ANALYSIS OF SOLAR THERMAL ENERGY AS A HEAT SOURCE FOR BIOREACTORS IN COLD CLIMATES: A CASE STUDY

A Thesis
by
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ABSTRACT

ANALYSIS OF SOLAR THERMAL ENERGY AS A HEAT SOURCE FOR BIOREACTORS IN COLD CLIMATES: A CASE STUDY

(May 2010)

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Two pilot-scale bioreactors were built to test the feasibility of using solar thermal heat as a means of heating in the process of anaerobic digestion. One 175-gallon bioreactor was built using an electric hot water heater as a heat source that provided a constant temperature of 95°F. An identically sized bioreactor was constructed that used heat from a 4x8 solar thermal panel. In the solar heated bioreactor the process of thermosiphoning was taken advantage of to eliminate the need of electrical inputs, such as a pump. During a 25-day test performed in March 2010 in Boone, NC, the bioreactor heat loss due to feedings and ambient air temperatures was greater than heat input from the solar panel over the given experimental period. Although the two bioreactors produced similar amounts of gas during the first 10 days of the experiment, a week of cloudy weather followed and the solar-heated bioreactor fell far behind the control bioreactor in gas production. Over a period of 25 days, the solar panel heated bioreactor only produced 285 gallons of biogas, while the control bioreactor produced 1100 gallons of biogas.

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This work could not have been accomplished without the help of my family, friends, and colleagues. My parents and family have shown an incredible amount of support throughout the last two years of my career as a graduate student. My father, Bill Dowell, and my brother, Luke Dowell, even made a trip to Boone to help me work on modifications to the systems over the Christmas holidays. We spent several long days in sub-zero temperatures preparing the two bioreactors for the formal experiment. My mother, Patricia Dowell, has also been a great source of encouragement and kind words during stressful times.

My friends and colleagues were of immeasurable help throughout this work. Erica Porras and Brian Johnson were with me every step of the way during the design and building of the bioreactors. My involvement in their previous study of biogas and its implementation in algae bioreactors had actually been my first exposure to bioreactors. I give them full credit for revealing to me this technology that I have ended up studying in my thesis research. My roommate Eric Urban and his training as a mechanical engineer have been of great benefit to this research. He spent many sleepless nights helping me work out bugs in the Labview software that controlled and measured data in both bioreactors. Anytime I asked for help, regardless of time and circumstance, he was always willing to stop what he was doing and give a hand.

I also owe much gratitude to my thesis committee for all of their input and help throughout this work. Dr. Marie Hoepfl and Dr. Brian Raichle, in particular, were at my side from the conception to the end of this research. I could not have completed this work without their advice and direction over the past two years.

In the past several weeks I have received some input on my study from David House, author of the *Biogas Handbook*. Although I have assaulted him with numerous questions that required time-consuming and thoughtful answers, his replies were always prompt and lengthy. I am appreciative that he found the time to give insight to my many inquiries; any inaccuracies in interpretation of his input are my own.

I would finally like to give thanks to my cousin and best friend Jason Mansur Dowell. My family and I lost him to brain cancer this past June. Since I could walk, he was my closest friend and confidant. Even when he was fighting for his life, he always gave me his support and assured me that what I was doing was meaningful and worthwhile. I dedicate the countless hours I have spent on this research to him.

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CHAPTER 1

INTRODUCTION AND OVERVIEW

Introduction

Bioreactors are vessels that use anaerobic bacteria to convert organic material into methane gas for fuel. This process is called anaerobic digestion (AD). The vessel used to foster this process may be called an anaerobic digester or a bioreactor. Warm temperatures are required to enhance the methane-producing activity of the bacteria. Electricity, oil, or some of the produced methane is generally used to maintain a proper temperature for methane production. Heating requirements for small-scale bioreactors have hindered their use in cold-climate regions.

In cold climates, small bioreactors sometimes require so large a heat source to support necessary bacterial growth that burning the acquired methane or using fossil-fuel derived heat-sources renders them unfeasible as a viable energy source (Dai, Chun, Xu, & Wang, 2005). In cold climates, heating the digesters can be difficult and there can be instability in the AD process, creating lower methane yields (Cavinato, Fatone, Bolzonella, & Pavan, 2010). Fry and Merrill (1973) noted that it is common to use 30% of a digester's generated methane as a heat source to maintain an appropriate temperature for optimum biogas production. Fischer (1979) found that when using conventional methods for heating a small-scale bioreactor in a cold climate in December, the bioreactor became a net user of energy. Implementing solar energy to heat small-scale bioreactors is a technique that could enhance the viability of AD. This strategy, if proven sufficient, could make the construction and use of bioreactors more feasible in more parts of the world.

Cheap energy is becoming a scarcity and AD may be a source of energy that could be utilized on a small-scale if an efficient design is developed, tested, and proven to be economic. The diversion of waste-streams into energy through AD should be considered as an option for communities throughout the world. Developing nations and self-reliant households and communities in developed countries that are located in cold climates could find a greater feasibility in the AD process for energy needs if a non fossil-fuel heat source can be obtained.

Aside from generated energy, benefits of AD include production of digestate that can be used for fertilizer, reduction in greenhouses gases by offsetting use of fossil fuels, and reduction of odors and flies around livestock fields (Minnesota Department of Agriculture, 2005). Many farms digest their manure anaerobically and release the methane to the environment (Westerman, Veal, Cheng, & Zering, 2008), contributing to greenhouse gas emissions. Capture and use of methane as a fuel inhibits its escape to the environment, where it has 21 times more global warming potential than does carbon dioxide (Balsam, 2006). AD has been given considerable attention in the scientific community, yet most research has neglected the use of alternative heating systems for small anaerobic digesters in cold environments.

Statement of the Problem

There is a lack of literature on appropriate technologies for small-scale AD in cold-weather climates. If a suitable heat source is proven effective, the use of bioreactors for energy production in cold climates should be considered in many areas of the world where temperature requirements have inhibited their implementation.

Literature on this subject is limited and varies in findings. Detailed studies of small-scale cold-weather bioreactors that require no energy inputs from pumps or heaters have either not been published or are so obscure that they cannot be found. There is research on the phenomenon of thermosiphoning in solar panels and there is limited research on solar heating for bioreactors. However, no evidence was found of research that analyzed the use of solar energy for heating in AD systems without the use of a circulation pump. All related research speaks of the use of a pump for circulation between the solar panel and the heat exchanger within the bioreactor, thus detracting from the net energy gained from the system.

Particularly in developing countries with cold climates and no available grid-source energy, a pumpless system, if proven to work, could be the determining factor in the acceptance and use of these systems. Areas in milder regions of the world using bioreactors might also find an improvement in the efficiency of their systems if solar heating is implemented.

Purpose of the Research

The purpose of this research was to determine whether a thermosiphoning solar panel can adequately heat a bioreactor in a cold-weather climate. Two identical bioreactors were constructed, one having an electrical heat source and one using solar energy for heating. By testing the constructed systems in a climate with high winds and significant wintry precipitation (Boone, North Carolina, USA), differences in methane production between the bioreactors were determined. Also, the continuous operation of this system yielded data that can be shared with others and provided a meaningful learning experience regarding other aspects of AD system design that can be used for improving small-scale bioreactors for use in cold regions.

Research Questions & Hypotheses

Research Questions

The primary research question was whether a thermosiphoning solar thermal system can serve as a substitute heat source for a bioreactor without decreasing gas production, as compared to a conventionally heated system. Sub-question 1 was: How will the inevitable temperature fluctuations in the thermosiphoning solar thermal system affect the performance of the experimental bioreactor in comparison to the conventionally-heated system? Sub-question 2 was: For how many days can the solar-heated bioreactor maintain sufficient temperatures to produce methane, in the absence of steady daily sunlight?

Research Hypotheses

H_1: A thermosiphoning system on a solar thermal heated bioreactor will provide adequate heat for continued methane production unless there is a period longer than seven days with no steady sunlight.

H_2: In a given experimental period with sufficient daily sunlight, output from the experimental bioreactor will be no more than 25% lower than gas output from the control bioreactor.

Limitations of the Research

The primary limitation of this research is related to its case study design. The AD systems that were constructed, operated, and monitored, by their nature, involve a large number of variables (e.g., ambient temperatures, insolation at this particular site, use of multiple feedstocks, and dozens of system components) whose interactions could not be controlled. Although care was taken to create comparable side-by-side systems and to establish controls to the extent possible, the case study design means that no broad generalizations about AD can be made based on the findings of this research. Nevertheless, these preliminary findings may be useful to others interested in small-scale AD systems incorporating a passive solar thermal heat source. Additionally, I have attempted to provide sufficient detail about the design of these systems so that others can benefit from the lessons I learned about their construction and operation.

A second limitation involves the lack of modeling of the built system. An examination of the literature on AD reveals many studies that involve system modeling using no empirical data. There are many variables that affect research findings on AD and gas production. These variables include temperature, feedstock materials used, their solid content, hydraulic retention time (HRT), and mixing, among other things. Field-based research that documents these variables and records methane production can provide a necessary foundation for other researchers dealing with AD system design variables and their effects on methane production.

This study involved the observation and recording of multiple phenomena, including thermal and gas qualities within the system. Wind speeds were not recorded during the study and they surely have an impact on the temperature within the tanks. It should be noted that collected data did not take wind speed into account when observing temperature changes within the bioreactors.

The feeding times for the bioreactors were primarily based upon solar cycles and administering slurry to the bioreactors during periods of high irradiation, when the solar bioreactor could recover from the resulting drop in temperature from the cold slurry. The feedings were also somewhat based upon the constraints of my schedule as a graduate student conducting this experiment in an off-site location. A more regimented feeding schedule would have been preferable.

Significance of the Study

This study is significant because the research involved the construction and testing of a novel bioreactor. A thermosiphoning solar-heated bioreactor could provide energy to many households located in cold climates that could use the gas generated for heating and cooking needs. Rural areas without grid power in developing nations would be the greatest benefactors of this technology if it is proven feasible. Observations of this novel design rendered data that may be a platform for others in the pursuit of a passive solar heating system for bioreactors. Finally, this study integrated three appropriate technologies whose combined use may not have been sufficiently explored before. These included AD, thermosiphoning, and solar thermal technologies. The marriage of these technologies may further the pursuit of new non-fossil-fuel energy source technologies, while simultaneously diverting waste streams.

Definition of Terms

Anaerobic Digestion (AD) - Process by which anaerobic bacteria consume biodegradable material in the absence of oxygen.

Biogas - The gas that is produced by the AD process.

Bioreactor - A vessel that is used to foster the growth of AD bacteria for the production of biogas.

Digestate - The dried effluent, which can be used as a high-grade fertilizer.

Effluent - The digested liquor that exits a bioreactor when new slurry is introduced.

Feedstock - The biodegradable part of the biodigester slurry.

Hydraulic Retention Time (HRT) - The amount of time that a chosen slurry is left within the bioreactor.

Influent - Slurry that is loaded into a bioreactor for digestion.

Inoculation - Introduction of populations of AD bacteria to a bioreactor for startup of the AD process.

Irradiance - Refers to the power per unit area of electromagnetic radiation falling on a given surface.

Methanogenic Washout - A state where a bioreactor has too low an HRT or too low a temperature, which inhibits the processing of volatile solids and lowers the methanogen population, thus halting the AD process.

Slurry - The mixture of biodegradable substances and water that is fed to a bioreactor.

Steady State of Operation - A state where a bioreactor steadily produces a consistent amount and composition of methane.

Thermosiphoning - Heat exchange where natural convection circulates liquid without the need of a mechanical pump.

Total Solids (TS) - The dry weight of an organic substance after drying.

Volatile Solids (VS) - The organic matter within the feedstock that produces the biogas.

CHAPTER 2

LITERATURE REVIEW

A review of literature on AD reveals research findings that vary greatly. Bioreactor designs and information on how AD bacteria operate are clear-cut, while findings on methane yields and their relationship with bioreactor temperature and different feedstocks are diverse. This may be because variables affecting the AD process are many and difficult to control. These variables fundamentally involve the bacteria's exposure to different temperatures and feedstocks, as well as factors related to bioreactor design. For example, Fischer (1979) claims that methane produced from a bioreactor depends upon ambient temperature, amount of agitation of the slurry, and the amount of insulation surrounding the bioreactor.

There is certainly a lack of published research on alternative heating methods for small-scale bioreactors in cold climates. Small-scale bioreactors are generally not found to be economically feasible in industrialized nations. This may be because small systems are rarely constructed in cold weather environments and many industrialized nations are located in cold areas (Gell, 2008). Warmer climates are found to be better suited for AD. This is because bioreactors require a warm internal temperature for optimal performance. Developing countries in warmer climates have been the predominant users of AD technology on the small scale. Developed nations and developing countries in cold climates could find AD to be a valuable fuel source if an alternative heat source can be found to foster the AD process. Solar thermal technology may be a viable source of heat for small digesters, but to date little research has been undertaken to evaluate their use for this type of application.

The Anaerobic Process and Its Benefits

AD is a naturally-occurring phenomenon in areas such as marshes and bogs, as well as in landfills and human-made bioreactors that convert organic waste into gas. Typical organic waste sources include manure, municipal solid waste, and wastewater (Buekens, 2005). Burke (2001) found that the efficiency of AD can be characterized by several factors. These include the feedstock, its concentration and temperature, the presence of toxic materials, pH and alkalinity, hydraulic retention time (HRT), and the ratio of food to microorganisms.

The AD process involves the decomposition of volatile solids in the absence of oxygen (Balsam, 2006). Volatile solids (VS) are the biological ingredients of carbon and nitrogen that are the source of biogas production. The carbon/nitrogen (C/N) ratio of a feedstock is another parameter that affects the performance of the anaerobic digestion process. Bacteria in both the aerobic and anaerobic process use around 30 carbon atoms for respiration and body building for every nitrogen atom that is used (House, 1981). The most efficient digestion occurs with a carbon to nitrogen ratio of between 15:1 and 30:1. Most animal manures are in this range and do not require adjustments before being fed to a bioreactor (Balsam, 2006). In AD, when the C/N ratio is too high, larger amounts of CO_2 will develop in the gas. This lowers its heat content and energy content. As a whole, however, the C/N ratio is not a critical parameter, because a wide variety of C/N ratios can promote biogas production (House, 1981).

AD takes place in several stages (Balsam, 2006; House, 1981). Hydrolysis is the first stage of anaerobic digestion. In this stage solids are broken down into soluble monomers. This stage can use separate aerobic, thermal, chemical, or enzymatic means. A warm environment is required for breaking down these solids (Hessami, Christensen, & Gani, 1996). Acidogenesis is the second stage, where acidogenic bacteria break down solid waste into simpler molecules. This produces acetic acid or volatile fatty acids. Gases produced during this stage are ammonia, carbon dioxide, and hydrogen sulfide. Other compounds produced include short-chain acids and alcohols. The concentration of these substances differs depending upon the bacteria present, as well as the temperature and pH of the slurry within the bioreactor (Buekens, 2005; Dearman, Marschner, & Bentham, 2005).

Methanogenesis is the last step, which yields the desired methane for capture and use as a fuel source. Bacteria called methanogens produce methane, CO_2, and minute traces of hydrogen and hydrogen sulfide (House, 1981). Methanogens are known to develop very slowly, and can fail to adapt to changes in their environments. When organic material is turned into organic acids, the pH of the system will drop. This is advantageous for the acid-forming bacteria. The methanogens, however, prefer a neutral pH, and if the pH falls below 6.0 they will die. The complex interactions between the numerous bacteria must be monitored to ensure that the digestion process is running smoothly (Buekens, 2005).

Frear, Fuchs, and Wallman (2004, p. 20-21) state the chemical reaction for AD as being:

$$\text{Organic Matter} + H_20 + \text{Bacteria (Acidogenic/Methanogenic)} \rightarrow$$

$$CH_4 + CO_2 + NH_3 + H_2S$$

There are two types of methanogenic bacteria that form usable amounts of methane in the digestion process. These two bacteria work at different temperatures. Thermophilic bacteria are most active in temperatures that range from 120-140 ºF.[1] These bacteria generate methane faster than any other bacteria. A system incorporating these bacteria for digestion

[1] Henceforth, temperature units presented will correspond to those used in the referenced works. Discussion of original research will give temperature units in degrees Fahrenheit.

requires large heat inputs to maintain a stable environment for maximum methane yields. Thermophilic bacteria are said to be less stable and more sensitive to temperature change than mesophilic bacteria (House, 1981). Because of the high temperature needed, thermophilic digestion requires more energy and is more complicated than mesophilic digestion (Angelidaki & Ellegaard, 2002). Some research indicates that thermophilic digestion may have the ability to destroy more pathogens than mesophilic digestion. There is also a faster processing of the feedstock, which enables the bioreactors to be smaller (European Anaerobic Digestion Network, 2005).

Mesophilic bacteria are most commonly used for AD in both small and large systems (House, 1981). These bacteria produce biogas in temperatures between 90 ° and 110 °F. These bacteria are commonly said to produce the highest methane levels at a temperature of 95 °F. A stable temperature is essential for optimum methane production. A 20 °F drop from that optimum temperature will inhibit gas production by up to 50% (Dearman et al., 2005). Even a 5 °F drop in temperature can reduce methane-forming bacteria in a bioreactor (Balsam, 2006).

There is value in the digested solids left over after the AD process has finished. This product, known as digestate, can be dried and used as fertilizer. The digestate has no odor after it has been properly processed. Yielding fertilizer enhances the desirability of AD to farmers who raise livestock and grow products for market in their fields (Koelsch, 2009).

Use of Anaerobic Digestion Throughout the World

Bioreactors have been used for thousands of years, by the Chinese, Assyrians, and Persians. Archeological evidence has identified the use of bioreactors before the beginning of the Christian era (Mattocks & Wilson, 2005). Many ancient cultures observed the existence of dancing flames over marshes emitting biogas from decaying matter. Some claim this promoted the myth of dragons (Gunnerson & Stuckey, 1986). In the late 19th century, biogas was used to light the streets of England. Bioreactors have also been used for many decades in Central America, South America, India, and Thailand to generate cooking fuel (Friends of the Earth, 2007). China and India have millions of village-scale bioreactors in use (Misi & Forster, 2001). Hundreds of small systems also made their way into underdeveloped communities in Europe throughout the 1970s (Balsam, 2006).

Although there are many large-scale anaerobic digestion (AD) systems used in developed nations and many small-scale systems used in developing nations, small-scale anaerobic digesters are uncommon in developed countries. Developing nations in cold climates have primarily not adopted AD, due to the heat requirements needed for a productive bioreactor (Nazir, 1991).

Large-Scale Anaerobic Digestion in Europe

European countries dominate the large-scale AD industry and have turned to this technology for waste diversion. Power generation is a secondary benefit, while waste stream management has been a focus due to the dwindling availability of landfill space. Treatment of food waste in the AD process prevents overloading of landfills, while at the same time offsetting greenhouse gases and producing energy. In these regions bioreactors have evolved from a focus on power generation into a waste management technique that pays for itself (Mattocks & Wilson, 2005). European nations anaerobically digest around four million tons of organic wastes each year (Neves, Goncalo, Oliveira, & Alves, 2007).

Taiwan, India, and Central America have all been using small bioreactors for some time. Particularly in rural areas, the use of bioreactors provides fuel for cooking (Lansing, Botero, & Martin, 2007; Nazir, 1991). In the Czech Republic there are numerous community-scale systems that process manure in a batch system. Remote areas of the Italian Alps utilize bioreactors for generation of fuel. Beni et al. (1994) claim the mountainous terrain of these regions prevents grid power from being installed economically.

Although India has used rural bioreactors for fuel for some time, the push towards urban use has been the current trend. The Appropriate Rural Technology Institute (ARTI) is installing small biogas plants in urban areas that use food waste as the sole feedstock. Over 700 of these systems are currently in use. The methane content of these bioreactors is very high and the retention time of the food waste is low, resulting in a system that creates household cooking fuel for homes in rural areas that do not have manure as a feedstock resource (Appropriate Rural Technology Institute India, 2006).

Bioreactor Designs

Small-Scale Bioreactors

There are countless types of small-scale bioreactors, and their designs vary greatly. A covered lagoon design is popular for use with manure in households of developing countries in Central and South America, as well as in Taiwan. Covered lagoon digesters consist of a flexible plastic cover that expands when gas is produced. These systems are usually used in warm climates for year-round gas production. This scenario requires no mixing of the feedstock (Lansing et al., 2007).

In Nazir's (1991) comprehensive overview of rural biogas systems, the following small-scale systems are described. In Thailand, rural areas utilize a bamboo ring packed-bed bioreactor. The Koreans implemented a low-cost bag digester constructed from masonry materials and topped with a removable polyvinyl chloride (PVC) sheet. A haplon bag bioreactor lined with rubber was developed in Taiwan. This technology uses a plastic bag for gas storage. The Indian biogas plants are generally built from brick and incorporate a steel drum that floats on the slurry for storing biogas.

The Chinese have used the floating dome system with great success for many years. A floating dome mounted on the holding tank rises and falls with the pressure of the generated methane. The dome provides resistive pressure that enables gas flow to the cooking source within the home (House, 1981). The Chinese bioreactor design has evolved and, in many cases, toilets and livestock manure flow directly from toilets and pigsties into the influent port of the bioreactor. Construction of these systems may take one week and cost around $80 USD (Henderson, 2009).

The Czech Republic uses a batch system consisting of a hopper and a bell. After an aerobic stage is completed, manure is loaded for 30 days and covered by an insulated metal bell. Due to cold ambient temperatures, the double-wall steel bells have an insulation layer of 100 mm. These moveable fermentation units were installed between 1979 and 1990. These systems are moved from town-to-town for converting manure into energy (Sarapatka, 1993).

The system developed by ARTI for urban use consists of cut-down, high-density polyethylene water tanks. A smaller tank is inverted and set inside the larger tank as a means of gas storage. As the gas is created, the smaller tank rises and a gas pipe feeds the household kitchen for burning of the fuel. It has been found that the gas produced in these food waste fed digesters has a higher methane content than the gas generated in manure-fed plants. ARTI claims this is due to the dissolving of some of the CO_2 when the bioreactor is under pressure. The high liquid content of the slurry is another reason that the CO_2 is dissolved within the bioreactor (Appropriate Rural Technology Institute India, 2006).

Large-Scale Bioreactors

Larger commercial AD systems used in developed nations can be very complex. These systems compress methane to fuel a generator. The commercial-sized plug flow system is continuously fed. Plug flow digesters are commonly used for processing of manure when the total solid content is more than 5%. These systems generally consist of an engineered tank constructed of concrete or steel. The tanks can be placed above or below ground. These bioreactors are common in all climates. The units are heated with a heat exchanger fueled by methane generated by the system, so they can be used in cold climates (Koelsch, 2009).

Covered anaerobic lagoon digesters can be installed over existing manure lagoons. This technology is on the rise in pig farms in the state of North Carolina. Farm manure lagoons are covered with a flexible membrane and gases are collected for combustion. After digestion, there is less potential for odor production from the effluent or the biosolids compared to the fresh or raw flushed waste (Westerman et al., 2008).

Large-scale European systems are diverse. Rapport, Zhang, Jenkins, and Williams (2008) produced a comprehensive overview of these technologies. A high solids rate is common in these digester designs. The Dranco design was created in the 1980s and is a single-stage system that utilizes thermophilic bacteria for digestion. This is a non-mixed system and because of the thermophilic conditions the HRT is only 14 days. The Kompogas system uses a horizontal plug-flow design. The HRT is 15-20 days under thermophilic temperature conditions. As of 2008, there were 30 Kompogas digesters in operation in Europe. The Valorga design is another high-solids design common to Europe. The solids rate is 25-30% and either mesophilic or thermophilic temperatures can be used for digestion. Pressurized biogas is used for mixing in this modified plug-flow reactor.

Feedstocks and Methane Content

Feedstocks are composed of different ingredients that can affect the methane content and viability of the AD process. Carbohydrates, fats, and proteins are easily digested, while rendering high methane contents. Lignin and cellulose are not easily processed (Fischer, 1979). Lignin, especially, is found to not break down easily and can also hinder the AD process (Burke, 2001). Table 1 addresses feedstocks and their potential for biodegradability.

Several studies have shown varying methane contents for different feedstocks. A study at the University of Agricultural Sciences in Vienna found that manure from cows yielded only 53% methane content, while food waste was shown to produce 70-80% (Steffen, Szolar, & Braun, 1998). A study in Costa Rica took samplings from seven different small-scale digesters and found an average 66% methane content from local food waste (Lansing et al., 2007). Table 2 shows the methane-generating potential of various feedstocks.

Table 1

Feedstocks and Their Potential for Biodegradability (Adapted from Steffen et al., 1998)

Compounds	Sources	Anaerobic Biodegradability	Disturbing Effects	Inhibitory Effects
Carbohydrates Sugars Starch Cellulose	Beets, Corn Potatoes, Maze Straw, Grass & Wood	Excellent Excellent Poor-Good	Foaming Lignine Incrustration	pH Decrease
Protein	Animals and Animal Products	Excellent	Foaming	Ph Decrease
Fats	Animals and Animal Products	Excellent	Scum Layers, Poor Water Solubility	VFA increase, pH decrease
Volatile Fatty Acids (VFA)	Fats, Grease, Oils	Excellent	Poor Water Solubility of Fats and Oils	Specific inhibition of diff. bacteria groups
Trace Organic Compounds	Pesticides, Antibiotics, Detergents	Poor	Foaming	Antibiotic Reactions
Inorganic Material	Salts, Food Additives, Silica Gel	No	Sludge Formation	n.a
Sand, Grit	Stable Walls and Floors	No	Precipitation, Tube Blocking	n.a.

Table 2

Feedstocks and Their Methane Potential (Adapted from Steffen et al., 1998)

Feedstock	%Total Solids	%Volatile Solids	C:N Ratio	Biogas Yield	Days Retention Time	%Methane Content
Pig Slurry	3-8	70-80	3-10	.25-.50	20-40	70-80
Cow Slurry	5-12	75-85	6-20	.20-.30	20-30	55-75
Chicken Slurry	10-30	70-80	3-10	.35-.60	>30	60-80
Whey	1-5	80-95	n.a.	.80-.95	3-10	60-80
Ferment Slops	1-5	80-95	4-10	.35-.55	3-10	55-75
Leaves	80	90	30-80	.10-.30	8-20	n.a.
Wood Shavings	80	95	511	n.a.	n.a.	n.a.
Straw	70	90	90	.35-.45	10-50	n.a.
Wood Wastes	60-70	99.6	723	n.a.	n.a.	n.a.
Garden Wastes	60-70	90	100-150	.20-.50	8-30	n.a.

There is great potential for digesting food waste in more locations in America to generate methane. Food waste has the potential to generate three times more methane than animal manure (Steffen et al., 1998). Because the manure has been processed by the internal organs of the animal, much methane is lost before it gets to the digester. Americans generate 5.5 million tons of food waste per year (Mattocks & Wilson, 2005). This unused feedstock could be an excellent resource for energy in the U.S., while also depleting the amounts of waste that is entering our country's landfills.

Europe has over 120 full-scale plants that are digesting food waste. This amounts to about four million tons of waste per year being diverted from landfills and converted into a carbon-neutral energy source (Neves et al., 2007).

A study conducted by the EPA in California found tremendous potential for using food waste as a feedstock. This study, conducted in San Francisco, revealed that the bioreactors being examined were producing an average of 73% methane (Zhang, El-Mashad, Hartman, Wang, Liu, & Choate, 2006). Another study conducted in the East Bay area of California found an average of 63% methane when anaerobically digesting food waste (Gray, 2008). These studies used varying anaerobic digester designs and all of the methane yields appeared to be higher than the amounts typically reported for manure.

Benefits of Co-Digestion of Multiple Feedstocks

Co-digestion involves the combination of two or more substances for the process of AD. This provides an improved nutrient balance that can yield higher methane contents and a higher grade fertilizer quality in the digestate. Manure is also an excellent pH buffer and adds needed nutrients for good bacterial growth (House, 1981). Steffen et al. (1998) found that the co-digestion of manure and food waste can produce more gas than either of the two alone. Misi and Forster (2001) claimed a 90-95% methane content when co-digesting manure and organic waste. Co-digestion also offers better operational feasibility for developing nations where manure might not satisfy local energy needs on a year-round basis.

Countless organic wastes can be used in the AD process. Maize is a popular added feedstock in Germany. In Zimbabwe users are experimenting with the use of Sudan grass, Napier grass, and water hyacinth. Water hyacinth is a perennial problem in dams of this region. Its use as a feedstock could alleviate this problem, while offering an added energy source for bioreactors (Jingura & Matengaifa, 2009). In China, feedstocks include manure, human waste, sweet potato vines, and weeds (Henderson, 2009).

European countries dominate in the use of co-digestion in bioreactors. Denmark is a leader in anaerobic digestion and the Danish Technological Institute reports a study where different types of organic material were added to pig manure, which increased the methane yield by 70% (Danish Technological Institute, 1993). In Denmark there are currently 20 centralized AD plants co-digesting manure with organic wastes (Cavinato et al., 2010). The rural location of many of these plants promotes the immediate use of the effluent as fertilizer. It has been found that the fees saved on waste-disposal make co-digestion even more lucrative. Denmark has also discovered that manure is an excellent substrate for mixing with drier feedstocks. There is a great potential to develop more bioreactors that co-digest multiple feedstocks in all parts of the world (Danish Technological Institute, 1993).

Denmark is not the only country in Europe that has discovered the benefits of co-digestion. AD users in the U.K. have put a focus on the co-digestion of manure and animal by-product wastes. This is largely due to fears of mad cow disease from use of these by-products for other purposes (Monnet, 2003). Similarly, Sweden's reluctance to use animal by-products as feed has resulted in co-digestion of manure and slaughterhouse wastes (Nordberg, 2002). A majority of the large bioreactors in Germany co-digest manure, human sewage, and food waste (Lusk, 1998). Spajic, Burns, Moody, Kralik, Poznic, and Bishop (2008) discovered that the co-digestion of numerous substrates drastically increased energy yields in swine manure bioreactors in Croatia. Food industry by-products had been previously used as feed additives for swine. These by-products included spent brewer's yeast and whey from cheese producers. Adding these by-products to feed created a savings of $307,000 per year. Research revealed that the possibility of diverting these feed ingredients to existing swine manure fed bioreactors would not prove profitable to farmers. It was, however, found that if corn silage was mixed with slaughterhouse waste and then co-digested, the overall income through produced energy would be $538,000 per year (Spajic et al., 2008).

Misi and Forster (2001) found advantages in combining feedstocks. Rural regions of developing nations use biomass (primarily wood) for cooking and home-heating. In some areas this amounts to 90% of total energy consumption, and problems of deforestation and resulting desertification are growing. Manure, which is also burned for fuel, can be added to organic wastes and fed to a bioreactor as a superior alternative energy source. Feedstocks in the Misi and Forster (2001) study included vegetable food waste; molasses; sheep, poultry and goat manure; and thickened waste activated sludge. Numerous combinations of feedstocks were digested with high methane yields with no adverse reactions in the bioreactor (Misi & Forster, 2001).

There is a lack of literature on the co-digestion of various feedstocks from available U.S. waste streams (Minnesota Department of Agriculture, 2005). While Europe and other parts of the world continue to take advantage of other wastes for additional feedstocks, manure is the primary substrate currently in use in the U.S. Cavinato et al. (2010) determined through a simulation that co-digestion of agricultural wastes and energy crops would provide a bioreactor a payback period of 2.5 years. Farmers could also gain the financial benefit of tipping fees acquired from organic waste producers. Organic waste streams that could be taken advantage of in the U.S. include crop residues, domestic wastes, paper and pulp industry wastes, as well as wastes from the food and grain industry (Minnesota Department of Agriculture, 2005).

Temperature Effects on the Anaerobic Digestion Process

Cold climates find some degree of heating a necessity for healthy bioreactors, although published work on exact correlations between temperature and methane production reveals varied findings (Feilden, 1981). Most research claims 35 °C is the optimum temperature for mesophilic bacteria (e.g., Chae, Jang, Yim, & Kim, 2008; Kim, Oh, Chun, & Kim, 2006).

Misra, Singh, Singh, & Pankey (1992) claimed that the production of gas slows down below 18 °C and completely stops at 9 °C. The mesophilic bacteria double their gas production for every 10 °C rise in temperature between the ranges of 15 ° and 36 °C. It was also said that 10 °C rises in the thermophilic range would also double gas production.

Chae et al. (2008) found smaller changes in gas production and its relation to temperature. They also claimed that small fluctuations in digester temperatures were not harmful to the productive rate of the system. Their study involved the digestion of swine waste for measurements of methane yields at 25 °, 30 °, and 35 °C. A temperature of 30 °C found only a decrease in 3% methane, as compared to the system maintaining a 35° C temperature. There was a more significant drop in gas production of 17.4% between the 30° and 25° C tanks. Another test involved adding a higher solid mix to the digesters (from 5% to 20%) and raising the temperature of the various systems and observing the new gas outputs. Methane output increased by only a small amount (see Table 3).

Table 3.

Methane Yields and Relation to Temperature and Feed Loads (Chae et al., 2008)

Temperature (°C)	Feed loads[a] (v/v %)	Methane yields		CH_4 yield of theoretical value (%)[b]	COD_i[c] (mg/L)	$SCOD_f$[d] (mg/L)
		(L/g VS_{added})	(L/g COD_{added})			
25	5	0.317 ± 0.017	0.114 ± 0.020	43.8	3310 ± 127	668 ± 31
	10	0.352 ± 0.017	0.127 ± 0.010	49.3	5620 ± 35	1667 ± 61
	20	0.312 ± 0.024	0.112 ± 0.024	43.1	10240 ± 85	2483 ± 18
	40	0.122 ± 0.031	0.044 ± 0.013	16.9	19000 ± 283	7900 ± 113
30	5	0.397 ± 0.010	0.143 ± 0.018	54.8	3310 ± 42	796 ± 82
	10	0.388 ± 0.025	0.139 ± 0.020	53.6	5620 ± 35	964 ± 20
	20	0.383 ± 0.018	0.138 ± 0.011	52.9	10240 ± 127	1184 ± 119
	40	0.170 ± 0.014	0.061 ± 0.007	23.4	19480 ± 141	6000 ± 191
35	5	0.437 ± 0.017	0.163 ± 0.010	60.4	3225 ± 86	908 ± 25
	10	0.421 ± 0.016	0.157 ± 0.013	58.2	5450 ± 99	1005 ± 33
	20	0.319 ± 0.014	0.119 ± 0.014	44.1	9900 ± 573	1510 ± 28
	40	0.228 ± 0.018	0.085 ± 0.010	31.5	18800 ± 184	5580 ± 113

[a] Feed swine manure% of total reactor volume.
[b] Chemical formula of feed swine manure was $C_{14.25}H_{28.80}O_{4.43}NS_{0.03}$.
[c] Initial COD concentrations in the reactors.
[d] Final soluble COD concentrations in the reactors after 20 days digestion, values are given as means and standard deviation of two replicates.

Kim, Oh, Chun, & Kim (2005) found similar results when increasing temperatures from 40-50° C. A decrease in gas production was discovered, however, increasing temperatures into the higher thermophilic range 55° C (see Table 4).

Table 4

Biogas Productions and their Relationship with Temperature and HRT (Kim et al., 2005)

Digestion condition		Gas production (l/d)		Methane content in biogas (%)
Temp (°C)	HRT (d)	Biogas	Methane	
40	10	7.3	4.5	61.6
	12	6.1	4.0	65.6
45	10	8.7	5.5	63.2
	12	7.4	4.9	66.2
50	10	10.4	6.7	64.4
	12	8.6	5.8	67.4
55	10	6.8	3.7	54.4
	12	5.6	3.3	58.9

Fielden (1981) found increases in gas production in the mesophilic range that correlated with the Chae et al. (2008) study. Although most literature points to 35° C, Fielden discovered even higher gas rates when temperatures rose above 35° C, which is the upper temperature limit of mesophilic digestion. His findings claimed thermophilic temperature ranges and gas production levels quite different from those of Kim et al. (2005). The graph in Figure 1 describes this observation.

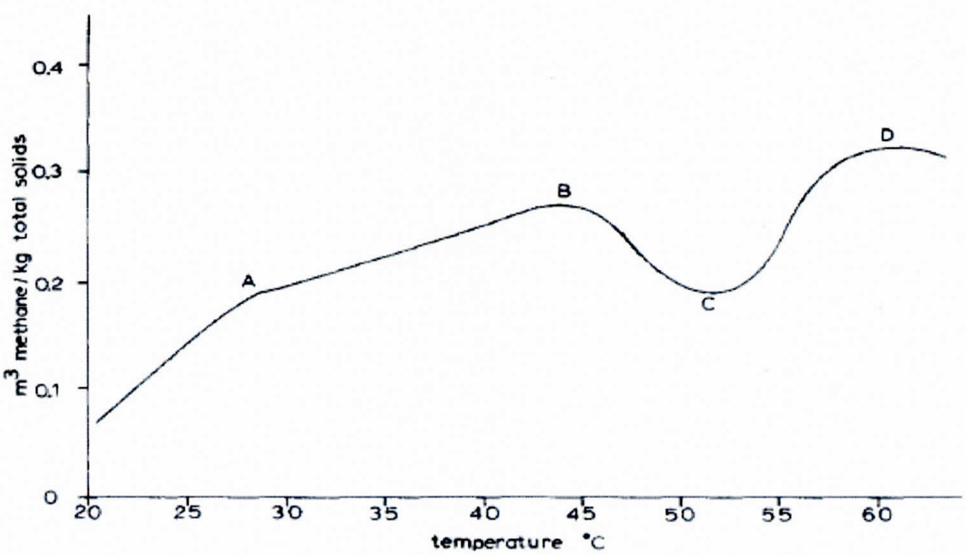

Figure. 1. Methane and temperature in mesophilic and thermophilic ranges (Fielden, 1981).

Biogas output and its relationship with temperature is a subject of debate. The many variables of the AD process yield varied research findings.

Mixing within Bioreactors

The performance of bioreactors can be affected by the degree of mixing within the reaction tank. Research on this topic varies as well. Mixing has been considered beneficial ever since research on the subject was conducted in the 1930s. It can reduce dead layers within the digester that often contain indigestible solids. The degree of contact between the newly fed slurry and the bacterial population within the tank can affect the duration that is necessary for complete digestion. Mixing also evenly distributes heat throughout the bioreactor. It prevents stratification of the slurry and the formation of a crust on the surface and keeps solids from settling to the bottom (Kaparaju, Buendia, Ellegaard & Angelidakia, 2008). Agitation of the slurry permits the release of biogas and can reduce the size of particles within the bioreactor. An exact regimen for mixing in AD is a subject of debate (Comerford & Picken, 1984).

Mixing can be achieved through several different methods. Techniques include mechanical mixing, biogas recirculation through the use of sparkless gas pumps, or slurry recirculation (House, 1981; Karim, Klasson, Hoffman, Drescher, & Depaoli, 2005).

Mixing can also be achieved through convection from a heat source (Comerford & Picken, 1984). Comerford and Picken (1984) studied convective flow within a circular digester with a heat exchanger located at the bottom of the tank and found that it provided mixing within the tank. It was concluded that thermal homogeneity is gained through the heat source being located at the bottom of the tank. The rise of the heated slurry creates a thermosiphon effect that can adequately heat the tank. However, there was no mixing of settled solids in the convective mixing process. It was also discovered that incoming slurry is very quickly heated to the bulk temperature of the rest of the slurry.

Lee, Cho, and Maeng (1995), in a pilot-scale experiment, employed the gas pressure from the digester for mixing purposes. A gas holding tank was used with a solenoid valve and a pressure sensor. When the pressure reached a certain level the gas was allowed to reenter the digester for mixing purposes. It was found that the performance of this digester was comparable to that of commercial digesters with either mechanical agitation or gas recirculation (Figure 2). These researchers claim that this technology could be applied to a farm-scale digester.

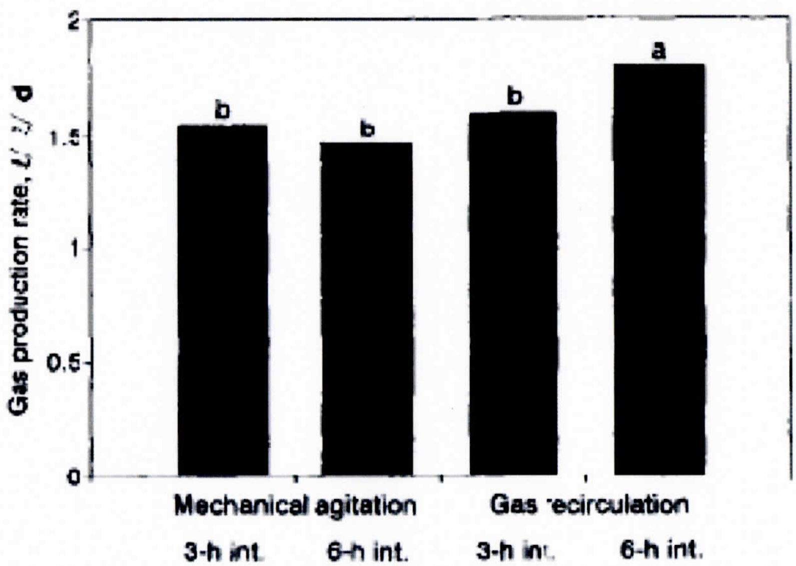

Figure 2. Effects of mixing methods (Lee, Cho, & Maeng, 1995).

Kaparaju et al. (2008) discovered that mixing schemes had some effects on the AD process. A pilot-scale study showed a 7% increase in biogas production during intermittent mixing, as compared to continuous mixing (Kaparaju et al., 2008).

Karim et al. (2005) conducted lab-scale experiments on mixing in AD and discovered that mixed and unmixed bioreactors performed similarly. They hypothesized that this may have been due to using a low solids concentration in the manure slurry. Perhaps the produced biogas bubbling through the bioreactors created mixing.

Biogas and Energy

Biogas Energy and Its Uses

A cubic foot of pure methane contains 1000 Btu. If biogas averages a 50-70% composition of methane, then the average Btu of a cubic foot of biogas equals 500-700 Btu. The combustion of this gas releases the energy. A 50% methane content is necessary for burning biogas without using a CO_2 filtering system. The methane content of biogas depends upon the feedstock entered into the system and the stability of the environment in which the bacteria live (House, 1981). The methane combustion process is defined as follows (House, 1981, p. 86):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Direct burning of the fuel is common on the residential level. Lighting, cooking, water and space heating, and cooling can all be achieved. Methane can also be used to heat the digester or it can be used as a fuel for compressor engines and electric generators (Balsam, 2006; Government of Alberta, 2007; House, 1981). Generally, equipment manufactured for natural gas needs to be modified to burn methane (Balsam, 2006). Table 5 shows a list of some simple household uses of methane and their needs in cubic feet of methane.

Table 5

Biogas Use and Rate (Adapted from Leckie, Masters, Whitehouse, & Young, 1975)

USE	RATE(ft^3)
Lighting	2.5 per mantle hour
Cooking	8-16 per hour per 2-4" burner
Gas Refrigerator	1.2 per hour per ft^3 refrigerator

On a larger scale, methane is generally burned in a generator. Electricity generation from methane is also found in on-farm use of AD, which supplies electricity for farm operations. When excess electricity is produced it is sold back to the grid. Payback times on the initial investment of the AD system can be short for farm systems (Government of Alberta, 2007).

Houser (1989) conducted a feasibility study involving the methane potential of a small farm with 50 head of cattle. An analysis of the farm's current propane use was considered in its relation to potential methane yields from anaerobically digesting the manure from the farm's livestock. His estimations of biogas production for this farm equated to 365,000 cubic feet of biogas per year and could replace the farm's propane needs several times over. The example in Table 6 is another illustration of the savings a small farm can attain through the use of an AD system.

Table 6

Cow Manure to Energy (Navaratnasamy, Koberstein, & Partington, 2008)

Example

Number of animals	= 100 dairy cows
Average cost of electricity	= $ 0.06/ kWh
Average cost of heat	= $ 5.5/GJ
Annual electricity potential	= 1,227 kWh (from the table)
Annual heating potential	= 5.5 GJ (from the table)
Savings from electricity	= 100 x 0.06 x 1,227 = **$ 7,362**
Savings from gas	= 100 x 5.5 x 5.5 = **$ 3,025**
Total annual savings from energy	= **$ 10,387**

Different farm animals produce manures that vary in methane yields. Analyzing farm livestock populations in their relation to methane and electricity potential can aid farmers who are considering installing AD systems. Table 7 presents several common farm animals and their manure's potential value in the AD process.

Table 7

Manure and Biogas Production (Navaratnasamy, et al., 2008)

Description	Manure quantity as excreted (kg/d)	Biogas production (m^3/d)	Electricity potential (kW)/year	Energy potential (GJ)/year
Beef	24.0	1.10	663	3.0
Dairies	62.0	2.01	1,227	5.5
Piglet *	3.5	0.16	98	0.4
Poultry (100 – layer)	8.8	0.85	516	2.3

* Multiply the table values for piglet by 12 for every sow in a farrow-to-finish operation.

Calculating Yields Based on Feedstock and Volatile Solids Content

Cow manure seems to be the most studied feedstock, with experts agreeing on its methane yield potential. House (1981) claimed an average of 1.1 m^3 biogas per beef cow per day. Wenxiu and Mengjie (1989) claimed that daily manure from a beef steer can yield 1 m^3 biogas. Sarapatka (1993) also observed similar methane yields from cattle, equating to an average of .9 m^3 per animal unit per day. Although the claims regarding average yields pertaining to this feedstock are similar, there is a more scientific approach to discovering methane contents of feedstocks.

Methane yields are generally calculated by determining the dry weight of the VS (Rapport et al., 2008). Figure 3 demonstrates the correlation between loading of VS, temperature, and methane production.

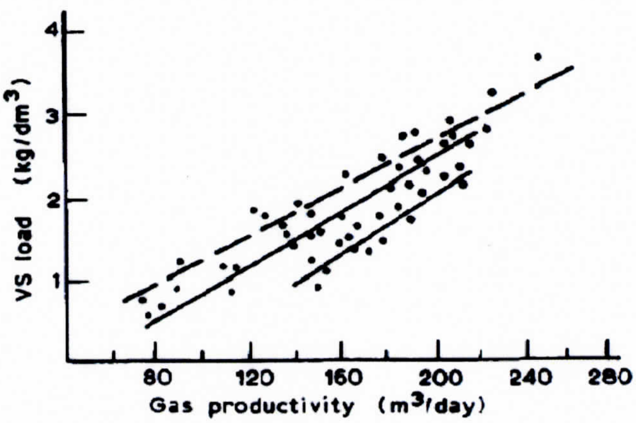

Figure 3. VS and methane production in an experiment conducted by Wenxiu and Mengji (1989).

Leckie et al. (1975) proposed a formula that incorporates TS, VS, and their relation to methane yields:

Cubic feet of methane/ lb. of raw material = 1 * %TS * %VS * ft^3 gas/lb * %methane/gas

(Adapted from Leckie et al, 1975, p. 257)

They claim that this formula will render a rough estimate of what one might expect for biogas yields.

Safety Issues with Bioreactors

Safety is of great concern when generating and handling methane gas. Gas storage and utilization equipment that is consistent with standard engineering practices for handling flammable gas should be constructed (Navaratnasamy et al., 2008). Even at proportions of 6% - 15%, methane is known to be explosive when mixed with oxygen. Air leaking into a small space filled with methane can be much more dangerous than methane leaking into a large area filled with air (House, 1981). Flame arrestors should be installed on all gas lines. Also, gas detection devices should be implemented around the burner within any building burning methane to ensure there is no leaking gas (Balsam, 2006). Biogas also contains hydrogen sulfide, which is another danger. Inhalation of high concentrations of hydrogen sulfide can result in human fatality (Navaratnasamy et al., 2008).

Maintaining positive pressure within a biogas system is another important safety factor to be considered. Positive pressure will prevent a flame from being sucked back into the bioreactor. This can prevent a major catastrophe from taking place (House, 1981).

Anaerobic Digestion and Solar Thermal Technology

Solar Thermal Flat Plate Collectors

Solar thermal collectors have been used for some time as a method of heating water. These devices gather the energy of the sun and transform its radiation into heat. The heat is then transferred to water within the collector. This solar thermal energy is most commonly used for solar water-heating, solar space heating, and solar pool heating. The flat plate collector is most commonly used where temperatures below 200 °F are required. These collectors are insulated metal boxes with a glass or plastic cover and an absorber plate within the box (U.S. Department of Energy, 2010). Although these collectors are not commonly used to heat bioreactors, the principle behind their operation can easily serve this purpose (Figure 4).

Solar thermal collectors do not have to be purchased and shipped from a manufacturer. Simpler options for those without financial means are available, by locating local materials and building the panel yourself. For example, the solar pond and bread box designs can both be readily made by do-it-yourselfers. Hills and Stephens (1980) tested two appropriate technology-style solar thermal units and found them both adequate for heating bioreactors (Figures 5 and 6).

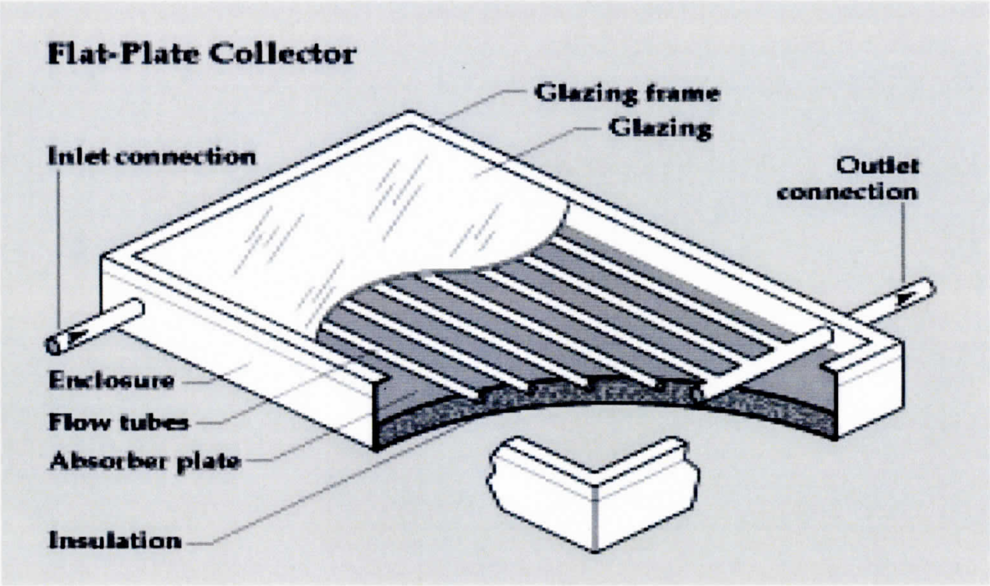

Figure 4. Diagram of solar flat plate collector (U.S. Deparment of Energy, 2010).

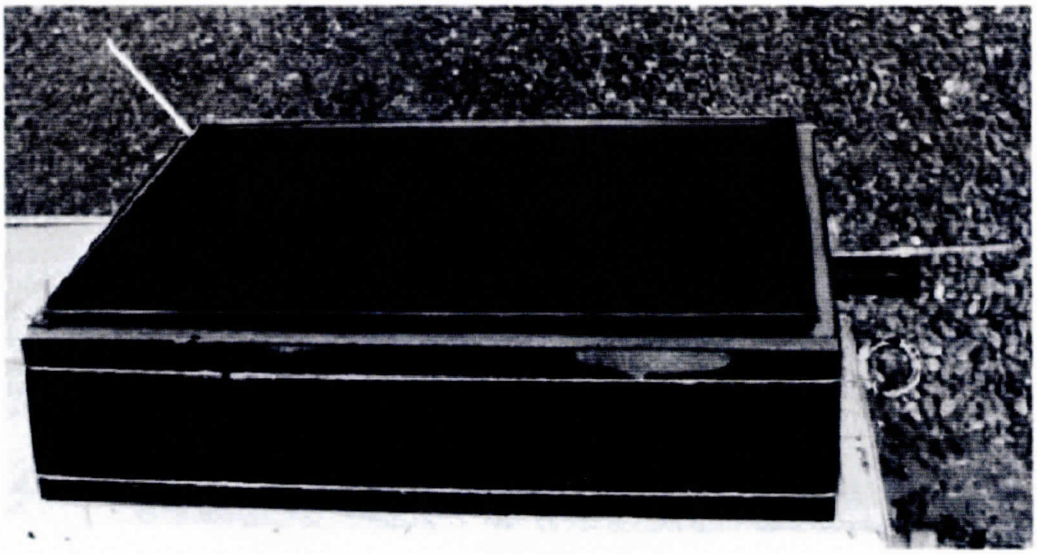

Figure 5. Solar pond-style homemade panel (Hills & Stephens, 1980).

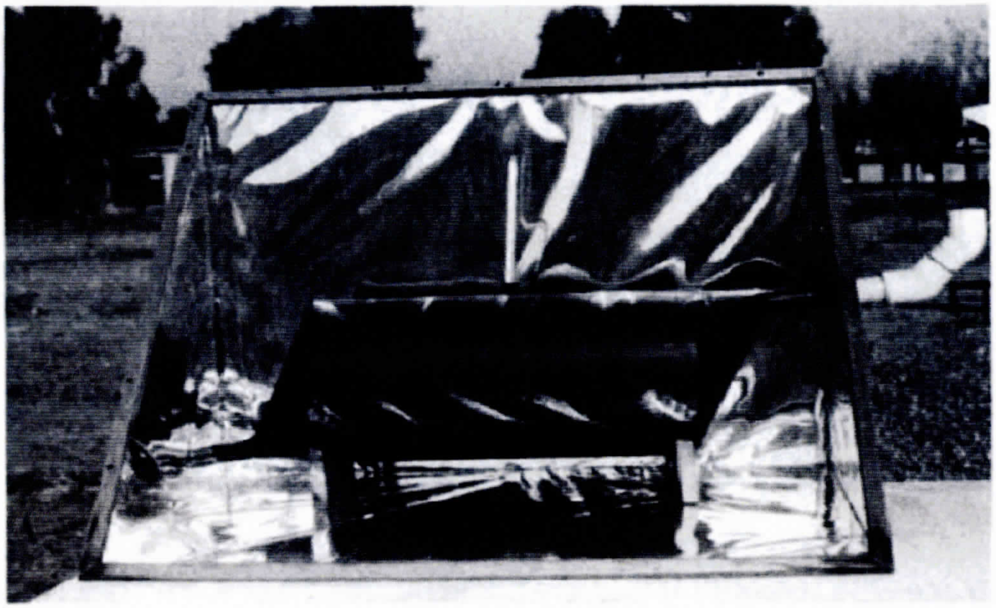

Figure 6. Low-tech bread box design (Hills & Stephens,1980).

Thermosiphoning

The use of thermosiphoning in solar water heating systems is not common, although it can be a sufficient transport system for gained heat. This is likely due to the need for the storage tank to be located above the collector (Figure 7). These systems operate most efficiently with a large change in temperature (ΔT) between the panel and the heat exchanger. Some claim that this results in a reduced solar efficiency (Beni et al., 1994). However, thermosiphoning could be easily accepted by those who do not have access to electricity for powering pumps.

Figure 7. Solar thermal flat plate collector thermosiphoning system (Kalogirou, 2008).

Beni et al. (1994) discussed the use of thermosiphoning in the Italian Alps for snow melting and for heating of a sewage treatment facility. Electricity was not available and the mountainous region allowed for locating the solar panels at altitudes that were adequate for thermosiphoning. It was said that on a sunny day, about 250 dm^3 of water was produced by snow melting using the thermosiphoning unit. Up to 450 dm^3 of water could also be heated for hot water purposes at an increase of 30 °C. Heating of a bioreactor was also the purpose of the thermosiphoning solar panels. Heat from the panels was capable of heating 300 dm^3 of waste that was generated in the community to temperatures of 5 to 25 °C.

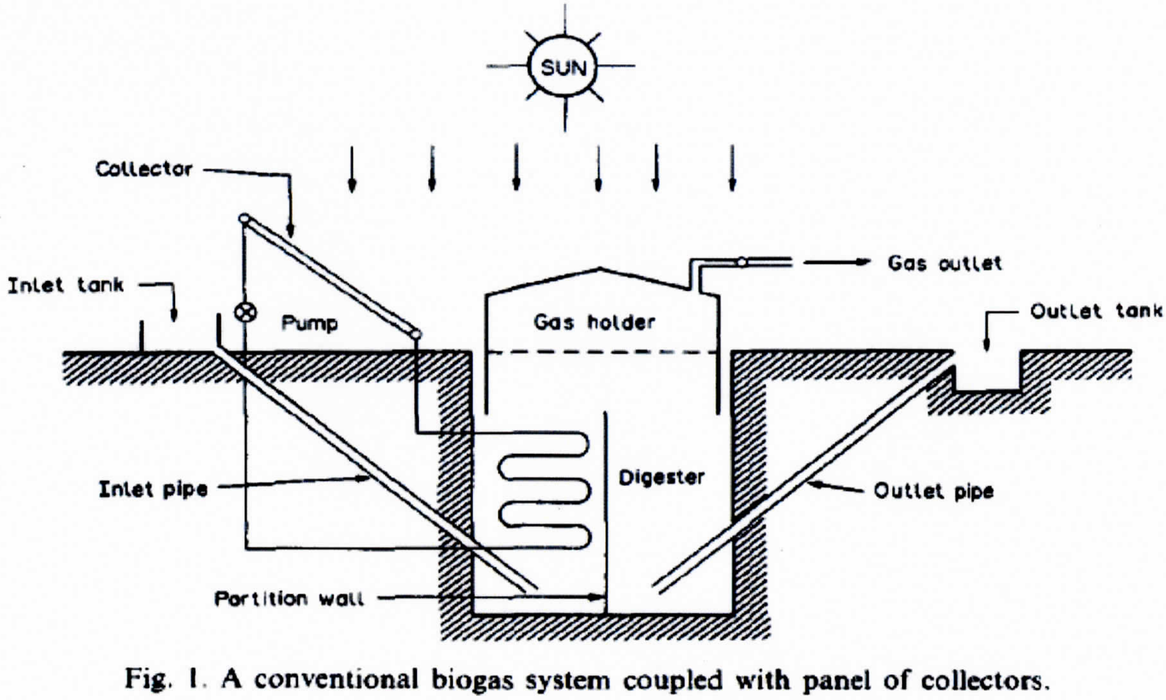

Figure 8. Conventional method of using solar thermal collector with pump (Tiwari, Chandra, Singh, Sucheta, & Yadav, 1989).

Kalogirou (2008) found that when operating a thermosiphoning system for water heating, the savings over electricity or diesel backup was around 70%. Heating water and heating slurry is of a similar nature. Being that fossil fuels are commonly used for digester heating, this research is relevant in the fact that thermal properties of water and slurry are similar.

Previous Research on Solar Thermal Technology for Bioreactor Heating

Solar thermal technology has been used as an energy source for the heating of bioreactors (Figure 8), but is fairly uncommon. Busyman (2009) addressed the fact that installing bioreactors in cold climates can be more economically feasible in the current era due to the carbon offsets, which now hold a market value in areas with clean development incentives. This is also known as the voluntary carbon market. The carbon offsets can be sold as carbon credits and used to further the adoption of AD where larger upfront costs are needed for cold-weather installations. This offset could help pay for solar thermal panels.

Although literature review revealed that solar energy for heating bioreactors has been used for some time, scientific studies documenting this technology are hard to come by. Only a few research teams have studied and documented the use of solar thermal panels as a heat source for anaerobic digesters. The findings are very encouraging and there is a need for further research in the marriage of these two technologies. Studies have been conducted in areas with high solar irradiance (Axaopoulos, Panagakis, Tsavdaris, & Georgakakis, 2001; El-Mashad, van Loon, Zeeman, Bot, & Lettinga, 2004; El-Mashad, van Loon, & Zeeman, 2003); however, there is a need for more research on the subject of heating digesters in areas with a lower solar irradiance. The following is a summary of five studies that were conducted involving the use of solar thermal panels for heating anaerobic digesters.

Experiments in Greece, an area with high solar irradiance, found that solar thermal technology was an efficient technique for providing heat for anaerobic digesters. A study conducted by the Agricultural University of Athens involved an experiment that recorded hourly climatic data, as well as ambient air temperature, wind speed, and the irradiance on the collectors (Axaopoulos et al., 2001). This system involved mounting the panels on the digester, thus using the heat radiated from the back of the panel, as well as the heat generated from the heat absorbers within the panels to heat the digester. It can be speculated that the use of this system is only appropriate for areas with a steady daily solar irradiance. Colder climates would lose considerable heat in the digester on cloudy days when the top of the digester is covered with a solar thermal panel that is not capturing heat. Colder climates would benefit more from a well insulated area on the top of the digester. This research did determine that the panels mounted on the top of the digester did disperse heat to the digester over the course of the night. The generated solar heat fed to the digester through a heat exchanger was the primary heat source to maintain a temperature for optimal methane production (Axaopoulos et al., 2001).

A research team from the Chinese Academy of Sciences conducted a study on the use of solar thermal evacuated tube collectors for the heating of a digester in a cold weather environment (Dai et al., 2005). The focus of this research involved determining the most economically sized solar thermal collector that could still heat a digester to a temperature that could produce substantial amounts of methane. These researchers weighed the costs of a less expensive solar thermal system that might not reach optimal temperatures and may have lesser methane outputs, against a digester that was set up as a control and had steady optimal temperatures for methane production. The system was tested in the coldest months in Beijing. It was determined that the solar system generated more methane than the control system. The solar system held an average temperature of 20 °C, which is much less than is common in normal anaerobic digestion practices. Their control system was maintained at 25 °C. It can be speculated that this system is modeled for a situation where maintaining an optimal temperature in the digester is not feasible because of economics involving the cost of a solar thermal system. Perhaps these lower, and less researched, mesophilic temperatures have different methane generating qualities than the higher and more common mesophilic anaerobic temperatures (Dai et al., 2005).

A study took place in India on the use of a solar-heated digestion system (Misra et al., 1992). These scientists used a unique solar system that involved circulating the slurry through a solar heated tank and then back into the main digester tank. The focus of this study was the use of a low-cost insulation on the digester tank and the recording of fluctuations in temperature that occurred. The goal was to find an insulation material that was appropriate to use in developing countries for small-scale community digesters. Several common and inexpensive insulation materials were applied to the exterior of the three different tanks as insulation. A mixture of glass wool, sawdust, and plaster of paris was applied to the first tank, while the second tank received a black cloth coated with pitch, sodium peroxide, and glass wool. The third tank was insulated with a mixture of thermocol and sawdust (Misra et al., 1992).

In this study the tanks were heated to 36 °C and then were left to cool. Graphs in the journal article showed similar drops in temperature within all three digesters. It was discovered that a slight drop in temperature took place in the first 60 hours and then a sharp temperature drop occurred. All tanks lost only 2-3 °C in temperature in the first 60 hours, while from 60-100 hours, a 20-25 °C drop occurred (Misra et al., 1992). Although this research was testing the insulation values of varying compounds, I found the information valuable for reasons not involving different insulating materials. The results of this experiment suggested that a period of 60 hours of no sunlight might be a window in which a solar thermal heated digester could continue to function adequately. Five cloudy days may be the longest period a solar-heated digester may properly function. This is also dependent upon vessel size and the particular insulation used.

The most impressive research on the use of solar thermal panels for heating in the anaerobic digestion process took place in Egypt in two different experiments (El-Mashad, van Loon, Zeeman, Bot, & Lettinga, 2004; El-Mashad, van Loon, & Zeeman, 2003). Both studies involved cattle manure as a feedstock under thermophilic conditions and were conducted by the same team of scientists. Egypt has a high solar irradiance and the pursuit of a steady thermophilic temperature, even in a sunny area, is a bold endeavor. The first study involved an analysis of solar thermal energy and its efficiency as a heat source in a digester (El-Mashad, van Loon, & Zeeman, 2003). The second research used the data from the first research to determine how temperature fluctuations in a digester might affect methane production. Because solar thermal panels only produce heat in the daytime, it is necessary to determine if a solar storage tank might be necessary to administer heat gained during the day to a digester over the course of the night (El-Mashad, van Loon, Zeeman, Bot, & Lettinga, 2004).

El-Mashad et al. (2003) first studied two continuously stirred tanks heated by solar thermal panels. One tank received solar energy to reach a temperature of 50 °C, while the other tank was set to maintain 60 °C. The loss in methane production over the course of the night was 12% and 20%, respectively. It was determined that it is possible to use solar thermal energy as a sole source of heat to maintain digesters at an appropriate temperature for anaerobic digestion in the thermophilic range. It was also deemed that the larger the digester size, the less efficient a solar thermal system would be as a source of heat. For smaller digesters it was found that solar thermal heat was 90% efficient as a heat source. High insulation amounts were necessary to maintain the heat over the course of the night and there is a high cost associated with this (El-Mashad et al., 2003).

This research also analyzed the roof panel system used in the experiment by the team of Greek scientists to determine if a colder environment would benefit from a roof panel system. They found that for larger digester volumes, a panel mounted into the roof of the digester is highly inefficient. For smaller digesters it is only possible to obtain 75% of the energy potential, as compared to moderate insulation (El-Mashad et al., 2003).

The second experiment involved more precise documentation of short-term temperature fluctuations and their relation to methane yields. The goal of the research was to determine whether the extra expense of a solar heat storage tank for supplemental heat in the nighttime would be a worthwhile financial expenditure. The results showed that temperature fluctuations greatly affect the hydrolysis stage of anaerobic digestion, but not to a point that methane production is greatly inhibited. It was also found that the nighttime decrease in temperature of the tank showed a lesser decrease in methane production than the shorter period of time in the morning when the tank would begin to rise in temperature after the solar panels began to absorb solar energy and send it to the tank (El-Mashad et al., 2004).

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

The Experiment

Two identical bioreactors were constructed for testing of bioreactor heating strategies and their relationship to methane yields and composition. A control bioreactor was heated with a 40-gallon electric water heater that pumped hot water through a heat exchanger inside the bioreactor to maintain a constant temperature of 95 °F. Its performance was compared with that of an experimental bioreactor that was heated through a 4x8 solar thermal flat-plate collector that relied on thermosiphoning to circulate hot water through the heat exchanger. Both systems were fed identical feedstocks at an HRT of 30 days. Feeding times were based on available solar energy. Loading rates were decreased during times of low irradiance and were increased during periods of high irradiance. The strategy was to maintain an average 30 HRT based on these loading rates.

On January 2, 2010, the control bioreactor was seeded and then operated for six weeks to gain an understanding of the intricacies of fostering the AD process in a cold climate, before startup of the solar heated bioreactor. Another goal was to achieve a steady state of methane production so that its contents could be split between the two bioreactors for testing and comparing with the solar-heated bioreactor.

The control tank was initially seeded with 20% sludge from an anaerobic pig lagoon and then filled with a 5% slurry of cow manure. This approach was taken due to information obtained during a personal correspondence with J. Cheng from North Carolina State University. The mixture was added and brought to a temperature of 95 °F. After an eight-day waiting period for growth of methanogenic bacteria, the digester was fed daily with a 5% slurry of cow manure at a 30 day HRT. A steady state of gas production was observed 10 days after the continuous feeding began. This refers to a state where gas production volume is constant. Methane content averaged 58%. Small amounts of food waste were then slowly added to the slurry. The slow addition of this feedstock to the existing manure slurry was essential to ensure that the methanogens would properly adapt to the new feedstock. The control bioreactor was continuously operated until February 21, 2010, at which point the formal experiment was begun.

On February 21, the mixture in the control bioreactor was split between the two tanks and a 3% manure slurry was added until both bioreactors were completely filled. Food waste was not part of the slurry that topped off the tanks, due to the fact that its high content of VS could potentially make the re-startup process more difficult.

Both bioreactors were then left unfed for seven days so that the methanogens could process the abundant available feedstock (65% of the total added slurry). Both bioreactors were brought up to a temperature of 95 °F. The solar bioreactor relied on a good day of solar energy for heat gain, as well as heated water for mixing of the slurry introduced to the tank. The control tank was then maintained at this temperature using the thermostatically controlled electric hot water heater, while the solar-heated tank relied on the sun for heating. After seven days both systems were fed at an HRT of 30 days. Because the slurry content within the tanks was 150 gallons, the HRT mandated a loading rate of 35 gallons slurry per week. Biogas composition measurements were taken at least once daily with a gas analyzer and biogas volume was recorded throughout the experiment. VS samples were taken twice per week and frozen for later examination of VS destruction.

The focus of the study was the comparison of methane outputs between a conventionally heated bioreactor and the bioreactor that utilized the novel design incorporating a solar thermal panel relying on thermosiphoning for heat transfer.

Bioreactor feedstock rates vary depending on the particular application of AD. A 3% solids rate was used for this experiment, due to constraints on gas storage; in other words, a richer mixture would have potentially yielded gas quantities higher than could be stored. Because a 3% solid rate of slurry is on the low end of solids content for bioreactors, it should be noted that findings of this paper represent gas production based on temperature fluctuations and their relations to this chosen feedstock solid content. With a greater solid content there would be a slower processing of the digestion of VS. This could further the possibility of acidogenic bacteria growth and methanogenic washout, which could take place in a long sunless period with ongoing slurry loading.

Experimental Bioreactor Design

Two 175-gallon bioreactors were specifically designed for a cold climate. Cylindrical polyethylene tanks (Figure 9) were covered with an ethylene propylene diene monomer (EPDM) rubber layer and then fitted with 1/4" steel lids. The lids were secured with 3/8" threaded rod that was fastened through the steel lid and into a 3/4" plywood layer that the tanks rested on. Bulkhead fittings allowed the use of 2" PVC pipe to be installed for influent and effluent pipes. The pipes were installed so that the influent would push the effluent out during feeding. The effluent collection pipe inside the tank was 5" below the waterline, which allowed 150 gallons of slurry to remain in the tank. The influent pipe was attached to a five-gallon bucket that rested upon the digester for adding of slurry (Figures 10 and 11).

The influent pipe was designed so that the incoming slurry would enter the tank at bottom and thus mix the contents upon feeding. A 3/4" PVC gas pipe was fitted 6" above the waterline of the tank for collection of gas. Figure 11 provides a diagram of the tank design.

Figure 9. Polyethylene tanks used for bioreactors.

Figure 10. Control (L) and experimental (R) bioreactors on site.

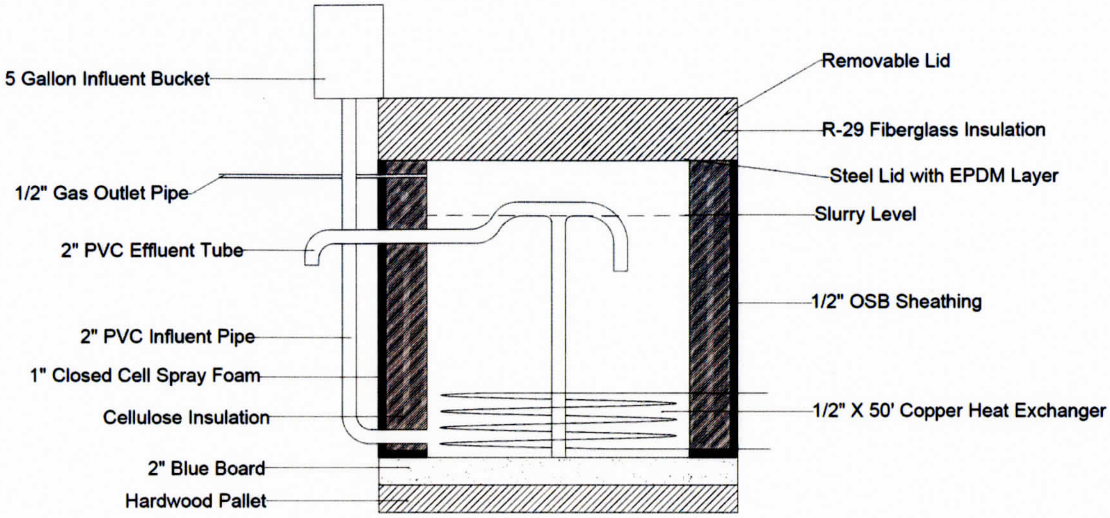

Figure 11. Bioreactor design.

Insulation of Bioreactors

The bioreactors were well insulated to combat the cold climate of Boone, North Carolina. A hardwood pallet created a base for the tank. This pallet was insulated with two layers of 2" blueboard, which held a total R-value of 28. A plywood box was built on top of the pallet and around the tank, leaving adequate space for insulation (Figure 12). The inside of the plywood box was sprayed with 1" of closed-cell polyeurethane foam that holds a value of R-7 per inch. This also served as an air infiltration barrier. The remaining 5" cavity was filled with cellulose insulation holding an R-value of 3 per inch. This produced a total R-value of 22 around the sides of the tank. A removable plywood top was installed that left room for R-29 fiberglass batts. Using batts on the top was essential to ensure easy removal of the top for cleaning of the tank. The computer software TRNSYS was utilized to project thermal loss of the contents within the tank, taking into account the insulation that was installed. Because the tank was insulated with several different materials holding different R-values, it was necessary to average the R-value at 25 when entering the insulation data into the program. Also, the thermal qualities of water were used as a substitute for the slurry that would reside in the tank. I calculated that in an ambient temperature of 20 °F with no supplemental heating, 150 gallons of water would cool from 95 ° to 85 °F in four days.

Figure 12. Tank enclosed in wooden box with closed cell spray foam insulation.

Gas Collection

The 3/4 " PVC pipe that was fastened to the tank with a bulkhead fitting was reduced to 1/2" pipe after it exited the plywood enclosure. The pipe was then routed to the bottom of a 55-gallon barrel and then entered the bottom of the metal barrel through the use of a bulkhead fitting. The pipe then rose to within 6" of the top of the inside of the barrel. The barrel was filled with water and the gas was left to bubble through the 6" of water in order to scrub CO_2. A plastic 40-gallon barrel was placed upside-down inside the water barrel for collection of gas. The 40-gallon barrel rose as gas collected inside. After gas volume was measured, the barrel's contents were routed out of the top of the barrel through a hose controlled by a ball-valve (Figure 13). Placing pressure on the barrel pushed the gas through the rubber hose on the barrel's top into an air mattress that served as the primary gas storage.

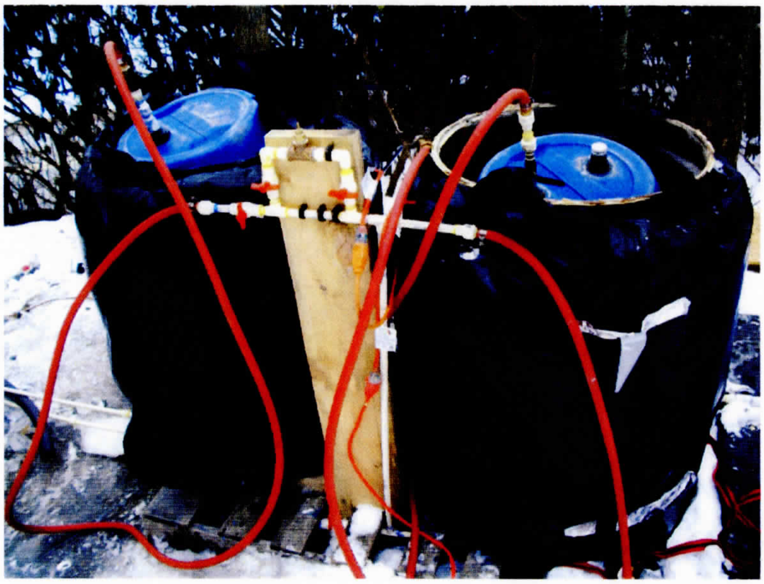

Figure 13. Gas collection vessels.

Design of the Bioreactor Heating Systems

Each bioreactor had a different heat source; however, the delivery of heat to the tanks was identical. A 50-foot long, 1/2" diameter coiled copper heat exchanger was installed at the bottom of each tank. Bulkhead fittings allowed the passage of entry and exit pipes that were then connected to their heat source (Figure 14).

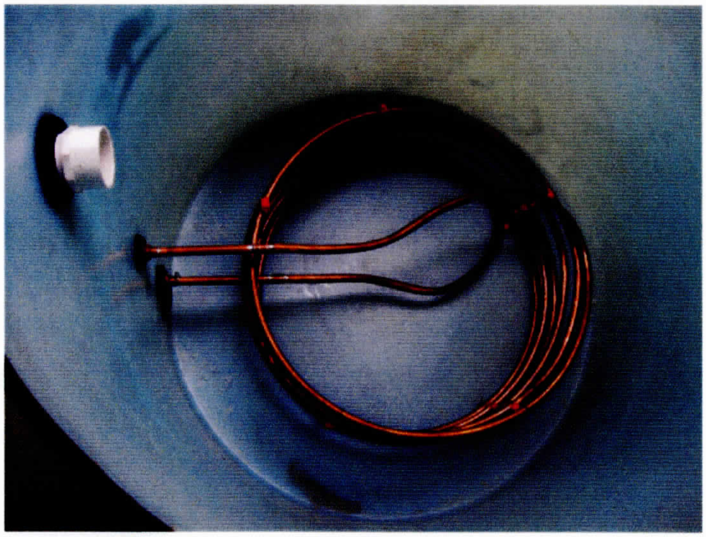

Figure 14. Copper heat exchanger inside bioreactor tank.

Control Bioreactor.

The control reactor used an electric hot-water heater as a heat source. The heater was set to a temperature of 130 °F. A Taco 006 circulation pump was installed and controlled by Labview to ensure that the tank maintained an internal temperature of 95 °F. A kilowatt meter was installed to measure the energy usage of both of these components.

Solar Heated Bioreactor.

The experimental reactor used a heat exchanger that was routed to a 4x8 solar thermal flat plate collector (Figure 15). This panel was located 30 feet away from the bioreactor and at an elevation approximately six feet lower than the bottom of the bioreactor. The process of thermosiphoning was relied upon to circulate hot water from the panel to the heat exchanger within the tank. A Taco zone valve was installed between the bioreactor and the panel to prevent overheating. Labview controlled the zone valve and would stop the flow of hot water after the internal temperature of the bioreactor reached 95 °F. The solar supply lines were charged with a 50/50 glycol and water mixture that served as a heat transfer medium. A psi gauge was installed and the lines were charged to a pressure of 10 psi. The 50/50 glycol and water mixture was necessary to prevent freezing.

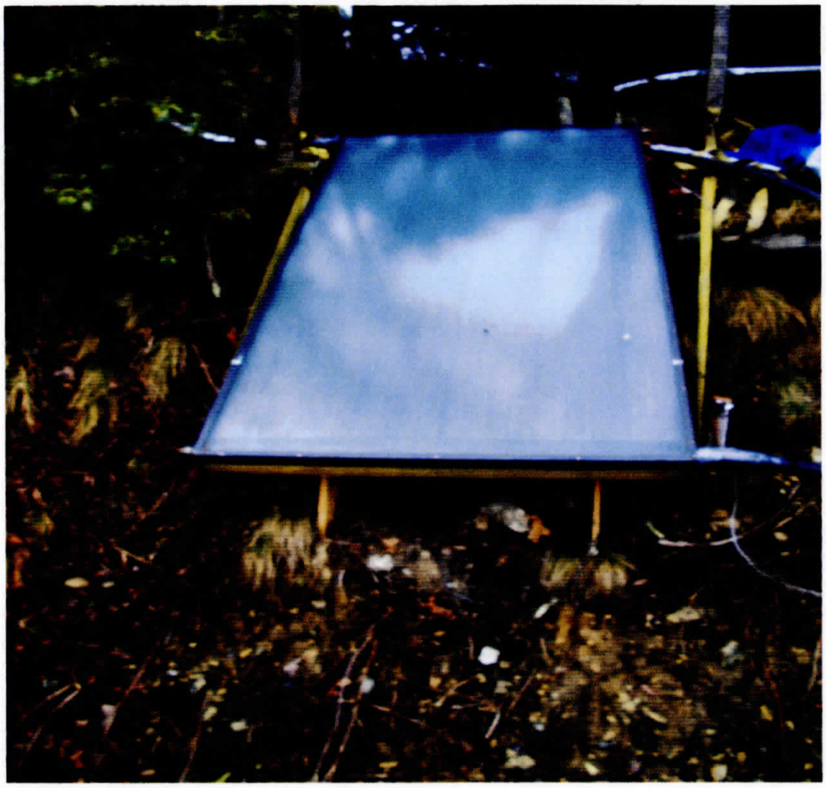

Figure 15. 4x8 Solar thermal panel that heated the experimental bioreactor.

Mixing Within the Bioreactors

A 1/3-HP pump capable of pumping solids was installed 6" above the bottom of each tank for mixing purposes. I soon realized that even a pump rated for residential solid waste was not capable of running without clogging. Also, when the pump was in operation, the thermisters inside the tanks would begin to show highly inaccurate readings. This was an unfortunate occurrence and electrical-pump mixing was abandoned.

Mixing was achieved through the loading of new slurry. When the bioreactors were fed, the influent entered at the bottom of the tanks. This helped mix the settled solids that accumulated at the bottom of each tank.

The placement of the heat exchanger at the bottom of the tank also helped mixing within the tank. In the control reactor, the electric hot water would create heat in the bottom of the tank. In the experimental reactor, a thermosiphoning effect took place as hot water entered the heat exchanger at the bottom of the tank. In both instances, the hotter water would rise and would create circulation within the tank.

Cold-Climate Adaptations for Freeze Prevention

Installing electric heat tape and insulation around the influent and effluent pipes of both tanks was necessary to prevent freezing of these pipes. Heat tape was wrapped around the pipes and then fiberglass insulation was installed over the heat tape. Black plastic was then taped over the insulation to hold in the gained heat. It was also necessary to install heat tape and insulation around the gas collection barrels to insure that the water within the barrels didn't freeze.

Instrumentation

Labview software was used for control and recording of temperatures. Four 10 KΩ thermisters were placed within each tank. One was put 6" above the bottom of the tank and one was placed 6" below the waterline. Two additional thermisters were installed at mid-height within each tank, one at the center of the tank and one near the outside wall of the tank, to monitor thermal stratification. Labview relied on these thermisters to measure and record temperatures every five seconds. Labview also used the temperatures recorded by these thermisters to determine when hot water needed to circulate through the heat exchangers to maintain the optimal temperature of 95 °F. Labview controlled the Taco zone valve on the solar heated system and the pump on the control system (see Appendix B).

The solar thermal panel's energy input to the bioreactor was analyzed through two forms of instrumentation. An insolation meter was installed next to the collector to monitor daily solar activity. A HOBO data logger was used for observing flow rates on the panel. A temperature-sensing thermister was installed on the hot output pipe and the cold input pipe of the panel. The relation between these measurements and the measurement within the tank was used to calculate the flow of the thermosiphon system and the number of Btu added to the tank.

Manometers were installed to measure gas pressure on both systems. Pipe nipples with 1/4" hosing provided access to check gas pressure. Ball valves allowed the operator to bypass the manometers until a pressure reading was needed. By simply turning the valve, the flow of gas would be directed to the manometer so that a water-column measurement could be recorded.

Measuring the biogas composition was performed using two different instruments. A CO_2 gas chromatograph was initially used. This instrument gave a catalytic reading and it was assumed that the remaining gas after measuring CO_2 was methane. A GEM 2000 Gas Analyzer was later acquired to obtain more exact measurements of gas content. Both units, when taking readings, were connected to nipples with 1/4" hoses that were located within one foot of where the gas line exited the bioreactors. Recordings were taken daily. Gases measured included methane, CO_2, and oxygen. A resulting balance of leftover gases was indicated by this instrument and it can be speculated that these gases were composed of hydrogen and hydrogen sulfide (House, 1981).

The volume of gas was measured through water displacement using upside-down 40-gallon barrels submerged within 55-gallon barrels filled with water. As the barrels rose, it could be determined how much biogas was being produced by each system. The volume of gas was recorded by measuring the distance in height by which the barrels had risen. On a daily basis, the barrels were pressurized by hand to empty the gas into the storage area.

The air mattresses that stored the gas were plumbed with 1/2" PVC pipe to the interior of the home where the bioreactors were located. A 10,000 Btu/hour wall-mount ceramic heater was retrofitted to burn the biogas. The orifices of the two burners within the heater were drilled out to 1/16" to burn the collected gas for heat (House, 1981). A manometer was installed in the gas piping inside the home next to the heater to ensure that proper gas pressure was present before igniting the heater. Weighting the mattresses was necessary to provide adequate gas pressure to reach and supply the heater within the home.

A kilowatt-hour meter was installed to monitor the energy consumption of both the electric hot water heater and the circulation pump on the control bioreactor. The kilowatt hour meter did not have a logging function, so it was left to run for a 30-day period and an average daily electricity usage was determined.

Feedstock

The primary feedstock used for the experiment consisted of a 50/50 ratio of cow manure and pre-consumer vegetable food waste. The food waste was collected weekly from Appalachian State University's Food Services. Because the pre-consumer food waste was sorted, it was possible to be selective in choosing what wastes would enter the digester. Due to their easy digestibility, lettuce, carrots, and cabbage were the main constituents of the food waste portion of the feedstock, although exact ingredients and their amounts were dependent upon availability during the week of their collection.

The manure was collected from a small local farm (Appendix C). The 50 head of free-range cattle were fed hay in the winter and left to graze in the warm months. Water was added to the combined manure/food waste feedstock to create the 3% solid rate, and then the ingredients were thoroughly mixed using a power drill with a mixing attachment. Feedings were five gallons each, due to the 30-day HRT in the 150 gallon bioreactors.

VS Sampling

Effluent samples were taken weekly and frozen for later examination of VS destruction within each bioreactor. Samples were later dried in an oven at a temperature of 250 °F to determine total solids (TS). The remaining TS of each sample was then incinerated in a muffle furnace at a temperature of 1000 °F. The resulting matter was then weighed for determination of VS destruction.

Burning of Biogas

Accumulated biogas was stored in air mattresses and then regularly piped to a space heater in the home and burned (Appendix F). The wall-mount, gas-burning space heater was modified for burning of the biogas. The two orifices within the heater were bored-out to sizes recommended by the *Biogas Handbook* (House, 1981). Orifices in this heater required drilling out with a 1/16" drill bit. PVC piping was routed from the storage vessels to the wall-mount heater. The vessels were weighted for a gas pressure of 6" water column (Figure 16). This produced an adequate flame (Figure 17).

Figure 16. Air mattresses used for gas storage.

Figure 17. Modified wall-mount heater used for burning of biogas.

Modeling of Expected Biogas Yields

The modeling of biogas yields through formulas can produce basic expectations of biogas volumes and their relationship with amount and type of feedstock. Table 8 represents feedstock qualities of this experiment and the biogas yields that are expected. Calculations were adapted from the work of Leckie et al. (1975).

Table 8

Representation of Feedstock Qualities of this Experiment.

	Feedstock A	Feedstock B
Slurry mixture	Cow manure	Food
weight (W) (lbs)	4.17	6.255
% of total weight	40%	60%
% moisture (%M)	85	90
% VS of %TS	80	80
VS (lbs)	.50	.50
Total VS	1.0	
VS (lb/cf)	.50	

Table 9 provides a projection of biogas volume generated from one feeding during this experiment. Total VS of both feedstocks were added to assume an equivalent between total daily added VS and daily biogas output.

Table 9

Projected Total of Biogas Generated from One Feeding.

Gas Production			
Total VS (lbs)	Methane (cf)	Biogas (cf)	Biogas (gals)
1.0	2.5	3.8	28.1

VS of the cow manure was determined through heating a sample to the temperature of 250 °F for determining TS. The remaining TS was incinerated in a muffle furnace to observe the remaining VS content. Food waste VS and TS was estimated from the Steffen et al. (1998) research that was presented in Table 2. Because food waste used throughout the experiment varied, it was necessary to use the food remains data in Table 2 for an estimate of VS and TS of food waste. This model is only an estimate of what might be expected, being that the biogas outputs during AD may vary due to the many variables at hand in any operating system.

Figure 18. Left to right: Eric Urban, Zak Dowell, Erica Porras, Brian Johnson.

System Troubleshooting

The AD systems and instrumentation strategies described in this chapter presented numerous operational challenges that required troubleshooting and monitoring. I remain indebted to this team of AD researchers and friends who generously gave of their time to assist with this process (Figure 18).

CHAPTER 4

RESEARCH FINDINGS AND DISCUSSION OF SYSTEM CHARACTERISTICS

Introduction

The focus of this research was to analyze the feasibility of using a solar thermal heating system that relied on thermosiphoning for circulation to heat a bioreactor for methane production in a cold climate. Two side-by-side bioreactors, one of which was heated using an electric hot water heater (the control) and one of which was heated with the solar thermal system (the experimental reactor), were tested. Some aspects of the experimental design presented in Chapter 3 changed because of uncontrollable situations that arose. Chapters 4 and 5 will reveal some changes in methodology that took place as a result of encountered obstacles.

A period of sunny weather came on February 21, 2010 and the contents of the control bioreactor were split between the two bioreactors for startup of the formal experiment. A 3% slurry of cow manure was then fed to each bioreactor until they reached their capacity of 150 gallons. A period of high irradiance was needed to insure that the solar-heated bioreactor would promptly heat its contents to as close to 95 °F as possible. Heated water was also used for mixing of the slurry being fed to the solar bioreactor. The bioreactors were left unfed until March 1 to insure that the inoculants fostered a healthy methanogenic bacteria population.

By the end of the day on February 21, the control tank had reached 95 °F and the solar tank had reached 88 °F. By February 22, the solar bioreactor was producing a large amount of gas and the control bioreactor was only yielding small amounts. I discovered on February 24 that the control side had a leak in the gas line, and the piping was fixed on February 25. Gas began to accumulate quickly after the fix. On March 1, 2010 the feeding cycle was begun. From this day on, formal data collection commenced.

It should be noted that before discovery of the gas leak, the plan had been to collect data on gas production starting on February 21. Because of the leak on the control side, a comparison of biogas between the two systems could not be made during this time period. The solar bioreactor steadily produced around 20 gallons of biogas per day until February 25, when the internal bioreactor temperature fell to 80 °F. At this point, biogas production ceased.

Primary Research Findings

Gas Production

Data revealed that the thermosiphoning solar heated bioreactor produced far less biogas than the electrically heated bioreactor during the experimental period. This study was conducted during a winter with few sunny days, enabling the control bioreactor to outperform the solar bioreactor by a large margin. For example, over the course of a long cloudy period that lasted eight days, the internal temperature of the solar bioreactor fell from 86 ° to 68 °F. At the end of the 25-day experimental period, the control bioreactor had accumulated a total of approximately 1100 gallons of biogas, while the solar bioreactor only generated around 290 gallons. Figure 19 shows the daily comparison in biogas output between the two systems. These reported biogas outputs do not reflect the effects of temperature and pressure on biogas volumes. Using the Ideal Gas Law, I was later able to estimate the degree to which temperature and pressure may have affected total biogas output and discovered that no greater than a 4.5% variance in volume measurements could have taken place as a result of these variables. It is for this reason that biogas outputs are listed as "approximate," reflecting the modest margin of error in my findings. Appendix A provides a detailed description of these variables and an analysis of the degree of which they may have affected measured biogas volumes.

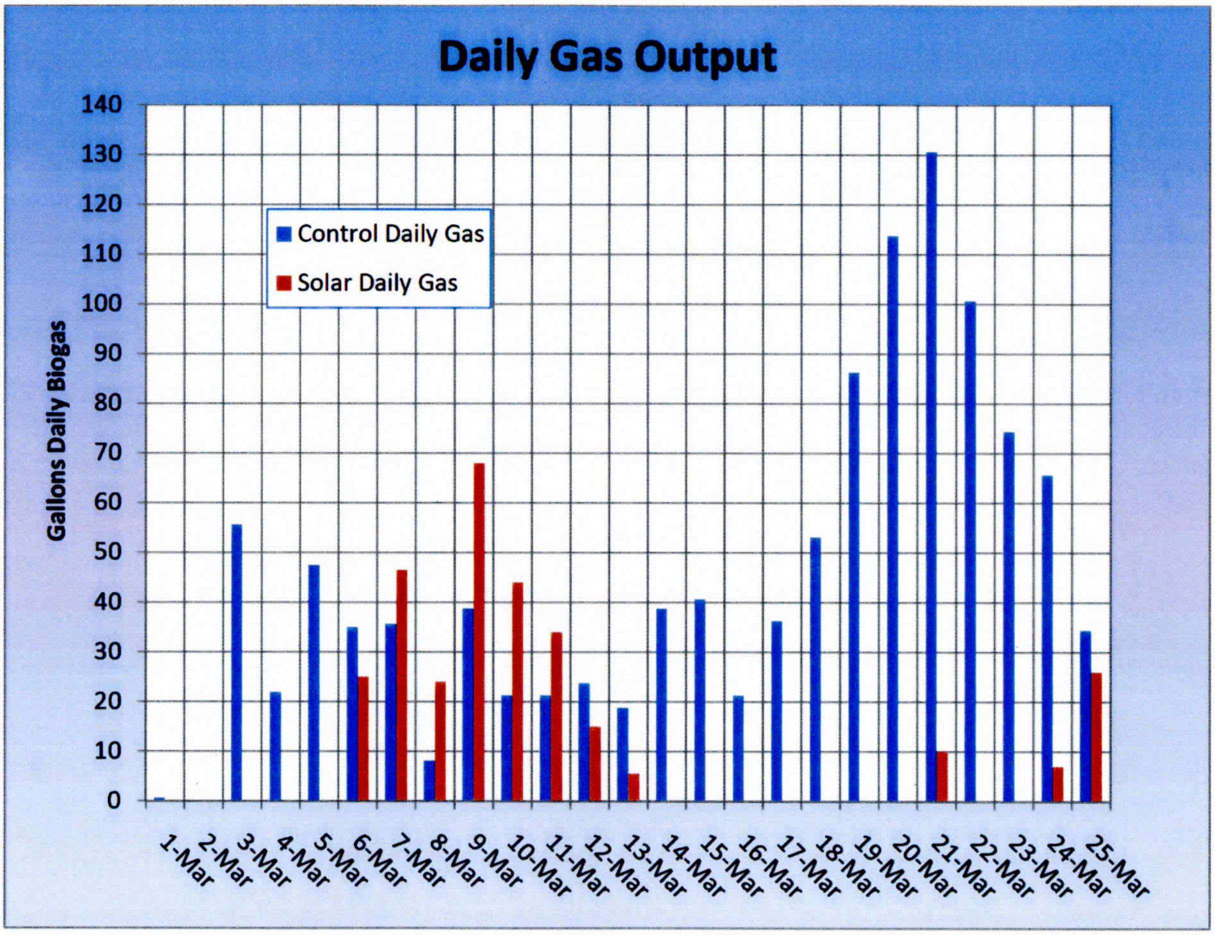

Figure 19. Daily gas output of both bioreactors.

On sunny days, the thermosiphoning panel did provide a generous amount of heat to the bioreactor; however, the daily feedings of organic material to the reactor combined with low ambient air temperatures brought the bioreactor temperature down below that required to produce biogas. Bioreactor heat loss from ambient air temperatures contributed to the overall heat loss, and these losses were anticipated; however, the amount of heat loss per day due to ambient temperature effects during the experimental period was actually less than what was expected based on the TRNSYS model. The TRNSYS model for heat loss was based on a bioreactor that was in a 20 °F average ambient air temperature. The heat loss projected in a 95 °F tank was projected to be 10 °F in four days, equaling a 2.5 °F heat-loss per-day. Actual ambient air temperatures were generally in the 30 °F to 40 °F range during the experimental period. At these temperatures, the internal tank temperature was affected by a drop of about 1.5 °F per day.

The cooling effect of feedings on bioreactor temperature was greater than anticipated and had an unforeseen negative effect on bioreactor temperature stability. Each five-gallon feeding of 45 °F - 50 °F slurry generally dropped the tank temperature by about 1 °F. However, average temperature changes based on ambient air temperature and feedings were hard to determine, and the figures given here are estimates. Not all feedings dropped tank temperatures the same amount. This issue will be addressed in depth later in this chapter.

Solar Bioreactor Temperature and Biogas Production

Temperature had a large effect on biogas production. The three spells of sunny weather revealed different findings relating to temperature and biogas production. Figure 20 displays the trends in temperature and gas production in the solar-heated bioreactor.

On March 5, 2010, the bioreactor temperature rose to 79 °F and gas production began. Biogas was produced steadily and the solar heated bioreactor outperformed the control bioreactor during this time period. Production rates did increase as the bioreactor temperature peaked at 92 °F, although the rate increase was minimal. On March 12, after a period of cloudy days, biogas production ceased when the bioreactor fell to 79 °F. Although the graph shows a cease in production on March 13, this was due to timing of biogas accumulation measuring. The small amount of biogas that was recorded on March 13 had been produced the previous day. After falling to a temperature of 79 °F, biogas production ceased completely.

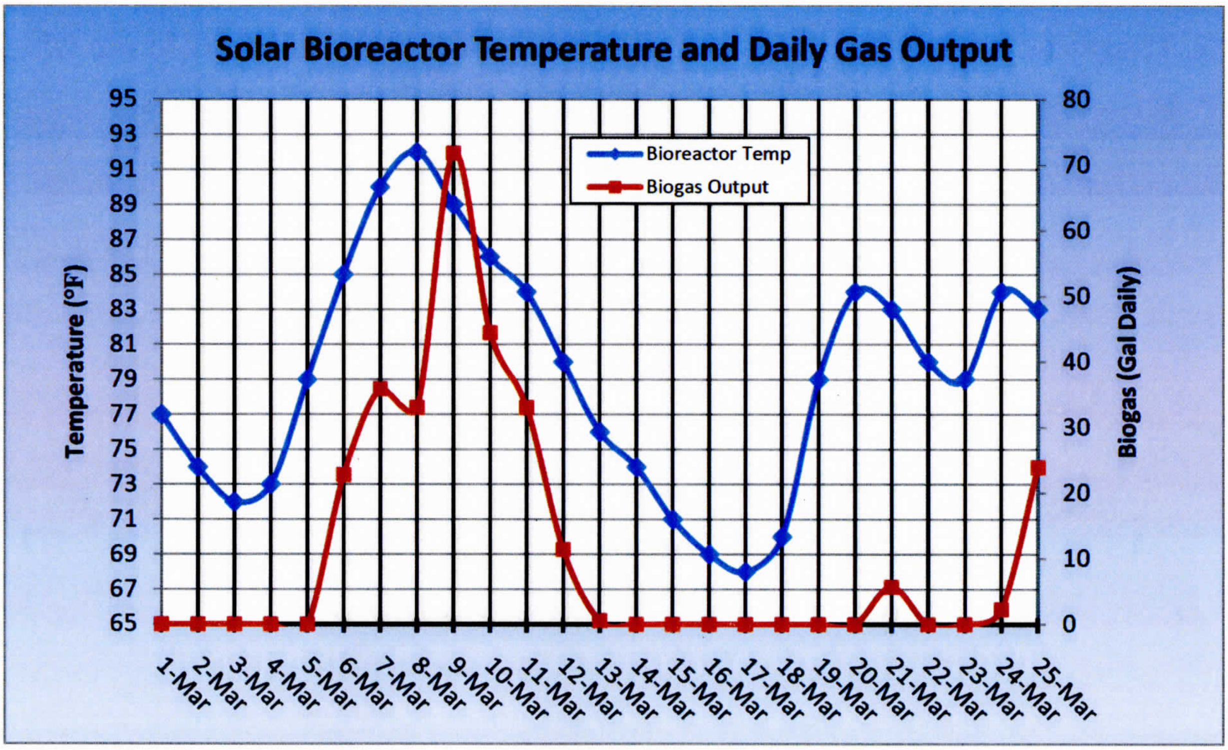

Figure 20. Solar bioreactor and temperature effect on gas production.

During the second spell of sunny weather, biogas production did not resume until the temperature of 84 °F was reached. Only a small amount of gas was produced during the two days after the temperature peaked at 84 °F. On March 22, when gas production ceased, the temperature was 80 °F. The final rise in temperature of the experimental reactor found biogas production to start at 82 °F. Although formal data collection ceased on March 25, It was observed that biogas output rates climbed dramatically and resembled the rates during the first period of sunny weather between March 5 and March 9. It is probable that the accumulation of VS in the bioreactor contributed to the lag time associated with biogas production in the later part of the experiment. The methanogenic bacteria count was probably low and it seems that a five day period of above 79 °F temperatures was required (from March 19 – March 24) for re-growth of methanogenic bacteria and the resuming of steady gas production.

Detailed Discussion of Findings Related to System Performance

Although the primary objectives of this research were to determine the ability of a solar thermal thermosiphoning system to achieve adequate reactor temperatures and the subsequent effects on biogas production, for readers interested in bioreactor research, details about system design are critical for replication and for better understanding of the findings reported here.

Performance of the Solar Thermal Heating System

On days of good irradiance there was as much as a 9 °F temperature gain from solar heat within the 150-gallon tank. I quickly discovered that to maximize output the bioreactor needed to sometimes be fed twice on days of high irradiance. An HRT of 30 days was still maintained, by lessening some of the feedings on days when the bioreactor was at a low temperature. On days when the tank temperature was in the 80 °F range, feedings took place in the mornings to cool down the bioreactor before its heat gain throughout the day. This enabled full use of the solar energy and avoided situations where the bioreactor might reach 95 °F before the end of a sunny day. This feeding routine did complicate the solar analysis, although data shows that significant temperature gains were made on all days that the solar panel received high amounts of irradiance.

After the first good days of sunshine and subsequent adequate heating of the tank, I discovered that the solar bioreactor had the ability to quickly catch up to the control reactor in gas output. As can be seen in Figure 21, the solar bioreactor did outperform the control bioreactor after two days of sunshine. This was likely due to the unprocessed VS that accumulated in the tank during the period when gas production was non-existent. This period of higher gas output in the experimental solar tank was brief. When days became cloudy, the tank quickly fell into a range where biogas output ceased.

Figure 22 displays bioreactor temperature increases from solar activity over the course of the experiment. The week-long period of extremely low irradiance during the middle of the experiment took a detrimental toll on bioreactor temperatures and gas production ceased for several days.

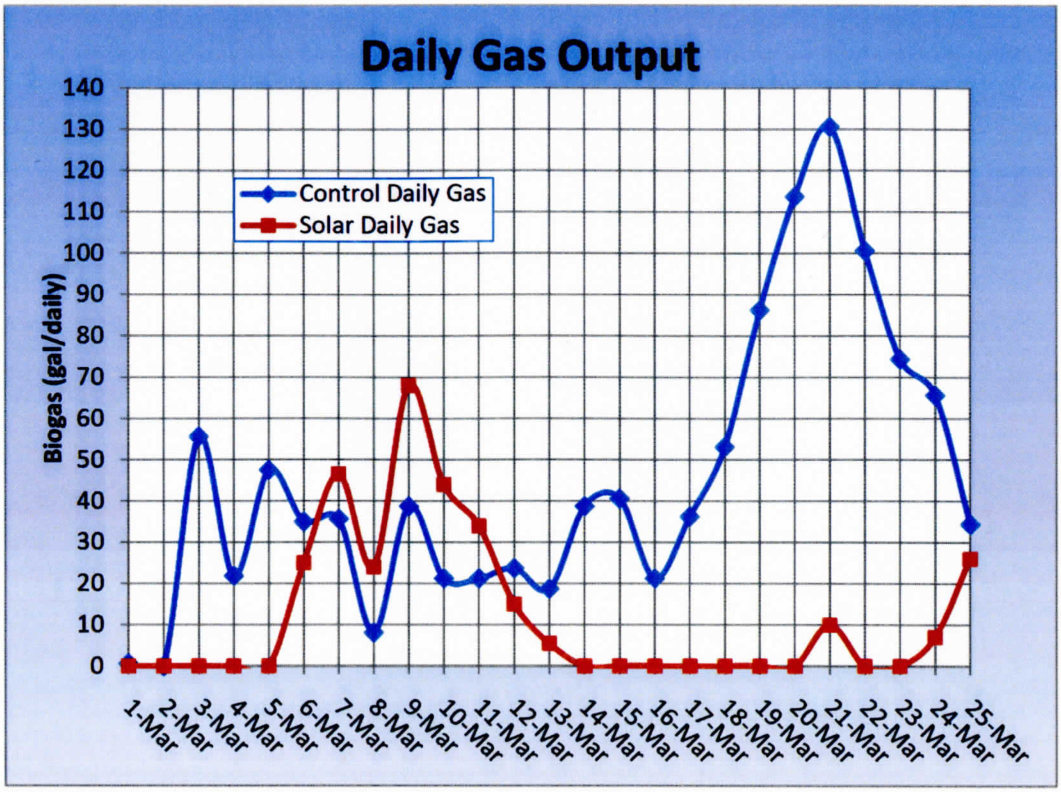

Figure 21. The solar-heated bioreactor outperforming the control bioreactor from March 6 – March 11.

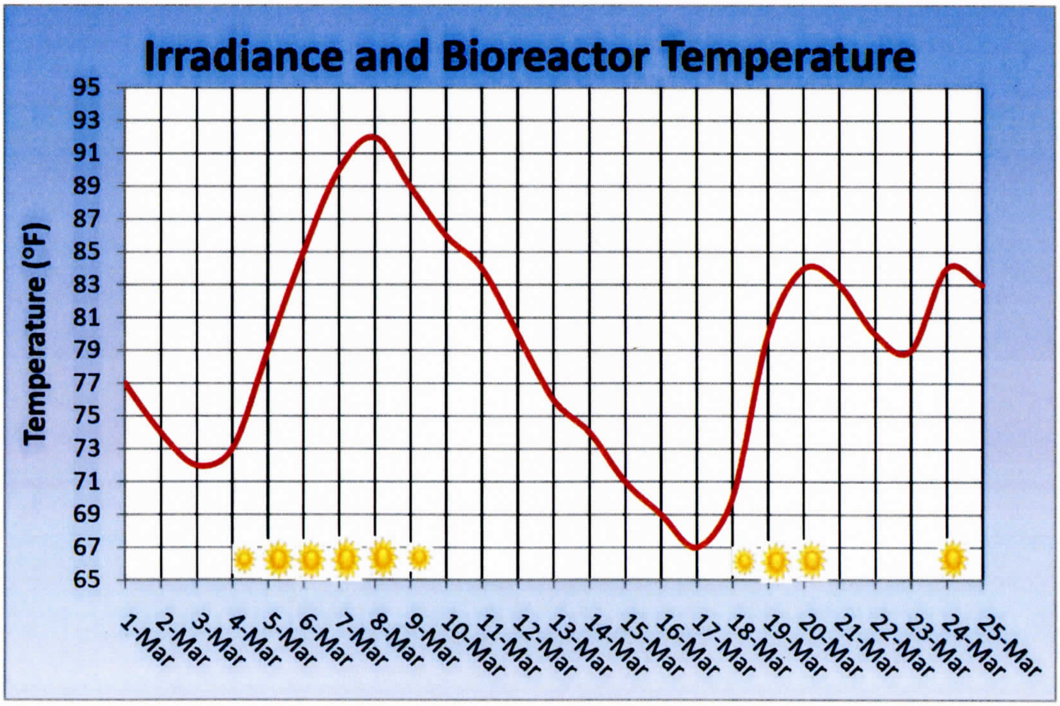

Figure 22. Effects of partly sunny and very sunny days on heat gain in the bioreactor.

During thermosiphoning, the panel sometimes heated water to a temperature over 200 °F. The outlet pipe temperatures on the solar thermal panel during the experimental period are shown in Figure 23. On days of high irradiance (such as March 8), differences between the inlet pipe and outlet pipe temperatures were over 100 °F. Figure 24 represents temperature gains in the bioreactor as a result of heat transfer from the solar thermal panel.

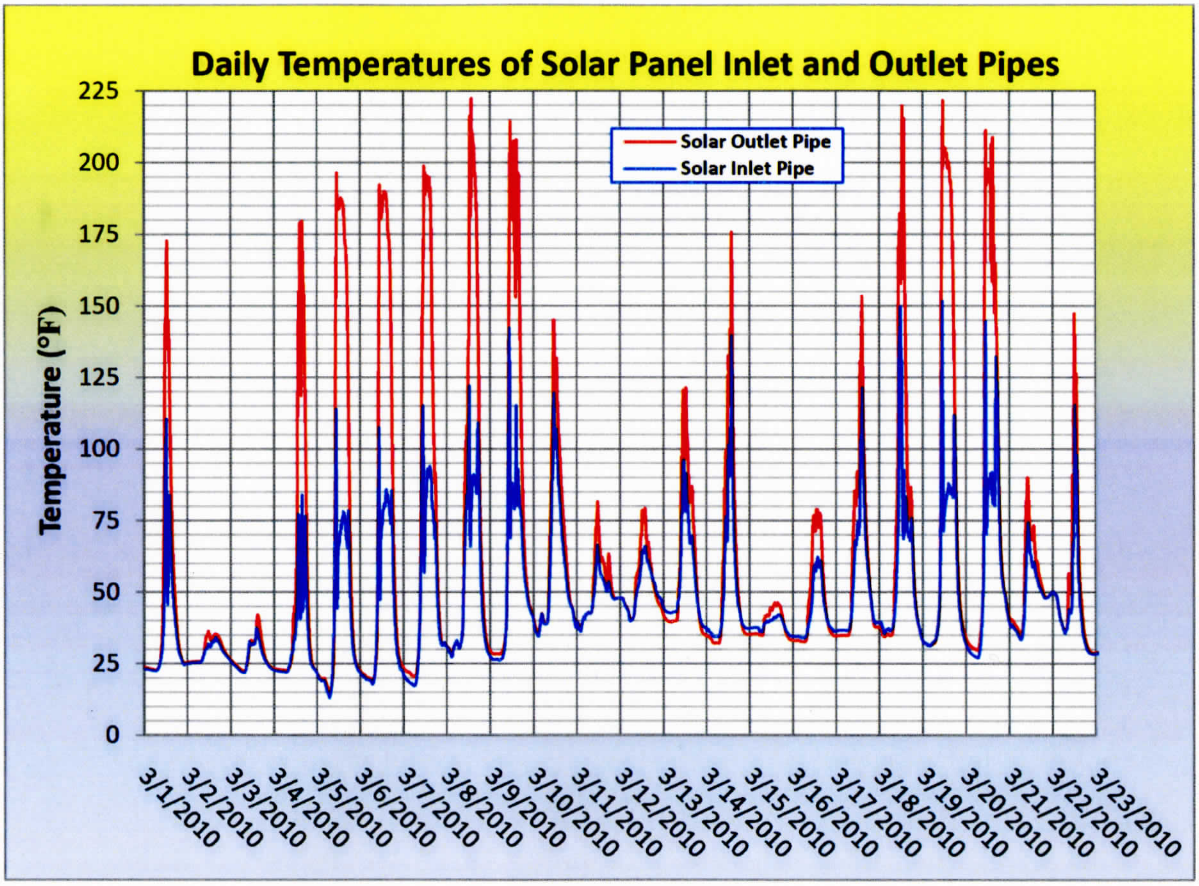

Figure 23. Solar panel inlet and outlet pipe temperatures. The outlet pipe sometimes reached temperatures well above 200 °F.

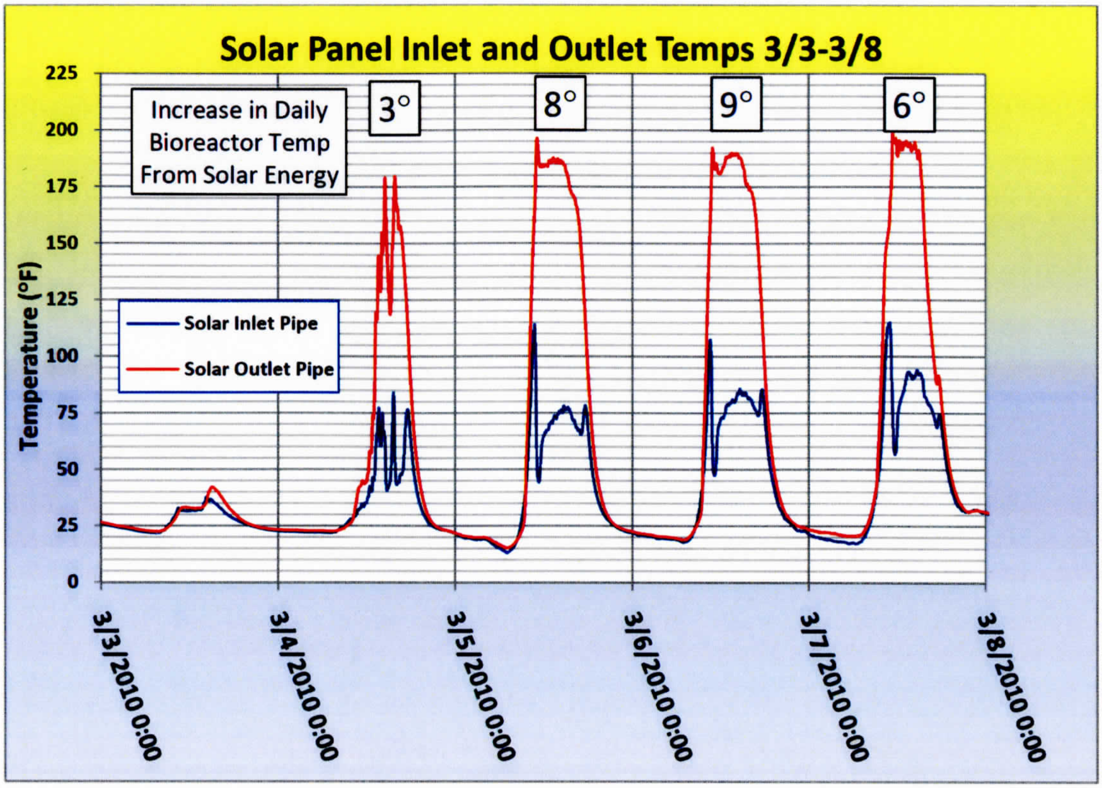

Figure 24. Inlet and out pipe temperatures and their relation to gained heat within the bioreactor on sunny days. Note that March 4th was a partly cloudy day.

To further explore the amount of energy that was being produced and delivered to the bioreactor, a flow meter was installed to log flow from the solar panel on a day of high irradiance. Although this step was not part of the original experimental plan, it became clear during the period of the formal experiment that more information was needed about heat delivery in the experimental system. A flow meter was installed on the return line, just above the solar thermal panel, for logging of flow on a very hot day in April, after the end of the formal experimental period. Ambient temperatures on this day were in the 70 °F – 80 °F range. The testing of flow with this instrument on April 8 turned out to be vital to the solar analysis of the experiment.

Heat delivered to the bioreactor from thermosiphoning had been a subject of debate until data on flow and solar panel inlet and outlet temperatures was recorded and analyzed to measure the flow of heat to the bioreactor. On the particular solar cycle of the day of testing, analysis of flow and ΔT of panel inlet and outlet pipe temperatures revealed the panel generated around 20,700 Btu. Of this, a total of approximately 19,900 Btu were delivered to the bioreactor. This raised the bioreactor temperature from 86° to 103 °F in one day.

Resolution of the flow meter was one gallon and its first gallon of flow was logged at 12:06 pm. Figure 25 demonstrates the relationship between heat delivered to the bioreactor every minute and irradiance measured every minute in W/m². Figure 26 displays the relationship between delivered Btu/min to the bioreactor and the resulting rise in bioreactor temperature.

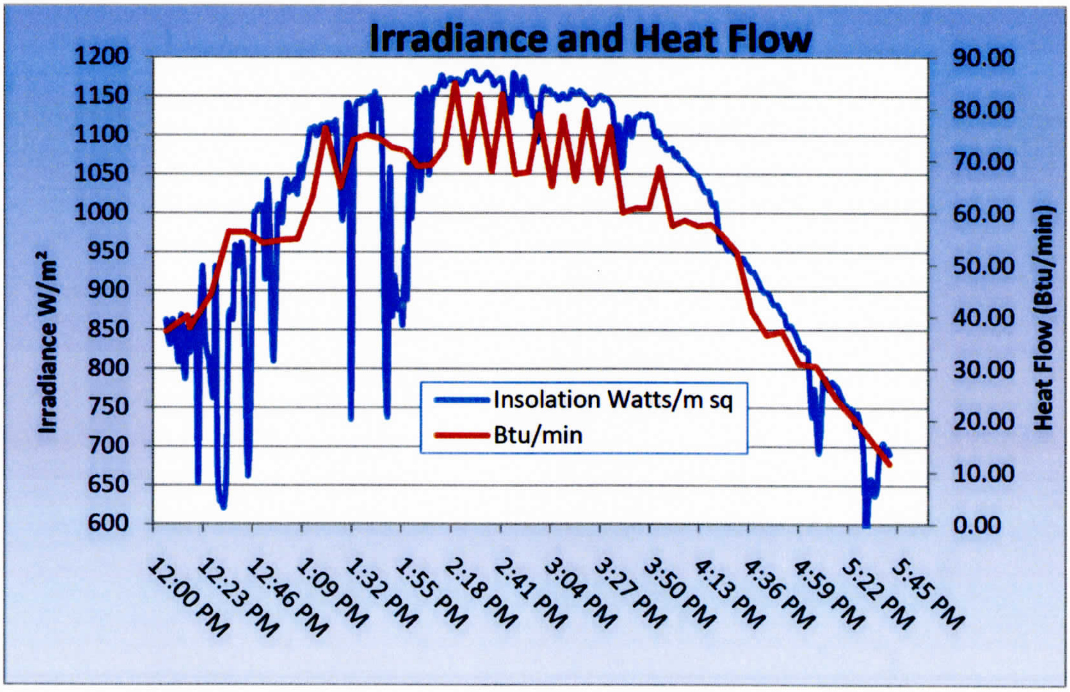

Figure 25. Irradiance and heat delivered to the bioreactor.

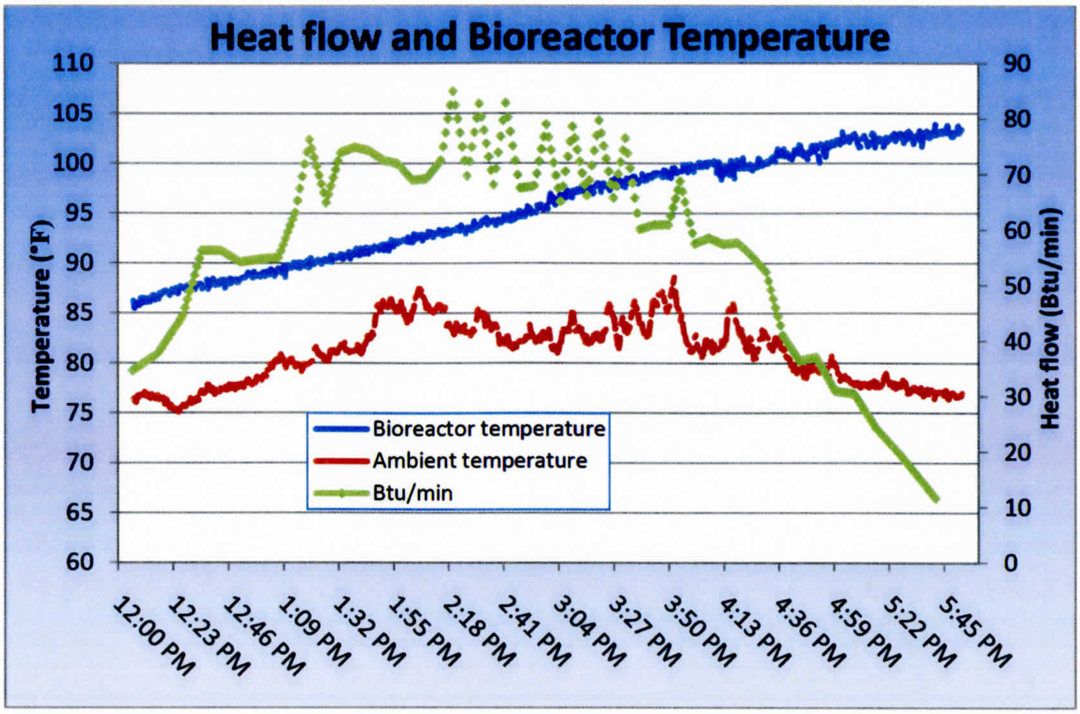

Figure 26. Btu delivered from the solar thermal panel to the bioreactor.

Temperature Loss

Temperature loss in the solar heated bioreactor was due to the feedings of cold slurry as well as to ambient air temperatures. Exact figures on average temperature loss were hard to determine. Throughout the experiment, effects of feeding and ambient air temperature on bioreactor temperature varied. Feeding times during periods of sunny weather would stir the tank and this would create some jumpy readings from the thermisters inside the tanks. The entry of the slurry into the bottom of the tank where the heat exchanger was located stirred up this hotter liquid, causing thermister temperature readings to drop and then rise by as much as .5 °F. In a short matter of time, the temperature would again drop, but at a pace similar to that logged before the feeding. Generally, within an hour or two, temperature readings would fall below levels displayed prior to the feeding. The average temperature loss per feeding was generally around a total loss of 1 °F.

Another factor that made temperature trends hard to pinpoint was stratification of the slurry at nighttime after a day of high irradiance. During the day, the bottom of the tank would be hotter than the top, due to the location of the heat exchanger. On some occasions, the solar heating system delivered liquid to the heat exchanger that was over the boiling point. Over the course of the ensuing night, this heated slurry would stratify and thermisters located in the middle and top of the tank would show slight rises and falls in temperature. Convection within the tank at night may have been taking place, as is illustrated in Figures 27, 28, and 29. These subtle rises and falls in temperature from convection may have taken place as the hot slurry rose and the cooler slurry fell, aided by the rising of methane from bottom to top of the slurry. The best method for speculating the causes and resulting degrees of temperature drops is through close examination of particular time periods.

Feedings took a toll on bioreactor temperatures. Although ambient temperature effects were modeled beforehand, the temperature-dropping effect of cold slurry fed to the bioreactor was not considered before the start of the experiment. The high amount of solids within the tank and the huge scum layer that developed also lowered the thermal mass of the bioreactors. The addition of 5 or 10 gallons of slurry, depending on the day of feeding, cooled the bioreactor contents down more than what was expected. During days when solar energy was heating the tank, sharp temperature drops of around 4 °F were observed in the experimental reactor, followed by immediate reheating within a couple of hours. Figure 27 demonstrates the effect of cold slurry on bioreactor temperature, followed by reheating from solar energy.

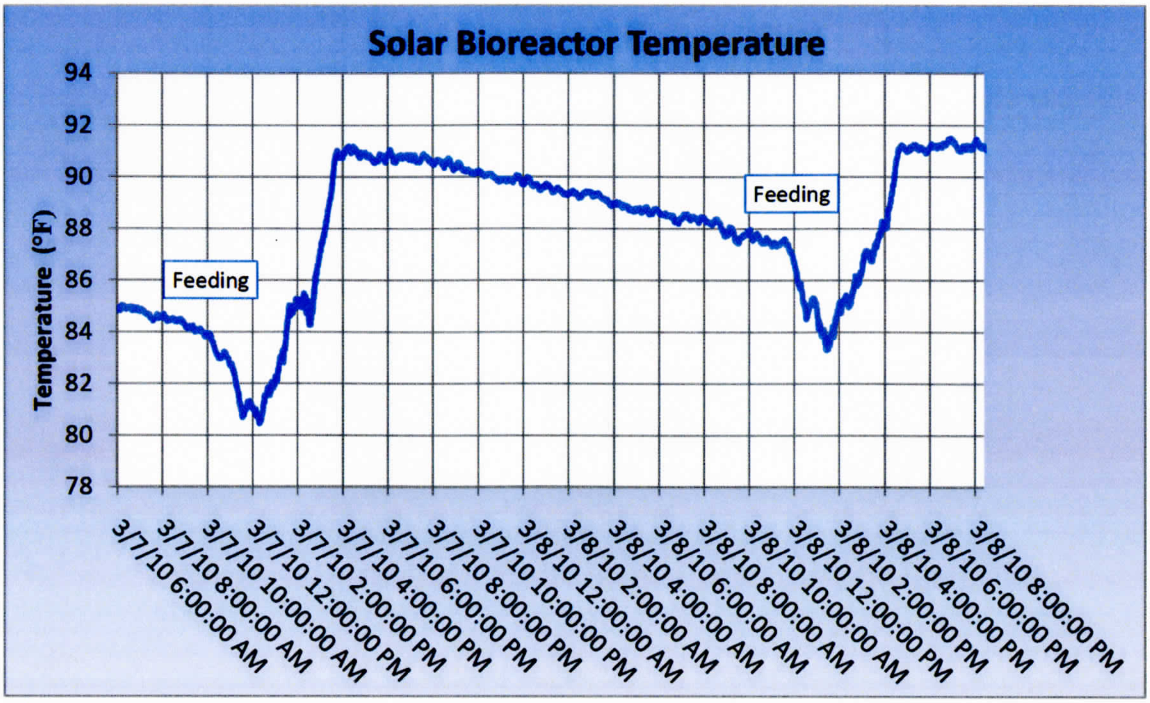

Figure 27. Solar energy, daily feedings, and their relationship to bioreactor temperature.

Bioreactor temperature reactions to feedings during time periods of no solar heat input showed a lower initial drop in temperature. A 1 °F to 2 °F drop was common. Sometimes this drop would be followed by a .5 °F increase in temperature, shortly after the initial temperature drop. On other occasions, especially after doubling the feeding amount, the temperature drop would remain. Figure 28 demonstrates how temperature responses and relationship with feedings varied.

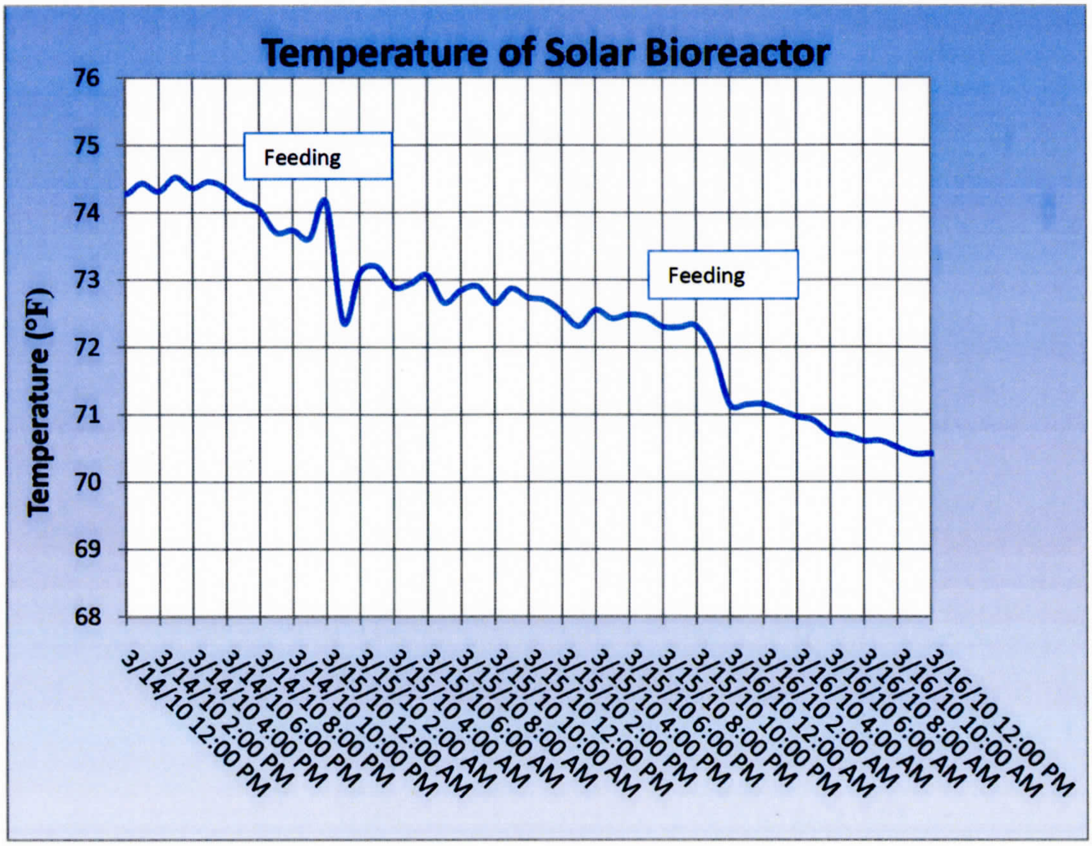

Figure 28. A close look at bioreactor temperature changes from feedings on 3/14 and 3/15.

Studying the data from the longest period when there were no feedings and no available solar energy provides the most accurate information on ambient temperature and its effect on temperature loss. The bioreactor was not fed for a two-day period that started on the night of March 12 and ended on the night of March 14. From March 13 to March 14, there was a 1.5 °F temperature drop in the bioreactor. The 12-hour period that followed showed exactly a .75 °F drop in temperature. The ambient temperature averaged 42 °F on March 13.

Data from March 16 revealed similar drops in temperature. The tank lost .75 °F between 2:00 am and 2:00 pm. In Figure 29, it can be seen that the temperature somewhat stabilized for a short period of time between March 14 and March 15. This was peculiar, because the ambient temperature had dropped to 37 °F and there was no available solar energy. A period of 46 °F ambient air temperatures through the day of March 11 showed larger drops in temperature. There was an atypical 2 °F temperature drop from 1:00 a.m. to 3:00 p.m. on March 11.

Averaging bioreactor temperature drops from feeding and ambient temperatures is difficult, due to the many variables at hand. For example, Figure 29 shows the variations in the effect of feedings on bioreactor temperatures during a time of low irradiance. This shows that temperature changes following feedings were not consistent.

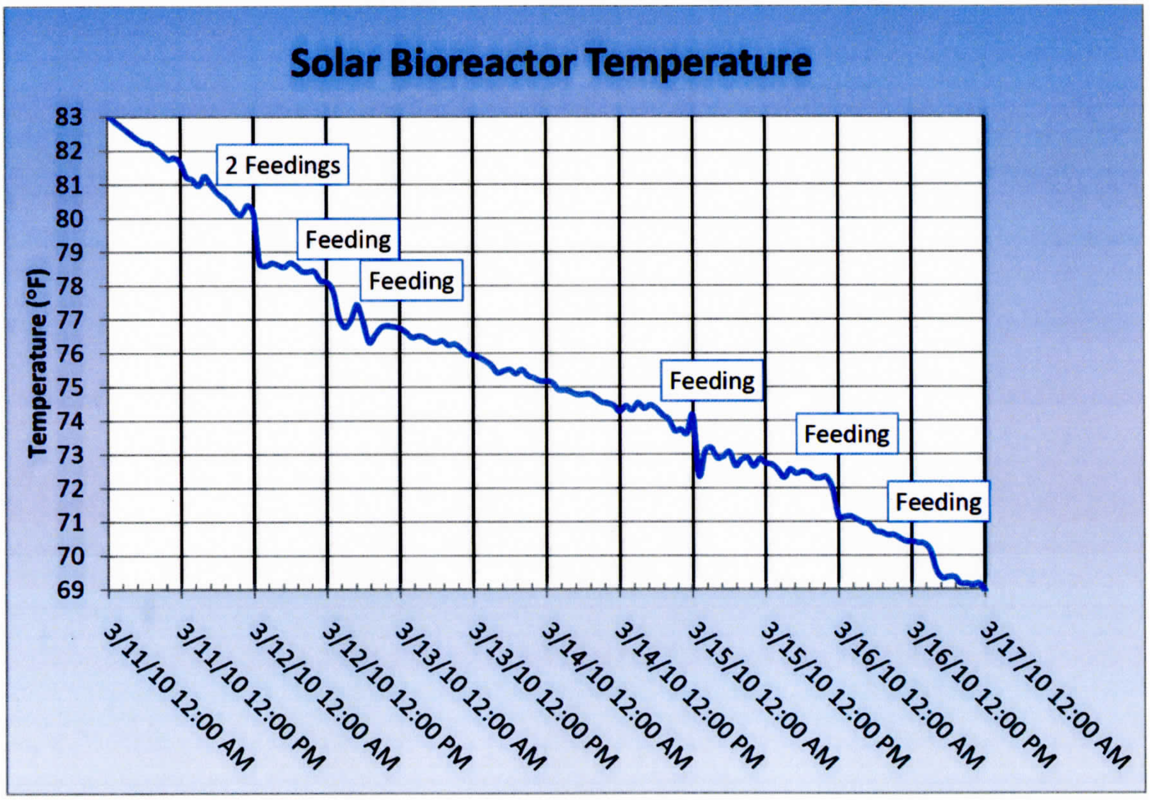

Figure 29. The effects of feeding on temperature within the bioreactor during long periods with no insolation.

Methane Content

Methane content measured in the two tested systems fluctuated with overall biogas output and with the feedstock used, although sometimes in contradictory ways. In the control system, higher amounts of biogas output usually rendered lower methane contents. The solar bioreactor generally held higher methane contents than the control system, even during periods with low tank temperatures and low gas outputs. After the feeding of the post-consumer food waste, both bioreactor methane contents fell into the 40's, before rebounding back into the 50's within a couple of days.

Solar Heated Bioreactor.

Methane content was sporadic and no clear trends can be discerned. During the system's first upward temperature swing on March 5, 2010, both gas output and methane content increased. Similarly, Figure 30 clearly shows that when biogas output fell on March 10, methane content fell also. Conversely, when biogas output ceased for the longest period of time, between March 13 and March 20, methane content reached its highest level. Measuring of methane content was still possible even though volume amounts were too low to develop pressure high enough to raise the barrels. However, sufficient gas was present in the bioreactor for the GEM gas analyzer to record methane content accurately. On March 19, the largest inverse relationship between methane content and bioreactor output was observed. Just after the first feeding of the post-consumer food waste, the methane content dropped from its highest level of 62.1% to its lowest level of 42%. This decline took place over the course of four days.

The second tangible connection between methane content and bioreactor activity took place between March 20 and March 21. During this period, methane content leveled off at

53% for a short period of time. This was also during the first sign of biogas output in over a week. The methane content mirrored the biogas output and when biogas output ceased after less than a day, the methane content continued its plummet into the low 40's.

When gas output began again on March 23, methane content raised dramatically until it reached 53% on March 25. This was also the day that biogas output once again reached a steady state that was similar to that of the control bioreactor.

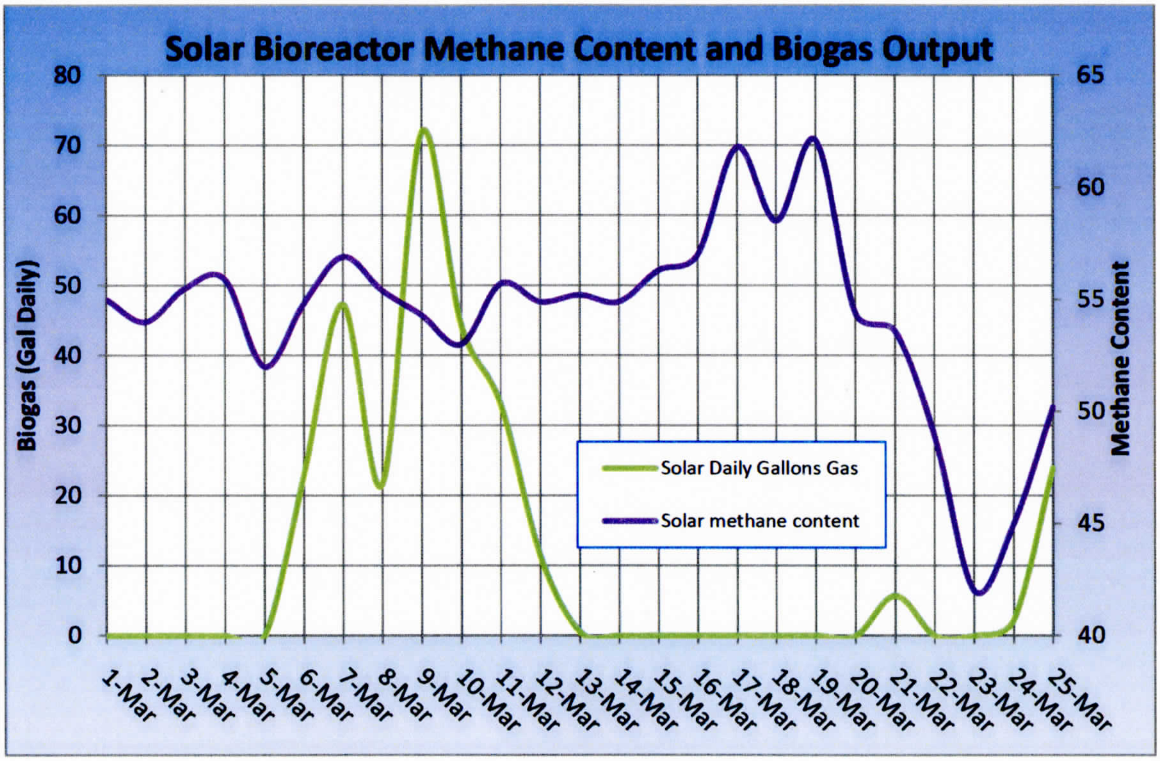

Figure 30. Solar heated bioreactor and methane content.

Control Bioreactor.

Trends in methane content in the control bioreactor were obvious. An examination of Figure 31 shows the direct correlation between biogas output and methane content. Rises in biogas output would result in falls in methane content. Lower biogas outputs resulted in higher methane contents. This was the trend until the introduction of the post-consumer food waste. On March 19, when the post-consumer food waste was introduced to the system, the methane content fell dramatically from 53% to 46% over the course of two days. On March 20, the system appeared to adjust to its new feedstock. On this day the methane content began to rise again. On March 22, and after a dramatic climb, the methane content leveled out at around 54%. This leveling also occurred when the feedstock was changed back to manure. Perhaps the methane content might have risen further if the post-consumer food waste feedings had been continued for a longer duration.

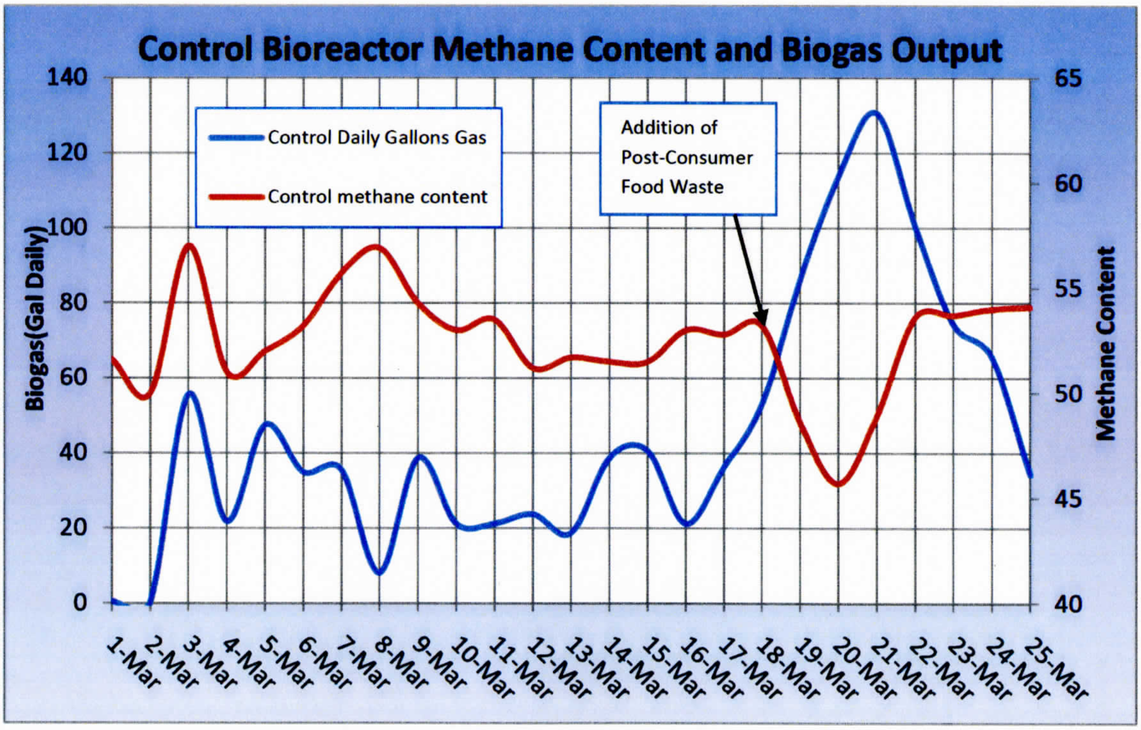

Figure 31. Control bioreactor methane content and biogas output.

Feedstocks

The effect of the feedstock on biogas output was tremendous. The original intent was to use a manure and pre-consumer food waste mixture as feedstock for the duration of the experiment. A few days in, the unavailability of pre-consumer food waste led to the use of straight manure as a feedstock. Post-consumer food waste was procured in the third week and it was mixed with the manure, producing significantly higher methane yields than what had been previously recorded (Figure 32).

The fresh cow manure used for the experiment was tested for VS and solid content before start of the experiment. The VS content was 80%. Solid content was measured to ensure that co-digestion ingredients were of equal solid proportions. The total solid content of the manure was 15%. Pre-consumer food waste collected before start of the experiment was left in a heated area for several days to break down in a covered barrel before being fed to the bioreactors. It was moved outside into colder temperatures after the matter had partially decomposed. The food waste and manure were generally near the point of freezing before being mixed for feeding.

When this pre-consumer food waste ran out, post-consumer food waste was gathered from the Broyhill Inn, a hotel and restaurant operated by Appalachian State University. Contents in this mixture included chili, tomatoes, rice, broccoli, lemons, salmon, turkey, strawberries, brownies, pasta, cheese, and bread. These ingredients were thoroughly mixed into a homogenous substance prior to being combined with the manure for co-digestion.

The measurement of these three different feedstocks and their biogas outputs led to some interesting findings. Straight manure was the lowest yielding feedstock. A 50/50% pre-consumer food waste and manure mixture showed a small jump in biogas output. When a 50/50% mixture of post-consumer food waste and manure was added, the biogas output increased dramatically. Figure 32 shows the dramatic difference in the biogas producing capabilities of these different feedstocks.

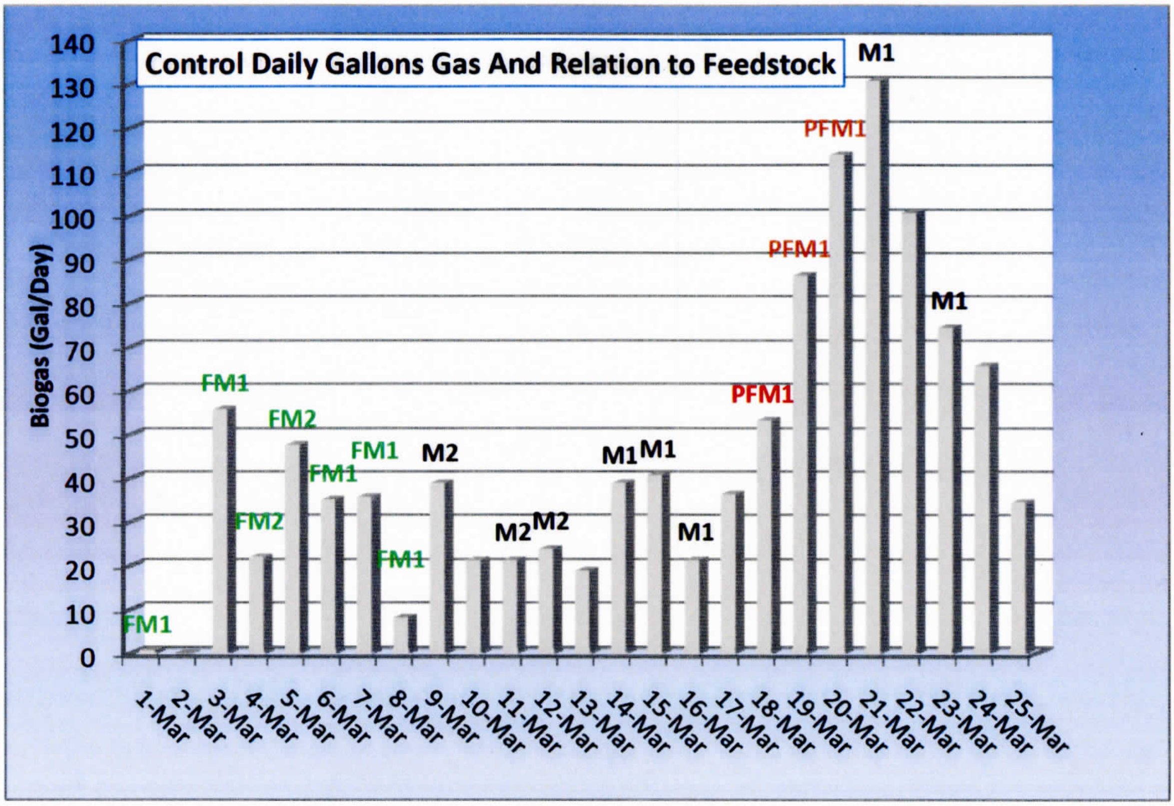

Figure 32. Three feedstocks and their differences in gas production. FM = Pre-consumer food waste and manure; M = Manure; PFM = Post-consumer food waste; 1 and 2 signify number of five-gallon feedings per day.

Biogas Yields in Relation to Feedstocks.

An average of 27 gallons of gas was produced daily by the control bioreactor in the first 18 days of the experiment, before the post-consumer food waste was fed to the bioreactor. The modeled daily yield of 28 gallons proved to be extremely close to the actual results of the experiment during this time period. Differences in production of daily gas when feedings consisted of pre-consumer food waste mixed with manure and manure as the sole feedstock were negligible. An average of gas production between the days of March 19 and March 22, after the post-consumer food waste was introduced, revealed an average of 108 gallons of gas produced per day. This is four times more gas than what was observed before the introduction of this feedstock.

Utilizing a biogas yield model that observes pounds of VS as an equivalent to gallons of biogas may not be a feasible method of determining biogas yields when post-consumer food waste is used as feedstock. While pounds of VS in manure has been studied and fairly accurate predictions can be made based upon performed research, the VS yield of mixed food waste is obviously higher per pound than that of manure, or manure mixed with only vegetative food waste.

Analysis of VS.

Results of VS destruction analysis were hard to interpret, although some basic trends may be identified. There were several variables that negatively affected the accuracy of the sampling. Samples were taken from the effluent exiting the tank, after a feeding had taken place. The proximity of the effluent pipe to the scum layer was a problem. Sometimes, during feeding, the effluent would pull small amounts of the scum layer into the bucket from which the VS samples were taken. Sample size was another contributor to some of the inconsistent data on VS destruction. After drying the samples in the 250 °F oven, the remaining solids were very small in quantity. The remaining solids were heated to 1000 °F in a muffle furnace to determine VS content.

Samples of effluent were taken on March 11, 20, and 28 (Table 10). After realizing the error in sample size, a larger effluent sample was taken from each bioreactor for more accurate examination on the 28th of March. Still, even with the March 28 sample, some of the scum layer might have rendered this data unreliable. The VS percentage within each effluent sample is presented in Table 10. Confidence in the reliability of the March 11 and March 20 samples is very low. Confidence in the reliability of the larger sample taken on the March 28 may be slightly higher, but is still fairly low. The collected data is presented merely for review and interpretation by the reader.

Table 10.

Results of Examination of Existing VS in Effluent Samples on 3/11, 3/20, and 3/28.

(TS = Total Solid; VS = Volatile Solid; FS = Fixed solids)

Sample name	Dry weight (g)	%Moisture	%TS	%VS	%FS
3/11Solar	0.35	97.20	2.80	22.86	77.14
3/11Control	0.07	99.36	0.64	42.86	57.14
3/20Solar	0.12	99.08	0.92	75.00	25.00
3/20Control	0.46	96.49	3.51	23.91	76.09
3/28Solar	0.35	99.23	0.77	82.86	17.14
3/28Control	0.85	98.62	1.38	50.59	49.41

As can be seen from Table 10, patterns of VS present in each bioreactor are fairly difficult to determine; however, some tangible assumptions can be hypothesized. The sample from March 11 shows a greater presence of VS in the solar bioreactor than that from the control. This was after a period when the solar bioreactor had been steadily producing gas from preceding sunny days. Still, VS present in the solar system was probably higher than the control due the several days before March 5 when the solar bioreactor was not producing biogas.

The three samples present a hypothetical correlation between VS buildup and the introduction of the post-consumer food waste. With the introduction of this new feedstock on March 19, VS content samples from March 20 show a rise in both systems. The solar bioreactor had a VS content of 22.86% on March 11. After a large buildup of VS during the week of cloudy weather that preceded the sampling on March 20, an increase in VS would be expected. The large jump from 22.86% to 75% may have also been a factor of the introduction of the post-consumer food waste. The control bioreactor found a decrease in VS from the period of March 11 to March 20. This could be due to the long HRT and the bioreactor's ability to gain in VS destruction through the growing population of methanogens. The low-solid feedstock also would enhance the control bioreactor's ability to destroy VS as the experiment progressed. The rise in VS in the control bioreactor that took place between March 20 and March 28 could possibly be from the introduction of the post-consumer food waste; however, it could be speculated that the week-long period before March 28 should have been a substantial time period for the bioreactor to process the accumulated VS that was introduced by the post-consumer food waste. Again, all of the aforementioned speculations regarding the VS data are hypothetical and confidence in the precision of the data is low.

Figure 33 is a photo taken on March 20, 2010 that clearly shows a difference in VS between the two bioreactors. The solar bioreactor sample was cloudy and dark, while the control bioreactor sample was much clearer, with some obvious floating particles present in the mixture. Close analysis of the samples revealed that the particles in the control bioreactor resembled pieces of straw. The effluent tube's proximity to the scum layer, which is largely composed of straw, may be the reason for the floating debris in the sample. Lignin does not break down easily and its presence in the scum layer upon start of the experiment was evident.

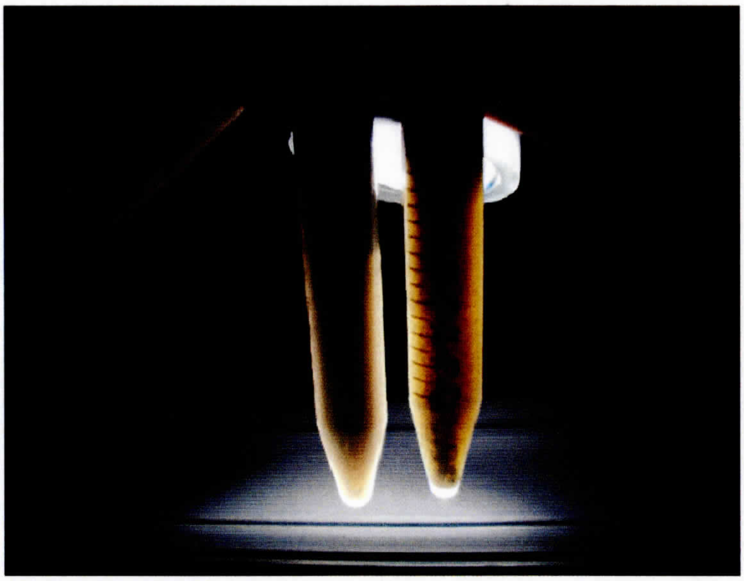

Figure 33. Photograph of effluents taken on 3/20. Solar bioreactor sample on left. Control bioreactor sample on right.

Mixing and Scum Layers

Much was learned about mixing and scum layers when the control bioreactor was opened for dividing of its contents between the two bioreactors for start of the formal data collection. The control bioreactor had been operated for over six weeks before start of the formal experiment. Over this course of time, a 5% slurry of cow manure was fed to the bioreactor at an HRT of 30 days. A steady state was achieved in 15 days. Biogas output was steady and methane content held at 58% from this time until the solar bioreactor was seeded. Although the bioreactor was operating efficiently, there was a great deal of undigested straw present in the scum layer.

Removing the lid showed that a 6-9" scum layer had developed on the top of the slurry (Figure 34). This layer was removed and the remaining contents were mixed before splitting. The remaining contents provided 65 gallons of inoculant for feeding of each bioreactor. The scum layer was composed of a tremendous amount of lignin, mainly straw that did not digest. This appears to be the downfall of using manure as a feedstock and not mixing. The scum layer had no odor and, aside from the lignin, it appeared to be completely digested. Upon its removal, methane bubbles quickly rose into the new cavities where the scum layer had been.

Figure 34. Revealing the scum layer after removing the tank lid.

It was obvious that this layer had been an obstacle for the methane rising from the slurry. At the same time, the system was performing excellently, with high gas yields and methane content, so the methane had been managing to pass through the scum layer and into the outlet pipe. This finding suggested that a large scum layer did not harm the operation of the system and that mixing is not required for manure digesting bioreactors. The downside to this discovery is that a small-scale, unmixed manure-fed system will need to have its lid removed every couple months for removal of the scum layer. Finding a 6-9" scum layer in a bioreactor that is less than four feet tall and has only been in operation for six weeks demonstrates that the scum layer has the ability to take up valuable tank space that should instead be used for new feedstock.

Clogging did occur on several occasions. The end of the influent pipe inside the tank was located 6” below the top of the slurry line. This pipe should have been placed at least 12” below the top of the slurry in the tank. Clogs were fixed by routing a plumbing snake down the pipe and dispersing the scum that was creating the clog. Large, tightly-knit chunks would commonly make their way out of the pipe during the unclogging process.

Not mixing did not prove detrimental to the operation of these two bioreactors. This is because of their short-term use. If testing continued for several months, then the tedious process of removing the lids would have been necessary to remove the scum layer.

The placement of the heat exchanger at the bottom of the tank was a good decision. It helped in creating convection and this surely provided some mixing in the tank, although how effective it was cannot be determined. Figures 27, 28, and 29 showed slight waves in the bioreactor temperature readings. This activity may be the hot liquid rising and the colder liquid falling, creating a convective loop that enhanced homogeneity within the tank.

The location of the influent pipe aided in mixing. Labview readings of thermisters placed at different levels in the tanks did show that the lower and higher areas of the tank were stirred when feedings took place. Furthermore, when the slurry entered the bottom and hit the heat exchanger, the heat that was lingering around the heat exchanger was pushed into other areas of the tank. The rate at which settled solids were mixed through the feeding process cannot be determined. It is probable that some mixing of these solids took place.

Electricity Usage of Control Bioreactor

The energy usage (from the electric hot water heater and the pump) of the control bioreactor was measured through the use of a kilowatt meter. The electric hot water heater consumed far more energy than the pump. Each was tested individually at the beginning of the experiment. The energy consumption of the pump was 50 watts. The water heater consumed 1000 watts.

The meter was installed on February 27, 2010 with the intention of recording a 30-day sample of electricity use. Moisture issues prompted its removal on the 15th of March; however, data for those 17 days was accurate and showed a reading of 95 KWh. The kilowatt meter only records total KWh and does not data log. For this reason, the total energy usage was averaged at 5.6 KWh per day. The average ambient temperature of those days was 37.4 °F. If the system consumed 5.6 KWh per day for 30 days, the total KWh usage of the pump and electric hot-water heater would be 168 KWh. The local rate per KWh is $.078. This equals a monthly energy usage of $13.10 and a yearly total of $157.20. Of course, this is estimating at an ambient temperature of 37.4 °F, which would not be the case in the summer months. On the other hand, the meter was not recording during the colder months of December and January, when ambient temperatures averaged in the 20's (°F).

CHAPTER 5

CONCLUSIONS

This case study revealed data that did answer the proposed research questions regarding temperature and biogas production. However, the numerous variables within the tested bioreactor systems rendered exact calculations regarding biogas production, heat loss, and solar heat gain very difficult.

Hypothesis 1 stated: A thermosiphoning system on a solar thermal heated bioreactor will provide adequate heat for continued methane production unless there is a period longer than seven days with no steady sunlight. During the experiment, there was a period of around seven days with no sun and the solar bioreactor only had the ability to produce biogas during the first four days of this cloudy weather. Thus, the null hypothesis is accepted.

Hypothesis 2 stated: In a given experimental period with sufficient daily sunlight, output from the experimental bioreactor will be no more than 25% lower than gas output from the control bioreactor. During the experimental period, biogas output from the solar bioreactor was more than 25% lower than the biogas output of the control bioreactor. The control bioreactor produced over 300% more biogas than the solar bioreactor. Again, the null hypothesis is accepted. However, this outcome is tempered by the fact that one-third of the way through the experiment, when solar conditions were favorable, the solar bioreactor was producing gas in amounts that fell within a 25% variance of gas produced by the control bioreactor. On March 11, 2010 the control bioreactor had produced 264.3 gallons of gas and the solar bioreactor had produced 241.1 gallons. The week of cloudy weather that followed that period quickly ended the close race between the two systems.

Temperature and Biogas Output

There was a distinct relationship between bioreactor temperature and biogas production. Temperatures between 79 °F and 95 °F produced very similar amounts of biogas. Although Dearman et al. (2005) spoke of a 50% decrease in biogas production from a temperature drop of 20 °F, this experiment found that a 20 °F drop below the critical temperature of 79 °F caused biogas production to stop completely. Balsam (2006) claimed that a 5 °F drop in temperature can reduce methanongenic bacteria. However, in my research the effect of a 5 °F drop was insubstantial, unless the 5 °F drop brought the bioreactor temperature below 79 °F. These findings contradict those reported by Misra et al. (1992), who claimed that gas production slowed down at 64 °F and ceased at 49 °F.

Findings from this experiment most resemble those of Feilden (1981) and the study by Chae et al. (2008), although only on some minor points. Chae et al. (2008) noted negligible biogas production differences between 86 °F and 95 °F and only slightly smaller gas outputs between the temperatures of and 77 °F and 85 °F. Gas production of the solar heated bioreactor was nearly identical to that of the control bioreactor between the temperatures of 86 °F and 95 °F, although no gas was produced at all at the temperature of 77 °F. The Chae et al. (2008) study did involve holding each of these three temperatures for a long period of time. Perhaps the fluctuations in temperature in the solar heated bioreactor played a part in the results of the solar bioreactor performance.

Feilden (1981) found a sharp drop in gas production at temperatures below 82 °F. He reported a minor increase between 82 °F and 95 °F. His findings did differ from mine in that he reported small amounts of biogas being produced all the way down to 68 °F. Again, the fluctuation of temperature in the solar bioreactor may be the variable that stopped its gas production at the temperature of 79 °F.

The halting of gas production at 79 °F and the failure to find other studies that have observed this prompted me to discuss this issue with David House, with whom I have been in correspondence over the course of this study. House pointed out that the particular methanogenic bacteria present in the solar bioreactor might be a species native to the inside of a cow. A lower temperature, far from what these bacteria have grown accustomed to, might inhibit their ability to produce gas. Although the bioreactors were initially seeded with sludge from an anaerobic pig manure lagoon, I speculate that the bacteria in the cow manure component of the feedstock that was fed to the bioreactors might have overtaken the ecosystem within the bioreactor and subsequently decimated the bacteria that were present in the 60 °F sludge from the pig lagoon. Another theory could be that the bacteria within the bioreactor might not produce gas at temperatures that were not only low but also fluctuating on a daily basis. Perhaps if the tank was stabilized at a low temperature, the methanogens would have produced some gas at temperatures below 79 °F.

Solar Thermosiphoning System

The solar aspect of this study demonstrated that the thermosiphoning method of solar heating could be used as supplemental heat for bioreactors in any cold climate. Thermosiphoning provided an increase of 9 °F per day within the bioreactor on a winter day in Boone. Sunny weather would be required at least every three to four days to maintain a proper digestion temperature during consecutive feedings. It should be noted that the very low solid rate of 3% could be increased to introduce more VS. This, in turn, could allow for a less frequent loading rate and lower thermal losses through feedings. For instance, if the bioreactor was fed a 9% solid mixture every third day, the heat-losses from feedings would be 300% less. This would allow for a system to require a sunny day every two to three days. This would be feasible in many areas of the world.

Although the recordings taken from the inlet and outlet pipes of the solar panel show thermal activity on many days of the study, it was discovered that only days with very high insolation added notable heat increases. The process of thermosiphoning is dependent on the steady buildup of heat and then the rising of the hot water into the heat exchanger where the heat is transferred. On moderately sunny days, less than half of the amount of heat was gained in the bioreactor compared to a day with no clouds present. It can be projected that the thermosiphoning process slows down during these cloudy periods and the time-consuming process must re-start after the sun reappears.

The experiment conducted with the flow meter was very fruitful. The amount of heat delivered to the bioreactor on this day was quite impressive, although the ambient temperatures of that day were hardly representative of winter months. The data do reveal that substantial amounts of heat can be delivered through a pumpless thermosiphoning system. A worthwhile future experiment might test the difference in performance between a pumped system and a thermosiphoning system to distinguish the exact differences in performance.

Exact solar gains in the system were often hard to determine, because the temperature effects of feedings made the solar gains harder to interpret. A system that incorporated mechanical mixing would have eliminated this problem. Future experiments observing temperature changes in bioreactors would benefit from utilizing some form of continuous mixing.

Solar assisted bioreactors in climates with high insolation could co-digest manure and post-consumer food waste for high biogas yields if the feedings were fewer, but with higher solids. Long periods of cloudy weather can occur in most climates. The storage of biogas during sunny weather could be used for supplemental heat during periods of cloudy weather that result in the bioreactor falling into a temperature range too low to produce gas.

Methane Content

This study found that methane content is not a large consideration when acknowledging the benefits of small-scale AD. Although both bioreactors held varying methane contents throughout the experiment, percentages were always high enough for burning. The most obvious trend in methane content involved its parallel with biogas output. Especially in the control bioreactor, the methane content always lowered when gas output increased. When gas output decreased, the methane content would increase. The reason for this is unknown. There was no literature found that noted this phenomenon.

The solar bioreactor generally held a higher methane content, even during periods with low tank temperatures. The larger scum layer in this tank could have been the reason. When the contents of the control bioreactor were split for startup of both bioreactors, the existing scum layer was removed, and the remaining contents were mixed before splitting. Perhaps more of the solids stayed in the control bioreactor even after mixing. This, in turn, may have left a larger scum layer in the control bioreactor. Perhaps carbon dioxide made its way through the scum layer easier than the methane. It could also be hypothesized that the increased pressure on the slurry would force more carbon dioxide into the slurry, making the methane content higher. The reason for the higher methane content in the solar heated bioreactor could also be that there is another bacteria working at this lower temperature that produces a higher methane content than the bacteria working at the higher temperature.

The feeding of the post-consumer food waste/manure mixture revealed the most noticeable change in methane content. The methane content dropped with the introduction of this feedstock; however, the benefit of increased biogas production far outweighed the drop in methane content. Methane content was also on the rise shortly after this feedstock was used and it might have been that, had the experiment continued with the feedings of post-consumer food waste, the methane content would have continued to rise into ranges that resembled those of other studies using food waste as a feedstock.

Although the VS analysis is somewhat questionable, an increase in VS after the introduction of the post-consumer food waste was present in both bioreactors. Lipids are known to have a long retention time and perhaps the presence of lipids in this mixture were the reason that the control bioreactor still held higher amounts of VS on March 28 as compared with March 20. Perhaps a week was not long enough for the processing of these lipids.

The effect of feedstock on gas output was tremendous. Household food waste and manure produced the largest amount of biogas during this experiment. Bioreactors could be installed in urban areas to use this waste product as a high caliber cooking fuel. Future experiments could be undertaken using food waste from U.S. restaurants to further analyze biogas outputs and methane contents. It would be interesting to observe the differences between co-digesting food waste with manure and using food waste as a lone feedstock.

Observing the difference in gallons of biogas in relation to pounds of VS of different types of food waste would be an extremely worthwhile study. As was observed in this study, a pound of VS is not just a pound of VS; there are demonstrated differences in the quality of the feedstock in relation to its biogas-generating capacity. The post-consumer food mixture used in this study had a plethora of ingredients. Perhaps by introducing sole food sources to a bioreactor and recording biogas output, data on expected yields per pound of VS present in certain foods could be recorded. This could, in turn, be valuable for future models that predict biogas outputs when using post-consumer food waste as a feedstock.

Instrumentation Issues

Throughout this study I encountered problems with the temperature-recording thermisters inside the bioreactors. There were a few instances when effluent temperature had to be measured and recorded manually to ensure that the thermister readings were accurate. During the trial run of the control bioreactor, prior to the formal study, two thermisters had to be replaced. The damaged thermisters that were replaced showed signs of degradation around the rubber coating and underlying epoxy where the low voltage wire connects with the thermister. Future experiments would benefit from a heartier thermister that is guaranteed to last in a harsh environment and that was constructed to be submerged in hot liquid.

Design Recommendations for Small-Scale Anaerobic Digesters

The findings of this research lead to several assumptions in the field of cold weather small-scale bioreactor design and operation. This case study provided quantitative data for analysis, as well as the opportunity to learn from encountered obstacles during the operation of a small-scale bioreactor in a cold-weather scenario.

Operating the bioreactors led to conclusions regarding several design changes that would be appropriate when building similar sized systems in the future. Burying the bioreactor would be the first and most important design change. Placing the tank in the ground would help reduce thermal losses as well as provide an easier method for feeding the reactors. Pouring the slurry into the five-gallon buckets located at eye level was a chore during this study. An in-ground bioreactor would enable the operator to place the feedstock into a mixing trough on the ground. This mixing trough could be fitted with a plug and an influent pipe that would deliver the slurry to the tank with ease.

A metal vessel with appropriate insulation would be a good choice for the bioreactor tank. Metal piping should be used for influent and effluent piping. The PVC pipes on the operated system were often under a lot of strain when opening and closing large ball valves during feedings. The cold environment made the plastic brittle and prone to cracking when under pressure. If PVC is to be used because of financial or other reasons, it is paramount that a heavy-weight plastic cement be used for gluing of joints. A larger diameter influent and effluent pipe should be installed as well. The small 2" diameter pipe used in this study clogged quite easily and snaking out clogs during feeding was fairly routine. Influent and effluent pipes should be at least 3-4" in diameter.

Influent and effluent pipes should be enclosed within the insulated area of the bioreactor to prevent freezing of pipes. A buried tank would not have this freezing problem, which is another benefit of using the earth as a barrier from wind and ambient temperatures.

A pump should not be used in a system that heats the bioreactor with a conventional heat source. Thermosiphoning should be used for heat delivery instead. Thermosiphoning accidentally overheated the control bioreactor during the trial run of the control bioreactor system. Several episodes were encountered when the pump was not delivering water to the heat exchanger from the water heater, yet the tank temperature would rise above 95 °F and keep climbing. In early January, 2010, the tank reached 120 °F without the pump running. The bottom of the water heater appeared to be at the same level as the bottom of the heat exchanger within the bioreactor. After some more exact measurements were performed, it was found that the bottom pipe from the hot water heater was 1.5” lower than the heat exchanger. A backflow-preventing valve was installed and the problem was solved. The rise in temperature of the tank through thermosiphoning closely resembled the ability of the pump to supply heat to the bioreactor. Eliminating the energy used by the pump would enhance the feasibility of small-scale systems, although admittedly energy use by the electric pump is low. A zone valve could be controlled by a thermostat to stop the flow of hot water to the heat exchanger after the bioreactor reached the desired temperature. Zone valves are much cheaper to purchase than pumps and a thermostat would be required on either system.

A long heat exchanger inside the bioreactor should be used in systems that thermosiphon to ensure that every Btu of heat is absorbed inside the tank. Pumped systems can be more forgiving in heat exchanger size, but when a thermosiphoning system starts the flow of water through the heat exchanger at a slower rate than a pumped system, a very long heat exchanger should be present to ensure that the change in temperature between the inlet and outlet pipe is very high.

Recommendations for Small-Scale AD System Operation

Lack of mixing was an issue throughout this experiment. After less than two months of the trial period, before the formal experiment was started, the control bioreactor developed a scum layer that was between 6-9" thick. The accumulation of this layer depletes the amount of liquid inside the tank. This results in a smaller bacteria population and a lower thermal mass. The scum layer also clogged the effluent pipe occasionally. This resulted in the need for snaking of the pipe to allow the effluent to flow out during feeding. Another benefit of mixing during bioreactor studies would be the enabling of a homogenous effluent for better analysis of VS destruction. The proximity of the effluent tube inside the bioreactor to the scum layer located only inches above it made for sporadic solid contents that exited the effluent pipes. Some of the lignin present in the scum layer could easily make its way out of the effluent tube, thus making VS destruction analysis inaccurate. A well-mixed bioreactor without a scum layer would not have this problem.

A system that holds a portion of the slurry within the tank for the next day's feeding would be an incredible improvement. This would allow the heated contents to be used for mixing of slurry, rather than the 48 °F – 50 °F water that was a contributor to bioreactor heat loss during feedings. By using a very high VS slurry, some of the losses in temperature through feedings could be eliminated.

The use of a photovoltaic (PV)-powered pump might enhance the solar thermal panel's ability to transfer heat on partly sunny days. This might greatly increase the solar heat delivered to the bioreactor during these times. Areas with high insolation might not need a pump for ample heat delivery, but areas such as Boone would. Boone, like many mountain regions, has many partly sunny days. Not being able to utilize the insolation potential on these days is a detriment to the solar bioreactor system. When the thermosiphoning process is interrupted by passing clouds, there is a loss of potential heat gain because of the long period of time it takes for the thermosiphoning process to restart. A small PV-powered pump is a one-time investment that can avoid the 50-watt energy consumption of a pump consuming electricity from the grid. A study comparing the performance of a pumped system and a thermosiphoning system would be valuable for determining the exact difference in performance on partly sunny days.

Gas Storage and Heating Issues

Finding a convenient gas storage method is crucial in the pursuit of small-scale anaerobic digester operation. This is especially true if a solar panel is used as the sole heat source. As was observed in this study, the solar heated system produced high amounts of biogas on sunny days that followed periods of low irradiance. This situation puts the bioreactor operator in a position where gas must be stored for use during cloudy weather.

The four air mattresses used for storage in this study did not allow for enough storage to hold surplus gas for long periods of cloudy weather. Although one could buy an infinite amount of air mattresses, the chance of leaks is then multiplied by the additional plumbing fittings and surface area of the many mattresses. A large, prefabricated storage vessel could not be found during my relentless Internet searches prior to beginning this experiment. A large EPDM bladder might be a wise choice for storage. Due to a lack of available products in the small-scale bioreactor world, it would probably be necessary to buy a roll of this rubber membrane and fabricate the storage vessel on- site.

A plywood platform weighted with vessels of water was used in this experiment to supply enough pressure to feed gas to the wall-mounted heater within the home where the bioreactor was located. This was a tedious procedure for the couple hours of heat that the accumulated gas storage provided. A geared system with a counterweight would be the most sensible pressurizing method.

Playing the Solar Game

People living off-grid in developed nations and those in developing nations who have no source of electricity should be the first in line for solar heated bioreactors. Although long periods of cloudy weather might hinder gas output, some days of high irradiance could generate enough gas for cooking. Taking advantage of the sunny days by storing gas would be important. A strategy for operating a digester with only solar heat would involve storing feedstock during cloudy weather and administering high VS slurry during periods of sunny weather. A higher VS content and fewer feedings would greatly reduce the thermal losses from feedings, while possibly supplying the same amount of biogas. It would be important to monitor VS or correlate loaded VS with produced biogas to insure that a system is not overloaded during periods of cloudy weather. There is the potential for methanogenic washout if overloading occurs and it should be avoided at all costs to keep a healthy methanogenic population.

A future study might also look at letting the bioreactor exceed the ideal temperature of 95 °F. If gas production was not significantly affected, this could serve as a method of lengthening gas production periods during spells of cloudy weather.

Final Thoughts

Lessons learned in this case study could provide information for conducting future experiments where the outcomes could be quite different. Lowering the feeding rate and increasing the solid content of the feedstock would have changed results of this study dramatically. Adding these attributes to a future system and conducting the experiment in a sunnier climate might decrease the vast difference in biogas outputs that was observed between the two tested systems. In a cold area with high daily insolation, the tested system from this study might have performed adequately, even without feeding decreases.

Playing out the scenario with decreased feedings is encouraging. Average daily heat losses of 1.5 °F due to ambient air temperature would equal a loss of 10.5 °F per week in the bioreactor. This weekly heat loss could be reduced by approximately 3 °F if three high VS feedings took place and by even more if a slurry preheating design was utilized. Observations from this study showed that compensating for this 13 °F heat loss would require only two sunny days that each supplied a 6.5 °F rise in temperature per day. If a homemade panel was used, then perhaps 3-4 days would be needed to provide ample heat to the digester.

Those living in cold climates without viable energy sources should consider building small bioreactors heated by homemade solar thermal collectors. Low-tech panels that can be produced from local materials, preferably salvaged, should be considered (see Appendix D and E). There are also many existing users of bioreactors in warmer climates who might find a generous boost in gas output from added heat from a solar collector. There are many areas of the world that are starving for energy. A cold region with high irradiance should look to the heating of small-scale bioreactors with solar thermal panels to provide their cooking fuel.

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APPENDICES

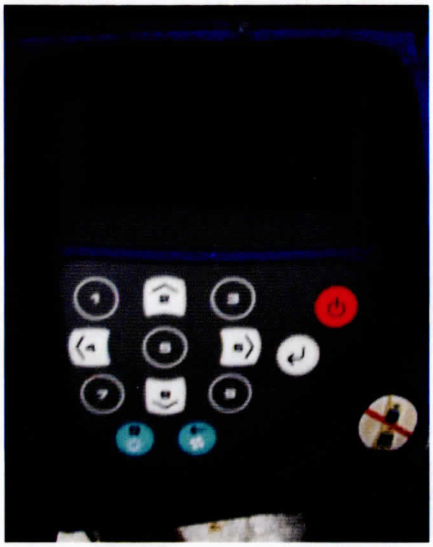
APPENDIX A

Limitations on Method of Biogas Volume Measuring

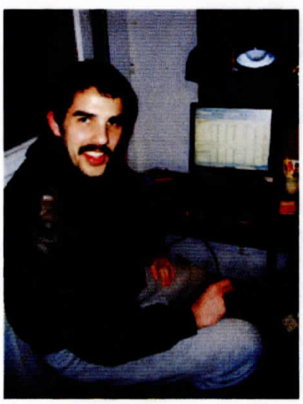
Reported biogas volumes from this research did not account for several variables that may have had an effect on exact volume measurements. The two primary variables pertaining to gas volume are temperature and pressure. The two bioreactors were operated under circumstances that made precise measurement of gas volume very difficult. Variables in this particular experiment were ambient air temperature, temperature of slurry within the bioreactors, temperature of water within the gas storage barrels, and possible losses of CO_2 absorbed into the water within the gas storage barrels. The ideal gas law was used for correction of gas volume estimates in relation to the coldest and warmest ambient temperatures (28 °F and 51 °F) recorded during the experiment. This revealed a potential 4.5% difference in recorded volumes, based upon the largest extreme in ambient temperature variation. The water storage barrels were heated with electrical heat tape that maintained a water temperature of 40 °F, which would mitigate the effects of the temperature extremes just mentioned. The effect of other variables on gas output/volume are difficult to determine. The reader should be aware that listed data involving gas volume for this experiment could be incorrect by a maximum factor of 4.5%.

APPENDIX B

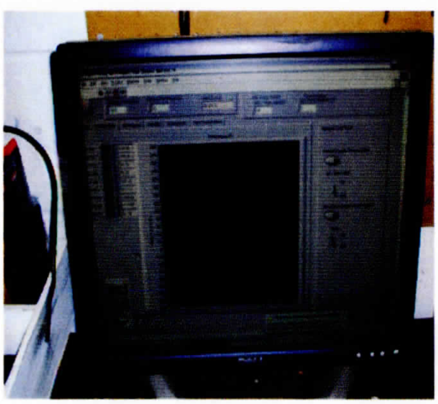
Instrumentation Descriptions and Photographs



The Gem 2000 Gas Analyzer unit was used for measuring methane content. This instrument measured methane, CO_2, O_2, and the remaining balance of other gases. Other gases are presumed to be Hydrogen and Hydrogen Sulfite. The balance reading was generally around .1%.



Eric Urban (left) performed a majority of the programming and maintenance of the Labview software that controlled system components and logged temperature data. Labview enables a researcher to view real-time temperatures, while simultaneously recording data (below left).



The picture at left shows the Labview wiring and hanging thermisters, just before their securing to the PVC pipe. Some thermisters malfunctioned during the experiment. Fortunately, placing four thermisters in each tank insured that there was always at least one thermister providing an accurate reading of temperature within the tanks.

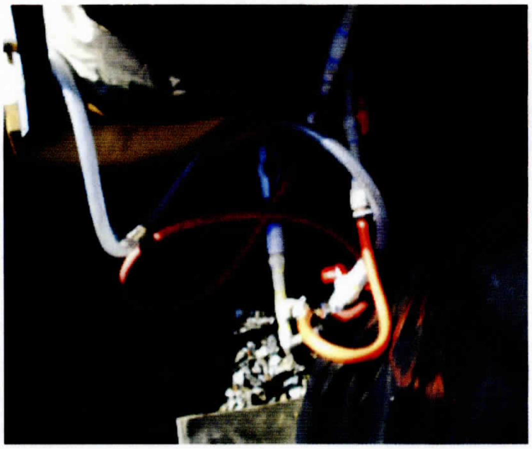
This conduit provided a channel for low voltage wiring from the computer system located in the garage to the bioreactors located out in the driveway. The abundance of wires located on top of the ground reveal that many wires were replaced throughout the experiment. Maintaining the wiring and its communication with Labview was a full time job, especially when they were covered with two feet of snow.

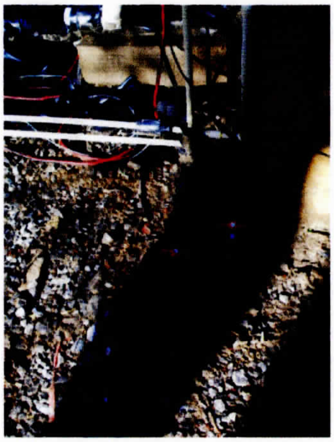
This flow meter was procured after the end of the experiment. Its recording of flow, when coupled with a HOBO data logger, provided the best data on thermosiphoning. The large rises in bioreactor temperature from good days of irradiance seemed too good to be true. This meter logged flow and verified Btu transfer to the bioreactor to prove that the thermosiphoning heat delivery was performing well above what was expected before start of the experiment.

This pyronometer measured daily insolation and data was recorded on a HOBO Data Logger.

This Taco Zone Valve provided a means of cutting off the thermosiphoning flow to the bioreactor when the temperature reached 95 °F. Labview controlled this valve, although its use was never required, due to the fact that the highest temperature reached within the bioreactor was 92 °F. A $60 Aquastat controller could also serve as the brains that operate this valve. This would be preferable to Labview in a real-world scenario.

The Taco circulation pump to the left was used for transport of hot water from the electric hot water heater to the heat exchanger within the control bioreactor. Thermosiphoning provided accidental heat to the bioreactor in the trial run and a backflow-preventing valve was installed to remedy this problem. If hot water heaters are used for bioreactor heating, the installation of a zone valve would eliminate the need for this pump.





Valves, valves, and then more valves! Those located in the picture at top left were for the many air mattresses that gas was stored in. The valves on the lower left were used for condensation traps in the gas lines.

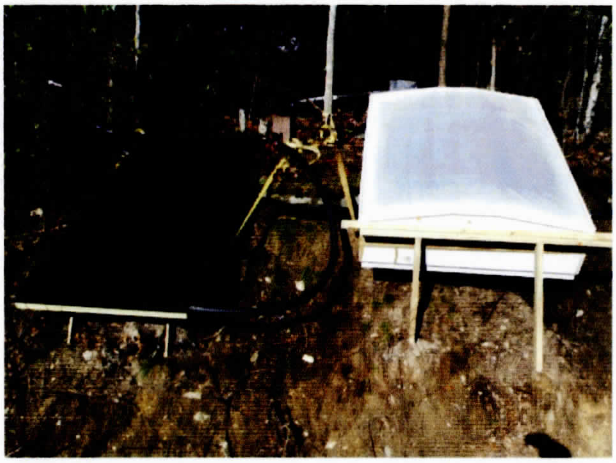
APPENDIX C

Collection of Photos and Description of Farm where Manure was Collected

Manure was collected from a picturesque farm nestled in the valley of nearby Valle Crucis. Locating the fresh stuff was never difficult, being that the area was covered in snow a majority of the winter. A trip was made every week for collection of manure for feeding of the bioreactors. The classic five-gallon bucket and shovel technique served me well on my adventures here. Locating the fresher manure was important to ensure that this feedstock was full of active methanogenic bacteria. These were happy, free-range cows. They are free of antibiotics and hormones.

APPENDIX D

Low-Tech Solar Thermal Panel Built at Appalachian State University

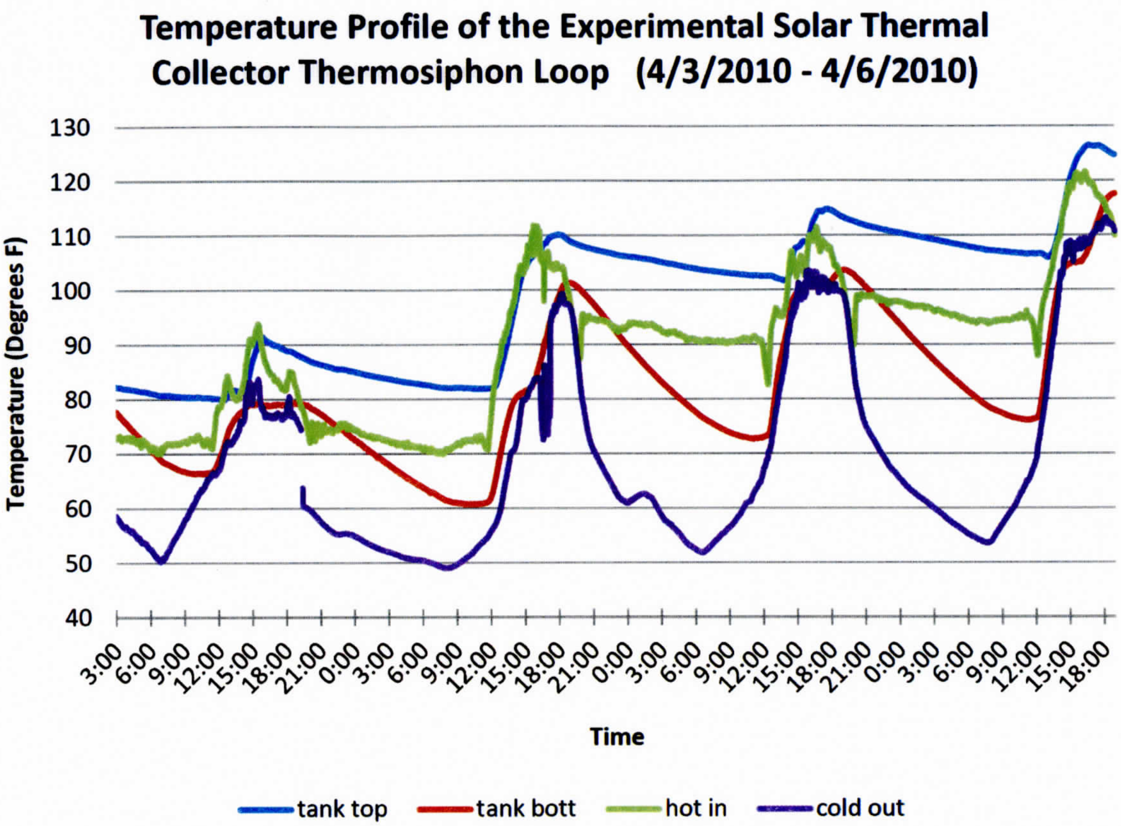


A low-tech solar thermal panel could serve the needs of bioreactor operators in developing nations. The panel on the right was built for a class project at ASU and was produced primarily from salvaged materials. The total cost in purchased parts was less than $100.

The panel was fabricated from an old welding tank, some used metal shelving, and a few pieces of black pipe. We call it the bread box/flat plat hybrid, being that it carries some thermal mass in the tank, but also collects heat through the sheet metal installed underneath it. A loop of 1½" black pipe was welded into the side of the panel for extra thermal mass and heat absorption

At left are Brooks Camp, Ethan Labowitz, and Daniel Law. They installed metal hoops to ensure that the 6mil plastic on the solar collector did not sag during days of high heat.

APPENDIX E: Testing Results of the Low-Tech Panel



The above chart represents data collected from the low-cost experimental solar thermal collector. The collector was connected to an 80 gallon water tank and was left to thermosiphon as a form of heat delivery. As can be seen from the chart, the collector did an adequate job of heating the water within the hot water heater. The water within the tank made generous gains in temperature, as can be seen from the above chart. Implementation of solar panels from salvaged materials should be further investigated as a low-cost option for heating of bioreactors in developing countries.

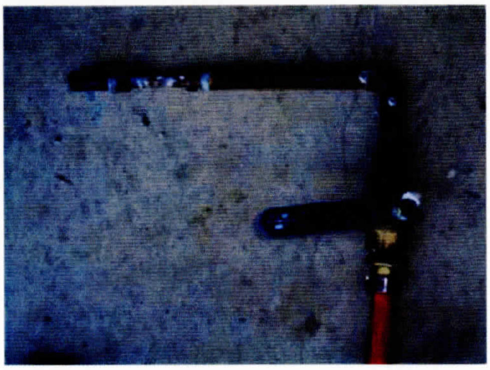
APPENDIX F

Alteration of Gas Fixtures for Burning Biogas

Alterations to gas appliances for burning of biogas is not difficult. Admittedly, the first time you light the appliance after alteration, there is always the feeling of uneasiness. If flame arrestors are installed, then no worries should be had. A fine copper mesh wire can be rolled into a ball and inserted into the gas line to serve as a low-tech flame arrestor. The important thing is constant pressure of gas to the fixture. When weighting your gas storage vessel, be certain there is no chance of a vacuum taking place during burning.

I converted this natural gas wall heater (upper right) by redirecting the main gas intake from the regulator directly to the burner. The thermostat has an automatic gas cut-off that initiates when the thermocouple located in front of the pilot is not heated by the pilot flame. An ill-fated attempt was made at drilling out the orifice on the pilot, but I wasn't able to obtain a steady flame in the pilot that hit the finicky thermocouple on the right. So I bypassed the thermostat, and directed the gas intake directly into the two burners of the heater. It works marvelously and has provided my little home with a couple of hours of supplemental heat on many cold and windy nights.

The burner in the upper left photo is the side burner on my gas grill. It is propane and requires about double the gas pressure for operation (.5 Psi). I drilled it out to 1/16th as well, and it works great. I just add a little extra weight on the mattresses that store the biogas.



The little homemade biogas flare in the photo at left was built for demonstration purposes. Some copper and a cutoff valve is all it took.

BIOGRAPHICAL SKETCH

Zachary David Dowell was born in Winchester, Virginia on May 12, 1974. He graduated from James Wood High School in 1992. He received a Bachelor of Science degree in Anthropology at Longwood University in Farmville, Virginia, in 1997. He then worked as an archeologist on numerous projects in several states for two years. Following this period, Dowell returned to Winchester where he began working for his father as a Residential Construction Superintendent. In 2002, he fulfilled the requirements for a Class A Construction License in the state of Virginia. In 2005, he moved to Richmond, Virginia, where he owned and operated a general construction and home building company.

Zachary Dowell began study towards a Master of Science degree at Appalachian State University in the Fall of 2008. He completed the requirements for this degree with concentrations in Appropriate Technology and Building Science in May 2010.

Dowell plans to seek employment in the field of large-scale anaerobic digestion design and installation.