Methane Electricity Generation Project Phase III

WA-RD 901.2

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METHANE ELECTRICITY GENERATION PROJECT PHASE III

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16. ABSTRACT:

The purpose of this project is to build off the previous design to create an energy recapture and generation system to test at the Scatter Creek Safety Rest Area (SRA). This system uses methane generated in the anaerobic digestion process to create electrical energy that could potentially run the SRA. The methane, carbon dioxide and hydrogen sulfide gasses from sewage systems escape into the atmosphere without treatment currently at SRAs. Utilizing this gas saves the Washington State Department of Transportation (WSDOT) energy costs, as well as diverting pollutant gasses into reuse. As a result, a physical prototype for conversion of methane from biowaste to electricity has been redesigned, updated, fabricated and reassembled based on a previous prototype for demonstration of this sustainability idea for WSDOT facilities.

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EXECUTIVE SUMMARY

Executive orders 18-01 and 20-01, signed by the Washington State Governor, mandate that all newly constructed public buildings and facilities shall be designed to be net-zero energy capable (Inslee 2018). To respond to the governor's order, the Washington State Department of Transportation (WSDOT) has asked for the redesign and testing of a system that can use biowaste generated at Safety Rest Areas (SRAs) to generate electricity to power the facilities. The goal of this project seeks to assist WSDOT by redesigning a system built by a previous project team, assembling the redesigned prototype system, and testing the capability of the generator prototype that can be scaled to fit the needs of any rest area. In this work, a net-zero methane generation system is presented to show how it can convert biowaste into methane for electricity at SRAs and other public facilities. The model is composed of a digester tank to store the biomaterial, a storage tank system that stores and applies a conveyance pressure to the biogas, a filtration system to remove hydrogen sulfide (H_2S) and carbon dioxide (CO_2), a generator that runs on methane gas, and a photovoltaic system that powers ancillary systems. Through testing, it was shown that this system could potentially generate energy through the use of bovine waste, which can be applied to human waste in future iterations. Further improvements are needed to increase methane production and make operation more efficient. Future testing on human waste from a safety rest area will be required before proving that the system can meet energy generation requirements.

INTRODUCTION

The search for new and improved energy renewal systems has been widespread for years at a global level. One of the techniques that is increasingly being employed involves the utilization of biowaste, both human and animal, to generate energy through an anaerobic digestion process. The methane obtained from this process is used as fuel to a generator (Angelidaki et al. 2018; Tabatabaei et al. 2020; Methane (Anaerobic) Digesters undated; IEA 2020). Under request of the Washington State Department of Transportation (WSDOT), the purpose of this project is to convert biogas from organic waste to usable energy at SRAs in Washington State, decreasing waste loading rates for existing sewage systems and providing a means to electrical-grid independence for these sites. The system obtained from this process will therefore constitute a significant improvement both from an environmental and financial standpoint, eventually producing net zero energy facilities.

The proposed system takes previously unused biowaste and extracts biogas from the waste. This biogas contains principally methane (CH_4) and carbon dioxide (CO_2), but also includes hydrogen sulfide (H_2S) and harmful substances that would normally escape into the environment. The project group also examined the work of the previous teams, and received a prototype produced in the 2020 iteration of the project (WA-RD 901.1). The preexisting methane generating apparatus was analyzed in order to identify its principal issues and propose appropriate modifications to solve them. These modifications were focused on increasing both efficiency and functionality of the system.

Temperature is rather important in the first stage of the methane generating process, as biogas production is generally more efficient between 30°C and 50°C. A heating mat was selected to provide heat to the sludge, and an agitator was included in the design of anaerobic digestor. The biogas then undergoes scrubbing to remove CO_2 and H_2S, with the use of a water column and iron sponge. Moisture in the biogas is condensed and removed by a water trap, and the gas is now principally methane, which is directed to a generator to produce electrical energy. A photovoltaic system is used to power ancillary systems until the entire system can reach steady state. A hospitable environment for anaerobic bacteria requires a relatively stable heat source and agitation. The team considered the possible advantage given by the application of biofilms, to 'seed' the digester tank with methanogen strains known to produce methane. Additionally, the team has proposed changes to the digester tank, which will prevent gas leakage. Biogas containment is a necessary factor for both safety and efficiency, and isolation from oxygen is critical to the anaerobic digestion process.

Reducing atmospheric methane by combustion for electricity serves a two-fold benefit: reducing greenhouse gas emissions and providing energy. Methane is an incompressible gas at standard temperature and pressure (STP), and its unsuitable as mobile fuel. Most rest stops in Washington release sewage it into facultative lagoons where the bio waste decomposes, or it is conveyed to local sewer systems. A portable, small-scale bio waste processing plant could utilize available biowaste from the rest areas to generate electricity and reduce greenhouse gas contributions and poisonous gases like hydrogen sulfide. These benefits are the purpose of this project, sponsored by WSDOT.

REVIEW OF PREVIOUS WORK

Previous work on this subject was performed by another team of SMU students during the 2019-2020 academic year, which led to the development of a physical prototype identified in (WA-RD 901.1). Their prototype demonstrated success in extracting sufficient methane from bovine excreta to fuel a propane-powered generator for a limited time period (Alhalwachi et al. 2020). This project aims to expand upon the knowledge gained by the previous team to improve the functionality and efficiency of the proposed system.

The previous project team experienced issues with the digestor's ability to retain heat, leaking in piping systems, as well as in the scrubbing of raw biogas as it is conveyed to the generator system. During meetings with team members from the previous iteration, key results and issues were identified and brainstorming of solutions was conducted. This resulted in guiding the current team towards implied success. This project focused heavily on sludge processing to increase the amount of available methane, and biogas upgrading and containment.

Figure 1: Picture. Previous team's prototype

RESEARCH AND DESIGN APPROACH

The proposed system generates electricity by combusting methane harvested from sewage. Methanogenic organisms feed on nutrients in the waste and produce biogas. Mild agitation and a thermally controlled environment increase biogas production. This biogas is collected and refined for upgrading by removing contaminants. Biogas has a high methane content but also contains hazardous levels of H_2S and CO_2, which are not fuel gases.

This biogas must be 'scrubbed' during the upgrade process to isolate the methane. The team designed separate stages of gas scrubbing to remove H_2S and CO_2. After scrubbing, water vapor is removed from the methane before it enters the storage tank. From the storage tank, the methane is compressed to achieve optimal concentration for combustion by the generator. The system relies on external power from a photovoltaic array, which provides enough power for several sensors and a gas compressor. The team utilized this external power source to power a heating mechanism for the digester, to maintain sludge temperature at optimal conditions for methanogenic activity.

The figure below showcases an outline of the entire system, which consists of five subsystems. In the figure, components that are green and yellow represent parts of the previous prototype that either function properly or need improvement. Red items represent components that needed to be designed and implemented. The designed system is composed of the following subsystems.

1. Digestor
2. Gas Processing Equipment – Scrubbers and Compressors
3. Gas Storage Equipment
4. Generator
5. Solar Array (Photovoltaics)

The biosolids obtained from this process could be deemed as class A, as they follow the requirements determined by federal regulation 40 CFR Part 503 by eliminating pathogens from the byproduct (Biosolids Laws and Regulations 2020) and could be available for use as fertilizer in the agricultural and farming sector, used on site, or at partner agencies. As the USA territory is divided into 10 separate EPA regions, Washington State belonging to Region 10 (EPA Regional and State Contacts for

Biosolids 2020), the regulations will be analyzed when a potential expansion in the unit's application is adopted.

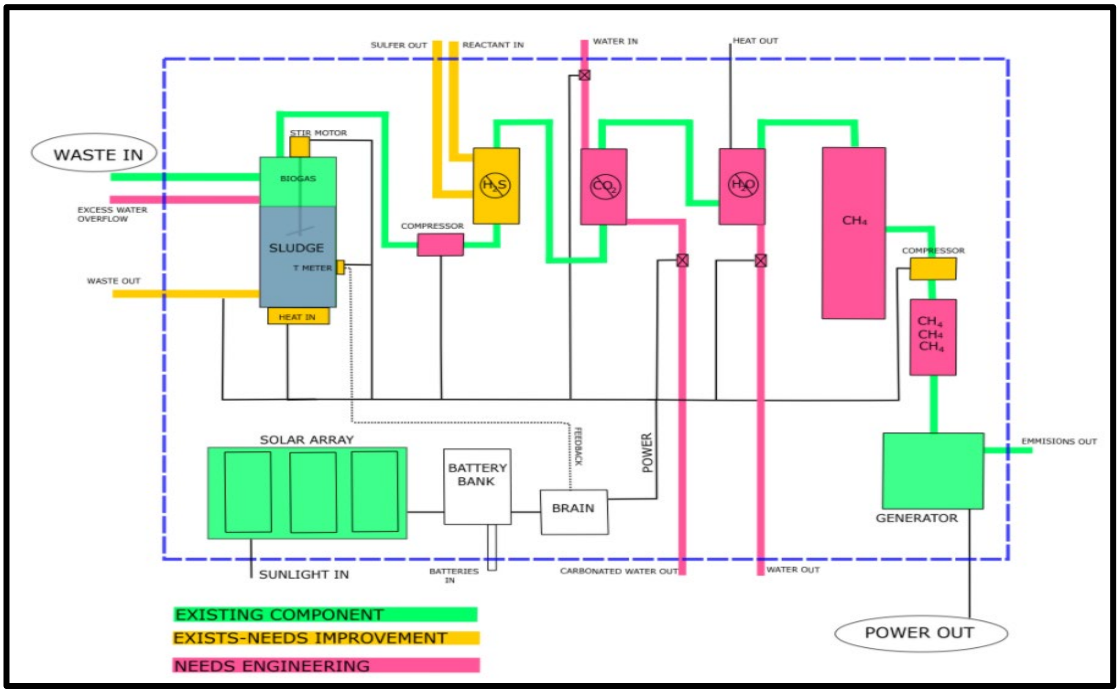

Figure 2: Diagram. Schematic of combined subsystems, color-coded to illustrate priority.

Designs Considered

The project considered two alternative preliminary designs, tasks 1 and 2 as indicated below.

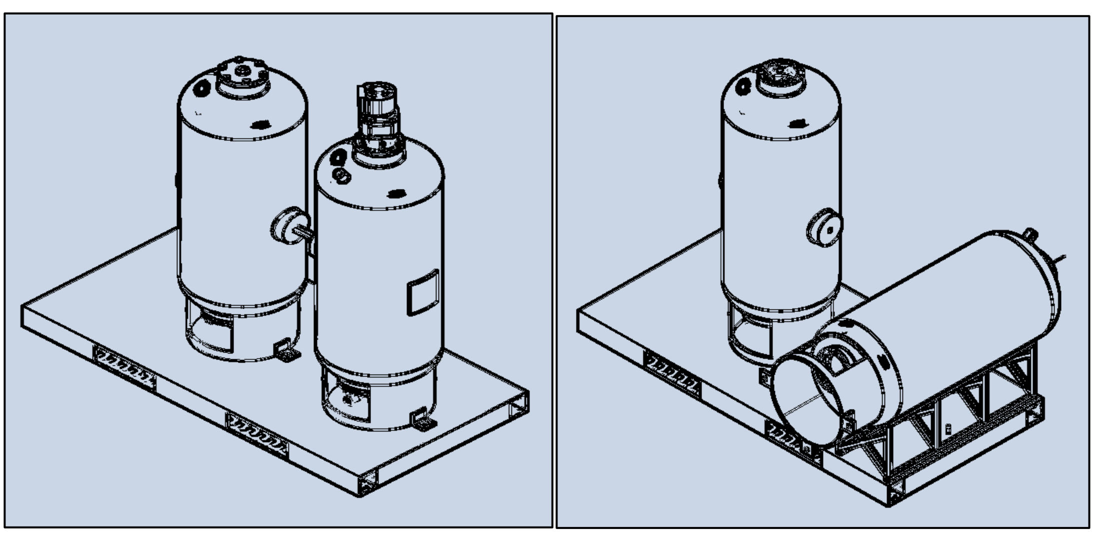

Figure 3: Drawing. Sketch of Task 1 (left) and Task 2 (right).

The biggest differences between task one and two is in the positioning of the tank selected to contain the sludge and biogas mix, as it's, in this case, laying horizontal.

Two alternatives were considered for the different values of sludge surface area. Considering the formula representing the production of the biogas, more surface area is ideal. In fact, a larger surface area would provide more contact between the sludge and air, and decrease depth, allowing the gas produced to reach the top of the tank more easily. The additional contact results in a more efficient system. In order to determine whether rotating one of the tanks would be beneficial enough, or at all, an approximation of the area of contact between sludge and gas was calculated for both a horizontally and a vertically positioned tank. The dimensions of the tank are displayed in the following figure and were utilized in the calculations.

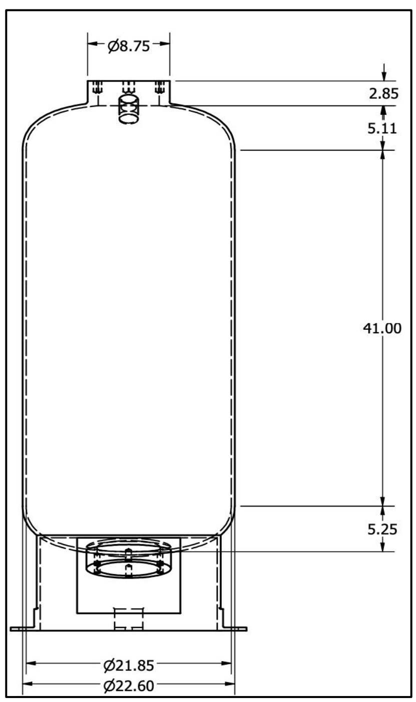

Figure 4: Drawing. Schematics and dimensions of each tank.

When maintaining the tanks vertically, the surface area of contact with the air of the sludge will be constant for a column height between 5.25 and 46.25 inches. The amount of sludge in the tank will, on average, be maintained within this interval while the unit is operating. The diameter of the vessel is 21.85 in within these parameters, and the surface area therefore can be calculated as follows:

$$A_s = \frac{D^2}{4}\pi = 375\ in^2 \tag{1}$$

When considering the tank in the horizontal position, the area will be calculated at 50% capacity to verify the maximum surface of contact between biogas and sludge. If the ratio between this value and the one obtained from Eq.(1) doesn't appear to be satisfactory enough to apply the change to the system, the design will be discarded. If the result seems significant enough, further data will be analyzed to verify that such an increase in the rate of biogas production is appropriate in the settings the system will be introduced into.

The following calculations are used to determine the data for the horizontal tank, which presents the same dimensions as presented in the figure above.

Area of elliptical end, $A_{e:}$

$$A_{e,1} = (5.11\ in \cdot \frac{21.85}{2}\ in \cdot \pi)/2 = 87.69\ in^2 \tag{2}$$

$$A_{e,2} = (5.25\ in \cdot \frac{21.85}{2}\ in \cdot \pi)/2 = 90.09\ in^2 \tag{3}$$

Central area, $A_{c:}$

$$A_c = 41\ in \cdot 21.85\ in = 895.85\ in^2 \tag{4}$$

The total surface area. A_{tot}, in the horizontal tank is then obtained:

$$A_{tot} = A_{e,1} + A_{e,2} + A_c = 1073.64\ in^2 \tag{5}$$

In order to clearly see the difference between the two scenarios, a ratio can be obtained:

$$\frac{A_{tot}}{A_{tot}} = \frac{1073.64\ in^2}{375\ in^2} = 2.86 \tag{6}$$

As seen in Eq. (6), the horizontal positioning of the tank containing sludge and biogas would allow for an area of contact almost three times the one observable in the vertical tank.

The validation process considered the methods selected for the following phases in the system, like the biogas upgrading or the condensation removal. These steps are necessary to remove particular elements from the biogas, in order to obtain more pure methane gas to be used to produce electrical energy. The following is the chemical formula representing the production of biogas as proposed by Buswell and Mueller (1952) and modified by Boyle (Achinas et al. 2016) to include nitrogen and sulfur within the reactant compounds, and ammonia and hydrogen sulfide within the product of the reaction:

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{2} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \tag{7}$$

This model, with the implied simplifications, was helpful to understand an approximate amount of ammonia and hydrogen sulfide to be removed in order to upgrade the biogas into methane. It is implied that some water will still be present in the gas, as the reaction won't usually reach full completion.

The production and collection of the biogas greatly depends then on its ability to leave the sludge and reach the upper part of the tank. The efficiency of this process can be increased with the use of an appropriate stirring system, which can move the material and allow for a greater rate of reaction of the biowaste. This step constitutes one of the principal issues identified in the prototype by the previous team during testing

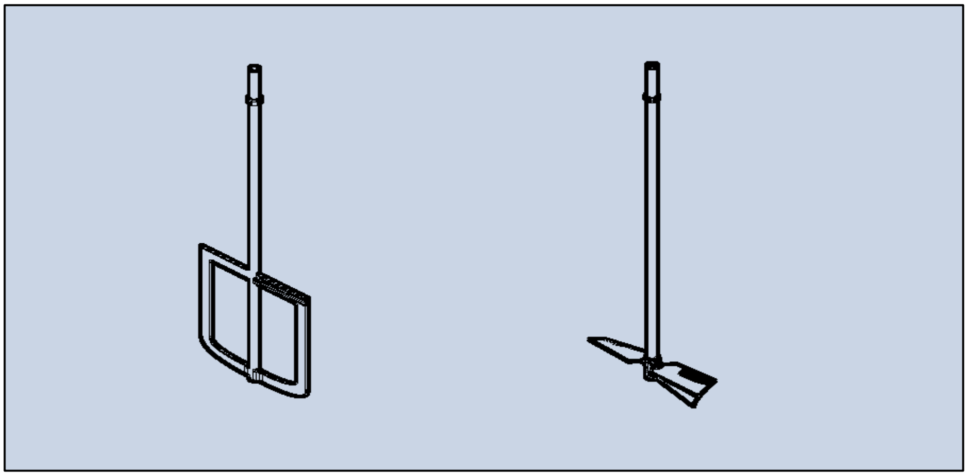

Figure 5: Drawing. Sketch of two stirring designs considered.

The average water content in human excreta is approximately 75% (Penn 2017). With the addition of water from toilets and sinks at SRAs, the viscosity of water proves to be an acceptable approximation for sludge. As such, the second impeller model was selected as it will allow for gentle agitation of sludge and allow heat to permeate throughout the sludge at a quicker rate, providing a more consistent environment for methanogenic growth.

This growth is important also because one of the steps in the denitrification of the biogas will potentially consist of a movable bed of methanogenic bacteria forming a biofilm reactor. The following is the representation of one of the options considered to be used as the base for the system, onto which the bacterial colony will be introduced.

Figure 6: Photo. Example of Moving Bed Biofilm Reactor (MBBR) (Trity Enviro Solutions)

The model displayed, according to the specs provided, would appear efficient due to its high efficiency both with attached and suspended bacterial growth, its increased nitrification ability, and ability to limit clogging and sensitivity to shock loading. For larger scale models, a Fixed-Bed Bioreactor (FBBR) could be instead considered, but in order to keep the system relatively low-cost, MBBR were selected as the most favorable option in the biogas upgrading system. Further analysis will be necessary after the production of the biofilm in order to validate its functionality and whether its application is indeed justifiable.

After consultation with professors from the Department of Biology at Saint Martin's University, the team was able to acquire valuable information on how to grow a potentially efficient methanogenic colony using the biofilm mentioned in the paragraph above, to be introduced to the tank. As the methanogenesis in this procedure is an anaerobic process, both the system and the material fed to the bacterial mass need to exclude oxygen, which represents an important aspect considered in the manufacturing and testing phases. The creation of an efficient and self-sustaining community is produced on average in one or two weeks, starting from a small phial that can be purchased from specialized manufacturers. In addition, the possibility of contacting researchers already working on the cultivation of the appropriate methanogens strains was discussed with the professor. This depends on the modality of shipment to the team and the conditions of the material.

The bacteria considered for this system tend to be thermophiles, which means they can survive, and actually thrive at higher temperatures compared to other kinds of bacteria. While the range can vary between different strains, this would be advantageous when considering the presence of pathogens and parasites in the sludge in the final application of the system. These, in fact, can't resist relevantly elevated temperature, allowing for the switch between hazardous communities and the methanogenic, relevantly innocuous one. The sludge leaving the first tank could be collected and utilized as fertilizer in the agricultural sector. This way, further waste could be avoided.

Another issue identified in the previous prototype was the presence of water in the biogas. The previous group was able to run the generator for about 30 seconds. It could only run for short amounts of time because the methane leaving the system had too much moisture. A water trap resolved this issue by removing most of the moisture in the methane. The water trap works by running the gas through a filter and removing any contaminants and most of the moisture from the gas.

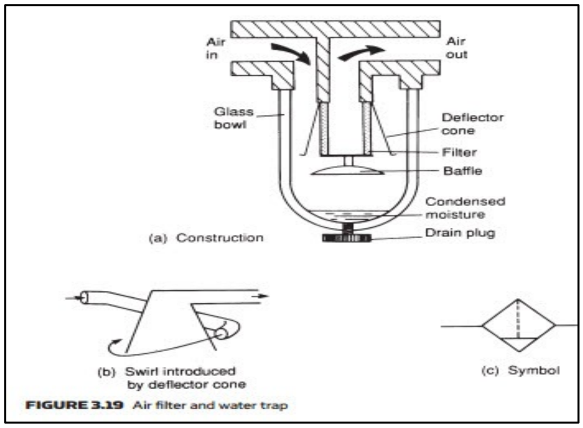

Figure 7: Diagram. Water Trap Diagram (Machinery Equipment Online 2015)

Another issue identified by the previous team revolved around the faulty sealing system, which allowed for leaks and problems with maintaining pressure within the system, necessary for the process to work efficiently. The team started to develop an improved sealing system.

Design Selection

The project team determined that the second design alternative, Task 2, was the preferred option due to multiple reasons, including the horizontal tank orientation. This was the design that was selected for further design analysis, simulations, and ultimately was used to build the system.

DESIGN ANALYSIS AND SIMULATIONS

Due to their relevance in the project, focus on the analysis was geared especially towards some specific components, in particular the tanks, the tank lid fasteners, the gaskets, and the agitator.

SF Based Design

Some features of the design, including dimensions and material used in some components, were selected by determining the most appropriate Safety Factor (SF) and calculating the data necessary to make sure that failure is avoided.

Tank

The first of the two tanks salvaged from the original prototype are used to hold and heat sludge during the biogas generation process. The second tank is a reservoir for biogas as it is released from the sludge. As the tanks are existing components being utilized in the design, safety factor analysis was done with regard to the maximum pressure allowable in each tank in their current state. No specific material properties or wall thickness dimensions were available from the tanks, so several assumptions were made to perform the analysis, based on industry standards and common practices. External dimensions of the tank were measured, and the tank was modeled as a cylindrical thin-walled pressure vessel with torispherical ends. The lids of the tank were measured to approximately 3/8 in. thick and the tanks are assumed to be of the same thickness. There is rust throughout the interior of the tanks and 1/16 in. was deducted from the measured thickness to account for corrosion. The safety factor range for thin-walled pressure vessels is 3.5-6 (Factors of Safety 2010). A conservative safety factor of 6 was chosen as the exact dimensions and material properties of the tanks are uncertain. Additionally, the tanks will potentially contain explosive and/noxious gases and are located near a combustion engine. A commonly used material for pressure vessels in the oil and gas industry is ASTM A516 Grade 70 carbon steel (Carbon Steel Plates for Pressure Vessels 2018). This alloy has a minimum yield strength of 38 ksi (SSAB 2019).

The expected operating temperature range for methanogenic growth is the mesophilic range, which is 30˚C - 38˚C (85˚F – 100˚F). Suboptimal operating temperature range is that which allows for methanogenic growth but is not ideal is 20˚C - 45˚C (68˚F – 113˚F) (Office of Water Programs 2019). External temperature is considered to span the lowest to highest temperatures on record for Washington State, which is -48˚F to 118˚F (Washington State Records 2020). Mechanical creep will not be significant in this scenario. To account for the torispherical shape of the tank ends, the measured dimensions of the tank were modelled using Autodesk Inventor CAD software. Circles were approximately matched to the section view of the tank ends and the radii of the circles was used in the calculations of hoop stress and longitudinal stress.

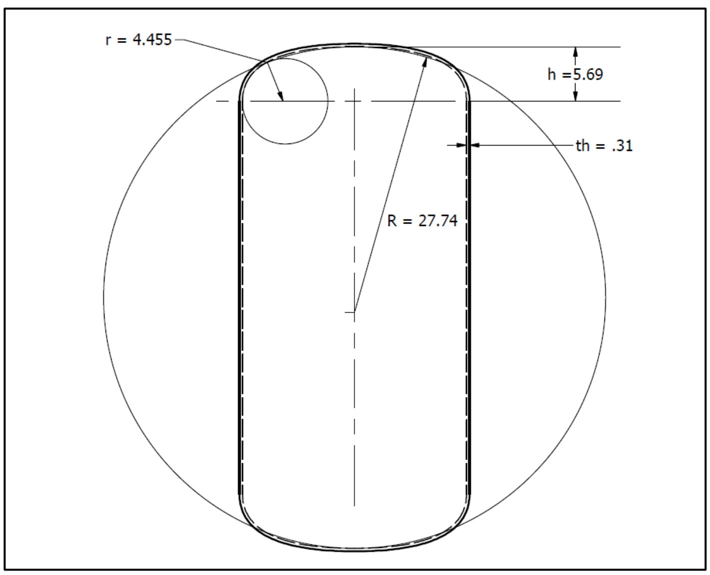

Figure 9: Drawing. Circle used for pressure vessel calculations.

Longitudinal stress and hoop stress were both calculated for the cylindrical portion of the tank and throughout the tank ends. These stresses were used, along with the minimum yield strength and safety factor to determine the maximum allowable pressure for the tanks. The calculations for this analysis included the following properties:

Safety Factor *(SF),* tank thickness *(th),* inner tank radius *(R_{in}),* yield strength of steel *(S_y),* large radius of end caps *(R),* small radius of end caps *(r),* height of end caps *(h)*.

$$SF = 6 \ , \ S_y = 38000ksi \ , \ R = 27.74in \ , \ r = 4.455in \ , \ h = 5.69in \quad (8)$$

$$th = (\frac{3}{8}in - \frac{1}{16}in) = 0.313in \quad (9)$$

$$R_{in} = 24in - (2th) = 23.38in \quad (10)$$

To determine maximum allowable stress S_a on modified tank, were maximum allowable stress the same for longitudinal and hoop stresses ($S_a = S_L = S_H$):

$$S_a = \frac{S_y}{SF} \rightarrow S_a = \frac{38000psi}{6} \rightarrow S_a = 6333psi \quad (11)$$

Solving for maximum allowable design pressure (P_{des}) in the tanks, considering longitudinal and hoop stresses for the cylindrical section, the crown, the knuckle edge and within the knuckle itself, the following equations can be employed:

For longitudinal stress in cylindrical section of tank:

$$S_a = (\frac{1}{2})P_{des}(\frac{R_{in}}{th}) \rightarrow P_{des} = \frac{2S_a th}{R_{in}} \rightarrow P_{des} = 169.34psi \quad (12)$$

For hoop stress in cylindrical section of tank:

$$S_a = P_{des}(\frac{R_{in}}{th}) \rightarrow P_{des} = \frac{S_a th}{R_{in}} \rightarrow P_{des} = 84.67psi \quad (13)$$

For longitudinal and hoop stresses in the crown:

$$S_a = 2P_{des}(\frac{R_{in}}{th}) \rightarrow P_{des} = \frac{S_a th}{2R_{in}} \rightarrow P_{des} = 1461.19psi \quad (14)$$

For hoop stress at knuckle edge:

$$S_a = (\frac{P_{des}R_{in}}{4th})(3 - \frac{R}{R_{in}}) \rightarrow P_{des} = \frac{4S_a th}{3 - (\frac{R}{R_{in}})} \rightarrow P_{des} = 157.4psi \quad (15)$$

For hoop stress within the knuckle:

$$S_a = \left(\frac{P_{des} R_{in}}{th}\right)\left(1 - \frac{R}{2R_{in}}\right) \rightarrow P_{des} = \frac{2R_{in} S_a th}{-R^2 + 2R_{in} R} \rightarrow P_{des} = 175.46psi \tag{16}$$

From these calculations the lowest value of design pressure, 84.67psi, is determined to be the maximum allowable pressure. This value was used in a simulation for stress analysis on the CAD model of tank 1.

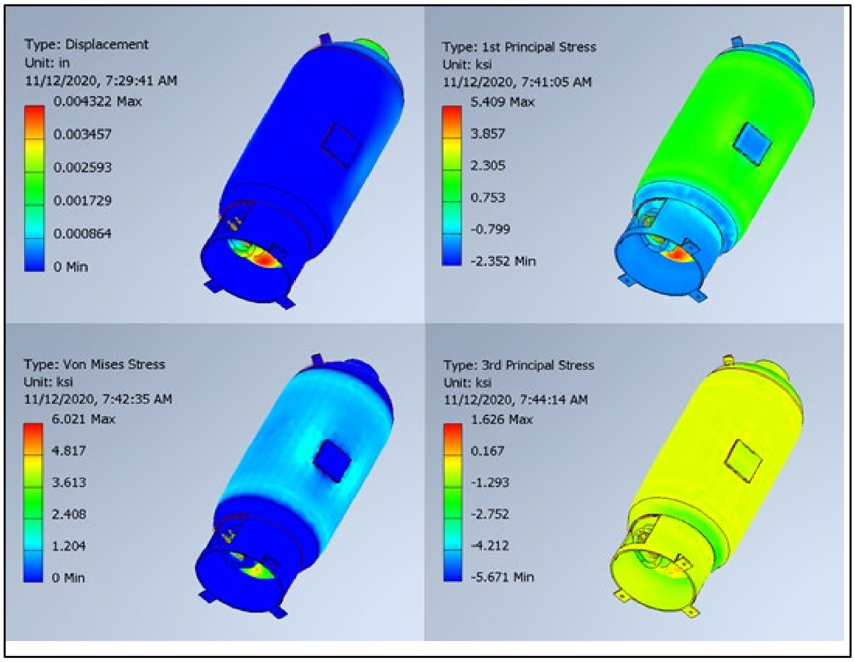

Figure 10: Diagram. Stress analysis simulation for tank 1, where maximum design pressure was applied to the interior surface of the tank.

This simulation shows that the design dimensions and material parameters will remain within a safe range. Additionally, the highest stresses and deformation occur at stress concentration areas which are deviations from the torispherical shape assumption. As expected, these areas experience higher levels of stress than an ideal model, but they do not present an indication of failure for the applied conditions.

Gasket

Safety factor of 2.5-3 was selected for the gasket, which is for use with brittle materials where loading and environmental conditions are not severe (Engineering Toolbox 2010). The group chose silicone as the material for the gasket. The elastic limit was from 348.09 to 797.71 psi (AZoM 2001). A conservative approach was taken and a safety factor of 3 and yield strength of 348.09 psi were selected to yield the following results:

$$SF = \frac{Yield\ Strength}{Applied\ Load} \tag{17}$$

$$3 = \frac{348.09 psi}{Applied\ Load} \tag{18}$$

$$Applied\ Load = 116.03\ psi \tag{19}$$

The maximum applied load should only result in 116.03 psi. Silicone tensile strength changes according to temperature. The highest temperature experienced during testing will be accounted for, and deformation of the materials must be considered.

Fasteners

Calculations inherent to the fasteners' design were performed using the data collected from measurements of the prototype, displayed below. In the design proposed, the yield strength of the internal strength is selected to be equal to the proof strength of the bolt, thanks to the same material being employed for both. This means that the bolt can be fully torqued. In order to facilitate the identification of the correct torque, the length of engagement is selected to be 1.5 times the nominal bolt diameter. This way standard torque tables can be used in the calculations.

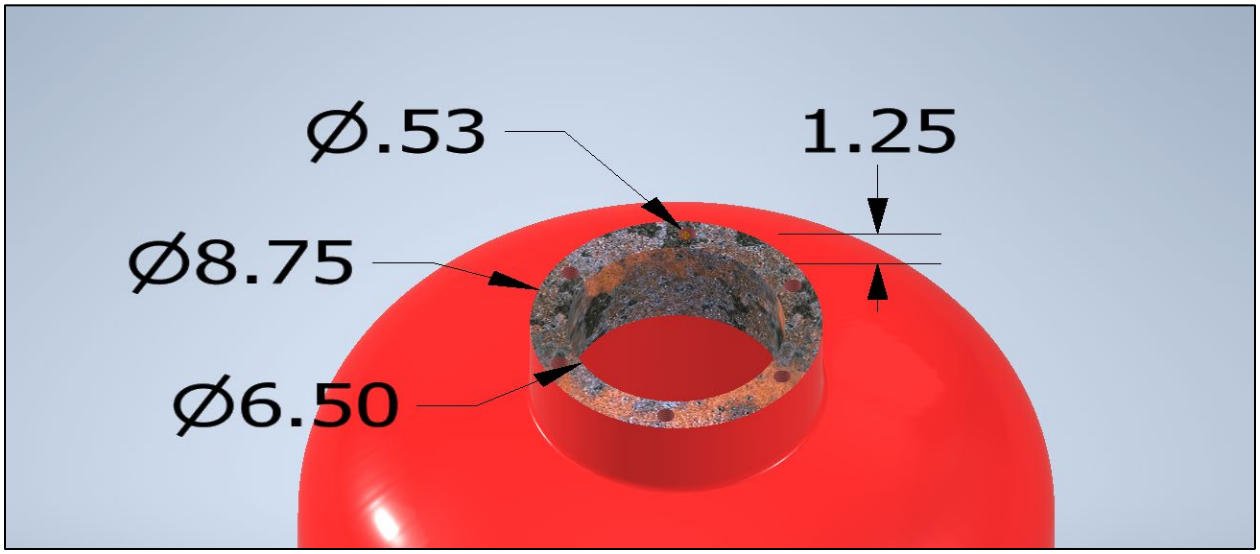

Figure 11: Drawing. Detail of the top of the tank; measurements in inches.

The nominal fastener diameter is 0.53 in, which means that, if the diameter selected was to be the same as the one already present, the engagement length to be produced will be at least 0.795 in, well within what the tank allows. Considering American Standard styles (Fasteners 2018), it was noticed that it would be advantageous to adapt some changes to the existing holes. This includes increasing the diameter of the hole to 0.5625 in, so that the standard fasteners would present a thread count per inch of 18, and a tensile stress area of 0.203 in^2, for fine threads, UNF. The engagement length will need to be at least 0.85 inches, still within allowable boundaries.

In order to find the appropriate material to be utilized for the fastener selected, a safety factor (SF) of 3.5 was chosen, due to the uncertainty of some of the materials used, but also considering the predicted average conditions for stress applied on the part. This value also constitutes a suggested value when working in the kind of scenario presented. Using this safety factor and the value for the stress produced by the tank, the ultimate stress of the material was found to be 294 psi, using the equation, Eq. (17), presented in precedence.

The options for the material to be used are the general ones for fasteners: aluminum, brass, copper, bronze, nickel and its alloys, stainless steels, titanium, and plastics. Due to the high corrosion resistance and the limited elongation while clamped, martensitic steel SAE 416 would be a potentially satisfactory choice, with tensile and yield strength of 180 ksi and 140 ksi respectively, and a relatively low 15% elongation per 2 inches. These values are well within the parameters set by using the selected safety factor, limiting the possibility of failure for the fasteners.

Propeller

The group has also looked into fatigue failure theory to design the propeller. Using the Goodman relation:

$$SF = \frac{s_n}{\sigma} \tag{20}$$

The safety factor selected for the propeller shaft is 2.5 due to the dynamic nature of the piece, and there is average confidence in the environment. The materials where selected, which identified the ultimate strength leading to the endurance limit.

The figure below presents the simulation conducted with these data for the propeller. The top part of the figure focuses on the rod, while the bottom on the propeller blade.

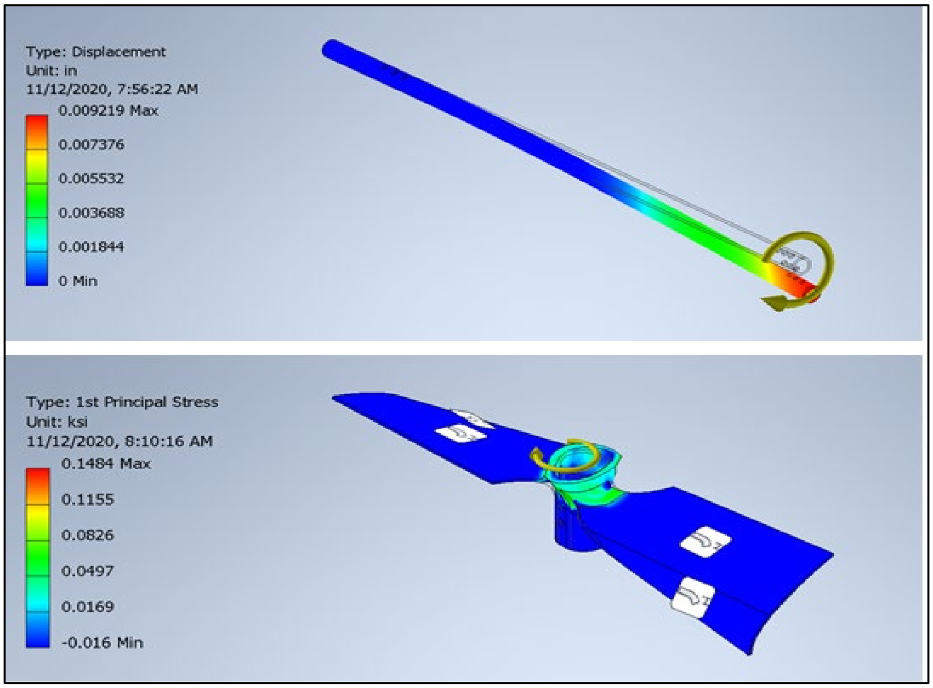

Figure 12: Drawing. Stress analysis for the propeller.

The simulation presented allowed the team to identify higher stress areas and the limitations that will have to be kept in mind, in order to maintain a constant desired speed and flow production in the sludge, in order to guarantee satisfactory conditions for the methanogens in the biofilm.

Design Results

As stated in precedence, the simulations executed for specific components in the system, the tanks and the agitator, determined that the features selected can be deemed appropriate. They, in fact, represent a fundamental aspect of the system, as some of the issues identified in the previous team's prototype during testing could be connected to these two components.

The proposed designs would prevent potential hazards and help the system's efficiency. The gasket and fasteners would prevent gas leakage. Any biogas leakage could be harmful to the environment. The water trap would remove moisture from the gas and allow the generator to run smoothly. The biofilm would increase methane production and reduce input energy needed to run the entire system.

Roadblocks

The production of the most appropriate design encountered a few obstacles of different nature, including the inability to collect data and measurements directly due to the characteristics of the preexisting prototype. There's an interest in the use of biohazardous material, in this case, human waste. The challenges arise with disposal and contaminant removal due to the possible presence of dangerous pathogens. More issues can be identified when trying to utilize different kinds of biowaste as substitutes, such as bovine waste. The problem lies in the different composition of the matter. In bovine waste, the amount of cellulose and plant material is significantly greater than in human waste.

Other issues revolve around the uncertainty of some aspects of the projects. For example, research is still ongoing for the creation and the testing process of a methanogenic bacteria biofilm reactor. While this process appears to be very effective for smaller-scale systems, yielding a gas composed of 90-95% methane, the bacteria's need for hydrogen could hinder the functionality in larger scales such as this prototype, as the amount of energy produced within the system wouldn't be able to compensate for the amount used for the reactor process. The team needed to consider the analysis method for the methane concentration after the biogas has been through this step.

Some potential issues were identified with the introduction of modifications or new elements in the system. The current characteristics of the tanks could constitute an obstacle for the sealing aspect of the system when the tanks are rotated. Furthermore, the importance of the condensation removal from the biogas will require attentive testing of the water trap added to the system.

Solutions to Roadblocks

After considering each roadblock, the team developed solutions to potentially limit their impact. To solve the inability to collect first-hand data, mathematical analysis was conducted and cross-referenced with the values available. The results that appear the most appropriate were adopted for analysis.

To limit the issues concerning the handling of the biowaste, the team researched ways to avoid using human feces, in particular the availability of imitations containing the appropriate concentrations of the components in the human biowaste. The use of bovine manure would limit the danger linked to the possible presence of pathogens, which are considered less hazardous.

Another option relies on the possibility to create an environment more favorable to the methanogens, which can become the main bacterial community. As previously mentioned, this was completed by selecting the appropriate temperature ranges for the sludge to sustain the biofilm colony, inhospitable for the pathogens and parasites in the sludge. The byproduct could theoretically be collected and employed as fertilizer.

Further research was also necessary for the production of a functional biofilm. The team contacted the biology department at Saint Martin's University to receive suggestions on the most advisable route to follow. The biology and chemistry faculty where later consulted to identify the most efficient method to determine the concentration of the methane.

For the condensation issue in the methane by the previous project team, the group installed a water trap in the system. This trap will passively remove water from the methane and collect the water. This system was employed for the new prototype but was upsized and refined to increase moisture removal.

Design Specifications

As the project revolves around improving a preexisting prototype, many aspects of the system are the ones recorded by the previous team. The following are the features that are maintained.

Table 1: Tank specification.

Part Description	Dimensions / Parameters	Notes
Tank Pressure Release Valve	1/4" NPT threaded connection. 250 F maximum temperature. Adjustable from 25 to 200 psi.	Control Devices NC25-1UK002 - air safety valve with soft seat. Set at 25psi release pressure. Two valves per tank
Tank Pressure Gages	1/4" NPT threaded connection. 130 F maximum temperature. 0 to 100psi. Polycarbonate lens	PIC Gages 201L-204E; 2" general purpose 0 to 100psi liquid filled gage. One per tank.
Pressure Tanks	Approx. 100-gallon capacity. Flanged inlet and outlet plate sections. 1/8" steel. Rated at 125psi pre modification.	ASME certified pressure vessels, rated at 125psi (before modification). Include 1 stirrer, 1 heat exchanger, 1 pressure gage and 2 air/pressure relief valves per tank.
Agitator Blade	Specialized geometry, see Production drawing	Custom order mfg. or source equivalent part.
Agitator Shaft	1 1/8" ID - 1 1/2" OD – 58" L, 304 Stainless Steel tubing	Purchase part, modify with bolt holes in mfg. lab.
Tank Lid Gasket	6 ½" ID – 8 ¾" OD, Full-face 6-.65" holes silicone gasket.	Manufacture in lab, purchase silicone sheet
Tank Lid Fasteners	Martensitic steel, 6 ea.	Purchase part

Design Refinements and Analysis

After the team spent several months in the preliminary design stage, revision and consolidation of a final design took place. A representation of the overall system is presented in the following figure.

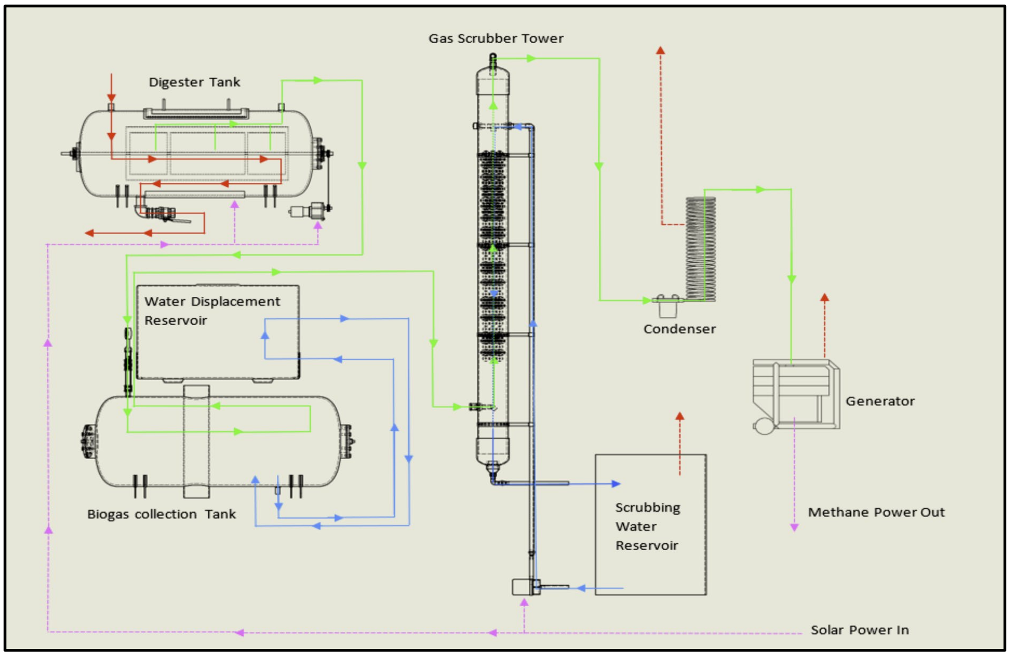

Figure 13: Drawing. Representation of system and subsystems.

One of the major issues revolved around the fact that methane is an incompressible gas. Therefore, the team needed a way to contain the expanding volume of biogas generated during the anaerobic digestion process and also to initiate the flow of biogas through the next stages of the process. In experiments by the previous team, an air compressor was employed for this function. This method introduced more air into the system, consequently decreasing the ratio of methane, and increasing the risk of explosion involved in the process. It is important that methane remain isolated from oxygen so as to maximize the fuel storage capacity of the system. Methane is particularly dangerous because it is highly explosive when in contact with oxygen, an instance which the team needed to mitigate. To accommodate the expansion and collection of biogases at a useful concentration and volume, it is necessary for the capacity of the gas storage space to change along with the volume of gas produced. The team designed an expandable volume container for biogas storage utilizing a double tank sub-system, which employs a transient volume of water to compensate for changes in biogas volume. In addition to an expandable storage volume, the water effectively creates a positive pressure on the biogas which helps to convey it through the scrubbing system.

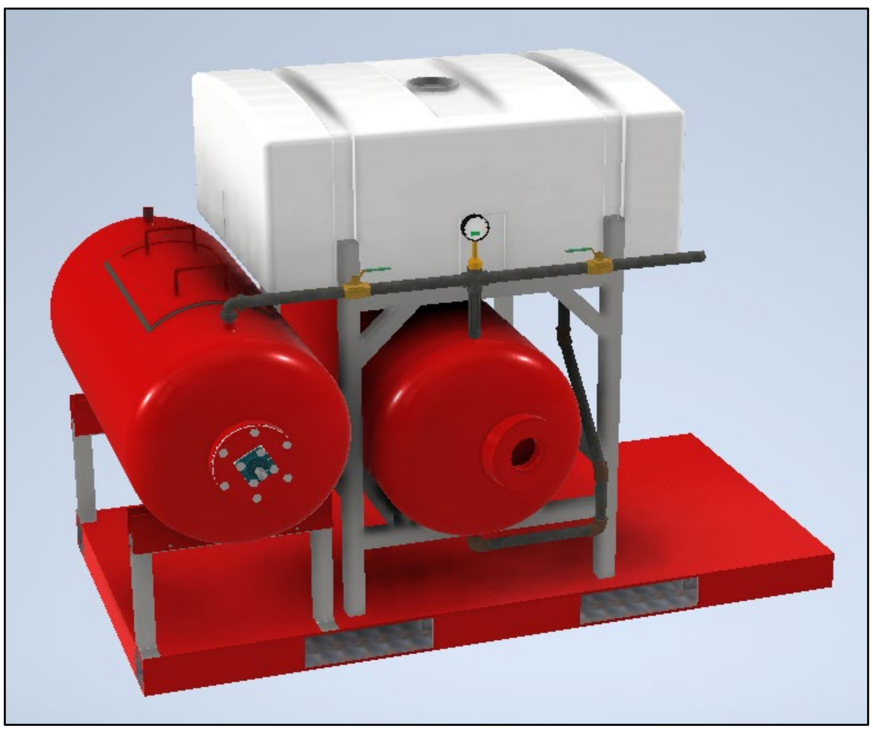

Figure 14: Drawing. CAD model of digester, biogas collection tank and water displacement tank for expandable gas containment.

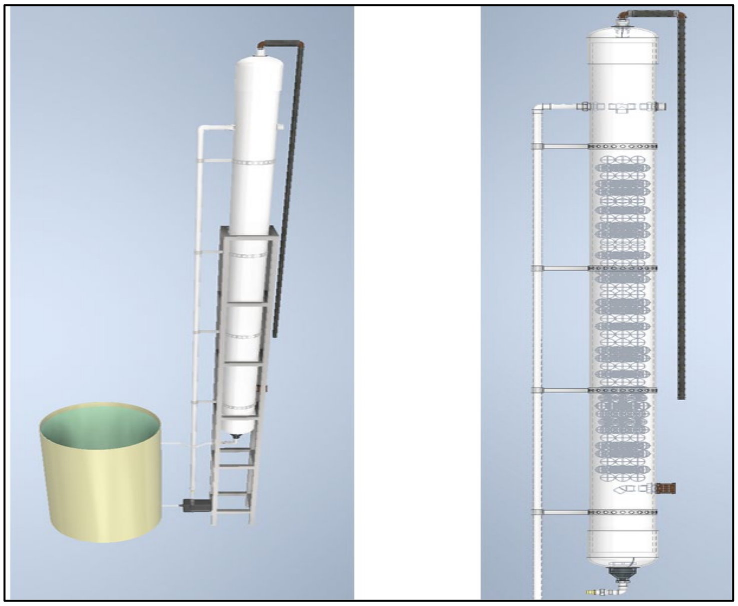

Figure 15: Drawing. Two CAD drawings of the water tower assembly

Starting the assembly process, the team manufactured the water column, which included a 6-inch PVC pipe and end caps. The end caps were machined to create openings for the water and methane outlets. Each end of the water tower is equipped with PVC fittings, the methane exit port was installed on the top end cap, with the water exit port on the bottom. An inlet for water and an inlet for biogas were drilled into the sides of the column and fittings were installed. A full-cone nozzle was installed near the top end of the column, allowing a one-foot gap at the top to minimize the amount of water passing through the methane outlet. Water is supplied to the nozzle by a centrifugal pump, installed near the base of the column, which draws from a 50-gallon reservoir. The pump is a Laing Thermotech brand, 0.6A, energy efficient unit that delivers 1/25 hp to the water. A six-foot section in the center of the water tower is packed with plastic “bio balls”, which are commonly used in pond filtration. The team purchased 2 cubic feet of bio balls from a seller on Amazon.com. The bio balls have a large surface area that increases the occurrence of water-biogas contact as water descends through the column and biogas rises. The resulting gas that exits the column will be highly concentrated methane. CO_2 saturated water drains out the bottom of the tank, back to the reservoir where the CO_2 can be removed via agitation.

Figure 16: Photo. Plastic bio-balls to increase contact area between water and biogas (Tabatakaei et al 2020).

An addition that appeared in the final design was the support frame to the tanks and the water column. Due to the great significance of these components for the appropriate functioning of the system, analysis had to be conducted to make sure that the frame, manufactured by one of the team members, wouldn't fail under loading. The following figure displays the results of analysis performed with Autodesk Inventor. The material selected was ASTM A513 Hot-rolled steel. Displacement and safety factor for the designed frame were in-line with industry standards, so the design in the figure below was incorporated into the manufacturing process.

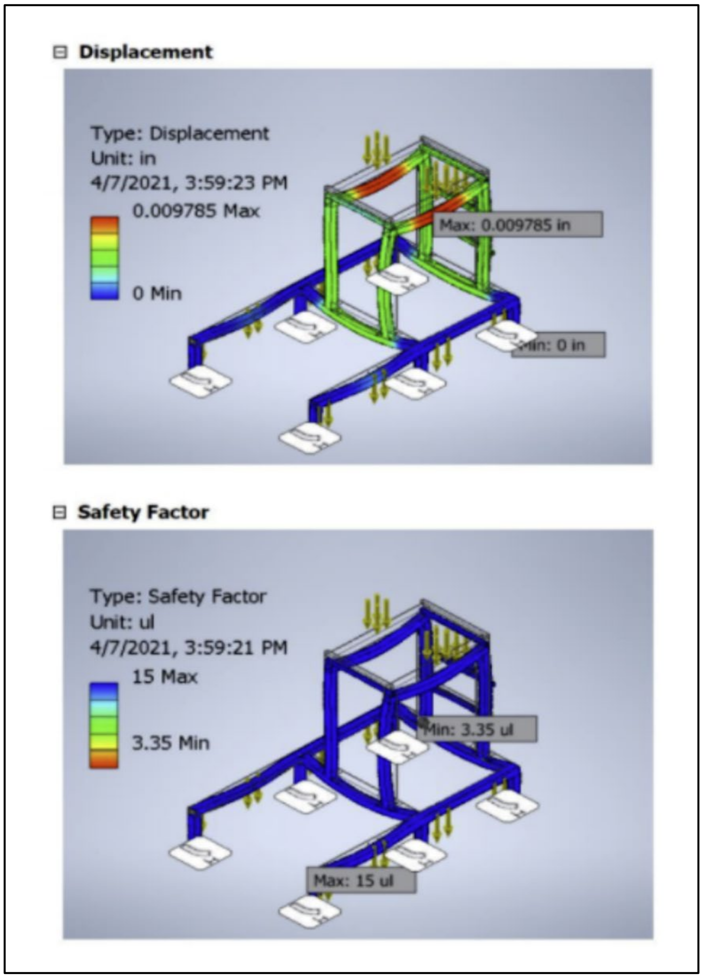

Figure 17: Drawing. Stress analysis of structural support frame for water in low and positions.

PHYSICAL PROTOTYPE MANUFACTURING AND ASSEMBLY

Different components required specific manufacturing processes. In order to construct the digester tank, a third tank that hadn't been modified by the previous team was located, cleaned, and inspected. A professional welder was contracted to modify the tank according to the team's design. A one-inch sludge inlet port, a one-inch biogas outlet port, and a two-inch drain port were welded to the tank. Brackets are welded to the bottom of the tank that the team used to attach square steel tubing leg supports. An access hatch was cut into the top of the tank allowed the team to install the mixing paddle, and the bottom of the tank was rebuilt, removing the existing drain flange to accommodate the shaft of the mixer. Additionally, the tank lid and the rebuilt end were drilled and tapped to install the flange bearings that support the mixer shaft.

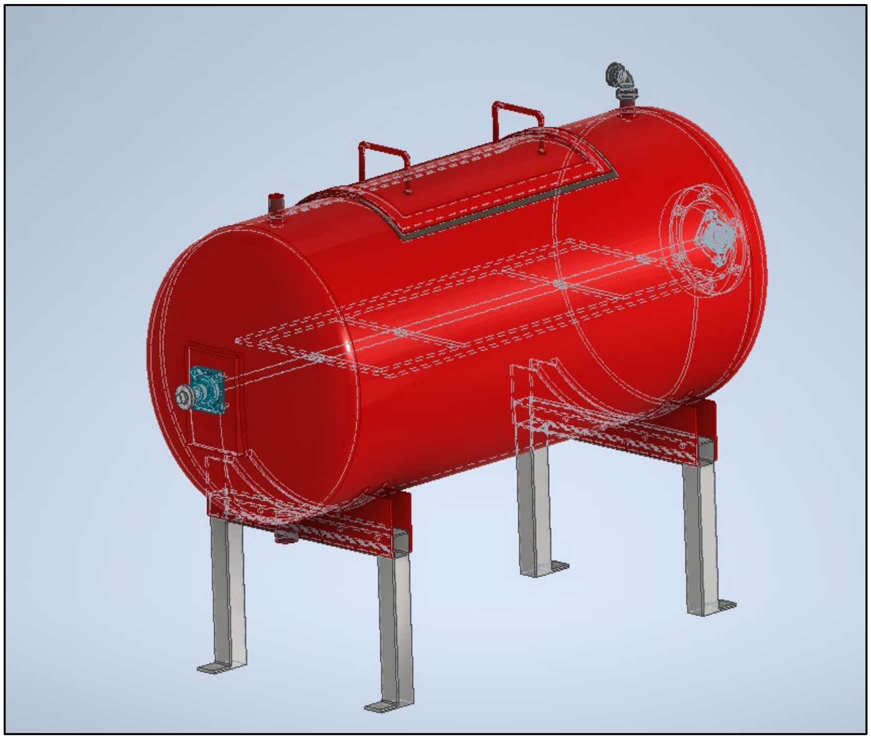

Figure 18: Drawing. Design modifications to digester tank.

Biogas Collection Tank

To accommodate the expansion and collection of biogases at a reasonably useful concentration and volume, it was necessary for the capacity of the gas storage space to change along with the volume of gas produced. The team designed an expandable volume for biogas storage utilizing a double tank sub-system. This apparatus employs a transient volume of water to compensate for changes in biogas volume. With the technique of water displacement, the water effectively creates a positive pressure on the biogas which helps to push it through the scrubbing system without introducing any vacuums. This eliminates the need for a compressor.

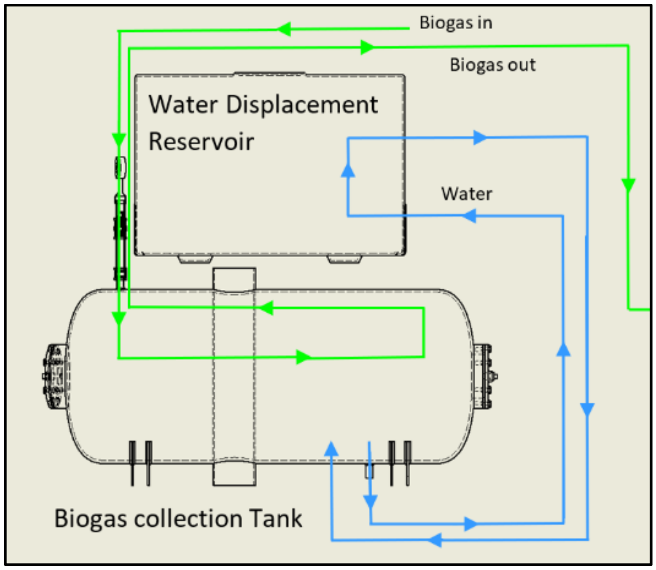

Figure 19: Drawing. Process diagram of the biogas collection tank

The following formulas represent the method used, making it possible to calculate the pressure of the gas collected in the tank, offering a possible way to improve the system. Eq.21 is a derivation of Dalton's Law of Partial Pressure, while Eq.22 represents the proportional version of the ideal gas law.

$$P_{total} = P_{gas} + P_{H_2O} \tag{21}$$

$$\frac{PV}{T} = constant \tag{22}$$

The number of moles of the gas produced can be calculated as well using the ideal gas law:

$$PV = nRT \tag{23}$$

Where $R = 8.3145\, J \cdot mol^{-1} \cdot K^{-1}$.

Digester Tank Seals

The original system design called for silicone rubber seals for the digester tank. It was determined that silicone is permeable to methane, which creates a potential for leaks and is a safety hazard. Digester seals were created using polytetrafluoroethylene (PTFE), commonly known as Teflon, which is less permeable and less susceptible to corrosion from biogas elements.

Water Column/Tower

The water tower is an integral part of the system as it removes CO_2 and H_2S from the biogas. CO_2 accounts for approximately 30% to 50% of biogas, while H_2S ranges from .01-1%. It is essential to remove these impurities to improve the concentration of methane, avoid possible corrosion of system components and the production of toxic emissions. The system designed for this purpose in the present project consists of an 8-foot-tall PVC pipe, 6 inches in diameter, filled with plastic "bio-balls", relatively small spherical structures usually employed in pond filtration systems.

In the scrubbing process, biogas travels upwards through the water tower and the bio-balls, while water is pumped from a separate water vessel to the top of the tower and sprayed downwards. The bio-balls then increase the surface area on which water can be deposited, allowing for a greater occurrence of water-biogas contact as water descends through the column and biogas rises. As CO_2 and H_2S are more soluble gases than methane, they dissolve more in the water throughout the system, while wet CH_4, now in a purer form, proceeds towards the upper part of the water tower, and leaves the apparatus.

Using gravity, CO_2 and H_2S then are flushed out of the system, as water drips towards the bottom of the column and is subsequently returned to the water vessel. CO_2 may be removed from the water by agitation and the water is cycled through the process again. When CO_2 dissolves in water, H_2CO_3 can be found in small amounts as well, according to the following formula (IEA 2020):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \tag{24}$$

This compound generally is found in lower quantities than CO_2, which, in its loosely hydrated state, represents the predominant species. This means that agitation will allow for the gas to rise and leave the water.

One of the other principal compounds produced in this process is NH_3. While this substance is not considered dangerous in small amounts, as it's commonly used for agricultural purposes, and its presence still requires attention. To avoid this issue, the unit is intended to utilize the outgoing wastewater system at the rest areas to empty the water vessel, making sure that the content is therefore disposed of safely.

The third main compound is H_2S, which can pose safety issues when it reaches higher concentrations. In the same manner as possible issues with ammonia are limited by relying on the wastewater treatment center, disposing and replacing the content in the vessel constitutes a satisfactory preventive measure.

Support System for Tank and Water Column

The team constructed a steel truss of 1-inch square steel tubing to support the water tower. The truss will be secured to the skid at the base.

Agitator

The agitator was machined in the manufacturing lab. It was determined that for purposes of this prototype, the cost associated with a custom-design agitator requiring specialty manufacturing would not add enough benefit to the project to be justifiable. Optimized flow patterns and material longevity should be considered by any subsequent research projects and certainly for extended use applications. The team anticipates a maximum of three weeks of testing to be the functional life of the agitator.

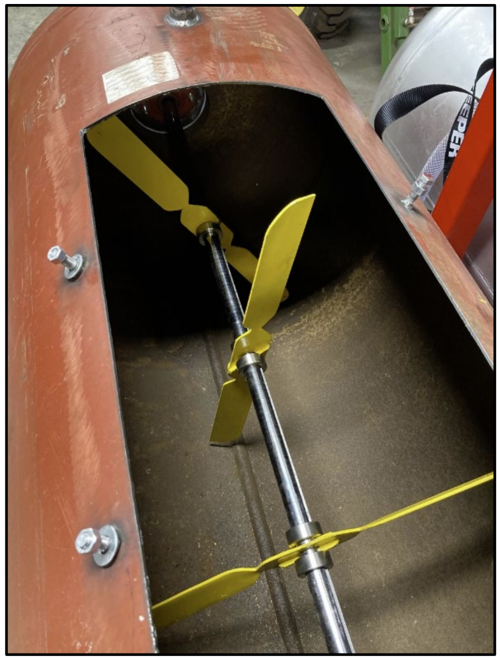

Figure 20: Photo. Agitator in digester tank

Copper Coil Tubing

After the scrubbing system, the biogas, now virtually pure methane, will only require removal of water to move onto the final stage of the process. The method selected for this purpose is a condenser consisting of a copper tube, coiled to increase the length utilized while limiting the area it occupies. The system takes advantage of the different properties of the compounds, as water is polar, while methane is nonpolar (Angelidaki et al 2018). Water also presents cohesive and adhesive properties, which means that the molecules are not only attracted to each other, but to other materials as well. Because of this, as the biogas travels through the copper coil, water drops will adhere to the inner surface of the tube and form condensation. Thanks to the configuration of the condenser, gravity will allow for the drops to move downwards.

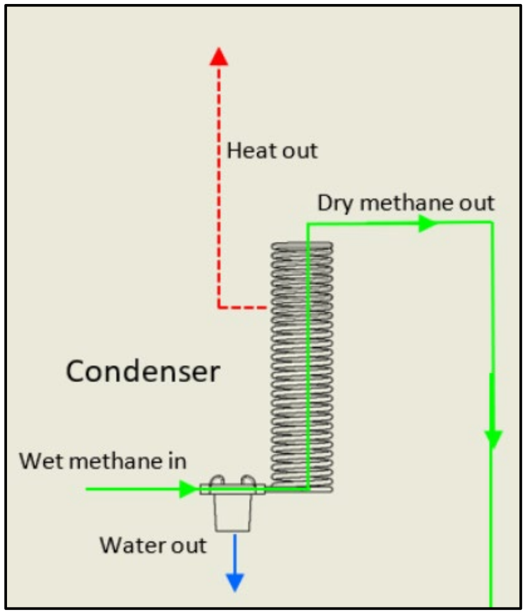

Figure 21: Drawing. Diagram of condenser

A water-trap is installed underneath the copper coil, collecting the condensation. This mechanism allows for the water to be disposed of without disturbing the pressure in the system and avoiding the introduction of air in the pipes.

FINDINGS AND DISCUSSION

This section includes information and data gathered from prototype testing, and the findings resulting from testing.

Physical Prototype Testing

Multiple validation processes were carried out on the physical prototype, focusing both on individual components and final assembly. This was done to test functionality of all parts before implementation. Particular focus was given to the eight most relevant aspects of each component, first identified and displayed in the table below in order to determine the most efficient testing methodology.

Table 2: Selected components and most relevant aspects, identified to select the most appropriate validation process.

Item/Component	Focus
Digester tank	Leak Prevention - gas and sludge
Storing tank	Gas leak prevention
Heating element	Time necessary to reach temperature Temperature maintenance
Blanket	Heat loss/insulation
Motor	Performance Torque Heat produced
Water Column	Gas Scrubbing performance Fluid Leaks Water pressure
Piping system	Gas transportation within the system Fluid pressure
Water Trap	Moisture removal from gas Water collection

Most of the validation stage for the individual components, before final assembly of the physical prototype, were performed in the manufacturing laboratory at Saint Martin's University.

As the main issue detected in the second tank, which contains water and gas, is a possible leak of either one of the fluids, testing was performed by using an air compressor and testing seals at all inlets, outlets, and valves. Positive results were obtained in all tests, indicating the absence of leaks. When considering the heating element, its function was observed, and its performance optimized to obtain the desired temperature outcome. Due to the relationship between the heating element and insulation system, the two underwent concurrent testing.

The original timeline included testing of the final prototype to be performed at LOTT Clean Water Alliance in Olympia, WA. The team contacted the organization to request permission to use their facilities for the validation process. This would have been done in April 2021, for a duration of approximately two weeks. The process previewed the introduction of 30 to 40 gallons of sludge, into the 100-gallon digester tank, half of which would be substituted with new material after 5 days. LOTT would provide primary sludge and allow the team to use their system to dispose of the process byproduct. On March 10th, 2021, the team received news from the Environmental Compliance Supervisor at LOTT Clean Water Alliance to let the project team know that prototype testing process wouldn't be possible due to the COVID-19 pandemic. The team decided on testing at the WSDOT Scatter Creek Safety Rest Area facility and used cow manure as a substitute for human biowaste.

The unit was transported from the manufacturing laboratory at Saint Martin's University to the Scatter Creek SRA at 9:30 am on April 29th, 2021. After arriving at the rest area, the students met Mike Noll, WSDOT Safety Rest Area Drinking Water Manager, Cross-Connection Specialist. The team was granted access to a fenced area at the location, and they were provided keys to the lock at the entrance gate. The unit was positioned in the same area selected for the previous iteration of the project.

Figure 4: Photo. Initial installation of prototype for testing at Scatter Creek SRA

In order to maintain the unit leveled, which constitutes a significant factor for proper function, a wooden board was placed under one side of the base to compensate for the uneven ground. The water source at the rest area was located and used to fill the storage tank in the system. The generator was placed on the side of the trailer.

On April 30th, 2021, the team obtained an initial 30 gallons of cow manure from a dairy farm located in Tenino, WA. Once at the site, the cow manure was filtered using a screen produced by the students using layers of metal wires. The team decided to add this step before introducing the manure into the digester to limit the possibility of grass and plant matter to interfere with the agitation system, or to clog the outlet of the tank. For the next step to be possible, the PV system needed to be functional. To make sure that risks were avoided when adding batteries to the system, a local expert was consulted. The team was made aware then of some issues that needed attention and revision in the PV system before it could be utilized, including the necessity to alter the breaker box (i.e., sanding down the wires holes and waterproofing it) . These issues required a considerable amount of time.

Additional obstacles appeared in relation to the PV system, principally due to weather conditions, as it was not waterproof and required specific temperatures to function. Leaving the system on while it was raining would cause the inverter to trip. Ambient temperatures of 70°F or more would occasionally cause the over temperature protection to activate and shut off the system. As the testing in the previous iteration of the project lasted only three days, the students weren't aware of these issues. A temporary solution was obtained by employing a canopy system using shrink wrap to block out weather conditions.

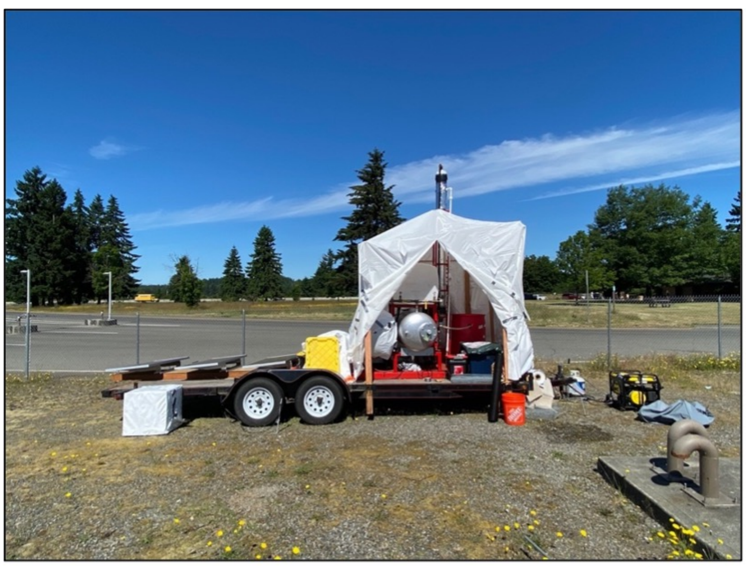

Figure 25: Photo. Prototype after adding insulation and the canopy system.

After fixing a relatively small water leak in the collection tank, confirmed by observing no change in the water level after a prolonged period of time, and solving the above-mentioned issues in relation to the PV system, the team proceeded to collect an additional 30 gallons of manure.

Findings

The student team tested the system up until the completion of this task order, so the findings in the report are reflecting the results at the time of submission.

Some components of the system have proved functional during the validation process, in particular the canopy system, which allowed for a better control of the internal weather conditions. As methanogenic colonies require a particular temperature range to perform efficiently, excess heat constitutes a considerable issue for the system. Hot conditions also interfere with the well-functioning of both the water-displacement system and the water column, causing evaporation and change in water density, a possible obstacle for the water displacement mechanism. Data was collected throughout the testing procedure, and the data from the day with the highest temperature, recorded on June 21st, 2021, at 12:20 pm, is presented in Table 4. The measurements were performed with the use of an infrared thermometer. The data suggest that the ideal environment for the methanogens was produced, and that the unit was maintained at an adequate temperature, despite various weather conditions.

Table 3: Temperature data for different areas of the unit.

Area	Temperature (°C)
Ambient	34
Trailer bed (exposed)	40.2
Trailer bed (covered)	30.8
Digester insulation	33
Digester tank	31.5
Storage tank	24.4

One observation was made regarding the time necessary to produce enough biogas to run the generator. As the team opted to dilute the cow manure to produce a density more like sewage, a longer period was needed before biogas production could be confirmed. While this appeared to be an obstacle in the testing process, as an uninterrupted sequence of days was made unavailable by weather conditions, this wouldn't constitute a significant problem in a permanent unit. In this scenario, the initial investment of time would appear only at the beginning, and continuous functionality would be unhindered afterwards. Even with the advances made to the current system, the team was unable to operate the generator on methane.

CONCLUSION AND RECOMMENDATIONS

This project presented some unique challenges regarding its scope, budget, timeline, and technology. The team was originally tasked with designing two systems simultaneously, in anticipation of two different possible budget outcomes. Budget finalization was realized quite late in the design process, but the team was able to successfully adapt their design and procure the necessary parts and components to construct a prototype. The team has successfully applied the concepts of heat transfer, fluid dynamics, manufacturing, coding, machine design, FEA, CAD, chemistry, and biology to design and produce a small-scale methane power plant. This system accounts for the incompressibility of methane, allowing for the collection and purification of this fuel-gas from biowaste and provides an effective gas scrubbing mechanism. The water displacement system is also proposed as a substitute for an air compressor, which would require more electricity and introduce air in the scrubbed gas. Even with the less than desired outcome with this phase of the project, the team is confident that the system will perform as designed with further analysis and refinement. Further work on this project should include optimization in all systems in addition to a focus on biowaste preparation and disposal.

The current project team identified the following areas of improvement:

1. Create a system better equipped to deal with changing environmental conditions
2. Design a photovoltaic system that is better suited for the climate of Washington State
3. Use custom designed digester tanks. The team experienced leaking and capacity issues with utilizing the current well water tanks, that have already been modified.
4. Operate the system on human waste instead of bovine waste, as it is a more energy dense source.

With the use of a more energy dense source, such as human waste, the current project team is confident that a future team could successfully operate the methane energy generator.

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