ANAEROBIC DIGESTION FACILITY IN RHODE ISLAND

An Interactive Qualifying Project Report

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by

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Abstract

The construction, operation, and feasibility of an Anaerobic Digestion plant are discussed. All aspects of the Anaerobic Digestion process are examined and its ability to produce and sell fertilizer and various forms of energy are evaluated. It has been determined that the facility can generate revenues of around 10 million dollars annually from fertilizer sales, with a two percent market capture. Energy sales will surpass that of fertilizer sales, although the regulations and methods for delivery have yet to be studied.

Abstract Addendum

The sections following are improvements and new research by Daniel Rapp that are addendums to the original Interactive Qualifying Report *Anaerobic Digestion* originally done by Gregory Cole, Daniel Rapp and Anthony Vello. It must be noted that only the first section will correspond to the original project while the other sections will not because they are new and therefore were not anticipated in the section outline.

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4.3 Construction Plan (Plant Design Feasibility)

Anaerobic digestion is a sensitive process that has to be efficient enough to not require substantial amounts of energy, but at the same time have the ability to produce an adequate amount of energy in order to alleviate or even compensate fort the energy used to complete the process. The reason for this is that bacteria require a minimal temperature to live. Consequently, the sewage entering a waste management facility needs to be raised to the temperature needed to sustain the bacteria. To accommodate for this severe inconsistency, energy must be supplied in the form of heat and used to raise the incoming fuel temperature. The lower the required temperature needed for the bacteria to thrive, the less the heat that must be added to the sewage. Thus, more energy is yielded from the process that can be applied to making profits, running equipment, or just plain lowering the cost of running the facility.

Until February of 2005, building an anaerobic based plant that would have the ability to break even financially was an unachievable idea. But now, however, since Dr. Zhang has published his work, there is hope for a financially thriving anaerobic digestion plant. For this reason, if we strive to design a very well insulated plant where the heat energy lost is completely under control, we can harness the power of this new process. These factors revolve around two main parts of the anaerobic process:

- how much energy is needed to heat the incoming sewage up to an appropriate level conducive to the bacteria, and
- how much energy results from actual digestion.

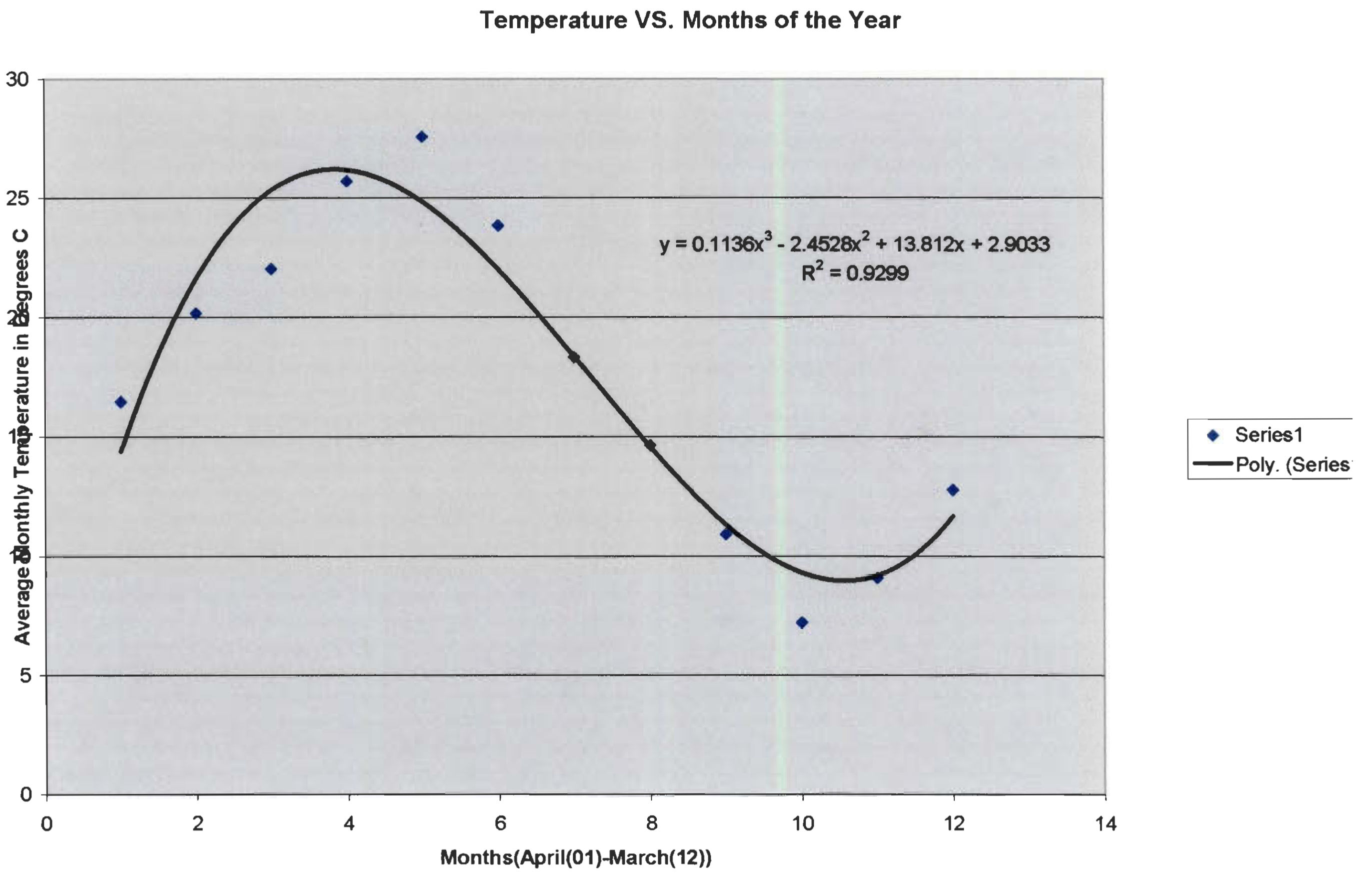
When analyzed, these variables combine to dictate the feasibility of running and maintaining a facility ran on the anaerobic process.

Beginning design of an anaerobic digestion plant starts by assessing the size of the population that needs to be accommodated. To define this variable, an analysis of what is trying to be accomplished with the plant leads us to the population that the plant is intended to work for. This is due to the fact that the heat analysis cannot be determined until the total amount of heat energy required to run the plant at any given time can be expressed and compared to the projected energy output of the facility. If the projected energy output of the plant is larger than the required input, based on a certain percentage inefficiency calculated, then the process is self-sustaining during that projected time interval. To decide this, a projection based on Bucklin Fields Waste Management Facility will be used in order to produce a more accurate representation of the first variable, Projected Capacity. The population that Bucklin Fields supports produces 65 million gallons a day (MGD) of waste. At this projected capacity, prototype digester tanks will have a volume of 16.5 liters in order to handle the amount of sewage that is going to be processed per day, and produce methane at a rate of 7.61 liters of methane per liter of digester space. These characteristics will result in a Hydraulic Retention Time (HRT) of 3 hours. For the purposes of design projection, a 100% safety factor will be used to compensate for any unseen influences, increasing the Hydraulic Retention Time from 3 to 6 hours. With these numbers, a projected capacity is established that will aid in determining the energy input needed to heat the sewage. The projected capacity variable also assists in calculating how large the reactor tanks have to be. This is accomplished by reducing the projected capacity of 65 million gallons per day into how many millions of gallons of sewage are treated during one HRT by converting the hours in a day to the number of HRTs in a day, then dividing the projected capacity by the number of HRTs. Even though the goal capacity of a 65 MGD plant is really only 45 MGD and is designed for 65 to handle overflow, the reactors should be oversized by 10-20%. We chose to oversize the reactors by 20% because this increased safety factor provides simpler calculations to carry through all of the equations. If, by chance, the design is too large because of the increased percentage, the worst that will happen is that there will be extra space in terms of tank volume. The projected capacity variable is now determined, which also gives us the total reactor volume, and when coupled with the hydraulic retention time, is an important base number to work out the other two main variables in the heat balance and energy economy equations.

Since the daily capacity has been established, we can derive the other variables and constants required to determine the larger variables: required daily heat energy and produced daily chemical energy. These two values and their ratio to each other are the sole variables that determine the economic veracity of the plant. The net amount of heat in is based upon the difference between reactor temperature and sewage input temperature. This needed heat is directly related to the conditions the bacteria sets need to be maintained at to sustain life. Most anaerobic digestion systems require a high temperature reactor, almost always between 35 and 58 degrees Celsius; however this particular reactor does not. This is due to two highly advanced factors of the machine:

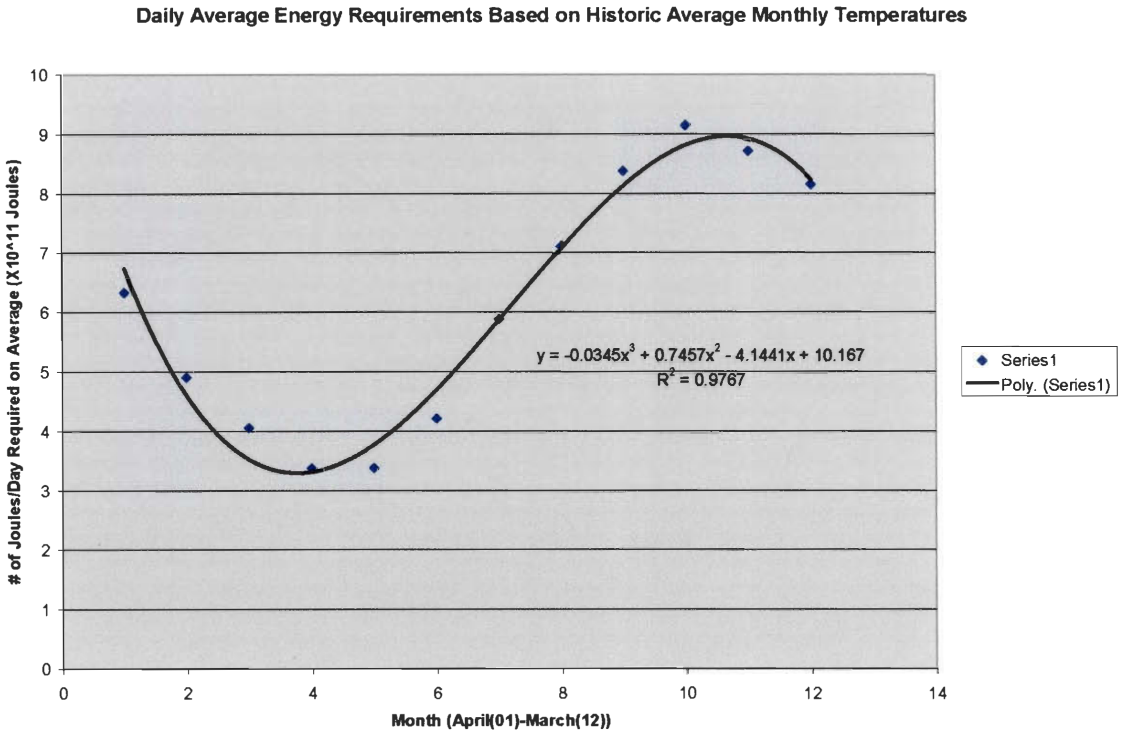
1. The reactor is computer controlled in real time so that it runs at nearly maximum efficiency all the time by monitoring and changing the nutrient and temperature levels.
2. The bacteria set used will be of the species Thermocellum Reesie which only requires an average temperature of 20 degrees Celsius, or 68 degrees Fahrenheight.

With this constant, the temperature of the sewage coming into the plant must be determined. To do this, the monthly average temperature must be combined with the average input temperature change for water, which is 7.22 degrees Celsius to 29.4 degrees Celsius. From this data can be gathered a linear interpellation graph, showing a range in the temperature per month in which a data point can be developed to produce the average pipe temperatures, based on how hot or cold the climate is outside the sewage pipe.

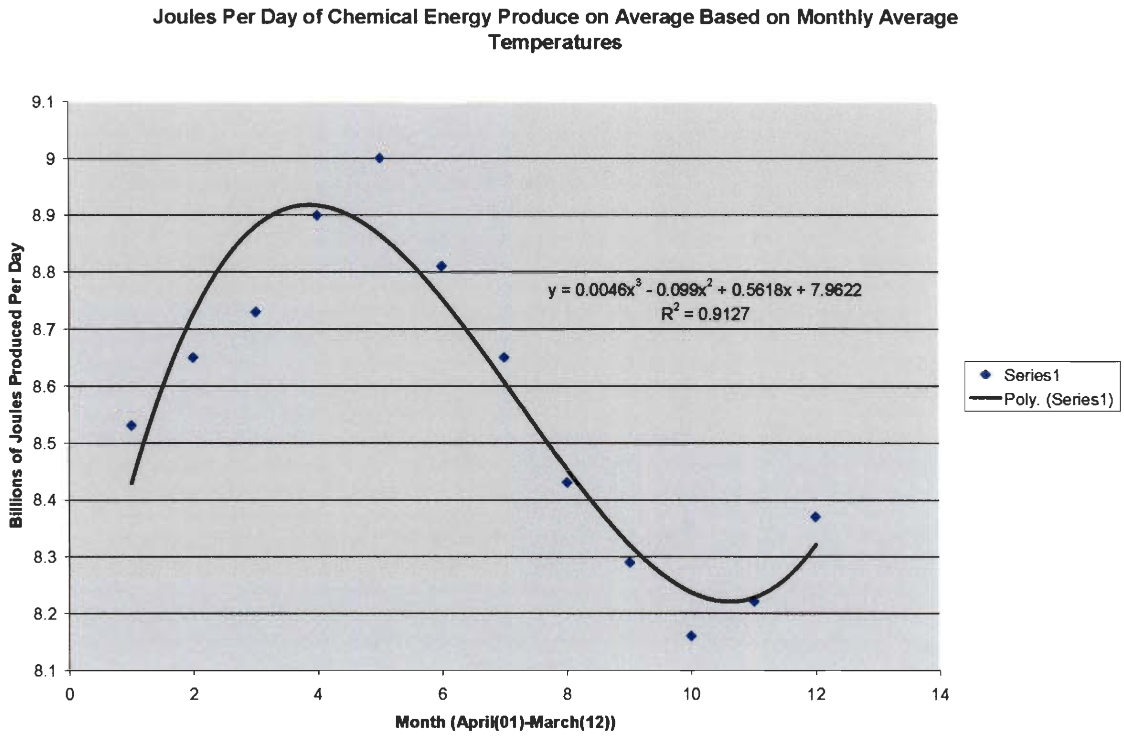


As seen by this graph, the temperature follows roughly a 3rd order polynomial curve. Since these data points are linearly interpolated, they are, of course, not actually a 3rd degree polynomial; however later sets of data do not follow a linear regression line closely, but do roughly follow the temperature curve of this original temperature graph. The later sets of data, with which it is far more important to have a more closely matching trend line, follow the 3rd degree polynomial much more closely.

By analyzing the temperature starting point of the sewage along with the final temperature point, a temperature shift requirement can be created that is the difference in temperature of the sewage from the temperature of reactor's required operating temperature.



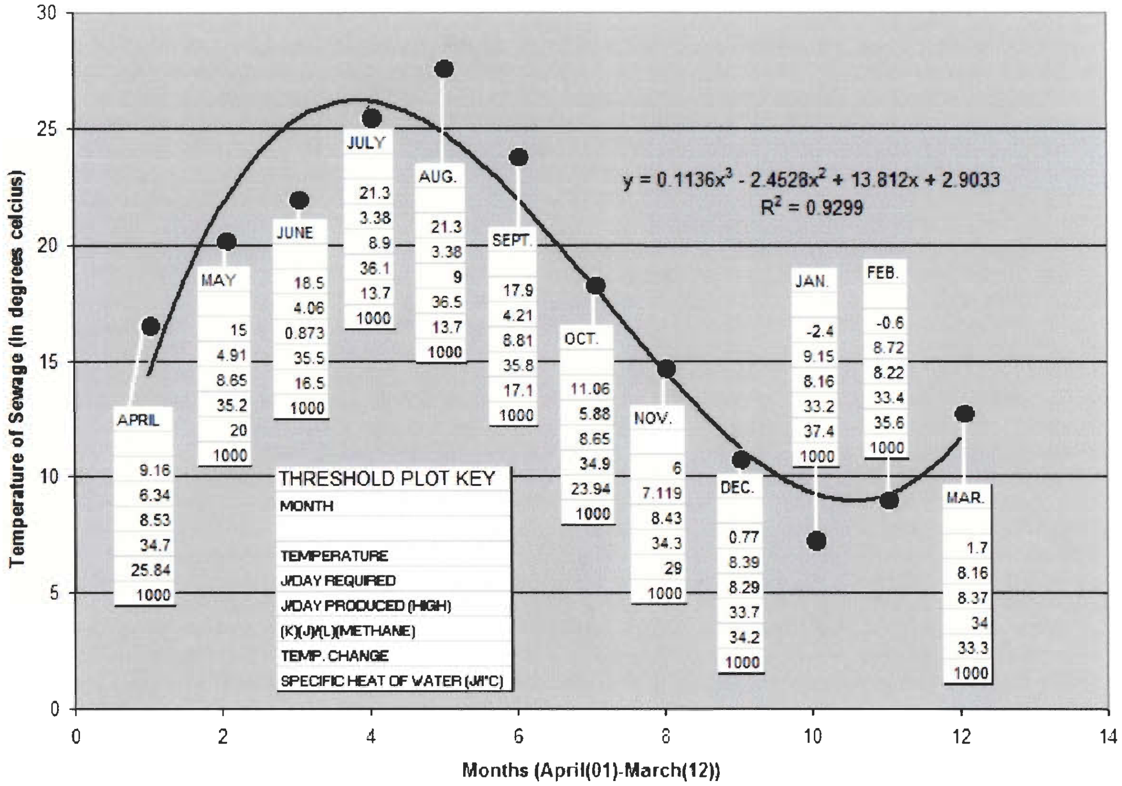
The values presented in the above graph represent the number of joules of heat energy that need to be added to the incoming sewage on an average day of each respective month. To explain this graph and how it was produced, we started introducing other constants and variables. The specific heat of water, though it changes with temperature, can be estimated as a constant due to the fact that it varies less than 0.2% over the temperature range we are considering, and it happens to be conveniently centered around 1000 J/Liter*Degrees C. The equation, complete with unit analysis of this combination of input temperature, specific heat, and reactor temperature, can be found in Appendix (D). To determine plant feasibility, there still needs to be an analysis of the heat requirement in terms of energy produced and whether or not the output can compensate for the required energy input to sustain the process. The required variables and constants for this chart include the following: the chemical energy content of methane in Kilojoules/Liter of gas at standard vapor pressure, the average incoming temperature of the sewage, the number of liters in a gallon needed to convert our projected daily capacity into the metric system which is much more readily used throughout the world, the number of liters of methane gas produced per flush per liter of reactor space which happens to be a constant once the plant reaches steady state, and judging from the fact that this is supposed to be the most stable system on earth, we assume it will, and finally, the conversion coefficient between joules and kW*h. The last constant is not used in this plot in particular, but is required to determine a rough estimate of the value of the leftover energy you produced. The previous constants and variables were used to determine the data points on the above plot, as well as setting up for completing the two large calculations to come: net energy surplus and energy surplus value.



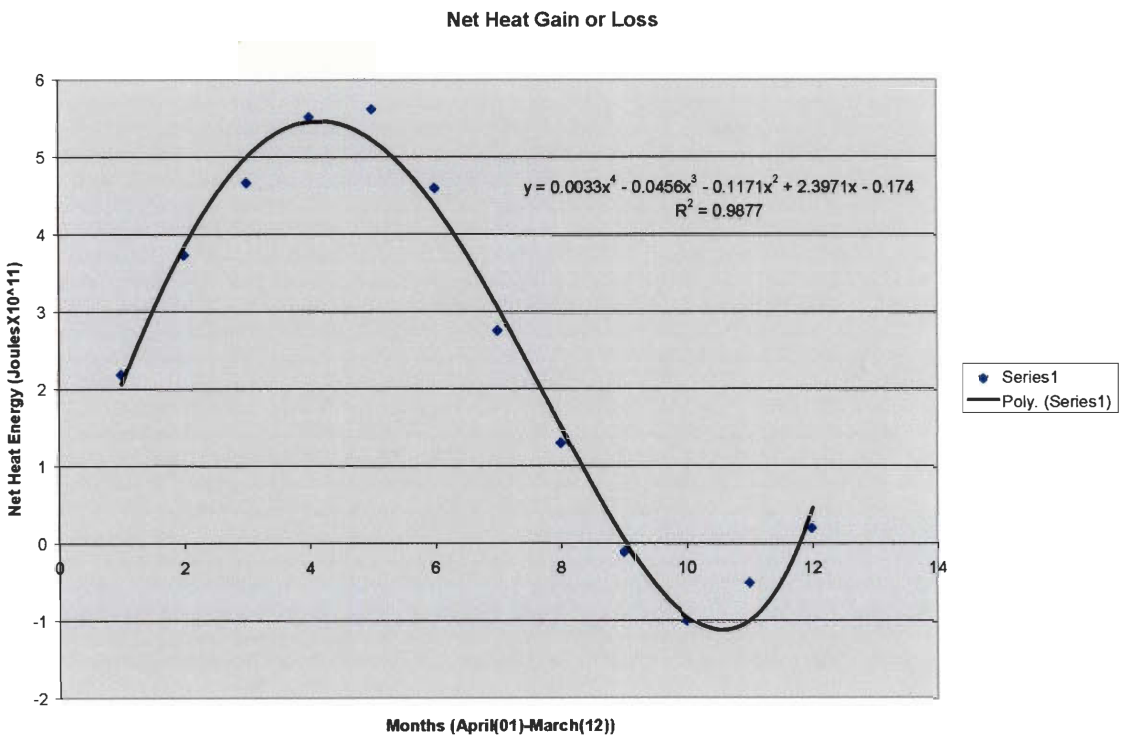
To name a specific value for the amount of chemical energy produced by the plant in methane with confidence would be nothing more than naïve and misleading. This process is simply too young and untested to be able to say for sure how it will perform on a large scale basis; however by scaling up the rates and values of Dr. Zhangs 1.8 liter prototype, might be able to acquire a good idea of the range of the reactor's output. The actual output will only be able to be determined with further prototyping. With this said, we will now move on to the energy production estimations presented in the above graph. The first thing to be discussed in assessing the energy production is, of course, converting all of the variables and constants into metric, since it is much easier to communicate with the rest of the world in metric, as well as, converting between units such as joules and kW*hrs. Once again, since the energy production is directly proportional with daily capacity and not flush or reactor sizes, we don't have to consider any calculations dealing with multiple flushes or separation of batches, we can simply use the projected daily capacity of 65 million gallons per day. Converting this into liters gives us 245 million liters per day. Using the tables in Appendix (D) we can fill in the entire heat production equation which is derived, once again, in Appendix (D). With the heat requirement variable and projected capacity variable established, all of the factors and constants have been considered. An examination of the data is now possible and design feasibility will be able to be determined in terms of heat energy input and output. All that must be done is to use the tables of values (chemical energy of methane<variable>, average monthly temperature<variable>, the number of liters per gallon<constant = 3.7843L/Gallon> and the number of methane gas produced per liter of reactor space<constant = 7.61L_M/L_R>). This variable layout is going to aid in streamlining the mathematical interpretation of the variables themselves.

The ultimate goal in determining the chemical energy produced per day, and the heat energy required per day is to figure out whether or not the plant is economically self-sustainable. According to our calculations, only during three months of the year does the required heat input exceed the amount of chemical energy produced, and in these three months, the balanced heat equations value is really rather close to zero considering the enormous amounts of energy it produces in its "hot season." Seasons are an important aspect when considering anaerobic digestion. They refer to the times when a reactor is self sustainable without stores of energy and when it is not. We have shown, that for our process, even with a safety factor of four times projected negatively impacting values, we have managed to bring our cold season down to just under three months. This is a very good length for a reactor cold season, especially considering the only other major plant actually existing to come close to that that actually exists has a cold season of almost 5.5 months. This plant is the Fields Point Plant, located in Massachusetts, but which is seriously subsidized by the government, and crippled as a viable business by their low methane conversion efficiency and really high HRTs <almost 2 weeks as compared to our 6 hours>). What is left is the required heat per day, which is in the range of (1.81) * (10^11) joules per day to (3.62)*(10^11) joules per day. With heat per day calculated, all of the variables and constants are compiled on a threshold graph. Going in the x direction of the graph will lead you along with the date, providing a monthly interpretation of the year. In the y direction the graph is defined by data points that include temperatures, joules per day required, joules per day produced, and the joules per day required. Combining these together with all the other data, variables, and heat plots for the input and output, will give a description of the threshold plot. This plot was designed to contain all of the important data points used in this section and providing them to the reader in a complete one page easy to follow graph. Please don't get us wrong, this graph is not meant to be read and understood by people who have not read our paper yet; a good understanding of the heat balance of an anaerobic system is required to understand anything of value from the plot. The plot is as follows, with the data key in the lower middleleft hand side of the center.

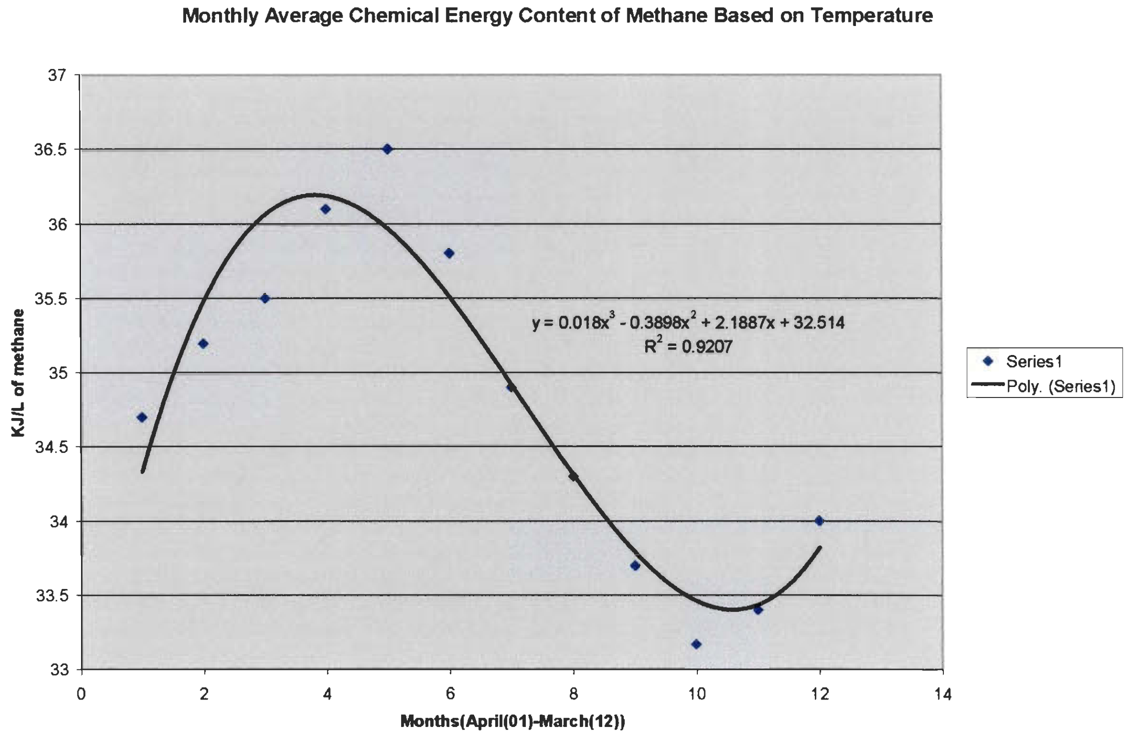
Threshold Plot (Month vs. Temperature w/A listing of Pertinent Data



The plant design is complete in terms of statistical data. Remaining to be done is to convert that data into a working projection by demonstrating what the data implies in terms of methane energy that is harvestable in terms of methane energy required to be stored or sold as futures in order to ensure the reactor will run through its cold season. The following is a graph of the total chemical energy produced minus the total amount of heat energy required to keep the system running.

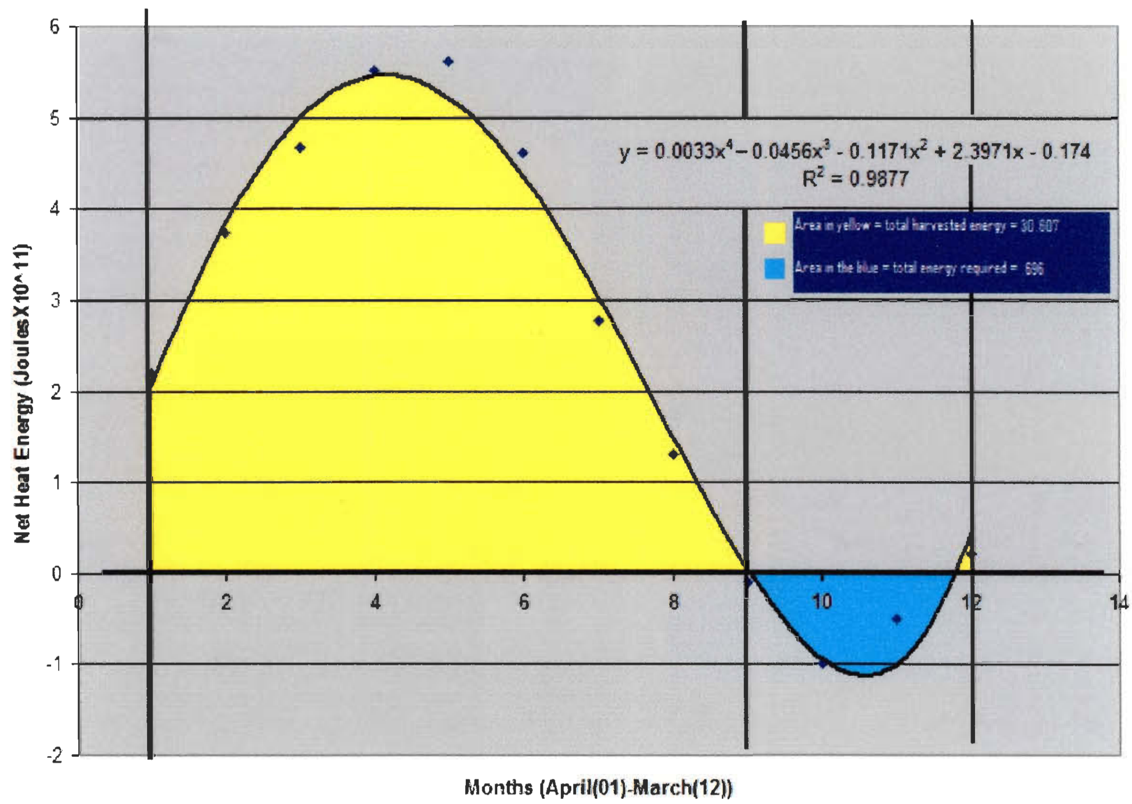


To determine the net methane of the facility, the sewage input in terms of liters per day must be multiplied by energy per liter of methane, and then, by multiplying this by liters of methane per liter of reactor space (7.61 liters of methane per liter of reactor space). Resulting is a range of methane energy produced, which is 8.892 * (10^12) joules per day to 8.015 * (10^12) joules per day.



As shown by all the data surrounding the implementation of the variables and the constants involved in the design process, the anaerobic based facility will work because the energy required to run the system is fully compensated by the energy produced, even greatly overcome. The next plot is a monthly time plot of the average daily chemical energy production minus the average daily heat energy required by the process. As you can see, the total average single day per month test, a total of twelve days per year is a reflection of the average heat requirements and energy production fluctuations that are inherent to the process with climate change.

Net Heat Gain or Loss



These 12 sample days can be multiplied by 30 to give a better picture of the massive year end productions of methane energy as compared to the heat energy required to be expended. The final values are as follows:

Chemical Energy of Methane Produced:	918.21 trillion joules
Total Heat Energy Used:	20.901 trillion joules
Total Energy Bottom Line:	897.309 trillion joules per year

This total year long energy balance clearly shows that the plant will theoretically produce, on average, almost 44 times more energy than it uses. This final heat balance analysis shows that if the process can be scaled up to this size while still keeping within the desired tolerances and constants used for this simulated model, it will not only be an economic success…it will be very financially profitable situation.

4.3.A The Current State of Anaerobic Digestion in the United States

In the United States, sewage treatment is a necessity that needs to be addressed. This makes sense for obvious reasons such as sanitation, health, and comfort. There are various techniques involved with the treatment of sewage. Newest and most efficient of these techniques is anaerobic digestion. In laymen terms, anaerobic digestion is the use of bacteria sets (different combinations of bacteria) to break down the sewage, or *digest* it, for the purpose of purifying it. Usually, when a process like this is employed, there are resulting byproducts due to basic mass and energy conservation laws because the laws simply state that mass and energy cannot be lost, but instead, are converted for the sake of conservation. In the case of anaerobic digestion, the byproducts resulting from the conservation laws are $CO2$, Methane, Hydrogen Sulfide, effluent water, digested bio-solids, and inorganic solids such as pebbles in a homogenous mixture with hard biological matter that can be easily converted into fertilizer. This equation of sewage and bacteria inputs and its resulting byproduct outputs is rather rare because it is not common for a process of this nature to output almost completely usable and even sellable byproducts. To understand the implications of this we will need to analyze the older, but much more prevalent method of sewage treatment.

For the last century, the U.S. has been employing sewage treatment techniques that have served their purpose for the most part. By understanding these older techniques, we will be able to make a comparative analysis to the newer technique of anaerobic digestion. One such older technique is the activated sludge process. Activated sludge is sewage that becomes sludge when you add the activating agents which are bacteria and other microorganisms. Using microorganisms and bacteria as activating agents breaks down sewage by using the sewage as an energy source in order to create new cells through synthesis. Resulting from this process are bio-solids that usually cannot be further broken down. Extended aeration is another older technique that is just an extension on the activated sludge process. The difference between the two is that extended aeration allows the microorganisms to break down the sewage for a longer amount of time, thus yielding a reduced bio-solid ratio once the process is complete. Since there are microorganisms and bacteria in the sewage, another method needs to be employed in order to further sanitize the sewage. This leads us to our next two currently used methods of water treatment, chlorination and de-chlorination. Chlorination is a stage in the sewage treatment process that involves introducing chlorine in order to disinfect the bacteria and other microorganisms. Because chlorine is harmful to any organic creature, another process needs to be implemented for the purpose of neutralizing harmful waste. De-chlorination is the name of this next technique, and all that it involves is the subtraction of the chlorine that still remains in the water. The combination of these techniques and some other ones is what gives us an overview of the main methods used today in waste management facilities. However, these processes are not terribly efficient, and have resulted in continued research for newer ways of sewage management.

The latest technique to be analyzed and deemed appropriate for the purpose of sewage treatment is anaerobic digestion. Due to the fact that the anaerobic process is relatively new, the implementation and facilities pertaining to it are still in their infancy. A direct reflection of this is the fact that there are only two completely anaerobic based facilities built in the United States, one in California and the other in Colorado. However, there are thousands of facilities that employ anaerobic methods into their waste water treatment processing plan at a comparatively smaller scale as they work on honing the new digestion process. These anaerobic methods are being updated at a rate that is going to allow them to be used on a larger scale in the immediate future. New bacteria sets have been discovered that allow for extreme efficiency outputs in terms of the energy used and the energy gained during the process. Overcoming the variables that dictate the net energy are the determining factors in calculating energy efficiency for the anaerobic process. It is only a matter of time until the newly discovered bacteria sets are fully ingrained into the current anaerobic process. When this occurs, the current state of anaerobic digestion will be the primary method in breaking down sewage at water treatment facilities. At the forefront, anaerobic digestion will make the previously talked about old methods that dominate the sewage treatment industry today obsolete. The main reason for this is that digestion accomplishes the same general task as the techniques currently being used, but is much more efficient. Also, the byproducts resulting from the anaerobic process supply enough energy to sustain the heat requirement of the facility performing the treatment and also generate an income revenue do to the selling potential of methane energy. As previously mentioned, only two completely anaerobic based waste water treatment facilities exist in the United States. This is soon to change because new bacteria sets, such as Thermeccullum Reesie, are the answer to the current digestion problem, which is cost efficiency.

4.3.C Electrical Potential Assessment

Demonstrated in the plant construction analysis (section 4.3) is the ability of an anaerobic digestion plant to output methane as a byproduct. Consequently, from this energy output can be derived chemical energy content which can be further converted into electricity. Thus arises a situational potential for an anaerobic digestion facility to input waste and output financially prosperous electricity. To accomplish this, a generalized equation set to carry the calculations through must be implemented. Comprising these calculations are factors such as the chemical energy content of methane created by the facility, electrical generator inefficiencies and transfer equations, and the potential selling price of electricity. As mentioned, the combination of these aspects will reveal a generalized financial equivalent based upon the facilities electrical production.

To initiate the financial prospect process, the chemical energy content of methane output must be determined, which has already been done in section 4.3, and is in the range of 8.892 * 10^12 joules per day and 8.015 * 10^12 joules per day. An average of the two, which is 8.454 * 10^12 joules per day, will be sufficient enough for our analysis once it is converted to joules per hour, which is 3.523 * 10^11. Needing to be equated next is the average efficiency of a gas generator. A natural gas generator with an average of 86% efficiency based upon the currently most technologically advanced generator will serve as the model by which to convert energy to electricity. A generator of this type requires 3.6 * 10^6 joules to create one kilowatt hour. All factors thus far considered, [(3.523 * 10^11 joules/hr)/ ((3.6 * 10^6 joules/1 kilowatt-hour) = (97,861.111 kw/1 hour). Then multiply (97,861.111 kw/1 hour) by 86% efficiency and that is the final total watts per hour produced by a methane to electricity generator, which is 84,160.556 kilowatts per hour. Before continuing, a population in terms of location must be chosen. This allows for more realistic electrical rates to be utilized for furthering our purpose. Assessing this situation is therefore dictated by Rhode Island's electrical rates due to our already chosen facility location. Regular going rates of electricity in R.I. are 6.23 cents/ kilowatt-hour. However, due to the nature of our environmentally friendly (very few environmentally unfriendly by-products after digestion) electrical source, people will pay a premium rate, which is 8 cents/hr. To compensate for this range in rate, an average of 7.115 cents/hr will be used. Lastly, we must simply multiply our rate of 7.115 cents/hr by 84,160.556 kilowatts per hour produced yielding a product of 598,802 cents per hour, which equals $52,455,086.38 per year. A cost deduction of an indeterminate amount must be made to alleviate the money required to remove impurities from the methane, such as 0.4% HSO4 and volatile organic chemical alcohols. Without this deduction however; $52,455,086.38 per year is our final amount of money made from the conversion of the methane by-product to electricity as a result of the anaerobic digestion process.

4.3.D Appendix D

Appendix D is designed to function as a reference guide for section 4.3 Construction Plan; containing equation sets, data tables, and diagrams that will serve as useful verification points in regards to the literature derived from them. Starting the appendix are the equation sets pertinent to the statistics contained within section 4.3.

Input Capacity Conversion Equation Set

(65 mg/d) * (1 d/24hrs) * (3 hrs/flush) = (8.125 mg/flush)

Heat Energy Requirement Equation Set

Lower Heat Requirement = (65 mg/d) * (3.7843 l/d) * (9945 J/l°C) * (5.6°C) = *(3.62 * 10^11 J/d)*

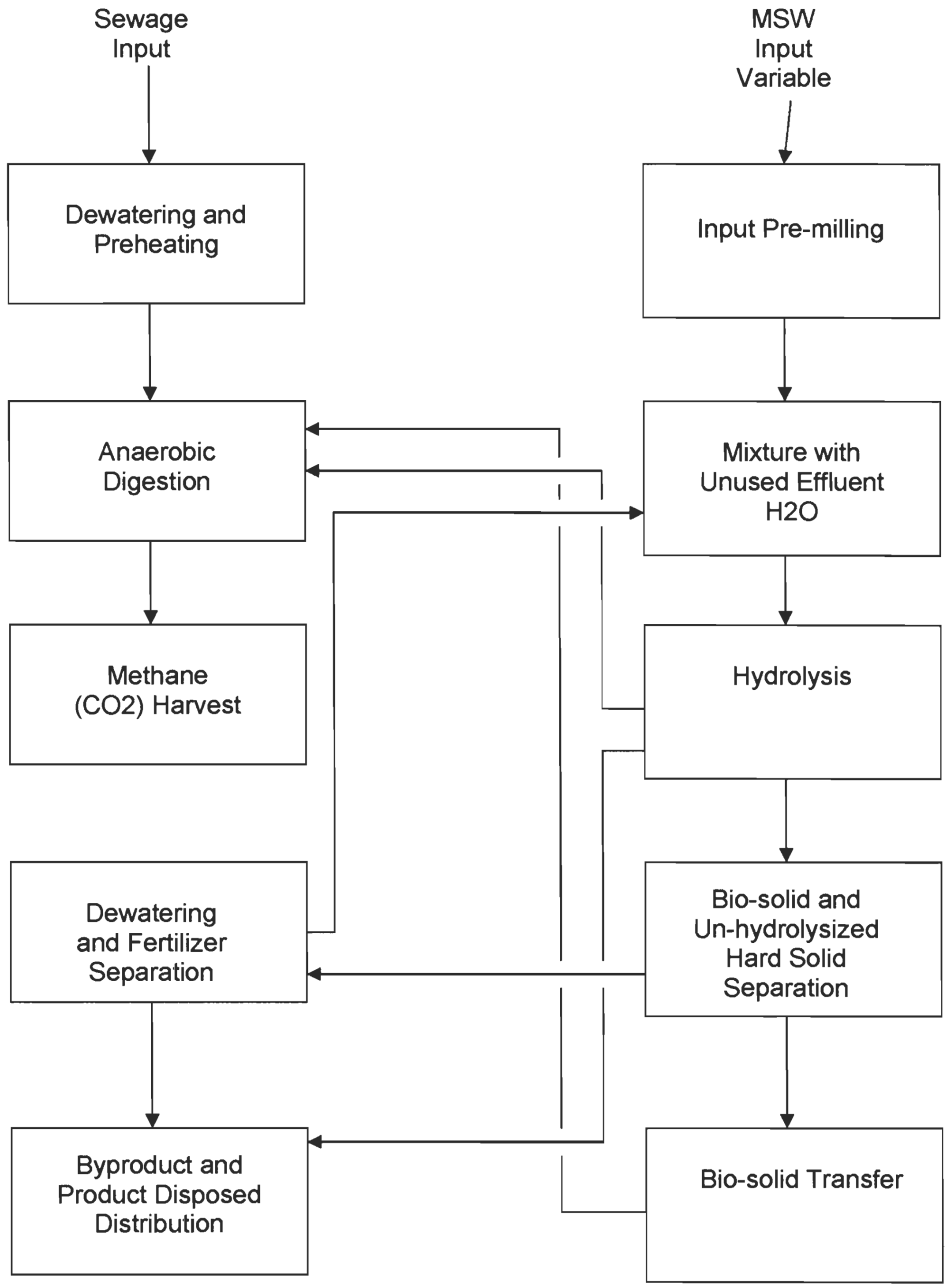
Upper Heat Requirement = (65 mg/d) * (3.7843 l/d) * (1003 J/l°C) * (27.78°C) = *(1.81* 10^13 J/d)*

Chemical Energy Output Equation Set

Upper Energy Requirement = (65 mg/d) * (3.7843 l/d) * (36.5 kJ/l of methane) = (8892.84 mkJ/d) = *(8.89284 * 10^12 J/d)*

Lower Energy Requirement = (65 mg/d) * (3.7843 l/d) * (32.9 kJ/l of methane) = (8015.74 mkJ/d) = *(8.01574 * 10^12 J/d)*

Below is a projected process flow diagram of an anaerobic based facility. There is great importance in creating a projection that serves as a layout for determining the sequential order of processes. The format resulting from the diagram will dictate the anaerobic facility's physical blueprint and act as a guide in the design procedure.



The process flow diagram entails many of the same characteristics as a process flow diagram for a current waste management facility such as, input pre-milling, mixture with unused effluent H_2O, hydrolysis, bio-solid and unhydrolysized hard solid separation, bio-solid transfer, and dewatering. Also, contained in the process flow diagram of an anaerobic facility are the steps involving the anaerobic process. As shown here, after the normal bio-solid treatment procedure hydrolysis is complete, the remaining product can then be processed through anaerobic digestion tanks to further break down the bio-solid into a usable byproduct. Likewise, incoming sewage can now be directly fed into the anaerobic tanks. Due to the nature of the anaerobic process, a much more efficient procedure for breaking down the sewage is being used, thus providing a drastically better output ratio of untreatable substance. Demonstrated in the diagram and talked about previously are two main anaerobic factors: the incoming sewage is immediately treated by digestion, and treated bio-solids can be further processed after hydrolysis by digestion.

Lastly, for Appendix D, are the data tables referred to in section 4.3 Construction Plan. Below are self titled data tables that require no explanation due to the fact that they are simply data tables, or collections of statistical characteristics and calculations.

Threshold Plot													
	DATE	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.
TEMPERATURE		9.16	15	18.5	21.3	21.3	17.9	11.06	6	0.77	-2.4	-0.6	1.7
J/DAY REQUIRED		6.34	4.91	4.06	3.38	3.38	4.21	5.88	7.119	8.39	9.15	8.72	8.16
J/DAY PRODUCED (HIGH)		8.53	8.65	0.873	8.9	9	8.81	8.65	8.43	8.29	8.16	8.22	8.37
(K)(J)/(L)(METHANE)		34.7	35.2	35.5	36.1	36.5	35.8	34.9	34.3	33.7	33.2	33.4	34
TEMP. CHANGE		25.84	20	16.5	13.7	13.7	17.1	23.94	29	34.2	37.4	35.6	33.3
SPECIFIC HEAT OF WATER		1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
(J/(L*C))													
Monthly Required													
Heat													
	DATE	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.
JOULES PER DAY		6.34	4.91	4.06	3.38	3.38	4.21	5.88	7.119	8.39	9.15	8.72	8.16
Methane Chemical													
Energy Constant													
Per Month	DATE	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.
(K)(J)/(L)(METHANE)		34.7	35.2	35.5	36.1	36.5	35.8	34.9	34.3	33.7	33.2	33.4	34
Chemical Energy													
Produced Monthly													
	DATE	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.
JOULES PER DAY		8.53	8.65	0.873	8.9	9	8.81	8.65	8.43	8.29	8.16	8.22	8.37
Monthly Average													
Temperature													
	DATE	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.
DEGREES CELSIUS		16.47	20.17	22.02	25.7	27.6	23.9	18.32	14.62	10.9	7.22	9.07	12.8