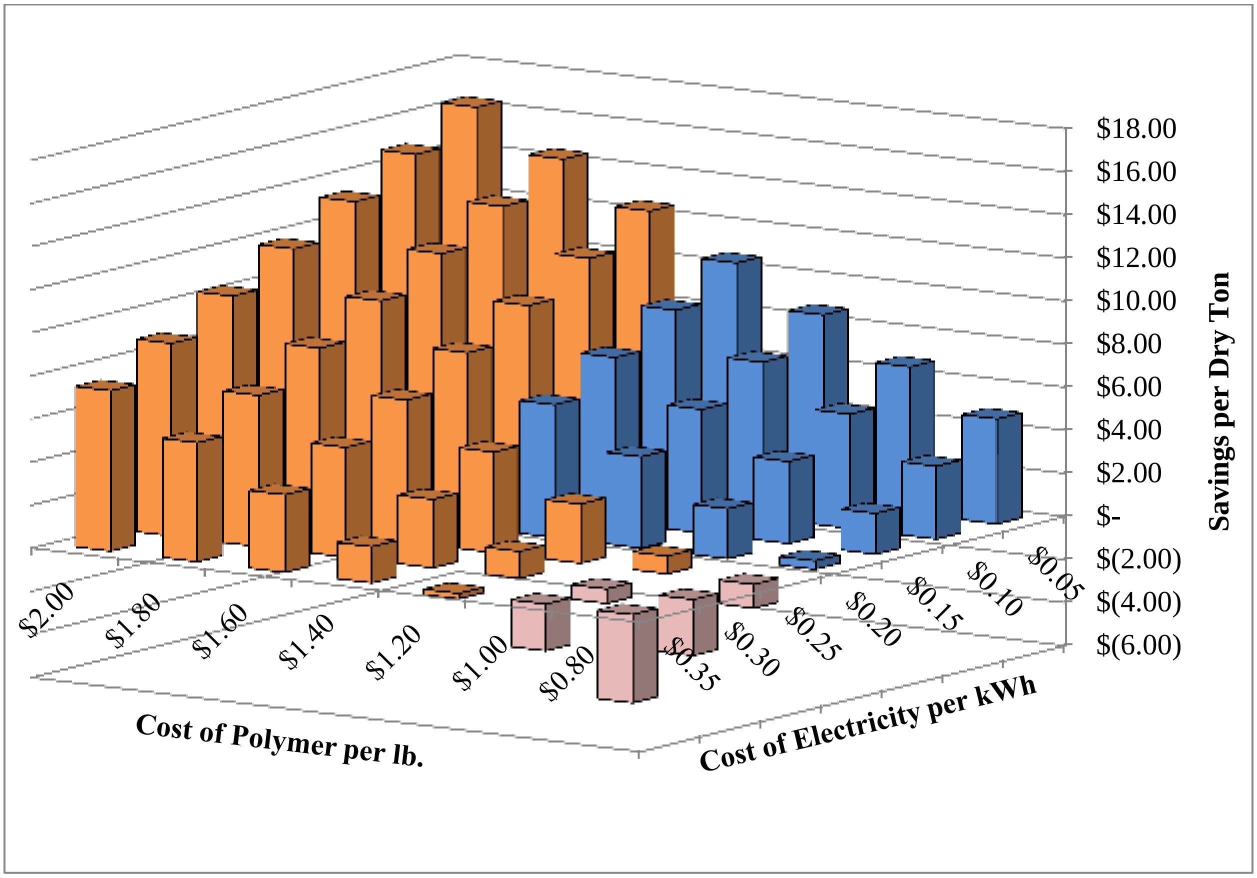

Figure 13. Difference in operational cost of thickening equipment (Savings = GBT costs – THK costs) to thicken one dry ton of WAS for varied costs of polymer and electricity – Blue = current market conditions, Pink = GBT favored scenarios, Orange = potential future market conditions

Each bar in Figure 13 represents the difference in operational costs between the average scenario for the GBT and the average scenario for the centrifugal thickener. Thought of another way, this difference is equal to potential operational savings that would be had in replacing the GBT with a centrifugal thickener for the average scenario. From this graph, it can be seen that for current market conditions (in blue) the potential savings range from $0.40 to $10.60 per dry ton of solids processed.

4.3.2 COST-BENEFIT ANALYSIS RESULTS

In order to evaluate the feasibility of replacing the existing GBTs with the centrifugal thickening machine now at the five plants where GBT data was collected, a 20-year project life was used and the five different cost-benefit analysis methods, simple payback, net present value (NPV), equivalent uniform annual value (EUAV), benefit cost ratio (BCR), and internal rate of return (IRR) were applied. The following criteria needed to be met to make the replacement economically feasible:

- NPV > 0
- EUAV > 0
- BCR > 1
- IRR > discount rate (where discount rate = 0.8%)
- Simple payback-? (depends on buyer's preference)

Based on those criteria, the overall results of these analyses are summarized in Table 5.

Table 5. Results of Cost Benefit Analyses

Method	GBT Site - A	GBT - Site B	GBT - Site C	GBT - Site D	GBT - Site E
Simple Payback (Years)	9.2	4.9	-1,518	(180.3)	18.4
NPV	$463,165	$917,830	($253,295)	($277,726)	$42,372
EUAV	$25,153	$49,844	($13,755)	($15,082)	$2,301
BCR	1.48	3.40	0.31	NA	1.13
IRR	9.8%	21.0%	-12.8%	-15.2%	1.4%

As seen above, three sites, sites A, B, and E, clearly meet the criteria for project implementation, while sites C and D fell short of paying for themselves within the 20 year project life considered. Knowing that cost of polymer had the highest influence on possible savings by replacement with the energy-efficient thickening centrifuge as seen in Figure 13, there must exist a threshold quantity of polymer consumed annually at a plant utilizing a GBT for which a project would break even at 20 years. To determine this quantity the "Solver" data analysis tool in Microsoft Excel was used by solving for the amount of annual polymer use needed to set the NPV to zero for the average scenario. This value was found to be 23,400 lb of polymer per year per GBT. Considering the average amount of solids processed for the three feasible sites, this would equate to 7.6 lb per ton neat as a minimum dose for a GBT plant. Following this exercise, a similar analysis was completed to determine the minimum amount of solids processed annually per GBT to merit replacement with the centrifugal thickening device. Again using "Solver" and assuming the average polymer dose found for the GBT sites (excluding Site B) of 10.6 lb per ton neat, the minimum quantity of solids processed annually to merit replacement was found to be 2,230 dry tons per year per GBT.

Following this assessment, the same procedure was carried out for each site again, however this time the analysis considered that the GBT equipment at each site was at the end of its useable life and the owner was faced with the need to purchase either a new GBT or an alternative technology. Moving forward this will be referred to as the 'buying new scenario'. In this case, the capital to be considered required to be paid back is only the marginal difference between the capital cost of GBT and that of the novel thickening centrifuge. The results of the cost benefit analysis in this case can be seen in Table 6.

Table 6. Results of Cost Benefit Analyses for Buy New Scenario

Method	GBT Site - A	GBT - Site B	GBT - Site C	GBT - Site D	GBT - Site E
Simple Payback (Years)	3.1	0.7	NA	NA	2.3
NPV	$690,350	$1,148,165	($153,295)	($177,726)	$293,370
EUAV	$37,490	$62,352	($8,325)	($9,652)	$15,932
BCR	1.94	8.56	NA	NA	2.21
IRR	33.0%	144.6%	-10.9%	-13.7%	43.0%

As seen in Table 6, results in terms of which sites where the novel thickening centrifuge was found to be economically viable, versus those where it was not, were identical to the results from the prior analysis as seen in Table 5, i.e., for GBT sites A, B, and E, replacement of existing equipment does make economic sense. The primary difference between the two analyses however, is the relative magnitude between the results for our economic indicators, for example the simple payback for GBT Plant A was reduced from 9.2 years to 3.1 years when considering only the marginal difference in capital costs between the two technologies.

Completing the same break even analysis for the buying new scenario, the resultant breakeven point in terms of annual polymer use was found to be 18,600 lb. per year, the equivalent of 6.0 lb per ton, neat. Looking at it from an annual solids processed perspective, the breaking point was found to be 1,710 tons per year.

5.0 STUDY LIMITATIONS

While completing this study, a number of limitations were encountered, and thus, there exist areas where further work could improve upon this study. First, the number of sites referenced is small, only five for each technology. A sample size of 20 to 30 plants would be far more desirable; however, such work will take considerable time.

When considering the data collected, a mass balance was taken across the process for each plant. Of the data presented in this paper, increases in %TS were given; however a more valuable metric would be percentage of time that discharge TWAS was maintained within the desirable range, though recording such data would have been substantially more difficult. The reason for completing such an analysis would be because many plants have a target %TS of TWAS and maintaining consistent operation near that target is considered very important for thickening equipment as devices are frequently operated 24 hours a day and slight fluctuations can have major impacts downstream such as for digester heating requirements.

For the environmental assessment, the biggest limitation was the LCI data available currently for flocculent polymers. While it is unlikely that embedded emissions associated with electricity consumption would outweigh the impacts associated with the production of polymer, the uncertainty for the magnitude of embedded emissions for polymer production is quite high given the assumptions that had to be made for this study. Thus, future research should work to better account for the production of the flocculent polymers.

Finally, considering the economic assessment, the primary limitation was the assumptions used for maintenance costs of equipment. Maintenance costs for the GBT operations was only made available for one of the five plants tested at and thus had to be extrapolated out for the other four GBT plants. Additionally, because the new centrifuge has only been in the market for a short time, long term maintenance of this device can only be estimated based on traditional centrifuge designs. However, this machine, in theory, should require lower maintenance over its life because for typical operation, the equipment runs at 50 ~70% of the speed of conventional centrifuge designs.

6.0 CONCLUSIONS

The purpose of this study was to compare the most prominent thickening technology in the industry for WAS thickening, GBTs, with the novel centrifugal thickening technology manufactured by Centrisys Corporation of Kenosha, Wisconsin, USA in terms of performance as well on an environmental and economic basis.

In terms of performance, the new energy-efficient centrifuge design reduces power consumption and improves solids recovery rates over pre-existing centrifugal thickening technologies. However, the GBT data gathered indicated that on average, the new centrifuge design does still consume more power than GBT installations, 0.13 kW per GPM vs. 0.07 kW per GPM for this study.

The new centrifugal thickening device was found to significantly reduce the amount of polymer required for the thickening process, from 10.6 lb per ton neat for the average GBT site to 1.0 lb per ton neat for the average centrifugal thickener test site. The reduction of polymer required for thickening was found to be the biggest advantage for the new thickening centrifuge. This difference in polymer consumption was also found to have large impacts on both the environmental and economic assessment.

The environmental assessment was completed using an LCA framework and the software tool EASETECH. Results of the comparative LCA indicate that use of the centrifugal thickening technology would result in a significantly lower global warming potential (GWP). The GWP for the average GBT site was found to be 14.1 kg CO_2 eq. per tonne of WAS processed where the GWP for the average thickening centrifuge test site was found to be 1.76 kg per tonne of WAS.

The economic assessment was completed in two parts, first considering the difference in operational costs for the two technologies and then further considered how the cost of polymer and electricity affect this difference. Second, each of the GBT test sites was considered as a potential site for replacement of the existing equipment with the new centrifugal thickening technology. For this evaluation, five different metrics were used. For GBT sites A, B, and E, replacement of the GBT with the thickening centrifuge was found to be feasible while for GBT sites C and D the ‘do nothing’ option was found to be more beneficial. The cause for the discrepancy between the ‘proceed’ sites and ‘do nothing’ sites was found to be most related to the amount of polymer used at those sites and the amount of solids processed per machine indicating an economies of scale scenario for the new thickening centrifuge. Based on the average scenarios for the data collected, it was found that the breakeven point, when considering a 20 year life-cycle, for the average plant is 23,400 lb of emulsion polymer at the unit price of $1.15 per pound for a GBT used annually prior to installation of the centrifuge for the investment to make sense. Likewise, if a plant used the average GBT polymer dose found in this study, 10.6 lb per ton neat, prior to installation of the new centrifugal equipment, the equipment would need to process a minimum of 2,230 dry tons of solids annually. It was further found that when considering the situation where each of the GBT plants is faced with end-of-life replacement of the existing GBT equipment and where thus only the marginal difference in capital cost between a GBT and the new thickening centrifuge was considered, the breakeven points were lowered for GBT plants A, B, and E; however it was not reduced enough to make projects at GBT plants C and D economically viable.

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