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Cleanout of a Plug-Flow Anaerobic Digester after Five Years of Continuous Operation

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Several plug-flow anaerobic digesters have been constructed on dairy farms in New York State in recent years primarily for odor control and secondarily for combined heat and power generation. One long-term concern with these systems is the accumulation of non-digestible solids within the digestion cell. A mesophilic plug-flow anaerobic digester in New York State was temporarily decommissioned in March of 2006 to perform emergency repairs to the internal heating system. This untimely need for repair provided an opportunity to extensively analyze the digester contents, both immediately after removing the flexible membrane cover in an undisturbed state and also during the cleanout process. Samples were taken from the crust, supernatant, and bottom and analyzed in a commercial laboratory to determine nitrogen, phosphorus, potassium, total solids, fixed solids, acetic acid, sulfate, and copper concentrations. The thickness of the floating crust and the depth of settled solids were also measured. This paper describes the manure treatment system, an analysis of associated data, resulting conclusions, and provides information regarding the heating system failure, how the repairs were made, and associated costs resulting from the event.

Keywords. *Anaerobic digestion, Economics, Operational costs, Plug-flow digesters*

Introduction

Several plug-flow anaerobic digesters have been constructed on dairy farms in New York State in recent years primarily for odor control and also for combined heat and power generation. One long-term concern with these systems is the accumulation of non-digestible solids in the digestion cell. Non-digestible solids, made up of fixed solids and/or non-biologically degradable volatile solids can enter a manure treatment system; typical sources include manure, animal feed, bedding, and stones and sand tracked in by equipment tires. Typically an anaerobic digester (AD) is designed for a target daily loading rate and hydraulic retention time (HRT). If a significant portion fills with non-digestible materials over time and lowers the HRT, biogas production may be reduced and the digester may not perform as desired.

A mesophilic plug-flow anaerobic digester in New York State was temporarily decommissioned in March of 2006 to perform emergency repairs to the internal heating system. This untimely need for repair provided an opportunity to extensively analyze the digester contents, both immediately after removing the flexible membrane cover in an undisturbed state and also during the cleanout process.

Farm description

Dairy Development International (DDI) was an 850-cow dairy farm and research facility located in central New York State; the farm has recently transferred ownership. DDI was newly constructed on a virgin site in 2000 and an AD designed by RCM was part of the original construction project. An AD was required as part of the site permitting process to reduce anticipated odor emissions from the 10.9 M liter (2.9 M gallon) above-ground storage.

Manure was conveyed to the center of each 4-row freestall barn by automatic alley scrapers. Conveyed manure dropped through a continuous 20 cm (8 in) wide transversely-oriented slot into a below-grade gravity flow channel that services all three barns. Manure flowed to one end of the channel and was temporarily stored prior to being conveyed with a piston pump to the AD. Approximately 88,196 L (23,300 gallons) of manure was pumped once daily for 3.5 hours to the AD for a calculated HRT, without any reduction in volume due to accumulation of settled solids, of 16 days. The pump inlet pipe was 20 cm (8 in) and the discharge pipe was 15 cm (6 in); therefore, any material 15 cm (6 in) and smaller could have been conveyed into the AD. Digester influent displaces some in-vessel manure resulting in a comparable portion to exit under a 0.30 m (1 ft) end wall (to maintain anaerobic conditions) then over the AD effluent weir. Biogas produced by the AD was contained under a flexible membrane cover prior to utilization by a 1.58 million kJ (1.5 million Btu) biogas-fired boiler. Hot water heat produced by the boiler was circulated within the AD to raise influent temperature to about 38°C (100°F) and to provide maintenance heat. A leak was suspected in the AD heating system following observation of a significant loss in heating water stored in a tank over the course of a few hours. Isolating each component of the overall AD heating system revealed the leak occurred in vessel. A more complete description of the AD can be found in Wright and Graf (2003).

Objectives

The objectives of this paper are to describe the manure treatment system, present and discuss constituent concentrations and the amount of fixed material in the AD, explain the repair procedure, a potential cause for the failure, and the cost of the failure to the farm.

Materials and Methods

Thickness measurements of crust and settled material

Thickness of the crust and settled solids in the AD were obtained after removal of the flexible membrane top cover prior to emptying. Crust thickness was determined by shoveling out an area of the crust until the manure supernatant/crust interface was reached. A tape measure was used to measure crust thickness.

Thickness of settled solids was measured prior to AD dewatering by attaching a 40.3 cm (15.8 in) diameter tin plate to a 5.4 m (18 ft) pole and lowering the assembly to the bottom of the AD under its own mass. When the assembly stopped lowering it was assumed that the top layer of settled solids was reached. Thickness measurements of the crust and settled solids were made at 3 m (10 ft) intervals along the perimeter of the AD.

Sampling of digester crust, supernatant, and settled material

Samples were collected along both longitudinal sidewalls of the AD at distances of 6, 18, and 33 m (20, 60, and 110 ft) from the influent end wall as shown in Figure 1. All samples were immediately labeled, placed on ice, and delivered promptly to the laboratory for analysis.

At each location (1-6) shown in Figure 1, a sample was collected from the top (crust), supernatant, and bottom (settled material). Overall, 18 samples were collected from the AD.

Samples of the crust were obtained by shoveling out a section of crust until the supernatant/crust interface was reached. A 473 mL (16 oz) sample was obtained from the center of the excavated crust material.

Samples of the supernatant and settled material were obtained using a sub-surface sampler consisting of a cable, spring/lock system and custom sampling cup attachment. The sampler contained a spring loaded plunger that was remotely opened and closed from above the liquid level by the use of a cable. Wide mouth plastic jars (473 mL (16 oz)) screwed into the bottom of the sampler. When the plunger was opened material flowed into the sample container through three 7.0-cm (2.75-in) wide and 3.2-cm (1.25-in) tall slots. The plunger was allowed to close before the sub-surface sampler was withdrawn. Samples were collected from the supernatant of the digester at a depth of 2.1 m (7 ft) from the top of the tank. Samples at the bottom of the tank were collected by lowering the sampler to the bottom of the tank until resistance was felt. When resistance was felt the sampler was worked into the settled material until a measured depth of 4.2 m (14 ft) was reached for sample collection.

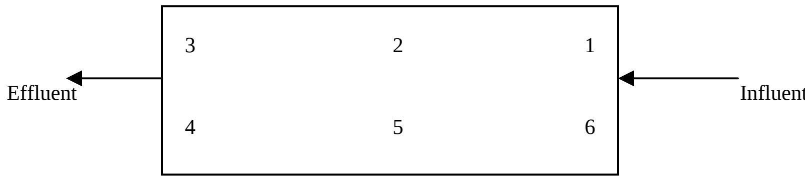

Figure 1. Top view of digester sampling locations.

Laboratory methods

Crust, supernatant and settled solids were submitted to a commercial laboratory for analysis of the following constituents: Acetic acid (Acetic A), total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), total phosphorus (TP), ortho phosphorus (OP), total solids (TS) and total volatile solids (TVS). Organic nitrogen (ON) was calculated by subtracting NH_3–N from TKN. In addition to the constituents previously listed, the settled solids were analyzed for copper (Cu) and sulfate (SO_4^{-2}); the copper analysis was performed at the commercial lab and sulfate tested was performed at the research laboratory in the Department of Biological and Environmental Engineering at Cornell University. Laboratory methods used are shown in Table 1.

Each sample was analyzed in triplicate for TKN, NH_3-N, TP, and OP. Supernatant samples were analyzed in triplicate for Acetic A in addition to nutrients. Bottom samples were analyzed in triplicate for copper.

Table 1. Laboratory methods used for analysis of samples.

Constituent	Analytical Method
Acetic acid (Acetic A)	Standard Methods – 5560 C
Total Kjeldahl nitrogen (TKN)	EPA 351.4
Ammonia (NH_3-N)	Standard Methods – 4500 F
Organic nitrogen (ON)	By subtraction
Total Phosphorus (TP)	EPA 365.3
Ortho Phosphorus (OP)	EPA 365.3
Total Solids (TS)	EPA 160.3
Total Volatile Solids (TVS)	EPA 160.4
Fixed Solids (FS)	By subtraction
Copper (Cu)	SW846 6010
Sulfate (SO_4^{-2})	EPA 375.4

Sample results were averaged horizontally along the crust, supernatant and bottom stratus to determine if the individual layers had higher concentrations of any particular constituent that would suggest settling. Samples were also averaged vertically at the influent, center and effluent ends to see if a difference in horizontal location along the length of the AD had an affect on constituent concentration.

Digester heating system damage and repair

Leak detection of the heat system required isolating and pressurizing individual heating loops on the farm until a single heating zone did not hold pressure. When it was discovered that the leak was within the AD system, fittings had to be attached to each AD heating loop to determine if the leak was in the piping system between the boiler and the AD or within the AD vessel. Ultimately, it was found that the leak was within the digester vessel heating loop.

Access to the vessel heating loop required removal of the flexible membrane biogas cover. When the cover was completely removed and initial sampling completed, manure removal commenced. Manure was removed by a pump truck outfitted with a hydraulic manure pump attached to a crane. The pump was lowered into the digester and manure was pumped to an adjacent above-ground long-term storage.

As manure was removed air was used to pressurize the heating loop that contained the leak. As the manure level was lowered the bubbles through the manure were observed to determine the exact location of the leak. Manure was almost completely removed from the vessel before the leak was no longer submerged and could be accessed for repair.

Voltage readings

An investigation of electrical currents was performed at the farm to determine if electrolysis could have caused the damage to the pipes. A remote ground was driven into the ground and all voltage readings were made relative to this reference ground. Voltage readings were made with a hand held digital multi-meter (Fluke 189) and with an oscilloscope (Tektronix THS720P). Measurements of resistance and current on wires connected to ground rods were made (AEMC 3700 Ground Rod Tester).

Results and Discussion

Crust and settled solids accumulation

Floating crust thickness increased between the influent and effluent end walls. At the digester influent end wall the crust was very thin with average measurements of 0 to 0.025 m (0.08 ft) thick. At a distance of 3.04 m (10 ft) the crust averaged 0.15 m (0.5 ft) thick and continued to increase in thickness to the digester effluent end averaging 0.61 m (2 ft).

Settled solids had a thickness of 0.61 m (2 ft) at the influent end wall. The thickness decreased to 0.45 m (1.5 ft) within the first 3.04 m (10 ft) of digester length. At a length of 18.2 m, from the influent end, settled thickness was 0.30 m (1 ft). The effluent end wall had a depth of settled solids of 0.15 m (0.5 ft). Directly under the influent pipe the largest depth of settled solids was measured. The influent pipe directed the flow to the bottom of the tank and is likely the reason there was a large amount of solids directly under the influent pipe.

Thickness of settled solids displayed the opposite behavior than that of the crust. This phenomenon resulted in a nearly constant working volume per unit length. As the thickness of the crust increased the thickness of the settled material decreased. When adding the entire measured volumes of the crust and settled solids accumulated over the five years of operation the digester lost approximately 226.5 m^3 (7,998 ft^3) of the 1,409.7 m^3 (49,784 ft^3) total volume, or 16 percent. The crust reduced the volume of the digester by approximately 7.1 percent while the settled solids reduced the volume by about 8.9 percent.

The average theoretical HRT for the digester at its loading rate was 16 days (Gooch et al., 2006). With the 16 percent reduction in volume the HRT was reduced to 13.4 days. Using a biogas model developed by Minott (2002), the reduction in HRT could theoretically decrease daily biogas production by 1.4 percent.

A system balance of fixed solids (FS) has been suggested as a means to assess the amount of settling in a digester over time (Martin, 2006). Gooch et al., (2006) reported average DDI AD influent TS content of 9.81 percent with TVS content of 8.21 percent and average effluent TS content of 7.25 percent and TVS content of 5.81 percent. Therefore, by subtraction, the concentration of FS in the AD influent was 1.6 percent and the concentration of FS in the AD effluent was 1.44 percent. Subtraction of effluent FS from influent FS results in 0.16 percent loss of FS to the AD. Daily loss of FS to the AD was calculated by multiplying the 0.16 percent loss of FS (assuming FS is the same density as manure) by the daily influent volume of 88.1 m^3 (3,114.7 ft^3). This calculation reveals a volume loss of 0.14 m^3/day (4.98 ft^3/day) as a result of FS accumulation.

Continuous operation of the digester lasted approximately 1,673 days (August 2001 – March 2006). Calculated accumulation of FS in the digester by multiplying FS daily loss and time of operation was 234.2 m^3 (8,331 ft^3). The calculated amount of accumulation compares reasonably well with the observed accumulation, overestimating by only 3.2 percent.

Constituent concentrations

The average concentration of the constituents in the crust, supernatant and bottom of the AD are shown in Table 2.

Table 2. Average concentration of constituents (vertical profile) in the crust, supernatant, and bottom of the AD.

	Acetic A	Cu	SO_4^{-2}	TKN	NH_3-N	ON	TP	OP	TS	TVS	FS
Units	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	%	%	%
Crust (n=6)	347	-	439	5,123	2,781	2,342	686	363	15.3	12.3	2.9
Supernatant (n=6)	793	-	548	4,474	2,709	1,765	465	237	7.5	6.0	1.5

Bottom (n=6)	193	24	343	2,298	1,717	581	874	507	58.3	5.3	53.0

Concentration of acetic acid was lower in the crust and settled material than in the supernatant. Methane producing bacteria utilize acetic acid to produce methane. Crust and settled solids would appear to have a longer retention time than that of the supernatant explaining the lower concentration of acetic acid. Sulfate concentration was slightly lower in the settled solids and was similar in the crust and supernatant. TKN had a decreasing concentration from the crust to the bottom sampling level. NH_3–N concentrations were very similar in the crust and middle layer and had the lowest concentration at the bottom. ON, like TKN, decreased from the crust to the bottom level. TP and OP concentrations were highest in the crust and bottom of the digester, with the highest concentration in the bottom of the digester. The settled solids were mostly fixed solids, while the middle and crust contained very few fixed solids. The average concentration of constituents for the influent, center, and effluent of the digester are shown in Table 3.

Table 3. Average concentration of constituents (horizontal lateral profile) at the influent end wall, center, and effluent end wall.

	Acetic A	Cu	SO_4^{-2}	TKN	NH_3-N	ON	TP	OP	TS	TVS	FS
Units	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	%	%	%
Influent (n=6)	509	18	490	3,737	2,395	1,342	627	301	30.1	7.5	22.5
Center (n=6)	425	28	491	4,110	2,419	1,691	725	403	26.9	7.9	18.9
Effluent (n=6)	399	28	372	4,048	2,392	1,655	672	404	24.1	8.2	15.9

The average concentration of constituents, when averaged at the influent end wall, center, and effluent end wall were consistent except for acetic A, total solids, and fixed solids. Acetic A, total solids, and fixed solids decreased from the influent to the effluent end of the digester.

The average biogas hydrogen sulfide concentration at the farm was measured to be 1,984 ppm with a standard deviation of ±570 ppm (Scott et al., 2006). There may be a correlation between the sulfate concentrations measured in the digester and biogas hydrogen sulfide concentration.

<u>Digester heating system damage and repair</u>

The AD was heated by a series of black iron steel pipes used to convey warm water heated by the biogas-fired boiler. The black iron pipes had an inside diameter of 6.35 cm (2.5 in). Pipes were attached by hangers on vertical supports located within the vessel. Damage to the pipe seems to have started on the outside of the pipe and continued through to the inner wall. Overall, corrosion of the pipes were isolated to one area, with corrosion noticed up and down stream of the leak on the same pipe and vertically up the pipe stand to one other pipe. A picture of the corroded pipe and resulting hole is shown in Figure 3. The hole in the pipe was measured to be 1.9 cm (0.75 in) long and 0.63 cm (1.5 in) wide and was located where the heating pipe contacted the pipe stand. Damaged sections of pipe were removed from the heating loop and new sections were welded in their place. After welding the heating system was pressure tested before re-filling the digester.

Figure 3. Corrosion of black iron heating pipe.

<u>Voltage readings</u>

Damage to the pipes was suspected to be caused by electrolytic corrosion. Voltage measurements were made from digester heating pipes and supports to a reference ground and are shown in Table 4.

Table 4. Voltage readings in reference to ground of digester heating grid.

Location	Vac rms	Vdc
Return line: source side of coupling	0.10	0.542
Return line: AD side of coupling	0.12 – 0.13	0.856
Heating system support	0.10	0.856
Pipe 1	0.084	0.85
Pipe 2	0.11	0.85

Results of the electrical measurements were inconclusive. However, several zinc bars were added to the digester as sacrificial anodes in an effort to preclude future damage to the pipes as the result of potential undetected electrical currents in the digester.

<u>Repair cost</u>

Total digester repair time was three weeks. Costs to repair the digester heating system were separated into six categories: management, digester design consultation, emptying, diagnosis, protection, and repairs, refilling and natural gas charges. The itemized categories and respective costs are shown in Table 5.

Table 5. Itemized costs to repair the heating system leak.

Item	**Cost ($)**
Management	2,500
Digester designer consultation	3,692
Emptying	5,575
Diagnosis, protection, and repairs	7,288
Refilling	500
Natural gas	4,182
Total	**23,737**

Total cost to diagnose, empty, repair, and refill the digester was $23,737. Diagnosis of the leak, repairing the broken pipe, and adding the zinc bars to the digester was the highest cost of the undertaking at 30% of the total cost. Pumping the digester out and removing both the crust and settled solids with an excavator was slightly less expensive requiring 23% of expenses. Natural gas was used while the system was down as well as to reheat and restart the digester and was significant to the total cost at 17%. The projected annual operation costs of the digester were $26,300 (Wright et al., 2004). Total cost for the repairs to the heating system almost doubled the projected annual operation cost for the year.

Conclusions

An AD was opened for heating system emergency repairs in March 2006 after nearly five years of continuous operation. Upon removal of the digester cover the thickness of the crust and settled solids were measured. Samples were collected from the crust, middle and bottom of the digester and analyzed for solids, nutrients, sulfate and copper.

The thickness of the crust increased in thickness from 0 – 0.61 m (0-2 ft) along the length of the digester from the influent to the effluent end. Settled solids decreased in thickness from 0.61 - 0.15 m (2 – 0.5 ft) along the length of the digester from the influent to effluent end. Crust and settled solids occupied approximately 16 percent of the total volume of the digestion tank. The reduction in HRT reduced theoretical biogas production by 1.4 percent according to a model developed by Minott (2002).

A system fixed solids balance resulted in 0.14 m^3/day (4.98 ft^3/day) for a total of 234.2 m^3 (8,331 ft^3) of accumulation over the period of operation gave a reasonable approximation of actual settling in the digestion vessel of 226.5 m^3 (7,998 ft^3).

Generally the lowest concentration of constituents was in the settled solids except for phosphorus and fixed solids. Phosphorus and fixed solids had the highest concentration in the settled solids of the digester.

Total cost to repair the heating system was $23,737 and almost doubled the projected annual operation cost of the digester for the year.

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