Business Case Analysis for Natural Gas Energy Savings
For the
Cullman Wastewater Treatment Plant
Anaerobic Digester Process Improvements

Introduction

The existing anaerobic digestion process utilizes 2-stage digestion process consisting of primary and secondary digester basins in series. The system includes one (1) natural gas-powered heat exchanger unit to maintain an optimal process temperature of 35º C (95º F) within the primary digester basin. The heat exchanger was installed in the mid-1990's during an upgrade to the digester facility, and replaced the operation of two (2) heat exchanger units installed during previous upgrades which occurred during the early 1980's. The facility has operated with only the one functional unit since it was put into service.

The proposed project will install a second heat exchanger unit to provide redundancy in case either heat exchanger must be temporarily removed from service for maintenance, inspection or repair. This arrangement shall offer uninterrupted performance of the digestion process and guarantee the optimal process temperature is sustained during normal operating conditions. Both units shall be capable of individually meeting the demand of the digestion process. Only one unit shall be activated at any time, and control parameters shall set so that units alternate service.

The methane biogas that is produced as a byproduct of the anaerobic digestion process is presently wasted through a burner unit which ignites to destroy the gas before dispersing into atmosphere. The existing and proposed heat exchangers exchanger unit is capable of utilizing the off-gassed methane as a fuel source for heating digester sludge. The project shall make use of an existing biogas supply network which has been inactive for many years now. It is likely some rehabilitation of this system will be necessary, however the extent of such cannot be known until the digester basins are emptied and their condition thoroughly ascertained. Utilization of the digester biogas a fuel source for the heat exchangers shall have the effect of significantly reducing the volume of natural gas required for operation. It is anticipated that an active natural gas service shall remain in place to supplement the methane gas energy source as necessary

To promote the digestion process and production of methane gas, the project shall also include the installation of a mixing system within the primary digester basin. The mixing system installation shall result in a completely mixed anaerobic reactor by utilizing an external pump and internal flow distribution manifold to agitate the substrate, thereby increasing the consistency of the matrix volume.

Existing Conditions

Existing Energy Requirements

A summary of the Cullman WWTP's natural gas consumption volume is provided below. The entirety of the volume was utilized by the single existing heat exchanger presently installed.

Month (2012)	Consumption (ft.^{3})
January	548,100
February	513,800
March	385,200
April	168,600
May	158,900
June	162,000
July	172,900
August	145,300
September	167,200
October	149,200
November	112,900
December	181,000
Total Consumption	2,865,100 ft^3
Average Daily Consumption	7,850 ft^3
Average Daily Consumption	222.3 m^3

As can be noted from the above monthly consumption volumes, natural gas demands are correlated to the ambient temperature, as more heating energy is required during periods of colder temperature. Generally speaking, the energy contained within the total volume of consumed natural gas shown above is equal to the amount of energy lost due to heat transfer through the digester basin structure to the surrounding soil matrix and atmosphere, plus the energy required to heat incoming sludge. To calculate the total energy requirement for the system, efficiency of the heat exchanger unit must also be considered. None of these factors shall be affected by the proposed project, and shall thus be held constant for the purpose of this analysis. Applicable constant values are shown below. The heating values for both natural gas and raw digester gas are accepted standards. The efficiency of the heat exchange unit has been supplied by the manufacturer.

Heating Value of Digester Gas = 0.224×10^8 J/m^3 (M&E, pg. 1525)
Heating Value of Natural Gas = 0.373×10^8 J/m^3 (M&E, pg. 1525
Heating Equipment Efficiency = 80%

The average daily amount of energy required for the entire system expressed in standard units can be calculated as follows:

Avg. Daily System Energy Requirement = (7,850 ft.^{3})(0.0283 m^3/ft^3)(0.373 x 10^8 J/m^3) = 82.9 x 10^8 J

To calculate the average daily amount of energy necessary to maintain only the 35°C temperature within the primary basin, the efficiency of the heat exchanger must be applied:

Avg. Daily Energy Requirement for Digester Basin = (82.9 x 10^8 J)(0.80) = 66.3 x 10^8 J

Next, the volume of digester gas required to operate the system can be calculated. It should be noted that raw digester gas is comprised of approximately 65% methane, which provides the source of energy.

$$\text{Avg. Daily Digester Gas Volume System Requirement} = \frac{82.9 \times 10^8 \text{ J}}{0.224 \times 10^8 \text{ J/m}^3} = 370.1 \text{ m}^3$$

Calculation of Digester Gas Volume Production

In order to determine the offset in natural gas, the expected volume of methane yielded during the digestion process - and thus that available for consumption by the heat exchanger – must be determined. Equations for calculating the volume of expected methane production may be applied for this purpose. Prior to direct application of the methane production formula, it is necessary to determine the actual value of several key variables through analytical laboratory testing. These variables include the mass of biodegradable chemical oxygen demand (bCOD) present in both digester influent and digester effluent, the daily net mass of cell tissue produced (P_x), flow through the system (Q), and volatile suspended solids (VSS) destruction.

During February, 2014, Cullman WWTP facility staff collected water samples and recorded flow volumes at the following locations:

1. Primary Clarifier No. 1 Effluent
2. Primary Clarifier No. 2 Effluent
3. Sludge Thickener No. 1 Effluent
4. Sludge Thickener No. 2 Effluent
5. Sludge Draw Lines from Primary and Secondary Digester Basins
6. Secondary Digester Supernatant Effluent Return

Items 1 – 4 above represent the influent flow into the primary digester basin, and thus the total volume of influent into the digester system. Item 5 above represents the total amount of settled sludge that is drawn from both digester basins approximately once per month, and is a point at which flow intermittently exits the digester system. Item 6 represents the effluent that is decanted from the secondary digester and returned to the primary clarifier. Item 6 is a point at which flow continuously exits the digester system.

Once the sample points were identified, it was necessary to calculate both the volume of flow and the constituent loadings present at each of the aforementioned points. Among other parameters, the primary analytes necessary for the stated purpose were bCOD and volatile suspended solids (VSS).

Biodegradable chemical oxygen (bCOD) is sometimes determined after first calculating the slowly biodegradable chemical oxygen demand (sbCOD) and readily biodegradable chemical oxygen demand (rbCOD). This method requires testing to determine a number of additional parameters for both sbCOD and rbCOD so that each can be first calculated before summing these together to yield the bCOD value. This method can prove to be very time consuming, costly, and more importantly, add additional risk and variability to the results. An alternate approach for determining the bCOD value is to first calculate the ultimate biochemical oxygen demand (uBOD), which represents the theoretical maximum amount of BOD present in a sample. To determine uBOD, the BOD of a sample is periodically measured and plotted on a graph to yield a curve indicating a diminishing BOD value with respect to time. The asymptote, or upper bound, of this curve represents the theoretical uBOD value. The least squares method statistical device is used to determine the applied uBOD value.

The Cullman WWTP staff collected samples from each of the sampling points once per week for a 2-week period. In addition to the other parameters, samples from the first week were analyzed to determine their respective uBOD value. To reduce the cost of the testing program, samples collected during the 2nd week of the program were tested only for BOD_5. Once analytical data was received from the laboratory, a comparison was made between the BOD_5 conducted during the 1st week sample uBOD test, and the BOD_5 value determined during through testing of the 2nd week sample. Results of the sample testing program are summarized in the attached spreadsheet.

The uBOD value determined from analysis must then be used to calculate the applicable bCOD value. A method of estimating bCOD from uBOD is given by the following equation:

$$\text{bCOD} = \frac{\text{uBOD}}{1 - (1.42 \times f_{BOD} \times Y_H)} \qquad \text{(M\&E pg. 670)}$$

Where the term f_{BOD} is a correction factor to account for the unbiodegradable endogenous residue created during the decay of biomass during the BOD tests, and is assumed to be 0.15 (M&E pg. 670). Y_H is the synthesis yield coefficient defined as g VSS/g COD used, and is generally assumed to be 0.4 (M&E pg. 670). This formula was applied to determine the uBOD values used in subsequent calculations.

The next step in the process to calculate the expected biogas yield of the system is to identify those variables to be applied to useful equations.

Variables:
V_{CH4} = Volume of methane produced at standard conditions (0^o and 1 atm), m^3/d
0.40 = theoretical conversion factor for the amount of methane produced from conversion of 1 kg of

bCOD at 35^o C

Q = flowrate, m^3/d = 144.62 m^3/d (per Cullman WWTP facility management)

S_o = bCOD in influent, mg/l = 228,712 mg/l (per analytical data and calculations)

S = bCOD in effluent, mg/l = 66,232 mg/l (per analytical data and calculations)

P_x = net mass of cell tissue produced per day, kg/d

Y = yield coefficient, g VSS/g bCOD = 0.05 (per analytical data and calculations)

K_d = endogenous coefficient, d^{-1} = 0.03

SRT = solids retention time, d

V_d = volatile solids destruction, % = 48% (existing, per analytical data)

Although values for most of the above variables have been determined at this point, the values for SRT, P_X and V_{CH4} remain undefined. We shall start by calculating the Sludge Residence Time (SRT). To compute the SRT of the system, we must first know the volume of both anaerobic digester reactors. Both existing basins are equal in size and dimensions, which are as follows:

Digester basin diameter = 22.9 m

Digester volume side depth = 6.1 m

Digester Basin mid depth = 7.32 m

$$\text{Basin Volume} = \pi(11.45)^2(6.1) + \pi\,(0.333)(11.45)^2(7.32 - 6.1) = 2{,}512.4\ m^3 + 167.5\ m^3 = 2{,}679.9\ m^3$$

$$\text{Total System Volume} = (2)(2{,}679.9\ m^3) = 5{,}359.8\ m^3$$

SRT is calculated differently for complete-mix reactors versus those which are not. The project shall install a mixing system within the primary digester basin, which shall effectively convert the primary basin into a completely mixed reactor and reduce the amount of sludge settling to the bottom of the basin. Although some sludge settlement will occur, and necessitate some sludge draw throughout the year, the SRT of the Primary Basin ($SRT_{Primary}$) value shall be theoretically equal to the hydraulic retention time, τ, for the purposes of this calculation:

$$SRT_{Primary} = \tau = \frac{V}{Q}$$

$$SRT_{Primary} = \frac{2{,}679.9\ m^3}{144.62\ m^3/d} = 18.5 \text{ days}$$

SRT for non-mixed basins requires the application of the standard SRT formula commonly used for familiar processes such as activated sludge: The formula is stated as follows:

$$SRT_{Secondary} = \frac{VX}{(Q - Q_W)X_e + Q_W X_R}$$

Where:

V = Volume of Digester Basin = 2,679.9 m^3
Q = Flow Rate = 144.62 m^3/d
Q_W = Sludge Wasted = 12.80 m^3/d
X = Biomass Concentration
X_e = Concentration of biomass in secondary basin effluent
X_R = Concentration of biomass in sludge draw line = 19,525 mg/l (VSS, per analytical testing)

For the purposes of this calculation, the value for X_R after implementation of the mixing system in the primary digester basin shall be assumed to be that measured during the City's sampling analysis. Since there are no values yet assigned to X or X_e, we must next assign values to these variables in order to calculate SRT in the secondary digester basin.

To calculate the biomass concentration entering the secondary digester, we must first recognize that it is equal to the biomass concentration flowing from the primary digester. The expected volatile suspended solids destruction through the improved primary digester can be estimated from the following equation:

$V_d = 13.7 \ln(SRT) + 18.9$ (M&E pg. 1513)

$V_d = 13.7 \ln(18.5) + 18.9$

$V_d = 58.9\%$

The existing average influent VSS into primary digester basin, per analytical samples, is 16,967 mg/l. The applicable effluent biomass concentration from the primary digester basin would therefore be:

$VSS_{P.Eff} = (1 – 0.589) \times 16{,}967 \text{ mg/l} = 6{,}973 \text{ mg/l}$

Since approximately 10% of total gas production - and thus 10% of the total process chemical reaction – occurs in secondary digesters (M&E pg. 1509), it has been estimated the total volatile solids reduction across the secondary digester will amount to 10% of the total reduction across the digester process. The effluent VSS from the secondary basin can thus be computed as follows:

$$VSS_{S.Eff} = 16{,}967 \text{ mg/l} - \frac{(16{,}967 \text{ mg/l} – 6{,}973 \text{ mg/l})}{(1 – 0.10)} = 5{,}863 \text{ mg/l}$$

To review, the SRT of the secondary digester basin can be calculated utilizing the following equation:

$$SRT_{Secondary} = \frac{VX}{(Q - Q_W)X_e + Q_W X_R} \qquad \text{(M\&E pg. 679)}$$

Where:

V = Volume of Digester Basin = 2,679.9 m^3
Q = Flow Rate = 144.62 m^3/d
Q_W = Sludge Wasted = 12.80 m^3/d
X = Biomass Concentration = 6,973 mg/l ($VSS_{P.Eff}$, calculated)
X_e = Concentration of biomass in secondary basin effluent = 5,863 mg/l ($VSS_{S.Eff}$, calculated)
X_R = Concentration of biomass in sludge draw line = 19,525 mg/l (VSS, per analytical testing)

Although the amount of sludge created and drawn from the entire system is expected to be reduced due to the addition of the mixing system in the primary basin, the total amount of sludge has been assumed to be the same.

$$SRT_{Secondary} = \frac{(2,679.9\ m^3)(6,973\ mg/l)}{(144.62\ m^3/d - 12.80\ m^3/d)(5,863\ mg/l) + (12.80\ m^3/d)(19,525\ mg/l)}$$

$SRT_{Secondary}$ = 18.3 days

The total SRT of the digester process can then be calculated by adding the values obtained for $SRT_{Primary}$ and $SRT_{Secondary}$:

$SRT = SRT_{Primary} + SRT_{Secondary}$ = 18.5 days + 18.3 days = 36.8 days

Once the applicable SRT value for the digestion process has been computed, the next step is to figure the cell tissue mass production utilizing the following equation:

$$Px = \frac{YQ(So - S) \times (10^3\ g/kg)^{-1}}{1+k_d(SRT)}$$

$$Px = \frac{(0.05)(144.62)(228,712-66,232) \times (10^3\ g/k\ g)^{-1}}{1 + (0.03)(36.8)}$$

Px = 558.4 kg/d

Using the variable values calculated to this point, we can now calculate the volume of methane expected to be produced by the system.

$$V_{CH4} = (0.40)\ [(S_o\text{-}S)(Q)(10^3\ g/kg)^{-1} - 1.42P_x]$$

$$= (0.40)\ [(228,712-66,232)(144.62)(10^3\ g/kg)^{-1} - 1.42(558.4)]$$

$$= 8,606\ m^3/d$$

Using the generally accepted fraction of methane to total digester gas production, we can calculate the total volume of digester biogas expected to be produced:

Gas Production $= (8{,}606\ \text{m}^3)(0.65)^{-1} = 13{,}240\ \text{m}^3$

Since 13,240 m^3 is greater than the minimum gas volume of 370.1 m^3 required to meet the system's energy demand, ample gas volume is expected on an average daily basis to completely supplant the existing natural gas fuel requirement. However, such a situation may be unreasonable to expect as fluctuations in temperature, sludge and digester gas characteristics, and other factors beyond the control of facility staff may affect the aggregate biogas yield for any given day. Therefore, it is prudent to assume that some amount of supplemental natural gas may be necessary throughout the year. Although difficult to predict, we shall assume a supplemental natural gas volume equal to 25% of the total for the purposes of determining a financial savings.

Financial Analysis

The Wastewater Treatment Plant is assessed a fee of $0.9533 per 100 cubic feet of natural gas consumed, which subsequently applies a 4.00% tax rate. The value of the yearly savings can therefore be calculated as follows:

$$\text{Monthly Reduction in Current NG Requirement} = \frac{(7{,}850\ \text{ft}^3 \times 365) \times (1 - 0.25)}{12} = 179{,}078\ \text{ft}^3$$

$$\text{Value of Monthly NG Reduction} = \frac{179{,}078\ \text{ft}^3 \times \$0.9533}{100\ \text{ft}^3} = \$1{,}707.15$$

Value of Yearly NG Reduction = $1,707.15 x 12 = $20,485.80

Assuming a monthly disbursement over a 20-Yr. analysis period, and a 1.60% real interest rate per OMB Circular A-94, Appendix C, the present value of the forgoing savings amount can then be determined:

$$\text{Present Value} = \frac{\$1{,}707.15}{(0.016\ /\ 12)} \times [1 - (1\ /\ (1 + (0.016\ /12)^{-240}] = \mathbf{\$350{,}019.77}$$

References

Metcalf and Eddy, Inc. 2003. *Wastewater Engineering: Treatment and Reuse*, 4th ed., revised by G. Tchobanoglous, F. Burton and H. Stensel. McGraw Hill, Inc., NY.