ABSTRACT

Title of Document: DESIGN AND ECONOMICS OF PLUG-FLOW, SMALL-SCALE ANAEROBIC DIGESTERS FOR TEMPERATE CLIMATES

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Anaerobic digestion is a manure treatment option that is gaining popularity throughout the world as a result of its multiple environmental and economic benefits. There exists a need for further research to make anaerobic digestion and methane recovery more readily available, cost effective, and manageable to small dairy facilities in the United States. This research analyzes the design and economics of plug flow digesters, modeled after low-cost digesters utilized in the developing world and modified to operate on small to medium-scale farms located in the temperate United States. The objectives of this research are to: 1) Describe the modified design and construction of the research plug flow digesters and analyze the barriers and design challenges to implementing this technology in the United States and 2) Conduct an economic analysis to determine the feasibility of installation and operation of these types of systems in the temperate United States.

DESIGN AND ECONOMICS OF PLUG-FLOW, SMALL-SCALE ANAEROBIC DIGESTERS FOR TEMPERATE CLIMATES

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2011

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Acknowledgements

This work was supported by funding from the Maryland Water Resources Research Center and University of Maryland Agriculture Experiment Stations. I would like to thank Jon Leith, Mike Kemp, Brad Green, and the rest of the crew at the USDA Beltsville Agricultural Research Center for their support and assistance during construction of the research system. I also wish to thank Gary Seibel and the staff at the ENST Project Development Center for their engineering assistance and component fabrication. Additional thanks are due to the Lansing Lab Group including Faaiz Ajaz, Scott Allen, Grant Hughes-Baldwin, Ashley Belle, Anisha Gupta, Kayoko Iwata, Caiti Jackson, PJ Klavon, Sol Lisboa Kotlik, Akua Nkrumah, Ryan Novak, Owen Williams, Freddy Witarsa, and special thanks to my partner and cohort Andy Moss for all his support, hard work, and sense of humor throughout the various phases of the project.

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Chapter 1: Introduction

1.1 Livestock Practices in the US

As of 2007, the United States had over 1 million livestock and poultry operations, 6.6% (69,890 dairy farms) of which were dairy facilities (US NASS, 2009). Maryland accounted for 663 of those dairy farm operations, with over 90% of the dairy farms having less than 200 cows (US NASS, 2009). For these farmers, one of their greatest challenges is waste management. A variety of methods are used to collect, store, and treat manure. In Maryland, the majority of dairy farmers, over 90%, use liquid/slurry or daily spread for manure management (US EIIP, 1997; US NASS, 2009). As concerns over water quality, methane emissions, and other environmental factors increase, improved methods for manure treatment, including anaerobic digestion, are being sought.

In 2007, 99% of dairy operations in the U.S. applied manure to their lands, with nearly 17% of small-scale operations giving away a portion of their manure resources (US NASS, 2009). The number of small-scale dairy farms (less than 200 cows) in Maryland fell from 1,040 in 1997 to 607 in 2007, as small dairy farms are struggling to remain profitable. Enhancing the value placed on manure from a waste nuisance to an energy-filled, nutrient-laden economically viable product could increase the viability of these small farms (US NASS, 1999; US NASS, 2009).

1.2 Anaerobic Digestion

Anaerobic digestion is a series of reactions occurring in a sequential process to transform organic material into methane and carbon dioxide by various bacterial groups (Amani et al., 2010). In the first phase, organics are broken down into simple sugars, fatty acids, and amino acids through the process of hydrolysis. In the second phase, the products of hydrolysis are degraded into organic acids, alcohols, and acetate through acid production and acetogenesis. During the final phase, the produced acetate, methanol, and hydrogen gas are transformed by methanogens into methane and carbon dioxide, in the process called methanogenesis (Gerardi, 2003). The majority of the bacteria involved in the process are facultative and obligate anaerobes, including methanogens, which are particularly susceptible to the presence of oxygen. The three stages of anaerobic digestion function in a dynamic equilibrium, in which the inhibition of one reaction will hinder the subsequent reactions (Wilkie, 2000a). Substantial research has been conducted on the microbial interactions within the digestion processes, and there have been attempts to isolate each step in separate reactors, with some success (Koutrouli et al., 2009; Rubio-Loza and Novola, 2010).

Anaerobic digestion can occur in the psychrophilic temperature range (5-20°C) (Lettinga et al., 1999; Masse et al., 2007), but it is more common to operate reactors in either mesophilic (25-40° C) or thermophilic (50-65° C) conditions (Gerardi, 2003). The microbial communities present in one temperature range are not necessarily the same as the ones present in another temperature range, resulting in severe decreases in biogas production when switching from one temperature range to another (Ward et al., 2008). Even small changes in temperature have been shown to reduce biogas production (Chae et al., 2008). Digesters have however, been shown to function effectively at the lower end of the mesophilic range (25-27° C) (Lansing et al., 2008b). This demonstrates that while microbes can adjust and be productive outside their optimal temperature range, sudden changes in temperature are detrimental to the microbial community.

In addition to temperature, the anaerobic digestion process is affected by pH and alkalinity. Alkalinity is necessary for pH control and acts as a buffer against declining pH during acidogenesis. Methanogens are sensitive to pH change and operate optimally between a pH of 6.8 and 7.2 (Gerardi, 2003). pH is affected by the production and consumption of volatile acids and the carbon dioxide content in the biogas (Gerardi, 2003). Decreases in alkalinity can occur when organic acids accumulate in the digester due to the failure to covert the acids into methane during methanogenesis or the introduction of organic acids into the digester through the feed material (Gerardi, 2003).

1.3 Benefits of Anaerobic Digestion

In addition to renewable energy production, the utilization of anaerobic digesters results in other benefits: (1) improved water quality, (2) decreased odor, (3) reduced greenhouse gas emissions, and (4) increased income from non-market benefits (tipping fees, digested fiber, and carbon trading). During digestion, over 80% of the pathogens introduced in the manure influent are reduced (Olsen and Larsen, 1987; Sahlström, 2003; Martin, 2004; Lansing et al., 2010) and solids are degraded by 25-90% (Martin, 2004; Lansing et al., 2008a). Utilizing anaerobic digestion also results in the reduction of odors (Pain et al., 1990; Powers et al., 1999). Anaerobic digesters reduce methane emissions released from livestock waste by capturing and utilizing the energy through combustion, resulting in the conversion of methane into carbon dioxide (AgStar, 2010b; Gloy, 2011).

1.4 Possible Benefits

A decrease in weed seed germination and viability is sometimes promoted as a benefit of the anaerobic digestion process (Lusk, 1998; Nelson and Lamb, 2002) and is included in some economic analysis as financial benefit due to a decreased need for herbicides (Yiridoe et al., 2009). However, at least one study has found no significant difference between digested and non-digested seeds (Katovich and Becker, 2004), and it is inconclusive whether any real savings occur.

There can be reductions in total nitrogen and total phosphorus due to microbial uptake and settling (Geradri, 2003; Inglis et al., 2007; Lansing, 2008b), although other studies have not found significant nutrient accumulation in the digester (Martin, 2004; Wright et al., 2004). Most nutrients are transformed during the digestion process from an organic form to an inorganic form, and, thus, are still readily available in the effluent (Lusk, 1998; Lansing et al., 2008a). While some studies have shown that digested manure improves crop yield through the conversion of nitrogen to a more readily available form, ammonium, other studies have found that digester effluent does not increase crop yield but rather results in equivalent yields to non-digested manure (Lusk, 1998; Allan et al., 2003). It is therefore, inconclusive if the installation of a digester would necessarily increase the value of the waste as fertilizer. One study has highlighted potential future income revenues from the extraction of fertilizer-grade struvite from digester effluent (Bishop and Shumway, 2009) and several studies have highlighted the possibilities of further treating the digester effluent through treatment wetlands, duckweed ponds, or algae growth (Cheng et al., 2003; Lansing et al., 2008b; Mulbry et al;, 2008; Lansing et al., 2010).

1.5 Treatment Methods

Anaerobic digestion, which is used in less than 5% U.S. municipal wastewater treatment plants, has been used in the livestock industry since the 1970s (Lusk, 1998; Tchobanoglous et al., 2003; CWNS 2008). A review of livestock-based digesters in the United States in 2011 is shown in Table 1.1.

Table 1.1 Status (2011) of livestock digesters in the U.S.

Status	Complete Mix	Covered Lagoon	Plug Flow	Fixed Film	Other	**Total**
Under Construction	8	1	16	3	7	**35**
Operational	49	23	81	3	14	**171**
Shutdown	11	8	13	2	4	**38**
Unknown	1	0	0	0	0	**1**
Total	**69**	**32**	**111**	**8**	**25**	**245**

Based on data from the AgSTAR Anaerobic Digester Database, updated July 2011, (AgStar, 2011b)

An initial driving force behind the installation of anaerobic digesters on agricultural lands was a need to control odors. Further interest in the technology was spurred by the energy crisis during the mid to late seventies as a means for renewable energy production (Lusk, 1998; Lazarus and Rudstrom, 2007). The most common types of anaerobic digesters used in U.S. agriculture, accounting for 89% of total agricultural digester systems in operation, are complete mixed reactors, plug flow systems, and covered lagoons (AgStar, 2011b). As anaerobic digestion increases in popularity, different methods of utilizing this technology are being studied. Additional digester designs used in agriculture include batch reactors, manure activation, fixed-media, and up-flow anaerobic sludge blankets (Colleran et al., 1982; Lusk, 1998; Wilkie, 2000b; Wright and Ma, 2003a; AgStar, 2011b).

1.6 Digester Successes and Failures

Numerous case studies have documented the successes and failures of digestion systems (Lusk, 1998; Kramer, 2010; Scott et al., 2010). Since the 1970s, there has been a 60% failure rate in agricultural based anaerobic digesters (Bishop and Shumway, 2009). The main reasons for failure include poor designs, improper installation, lack of effective management, and low economic return (Lusk, 1998; Weeks, 2003; Lazarus, 2008; Bishop and Shumway, 2009). Common themes for failed digesters include poor gas production caused by the inability to properly heat the digester, gas leaks, clogging issues with the manure handling systems, and hydrogen sulfide corrosion (Lusk, 1998). Although designs have improved, there have been numerous failures since the 1990s with systems not functioning within designed parameters (Scruton, 2007).

There have also been successful digesters in the U.S. The Mason Dixon Farms, located in Gettysburg, PA, has been successfully operating a plug flow digester since 1979 (AgStar, 2011b). There are an additional 16 digesters installed in the 1980s and 1990s that remain operational, and of the 183 digesters installed since 2000, 154 are still operational (AgStar, 2011b). In 2009, AgStar, an outreach program supported by the USEPA, USDA, and USDOE to promote the use of anaerobic digesters among U.S. livestock owners, estimated the annual energy production from anaerobic digesters to be 385 million kWh (AgStar, 2010c; AgStar, 2011a).

1.7 Current Status of Anaerobic Digestion

Worldwide, there are over 30 million small-scale anaerobic digesters located throughout the developing world, mainly in China and India (Chen et al., 2010; Rao et al., 2010). As of July 2011, AgSTAR estimated 171 anaerobic digesters were operational in the U.S., a 71% increase from 2005 (AgStar, 2006; AgStar, 2011b). This increase is due mainly to large-scale installations, with an average capital investment of 1.5 million dollars (AgStar, 2010a; AgStar, 2011b). AgSTAR does not recommend biogas recovery systems for facilities with less than 500 cows, as it is not seen as economically viable (AgStar, 2010b). In the United States, 89% of dairy farms have less than 200 cows and are thus deemed ineligible for the benefits of digestion technology (US NASS, 2009). To address this need, improved designs have been explored and multiple analyses have been conducted on the economic feasibility of small-scale digesters.

1.8 Small-Scale Anaerobic Digesters

A number of organizations are addressing the need for further research of small-scale digesters. The Minnesota Project, a group funded by AgSTAR, evaluated six theoretical anaerobic digestion systems designed for small dairies, 100-300 cows (Goodrich, 2005). The report concluded that while the theoretical systems discussed were a good opportunity to explore available digester designs, continuing research on pilot systems was needed (Goodrich, 2005). The study was followed by the construction of a small-scale, up-flow tank digester for 160 milking cows, which is currently operational in Minnesota (Lazarus, 2009).

Additional small-scale digesters are operating around the country. The Beltsville Agricultural Research Center at the USDA has been operating a complete mixed digester sized for 220 cows since 1994 (AgStar, 2011b; Weeks, 2011). Freund Farm, a Connecticut dairy with 250 cows, has been operating a plug-flow digester since 1996 (AgStar, 2011b; Freund, 2011). In the past decade, approximately ten small-scale digesters have been installed around the country (Beddoes et al., 2007; AgStar, 2011b). Among these include a plug flow digester for 120 cows at the Northeast IA CC Farm in Indiana, a fixed-film digester for 100 cows at the Farber Dairy Farm in New York, and a manure activated digester, named for its unique manure seeding design, for 236 cows at the Spring Valley Dairy in New York (Wright and Ma, 2003a; Wright and Ma, 2003b; Beddoes et al., 2007). At least six small-scale digesters were shut down between 1998 - 2007 (AgStar, 2011b). However, interest in this technology continues to grow as private companies begin to invest in the technology.

Avatar, founded in 2005, specializes in modular, plug-flow digesters for small to mid-sized farms (100-1,000 cows) (Avatar, 2011). They currently have a 95 cow digester operating in Stowe, VT (AgStar, 2011b). In October, 2010, AGreen Energy, LLC, a farmer-owned company, began construction on the first of five anaerobic digesters on small (250-400 cows) farms in western Massachusetts (AGreen Energy, 2011). BioProcess, a Rhode Island based remediation company, partnered with a 250 cow farm to install an innovative biological process to reduce retention times and remove nutrients (Scruton and Whitcomb, 2005; BioProcessH2O, 2008). An additional four small-scale digesters are currently being constructed, three of which were developed by AEnergy and are being installed on Pennsylvanian farms (AgStar, 2011b).

Globally, small-scale, or household, digesters are successfully operating on a much larger scale. China has the largest number of household digesters in the world, estimated at 26.5 million in 2007 (Chen et al., 2011). The traditional Chinese dome digester design made of brick and concrete was mainly utilized from the 1920s through the end of the twentieth century (Chen et al., 2011). Beginning in 2000, the use of fiberglass digesters began to replace concrete digesters due to its quicker construction time and lower maintenance requirements (Chen et al., 2011).

India was estimated to have 3.71 million digesters in 2005 with the potential for 29 million household digesters (Purohit et al., 2002; Rao et al., 2010). The traditional Indian floating dome digester design is made from local materials, typically bricks and concrete, with a floating cover that expands for gas storage (Gunnerson and Stuckey, 1986; Ravindranath and Balachandra, 2009).

Small-scale digesters are also gaining popularity in Southeast Asia, Africa, and Latin America (An et al., 1997; Akinbami et al., 2001; Lansing et al., 2008q). The Taiwanese digester, a popular design used throughout Latin America and Southeast Asia, consists of a plug-flow reactor constructed of a tubular polyethylene bag and PVC piping (Gunnerson and Stuckey, 1986; Botero and Preston, 1987). While these digesters are performing well in the developing world, additional barriers that exist in the United States are currently limiting their application.

1.9 Barriers to Small-Scale Anaerobic Digestion Implementation

Studies have identified several major barriers facing widespread implementation of anaerobic digestion in the U.S., including: marginal economics, high maintenance requirements, poor replication, and the need of service sector support for digesters (Lusk, 1998; Weeks, 2003; Scruton et al., 2004; Garrison and Richard, 2005). To address these barriers, studies have recommended additional research to make anaerobic digestion and methane recovery, simpler, less labor intensive, more efficient for the farmer, and which yields a greater rate of return (Scruton, et al., 2004; Garrison and Richard, 2005).

To overcome the barriers to anaerobic digestion adoption in the U.S., there are numerous design challenges that need to be addressed. These design challenges include: utilizing less expensive materials, increasing automation and monitoring to decrease farmer time commitment, and improving the most operationally challenging components: heating, conveyance, and biogas collection and utilization.

To make anaerobic digestion economical for the smaller farm, lower initial capital costs and additional income sources need to be realized. Traditional income sources for anaerobic digesters include the creation of biogas and the sale of electricity. Revenue from electricity sales has been successfully achieved at large-scale operations (Nelson and Lamb, 2002; Wright and Inglis, 2003); however, revenue generation from electricity is often not profitable for small-scale systems due to the high cost of the infrastructure needed to sell electricity back to the grid and lower biogas production in smaller-scale systems (Ghafoori and Flynn, 2007; Giesy et al., 2009; Gloy and Dressler, 2010). Conversely, direct biogas use on the farm has been shown to be economical for smaller systems (Bracmort et al., 2008; Bishop and Shumway, 2009).

Additional income sources can be generated through 'tipping fees' paid to farms for receiving off farm food wastes (Bishop and Shumway, 2009; Yiridoe et al., 2009). When the food wastes are placed into a digester, the result is often a large increase in methane production (Scott and Ma, 2004). Solids from the effluent of a digester can be separated and the digested solids can be reused on the farm for bedding or sold for additional income (Bishop and Shumway, 2009; Yiridoe et al., 2009). In addition, carbon credit payments can be received through the carbon trading markets due to the decrease in on-farm greenhouse gas emissions when digesters are utilized (Key and Sneeringer, 2011).

1.10 Objective

The majority of the approximately 30 million digesters operating around the world are low-cost systems, concentrated in the tropics where the ambient temperature is at or near the optimal digestion temperature (Chen et al., 2010; Rao, et al., 2010). Transferring digestion technology from the developing world to the U.S. had not been explored but could offer a potential renewable energy opportunity for small and medium scale dairy farmers with abundant waste resources. In this study, the design process to modify low-cost digestion models from the developing world and transfer of this technology to temperate climates was explored and the economic feasibility of these systems was analyzed.

Chapter 2: Design Challenges to Anaerobic Digestion

2.1 Introduction

Worldwide, there are over 30 million small-scale anaerobic digesters, the majority of which are located in the developing world, mainly in China and India (Chen et al, 2010; Rao et al., 2010). There are approximately 15,000 medium to large scale agricultural digesters located mainly in China and Europe (van Nes, 2006; Wilkinson, 2011). In the United States, the Environmental Protection Agency (US EPA) estimates that there are 171 operating agricultural digestion systems, with approximately 15 new digesters installed annually (AgStar, 2006; AgStar, 2011b). Implementation of anaerobic digestion systems in the United States began during the 1970s energy crisis due to their ability to transform waste into energy (Nelson and Lamb, 2002; Lazarus, 2008). Unfortunately, the majority of these systems failed due to poor designs, improper installation, lack of effective management, and low economic return (Lusk, 1998; Weeks, 2003; Lazarus, 2008; Bishop and Shumway, 2009). Although designs have improved, there have been numerous failures (approximately 30) since the 1990s with systems not functioning within designed parameters (Scruton, 2007; AgStar, 2011b).

2.1.1 Digestion Designs

To understand digester design failures, it is first necessary to understand the various types of digesters utilized in the U.S. and worldwide. In the U.S., three digester designs have been installed on 89% of the farms utilizing anaerobic digestion technology: compete mixed reactors, plug-flow systems, or covered lagoons (AgStar, 2011b). In the U.S., 51% of digesters use the resulting biogas in a co-generator to produce electricity and waste heat to heat the digester (AgStar, 2011b).

Complete mixed digesters typically receive influent with a total solids (TS) concentration of 3-10% (Roos et al., 2004). Within the reactor, the manure is mixed to maintain the solids in suspension creating a more homogeneous substrate. Complete mixed digesters can operate at either thermophilic (50-65° C) or mesophilic (25-40° C) temperatures and typically have a hydraulic retention time (HRT) of 10-20 days (Lusk, 1998; Krich et al., 2005). The biogas collection system captures the produced biogas and removes it from the digester.

Plug flow digesters are capable of handling waste with a higher solids concentration (11-13%) than complete mixed or anaerobic lagoon digesters (Roos et al., 2004). Plug flow digesters consist of a linear trough with a width to length ratio of roughly 1:5 (Lusk, 1998). The digesters are often constructed below ground for improved insulation. Manure is added daily to one end of the digester and moves through the system along a lateral path as a 'plug' with the addition of manure at the influent end displacing the same volume from the effluent end of the system. Unlike the complete mixed digester, there is normally no mixing in the vertical direction. An expandable cover located above the trough captures the produced biogas (Lusk, 1998; Krich et al., 2005). Plug flow systems are normally operated in the mesophilic temperature range with a HRT of 20-30 days (Lusk, 1998; Krich et al., 2005).

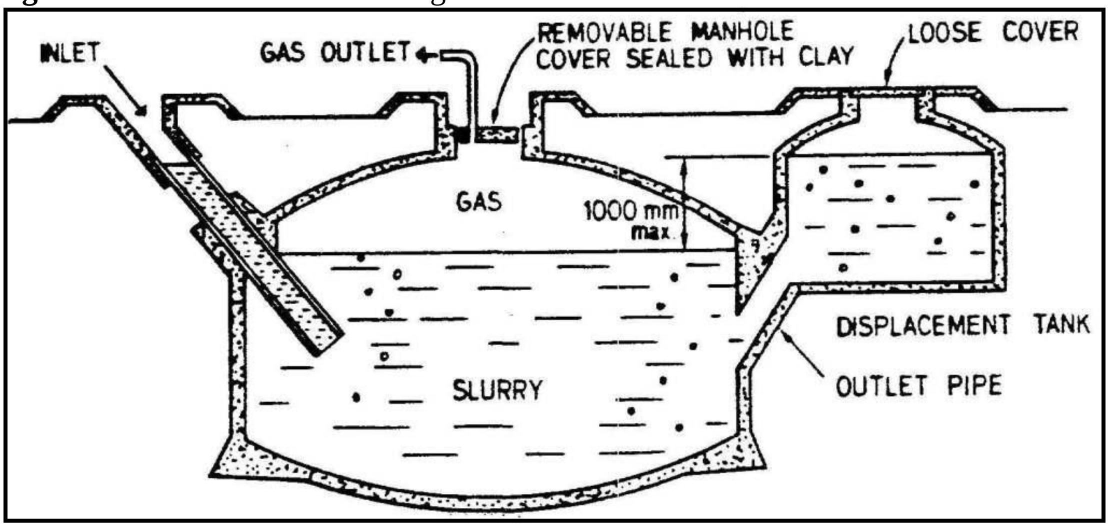
Covered lagoon digesters are often used in farm operations with hydraulic flushing systems for manure collection, which results in a TS concentration (<3%) that is too low for efficient use by the other systems (Lusk, 1998; Roos et al., 2004).

Anaerobic lagoons are typically not heated. Due to the lower operating temperature, the HRT can exceed 60 days (Beddoes et al., 2007). The produced biogas is captured under a flexible cover and removed via a collection system, such as a perforated pipe, placed under the cover. Of the three systems, the covered lagoon has the lowest operation and maintenance costs and is more viable in the southern part of the U.S. where the temperature is less variant (Lusk, 1998; Krich et al., 2005). The typical useful life-time utilized for digester feasibility assessments is 10-20 years, although multiple existing plug flow systems have been in operation for 25-30 years (Lusk, 1998; Beddoes et al., 2007; AgStar, 2011b; Eastern Research Group, 2011).

In contrast to the digester designs used in the U.S., predominant digester designs in developing countries are the Chinese fixed dome, the Indian floating dome, and the Taiwanese-model plug-flow digester. All are constructed using low-cost materials and without the use of mechanical parts (Akinbami et al., 2001; Lansing et al., 2008b; Ravindranath and Balachandra, 2009). Once installed, the digesters have an expected lifespan of 20 years or more (Gunnerson and Stuckey, 1986; Buxton and Reed, 2010). The produced biogas is used mainly for direct heating and cooking (Li et al., 1997; Beddoes et al., 2007; Lansing et al., 2008b).

The digester reactor is similar for both Chinese fixed dome and Indian floating dome digesters, although the gas collection system varies. The Chinese fixed dome digester reactor is typically constructed with straight sides and a hemispherical top and bottom made of bricks, concrete, or fiberglass (Gunnerson and Stuckey, 1986; Buxton and Reed, 2010). The digester is fed daily through a straight inlet pipe and the produced biogas displaces the slurry into an effluent chamber as seen in Figure 2.1 (Gunnerson and Stuckey, 1986).

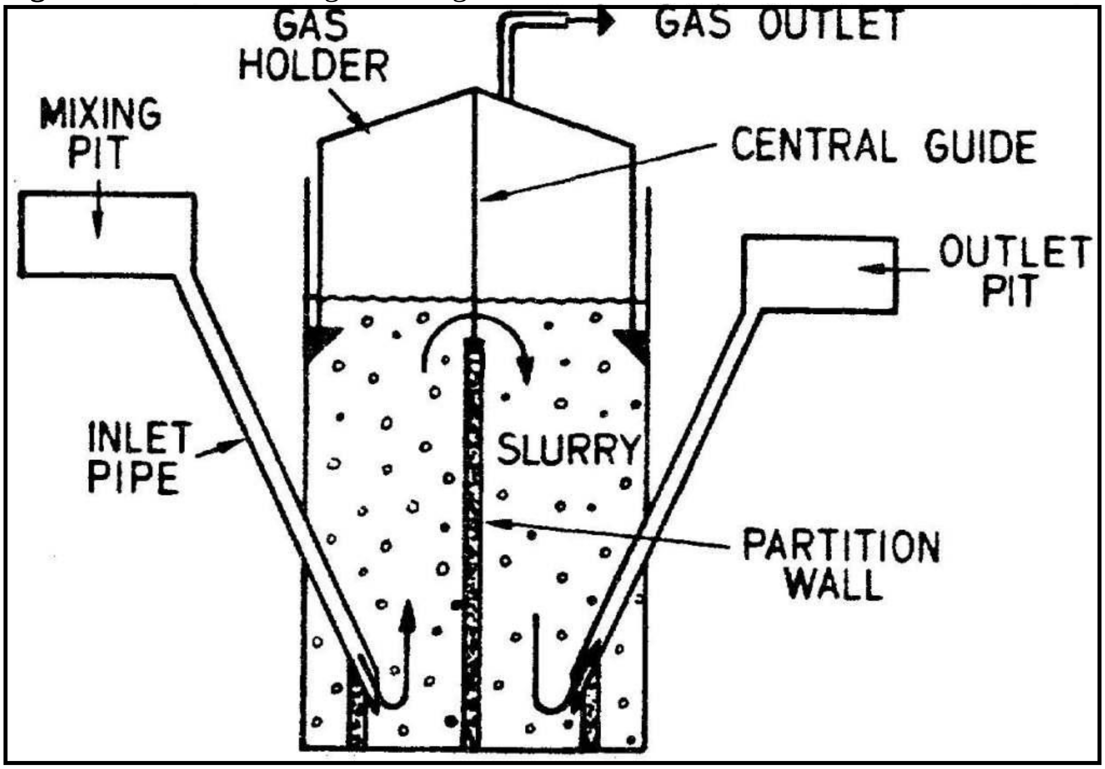
Figure 2.1 Chinese fixed dome digester



(Image source: Gunnerson and Stuckey, 1986)

The Indian floating dome digesters also have straight sides but instead of a fixed roof, there is a floating cover that rises and falls along a central guide, which allows for expanded gas storage within the reactor as seen in Figure 2.2 (Gunnerson and Stuckey, 1986; Ravindranath and Balachandra, 2009).

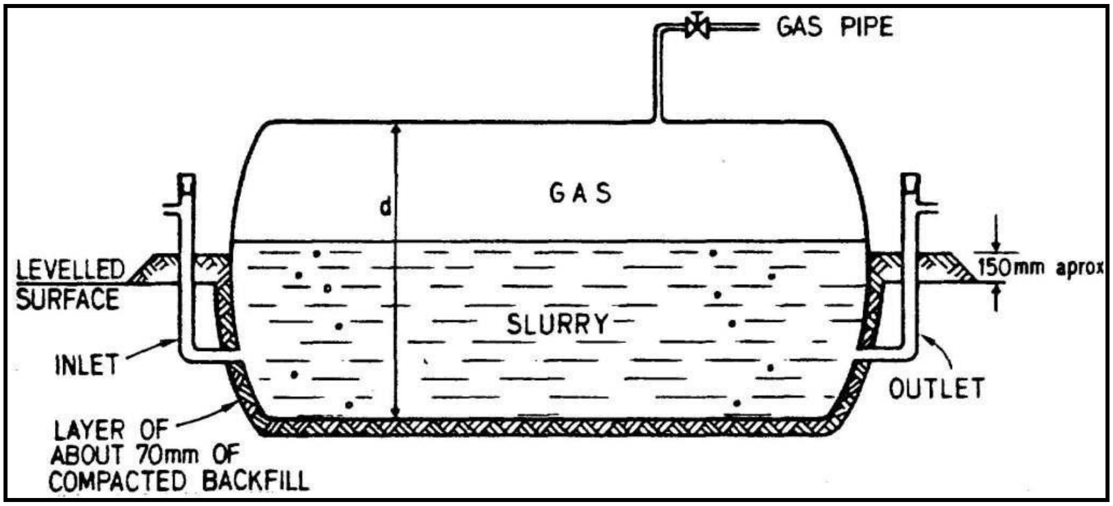
Figure 2.2 Indian floating dome digester



(Image source: Gunnerson and Stuckey, 1986)

The Taiwanese digester is a plug-flow reactor constructed of a tubular polyethylene bag and PVC piping and is utilized mainly in Latin America and Southeast Asia (Gunnerson and Stuckey, 1986; Botero and Preston, 1987). Digesters are constructed by placing the tubular polyethylene bag in a shallow trench, attaching a biogas outlet in the top of the bag using readily accessible PVC fittings, and inserting pipes diagonally at the influent and effluent of the bag secured with rubber as seen in Figure 2.3.

Figure 2.3 Taiwanese plug-flow digester



(Image source: Gunnerson and Stuckey, 1986)

During installation, the digester is filled with air to test for leaks and provide a spherical digester shape. As waste is added the hydraulic grade line rises above the digester outlet, creating a liquid/gas seal at the influent and effluent pipes. (Rodriquez and Preston, undated).

2.1.2 Barriers to Digestion Adoption in the U.S.

Several studies have identified the barriers to adoption in the U.S., including marginal economics, high maintenance requirements, poor replication, and the need of service sector support for digesters (Lusk, 1998; Weeks, 2003; Scruton et al., 2004; Garrison and Richard, 2005). Scruton et al. (2004) found that many of the anaerobic digesters built since the 1990s are not producing energy at the designed levels, resulting in the authors concluding that digestion technology is still in the research phase. The authors stated that traditional U.S. designs tend to be suitable only for large-scale operations, as the designs are customized, difficult to replicate, and require high maintenance (Scruton et al., 2004; Scruton, 2007). Lazarus (2008) reported instances of digester operation being discontinued due to farmers' reluctance to continue investing the necessary time and money in the operation and maintenance of the digestion system rather than design failures.

Garrison and Richards (2005) reported that the major obstacles to widespread implementation of anaerobic digesters on U.S. dairy and swine operations are current policies (lack of incentives and subsidies), economics (price of electricity), and a lack of sufficient research to make anaerobic digestion and methane recovery simpler, less management intensive, and more efficient for the farmer.

There are numerous design challenges that need to be addressed in order to overcome these barriers to anaerobic digestion adoption in the U.S. These design challenges include: utilizing less expensive materials, increasing automation and monitoring to decrease farmer time commitment, and improving the most operationally challenging components: heating, conveyance, and biogas collection and utilization.

From an economic perspective, lowering digester capital costs results in significant increase in the net value of the digester when the biogas is used directly, while increasing digester efficiency does little to increase the net value of the digester (Anderson, 1982). By focusing on easily obtainable, lower-priced, 'off the shelf' components, digester costs can be reduced and duplication of designs can become more achievable (Coppinger et al., 1980; Trivett and Hall, 2009).

Due to their simplicity, the prevailing digester designs in developing countries have fewer operational challenges than their U.S. counterparts (An et al., 1997). The digesters are heated only through solar radiation, there is no mechanical mixing, and conveyance is often accomplished with gravity or human labor, thus negating the need for pumps. Design challenges to these designs have been attributed mainly to material failures. The Chinese fixed dome design has limited biogas storage capacity and leaking is a concern if the reactor is not constructed correctly (Ravindranath and Balachandra, 2009). The Indian design is more expensive to construct compared to the Chinese design and the flexible gas holder needs to be replaced periodically adding to the maintenance costs of the system (Gunnerson and Stuckey, 1986). A study analyzing the success of Taiwanese-model plug flow digesters, found digester damage was due mainly to sunlight, falling objects, people, and animals, but most damage was repairable by the user (An et al., 1997).

The direct transfer of developing world designs to the temperate U.S. is not feasible due to climatic, cultural, and operational factors. Most digesters in the developing world are located in tropical climates where solar heating and burying is sufficient to maintain the digester temperature in the mesophilic temperature range (25-40° C). Utilizing human labor to load manure into a digester is rarely cost effective in the U.S. and the feasibility of installing a completely gravity-driven system is site dependent. Most digesters in the U.S. are constructed on existing farms, requiring the digester to fit within the existing farm infrastructure.

2.2 Objective

Given the complexity of modern-day dairy operations, many of the design barriers with traditional U.S. designs need to be addressed. The main objective of the research was to design and construct a plug flow digester system, using simple, successful designs used in developing countries modified to function in a temperate climate. The system was modeled after the low-cost Taiwanese digester design utilized in the developing world and adapted for use on a small to medium-scale farm located in the temperate United States. The modifications include the addition of improved insulation and heating of the digester influent. This paper will specifically describe the process for designing the low-cost anaerobic digestion system, modified for temperate climates and analyze how design challenges were addressed in an attempt to overcome existing barriers to anaerobic digester adoption in the U.S.

2.3 Design

2.3.1 Site Location and Layout

The research digesters were constructed at the USDA's Beltsville Agricultural Research Center (BARC) located in Beltsville, Maryland. Beltsville has a humid subtropical climate within the temperate zone with an average maximum temperature of 86.8°F (July) and an average minimum temperature of 22.8°F (January) (SERCC, 2011). BARC operates a 120 cow dairy facility that uses a manure scraper system and complete mixed digester for waste management. A plan view of the BARC system is shown in Figure 2.4.

Figure 2.4 Manure treatment system at the USDA Beltsville Dairy Facility

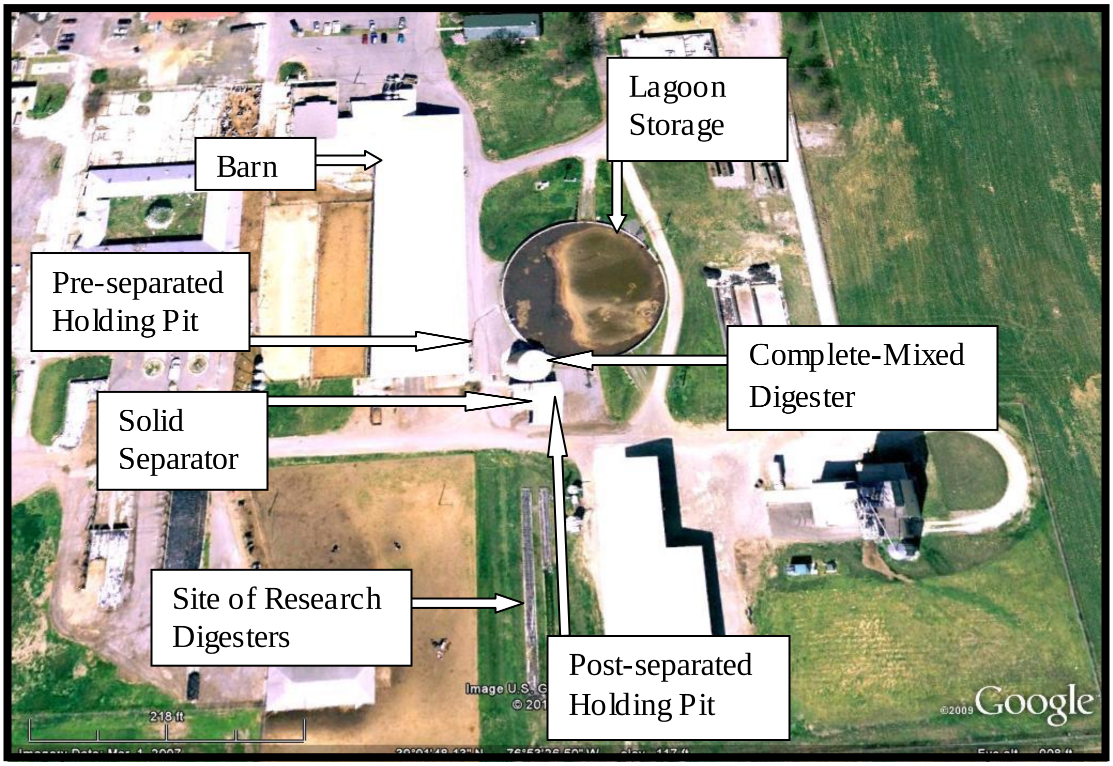


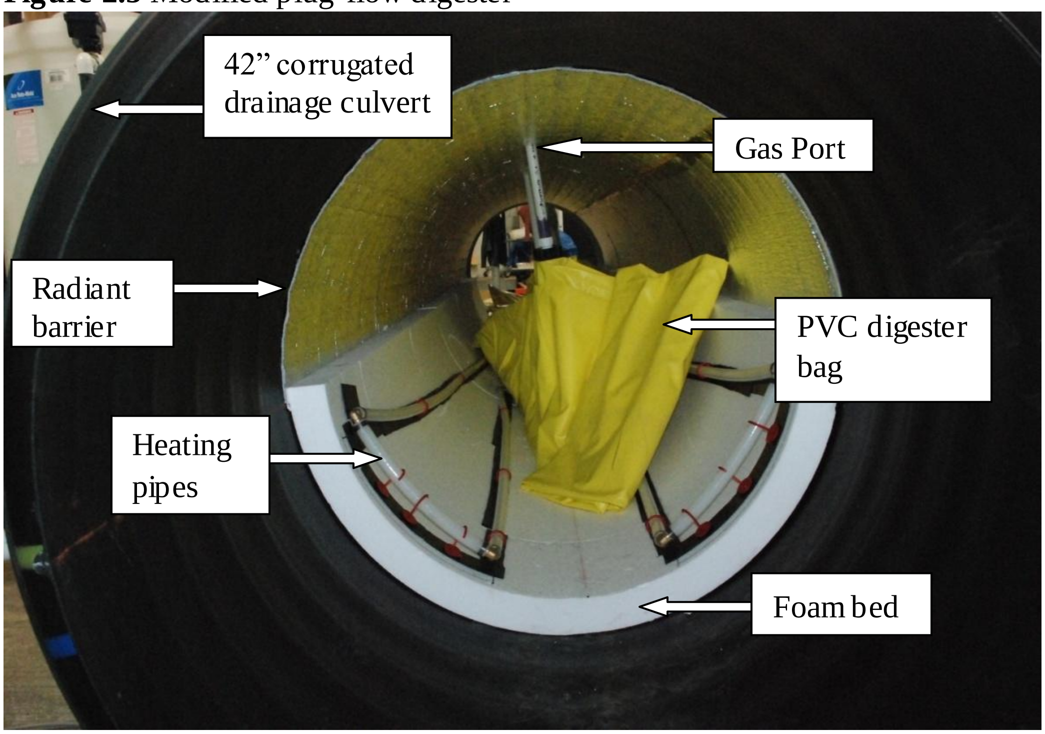
Image from Google Earth

In the current digestion system, manure from the dairy is scrapped into holding pits and then pumped to a solid separator system. The solids are collected and composted, and the liquid portion is stored in a separate holding pit and then pumped daily into a complete mixed digester for treatment. Following digestion, the stabilized waste is stored in a lagoon until spray application to the fields.

Beginning in 2009, nine modified Taiwanese-model research digesters were built by the University of Maryland (UMD) at the BARC site, six of which receive pre-separated manure (containing approximately 12% solids) and three of which receive post-separated manure (containing approximately 5% solids). The total system treats 225 gallons of manure daily or the waste from approximately 15 dairy cows. The UMD research digesters were designed for minimal interference with the existing BARC manure treatment system, connecting into the BARC system at three locations: an influent line from the pre-separated holding pit, an influent line from the post-separated holding pit, and a return line to the lagoon.

Each digester is composed of PVC-based digester bag laid in insulative foam beds surrounded by radiant barrier, and enclosed in 42 inch HDPE drainage culverts to protect, insulate, and help maintain the desired shape of the digesters. Heating is accomplished through the use of an influent heating kettle and heating pipes circulating beneath the digester bags. All the digester components are shown in Figure 2.5.

Figure 2.5 Modified plug-flow digester



2.4 Discussion

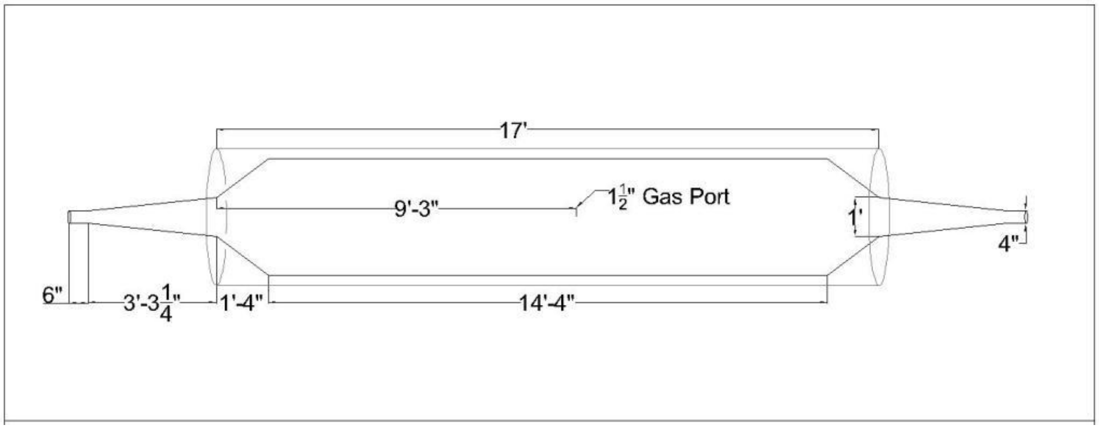
The research system was built over a 23-month period. Construction took longer than expected due to complications with flooding, existing unmarked utilities, and labor shortages. The most time consuming aspect of construction was the installation of the conveyance system due to its complexity and the above mentioned complications. Design calculations and schematics of the conveyance system are located in Appendices A and B. The total cost of the digestion system was $83,970 (2010$), with the most expensive cost being the digesters themselves. The list of materials and costs is in Appendix C.

2.4.1 Digestion Reactors

In the United States, digester reactors for complete mixed or plug flow systems are typically constructed of cast-in-place, reinforced concrete, fiberglass, or glass-coated steel plates (Lusk, 1998; Beddoes et al., 2007; Scott et al., 2010). Studies have shown difficulties in consistently constructing air-tight concrete reactors (Scruton et al., 2004). This has to led to the practice of covering concrete reactors inside and out with a poly-urea, epoxy-coating, or other sealant (Lusk, 1998; Scott et al., 2010). Covered lagoon digesters are usually in ground systems that are earthen, clay-lined or geomembrane-lined to prevent groundwater contamination due to leakage (Lusk, 1998; Beddoes et al., 2007).

To avoid issues with leaking and in an effort to decrease costs, the UMD research digesters use PVC-membrane flexible bags. This type of material has been successfully used in Central and South America (Lansing et al., 2008b). The membrane has a 40 mil thickness and was manufactured to the desired shape shown in Figure 2.6.

Figure 2.6 Research digester bag dimensions, plan view



The bags costs $4,140 dollars compared to equivalent concrete digesters at approximately $9,800. The bags are easily bonded to PVC piping using readily available PVC primer, PVC cement, and rubber ties creating an airtight seal. Each digester has a total capacity of 700 gallons and is operated at a liquid capacity of 75% (525 gallons) with 25% headspace for biogas collection.

2.4.2 Covers

Traditionally designed U.S. digesters have various types of covers or roof structures for biogas collection. Complete mixed digester reactors use fiberglass, concrete, or flexible membrane roofs (Lusk, 1998; Scott et al., 2010). Plug flow digester covers are typically a flexible membrane but are occasionally hard topped (Scott et al., 2010). Covered lagoon digesters use airtight covers that are either flexible or floating to allow space for biogas capture (Lusk, 1998; Beddoes et al., 2007). Flexible covers are made of various materials including XR-5, hypalon, polypropylene, polyethylene, permalon, or HDPE (Lusk, 1998; Beddoes et al., 2007).

Studies have shown that the flexible covers used to collect gas have been problematic for various digesters. Numerous case studies have highlighted digesters with flexible covers issues caused by either weather, poor manufacturing, or failed design leading to tearing and sinking (Lusk, 1998; Moser et al., 1998). In addition, failure to maintain an air-tight seal against concrete reactors and earthen berms has occurred (Lusk, 1998; Scruton, 2007).

The UMD research digesters address this problem by using PVC-membrane digester bags with the Taiwanese plug-flow design. Creating an air-tight environment becomes much simpler with this design because the PVC-membrane does not connect to concrete or earth and the connection to PVC conveyance pipes is easily accomplished as described above. The use of PVC-based material also makes repairs to the bag a simple and inexpensive process requiring only readily available PVC primer, PVC cement, and a PVC-membrane patch. To protect against damage caused by wind, falling objects, or wildlife, the PVC-based digester bags were placed inside 42 inch dual wall HDPE drainage culvert.

2.4.3 Insulation

Traditional U.S. complete mixed and plug flow digesters are typically located in a temperate climate and therefore require insulation. Insulation is usually installed around the bottom, sides, and covers of the reactors and in some cases the digesters are constructed below ground for additional insulation (Lusk, 1998; Scott et al., 2010). Common insulation used to surround digestion reactors includes urethane, polyurethane, and polystyrene foam typically 2 -4 inches thick (Lusk, 1998; Scott et al., 2010). The exact installation of insulation varies between digester designs.

Researchers have suggested that due to the natural foam layer that can form on top of the liquid slurry in a digester, many soft-top digesters do not need top insulation, as the foam itself acts to keep the manure at a constant temperature (Scruton et al., 2004). There have been cases where insufficient insulation negatively impacted digester operation (Lusk, 1998; Freund, 2011).

Lusk (1998) reported that several farmers with failed digesters cited manure freezing and insufficient insulation as two of the main reasons for discontinued use of the digester. The Freund Dairy located in East Canaan, Connecticut, was originally installed with insufficient insulation to keep the system's temperature at 35°C (Freund, 2011). An additional $115,000 was invested to upgrade the system resulting in excess biogas production in the summer but still insufficient biogas in the winter (Freund, 2011). This requires the biogas to be supplemented with propane in the winter months to maintain an operational digester resulting in an annual net zero biogas production (Freund, 2011).

Due to the colder climate in Beltsville, the modified Taiwanese digester design required insulation. The UMD research digester bags are placed inside a foam nest of custom cut 3 inch thick expanded polystyrene. The foam bed extends halfway up the sides of the bags providing insulation. Above the digester bags is a radiant barrier composed of a polyethylene-core between two layers of aluminum foil for additional insulation. The radiant barrier functions by reflecting rising heat down towards the digester. The digesters are partially buried for additional insulation and protected from the elements by a windshield structure. A cost breakdown of the digester components is listed in Appendix C.

2.4.4 Heating

Heating is an important aspect of traditional complete mixed and plug flow digesters in U.S., as a heat source is necessary to maintain mesophilic (35°C) temperatures in the digester throughout the year. To accomplish this, many digesters utilize heat exchangers to capture waste heat from biogas generators and reuse it for heating the digesters. Farmers with failed digesters often cite insufficient heating as a reason for failure (Lusk, 1998; Scott et al., 2010) and some digesters consistently see a drop in biogas production in the winter (Moser et al., 1998; Freund, 2011). While operating digesters at lower temperatures in lieu of constant heating has been found to lower capital costs as well as operation and maintenance costs in specific cases (Bohn et al., 2007), if a digester is operated at too low a temperature, it will retard the formation of methane (Gerardi, 2003).

Many U.S. digesters utilize radiant heating pipes that run within the reactor as the main heating source (Lusk, 1998; Scott et al., 2010). The heating pipes contain a water/glycol solution that has been warmed in a boiler or with heat captured from the engine (Lusk, 1998; Scott et al., 2010). The heated water/glycol mixture runs through a piping system suspended in the manure and releases the heat into the surrounding manure. However, problems with locating heat exchangers inside the digesters have been cited (Moser et al., 1998; Inglis et al., 2007; Scruton, 2007).

Heating pipes can become caked with manure, impeding the heating of the manure, and/or become damaged through corrosion/breaking inside the digesters (Moser et al., 1998; Scruton, 2007). In one case study, internal heating pipes made of 2.5 inch black iron corroded, resulting in the formation of a hole in the piping system

(Inglis et al., 2007). The cause of the damage was believed to be from electrolytic corrosion and zinc bars were added to the digester as a preventative measure against future damage. The repairs cost the owner $23,737 and 3 weeks of non-operation to repair the digester damage (Inglis, et al., 2007). Other digesters have reported similar problems with in-vessel heating pipe damage, requiring the digesters be shut down to repair the lines (Scott et al., 2010).

Alternative methods of digester heating have been employed. Steam injection has been cited as a good alternative for digester heating (Scruton et al., 2004). Other digesters operate with only influent warming. The Twin Birch Farm located in Skaneateles, New York, only heats the influent manure with no heat added to the digester with only a 3°F temperature drop between the digester influent and effluent (Scott et al., 2010).

Solar heating is another method that has been investigated for heating digesters (Axaopoulos et al., 2001; El-Mashad et al., 2003; Kumar and Bai, 2008). Studies in the eighties found the addition of a greenhouse over the digester increased the temperature from approximately 18°C to 37°C (Kumar and Bai, 2008). Building upon these studies, Kumar and Bai (2008) found the use of plastic digesters in combination with solar heated greenhouses increased the reactor temperature and biogas production compared to traditional masonry digesters in India. A study by El-Mashad et al. (2003) found that solar heating can be used effectively to help maintain thermophilic temperatures under Egyptian conditions. Other researchers have experimented with new digester designs utilizing solar heating. Axaopoulos et al. (2001) developed a flat-plate solar collector roof, attached to a heat exchanger located inside the digester and concluded that solar heating decreased thermal losses in the digester, maintaining a mean manure temperature of 33.4°C ± 0.3. However, the experiment was conducted during September and the ambient temperature did not fall below 18°C (Axaopoulos et al., 2001).

As with the traditional U.S. digesters, the modified UMD research digesters also needed heat addition to operate in a temperate climate. The UMD research digesters were designed with influent and radiant heating. Manure is pumped into a heating kettle and warmed to 35°C before draining into the digesters. Preheating of manure influent is a technique that has shown promise in past experiments but has not been tested as a modification to the Taiwanese design.

The heating kettle design is similar to that of a tempering tank used in the confectionary food industry. The kettle is fabricated from stainless steel with an inner vessel, outer vessel, and heat shield as shown in Figure 2.7.

Figure 2.7 Research system heating kettle

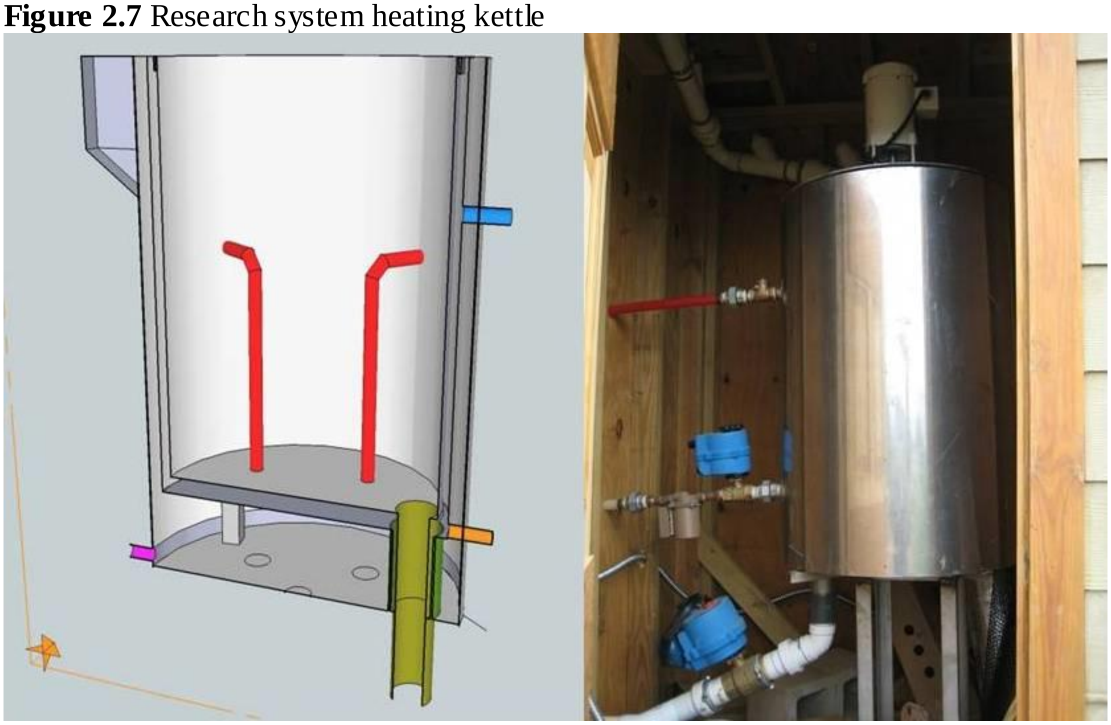
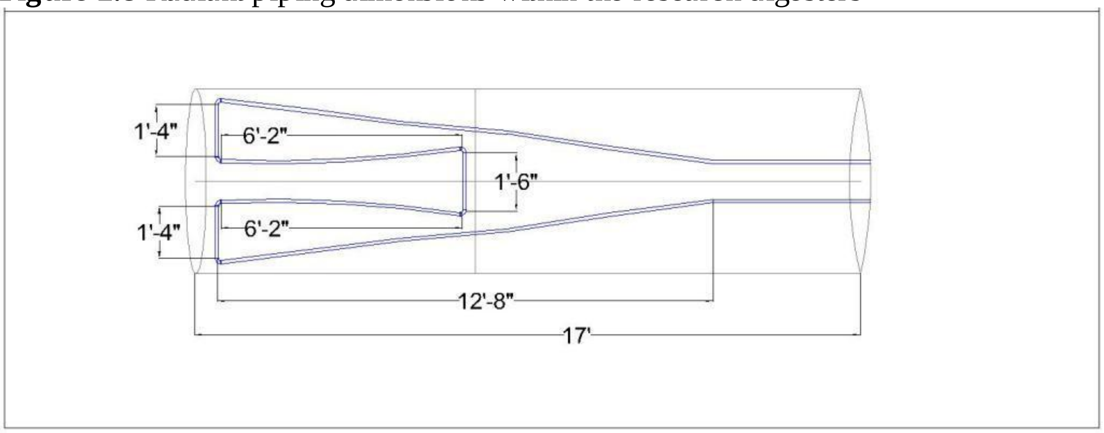


Illustration courtesy of Andrew R. Moss

The manure is stored in the inner vessel surrounded by an outer vessel filled with a water/ethylene glycol solution. Utilizing a portion of the biogas produced from the digesters, the water/ethylene glycol solution in the outer vessel is heated, providing more even heat distribution to the manure in the inner vessel, while protecting the microorganisms from scalding.

Once the manure reaches 35°C, it is released into a digester with the hot water/ethylene glycol solution from the jacket simultaneously circulated through radiant piping located underneath the digester bag in an effort to provide additional heating to the length of the digester. The radiant piping is concentrated on the effluent side of the digester as shown in Figure 2.8.

Figure 2.8 Radiant piping dimensions within the research digesters



The radiant piping was placed outside of the digester bags to prevent cited concerns with corrosion and breaking when the piping comes into contact with the manure. Each digester has an individual radiant piping system to aid in isolating potential leaks or plugs. The design aims to maintain a temperature of 35°C in the summer and 28°C in the winter throughout the digesters. A cost breakdown of the heating systems is located in Appendix C.

The UMD research digesters were also designed with recirculation capabilities to aid in the redistribution of microorganisms and allow for additional heated material to enter the digester. With recirculation, the digester receives hot plugs as necessary, not only when the digester is fed daily. By combining recirculation with influent and radiant heating, the digester design has a unique design that will be monitored to determine if recirculation will positively affect digester performance and determine the market competitiveness of such an anaerobic digestion system. Recirculation is designed to deliver a pulse of reheated manure only when the digester temperature falls below 28°C.

2.4.5 Conveyance and Mixing

Two of the greatest operational challenges of traditional U.S. digesters have been mixing and conveying the manure (Coppinger et al., 1980; Lusk, 1998; Scott et al., 2010). Centrifugal pumps have been used due to their expected ability to handle the solids and debris that may be found in the manure slurry (Coppinger et al., 1980). Other designs utilize piston pumps to move manure into the digester (Inglis et al., 2007; Scott et al., 2010), while others use grinder pumps to masticate the solids in an effort to prevent clogging and top crust formation (Lusk, 1998; Scruton et al., 2004).

Multiple farmers cite pump and conveyance line clogging as two reasons they no longer operate their digesters, specifically in systems with 90 degree elbows and without the use of grinder pumps (Lusk, 1998). To simplify operations, it has been suggested that gravity-flow be utilized when possible (Coppinger et al., 1980). While many digesters owners report success with their gravity system, at least one case study cited a system that found gravity flow to be inadequate and had to redesign the system (Lusk, 1998). Some U.S. farmers simply haul manure from the barn into the system (Lusk, 1998).

When designing conveyance systems, the most important design criteria are minimum pipe size to prevent clogging, minimum velocity to maintain the solids in suspension, and maximum velocity to prevent excessive wear on the pipes. When designing specifically for manure conveyance, it is important to address the unique characteristics of manure. Lusk (1998) noted that many of the earlier digester failures were due to designers using municipal wastewater characteristics and failure to account for the "corrosiveness, abrasive fibers, grits, and higher viscosity" that accompany animal manure. Manure rarely acts as a Newtonian fluid and the flow properties are dependent on the temperature, shear rate, and apparent viscosity of the slurry (El-Mashad et al., 2005).

Although often not a component of developing world digesters, due to the flat terrain at the USDA facility, pumps were required to convey the manure between the BARC system and the research system. Gravity flow was utilized when possible within the research system to simplify the design and decrease operational and maintenance costs.

To properly size pipes and pumps in a pressure system, a system curve was developed based on flow rate and total head loss. These system curves were overlaid with manufacturers pump curves to determine the proper pump size and operational flow rates. The target minimum velocity in all pipes is 3.50 ft/sec. Pump curves and systems curves can be found in Appendix A.

For the design of a gravity system, it needs to be determined whether the system will flow full pipe or partially-full pipe. For the purposes of the research system, both full pipe and partially-full flow calculations were performed. The majority of the influent flow was considered to be full pipe and the Hazen-Williams equation was used to determine the total losses and the minimum height difference needed for flow to occur. To assure the majority of the manure leaving the heating kettle would reach the intended digester, partially-full calculations were also performed using the Manning's Equation to determine the required minimum slope. A safety factor of 2 was applied to all slopes. All flow calculations and minimum slope requirements are located in Appendix A.

Plugging, especially with un-separated manure, is a potential operating concern in the 620 feet of pipe that were used, and therefore, clean-out locations were included in the research system at distances not greater than 100 feet, resulting in a total of 15 clean-out locations (9 system clean-outs and 6 digester clean-outs). The system hydraulics schematic with clean-out locations is located in Appendix B. A cost breakdown of the research conveyance system is located in Appendix C.

In continuously mixed digesters in the U.S. multiple agitation methods are utilized. Some systems use a blower to bubble the produced biogas through the reactor (Lusk, 1998; Scott et al., 2010). Potential problems reported with using this type of mixing system include corrosion, crusting, and plugging of the bubble system (Lusk, 1998; Tchobanoglous et al., 2003). Other systems use impeller agitators or pump/agitators to mix the contents of the digester reactors or the thermal convection created around the heating pipes to mix the digester contents (Lusk, 1998; Scott et al., 2010). Farmers with failed digesters have cited inadequate mixing and subsequent grit and solids build-up as a main reason for the digester failure (Lusk, 1998).

Digesters that run un-separated manure have higher biogas production due to the increase in volatile solids but are more prone to crusting and plugging issues (Scruton, 2007). After five years of operation, a plug-flow digester in New York was emptied for an emergency repair. During this process it was found that crusting and settled solids had decreased the operational volume of the digester by 16% (Ingis et al., 2007). To address this operational concern, some plug flow digesters are now designed with mixing. For example, a plug flow digester in Vermont uses vertical gas re-circulated from the head space to agitate the manure (Scruton et al., 2004).

Another method to address sediment accumulation is to design with the expectation of sediment accumulation and install mechanisms for sediment removal. In plug-flow digesters the use of sediment traps and suction pumps is a viable method, while complete mixed digesters can be designed with conical bottoms, as seen in the municipal waste systems, to aid in easy sludge removal and cleanout (Scruton et al., 2004; Wright et al., 2004).

The UMD research digesters are operated without mixing as is typical with the original Taiwanese design. Small impeller mixers are used in the heating kettles to aid in uniform heating of the manure.

2.4.6 Biogas

Biogas produced from anaerobic digestion of dairy manure contains hydrogen sulfide (H_2S), which will condense and corrode any metal parts in the system (Scruton, 2007). Corrosion from H_2S is one of the most common complaints issued by farmers of failed digesters (Lusk, 1998). H_2S removal is being actively researched in both academia and the private sector (Lazarus, 2008). Some methods for H_2S removal used in the U.S. include GHD, Inc. patented biological H_2S removal systems, iron sponge scrubbers, limestone flakes, and Mercaptan filters (Lusk, 1998; Scott et al., 2010).

Some operators choose not to use H_2S scrubbers and instead rely on frequent oil changes to prevent corrosion in electric generators (Lusk, 1998). Engine overhauls are required each 3-5 years depending on the quality of regular maintenance and the presence of H_2S scrubbers (Lusk, 1998; Lazarus, 2009). Other methods employed to reduce corrosion include the use of aluminum fittings in lieu of copper or bronze, replacing iron pipes with high temperature plastic pipes, and constructing with vinyl instead of steel (Lusk, 1998).

The UMD research digesters use water traps and iron pellet scrubbers to remove unwanted water condensation and H_2S. Iron scrubbers have been shown to reduce H_2S levels to below 50 ppm and need to be replaced approximately every six months (Lansing et al., 2008b; Scott et al., 2010).

In most U.S. designs, biogas storage is maintained in the headspace of digesters and excess biogas not used in the boiler or generator is often flared (Beddoes, et al., 2007). Developing world digesters are often designed with in-vessel biogas storage and additional external storage to minimize the amount of biogas that is wasted. The UMD research digesters modeled this concept with the installing of additional biogas collection and storage units. Biogas storage bags made from double lined silage bags were hung from the rafters of the windshield structure above the digesters. A plan and profile view of the biogas collection system is located in Appendix B. The storage bags insure that excess biogas can be stored instead of flared until it is needed for heating purposes. A breakdown of costs for the biogas system is located in Appendix C.

2.4.7 Electrical/Automation/Monitoring

Time commitment required by the farmer to operate a digestion system is one of the greatest operational barriers affecting digester implementation in the U.S. (Scruton, 2007). While AgStar estimates labor time commitments to be 15-30 minutes a day, actual time commitments vary from digester to digester (Roos et al., 2004). A Connecticut farmer estimates he spends 45 minutes a day on the digester, while a Minnesota farmer estimates he spends an hour a day running the pump and monitoring the generator and other equipment (Lazarus and Rudstrom, 2007; Freund, 2011). Both farmers have additional time taken each week to give tours and talk about their digesters to interested parties (Lazarus and Rudstrom, 2007; Freund, 2011). Farmers are addressing time commitment issues with the addition of automation to their systems. This can be accomplished through the use of automatic controls or timers on pumps and mixers (Scott et al., 2010)

A shortfall that has been noted in digester design is the lack of sensory equipment for system monitoring. Sensory equipment tied to automatic control systems aids not only the optimization of digester performance but also decreases the time requirement of the farmer (Ward, 2008). Monitoring and control systems are currently improving with advances in the utilization of cell phone and internet technology (Lazarus, 2008).

While automation and sensory equipment is not used in the developing world, it is an integral part of successful digestion systems in the U.S. and was included in the UMD research digestion system. All valves, excluding clean-out valves and biogas valves, are electronic valves and actuators. All pumps, valves, heat ignition, and mixers are controlled electronically though a Labview software program. By installing such a system, an operator is not needed for daily operation.

In order to automate and monitor the system, both 110-120 volt wires to deliver power to the components and low voltage wire for the control system were installed. Temperature is continuously monitored within each digester, in the heating kettle, at the effluent, and in the soil around the digesters. By monitoring the temperature both within and around the digesters the effectiveness of the insulation can be calculated. Monitoring the internal temperature also aids in determining the frequency and effectiveness of recirculation/heating. The cost breakdown of the electric system and automation/monitoring system is located in Appendix C.

2.5 Conclusion

For anaerobic digesters to become more widely utilized in the United States, digester designs need to address the existing barriers facing anaerobic digestion adoption. These barriers include: marginal economics, high maintenance requirements, and poor replication. By designing a digestion system for the temperate United States modeled after the low-cost Taiwanese digester design utilized in the developing world, design challenges were addressed to overcome adoption barriers. Designing the system with less expensive, readily available materials leads to lower capital costs and easier replication. Increasing reliance on automation and monitoring and improving the most operationally challenging components: heating, conveyance, and biogas collection and utilization, decreases the time commitment needed to maintain the system.

This study illustrates the process of designing a low-cost anaerobic digestion system, modified for temperate climates. Further research needs to be conducted on the waste transformations, biogas production, operating costs, and maintenance time of the low-cost system. The results from that research should be used to improve upon future designs and scaled-up models of the system.

Chapter 3: Economic Evaluation of Small-Scale Anaerobic Digester

3.1 Introduction

Anaerobic digesters were first widely constructed in the United States during the 1970's energy crisis (Martin, 2004; Lazarus and Rudstrom, 2007). The ability of digesters to harness natural microbial processes in order to transform organic matter into biogas was a sought after attribute. Within an anaerobic environment, methanogenic microorganisms are able to utilize organic matter, carbon dioxide, and hydrogen to produce methane (Gerardi, 2003). Unfortunately, poor economic viability and technical flaws led to a 60% failure rate of these systems (Bishop and Shumway, 2009). Through improved designs, the world is currently seeing a revitalization of anaerobic digestion technology with over 30 million manure-based digesters operating globally (Chen et al., 2010; Rao et al., 2010). This trend is the result of a renewed global focus on producing energy from renewable sources and reducing greenhouse gas emissions and noxious odors (United Nations, 1998; USEPA, 2010).

The US EPA has stated that if large-scale U.S. dairy operations (>500 cows) were able to harness the energy inherent in their waste products, more than 6.8 million MWh of renewable energy could be created annually (AgStar, 2010b). Small-scale dairy operations (<500 cows) have the potential of producing an additional 3.4 million MWh annually if anaerobic digesters were employed on these facilities, which corresponds to 780 kWh/cow annually (calculated with data from Van Horn et al, 1994; US NASS, 2009).

In recent years, owners of large-scale livestock operations in the U.S. have made progress utilizing manure for bioenergy production with the number of digesters increasing from approximately 100 facilities in 2005 to 171 facilities in July, 2011 (AgStar, 2006; AgStar, 2011b). With an average capital investment of 1.5 million dollars (AgStar, 2010a; AgStar, 2011b), the USEPA does not recommend biogas recovery systems for facilities with less than 500 cows (AgStar, 2010b). There have been other studies that have shown at least 200-400 cows are needed for anaerobic digestion systems to be economically viable (Metha, 2002; Moser, 2005). In the United States, 89% of the dairy farms have less than 200 cows, making digestion technology economically inaccessible to the majority of these farmers (US NASS, 2009). To address this need, improved designs have been explored and multiple analyses have been conducted on the economic feasibility of small-scale digesters.

The most traditional sources of revenue from anaerobic digestion are the creation of biogas and the sale of electricity. Revenue from electricity sales has been successfully achieved at large scale operations (Nelson and Lamb, 2002; Wright and Inglis, 2003); however, revenue generation from electricity production has been shown to be connected to economies of scale, and thus, is often not profitable for small-scale systems (Ghafoori and Flynn, 2007; Giesy et al., 2009; Gloy and Dressler, 2010). Studies have found that smaller farms are more dependent than larger operations on electricity prices in order for electrical generation to be economical (Garrison and Richard,2005; Metha, 2002; Lazarus and Rudstrom, 2007). Two small dairy farms (130 and 70 cows) in Ontario were found to be economically successful electricity producers, crediting their success to the receiving of additional waste (130 cow farm only), having a buyer for their electricity, and substantial time dedicated to the project development stage (Millen, 2008). In instances where electrical generation was not economically viable, multiple studies have found the direct use of biogas could be economically feasible on smaller farms when the on-farm heating requirements were high enough to regularly utilize all the produced biogas (Bracmort et al., 2008; Bishop and Shumway, 2009).

In addition to renewable energy production, economic studies of anaerobic digesters have shown that systems which include non-market benefits: odor control, water quality improvement, bedding reuse, carbon credits, and tipping fees, were more economically viable due to the additional income from these sources (Bishop and Shumway, 2009; Yiridoe et al., 2009).

The use of an anaerobic digester nearly eliminates odors and is often cited as one of the main reasons for farm installation (Lusk, 1998; Powers et al., 1999; Mehta, 2002; Yiridoe et al., 2009). While hard to quantify, and often not included in economic assessments, odor control could be considered the price of staying in business as residential areas continue to encroach on once-rural farms (Lusk, 1998).

Improved water quality is another benefit of anaerobic digestion that is difficult to economically quantify. Due to the reduction in volatile solids and chemical oxygen demand (COD) and thus a lower potential for oxygen depletion, digested manure has a deceased impact on water bodies than non-digested manure but is still not suitable for direct discharge into water ways (Martin, 2004). Currently, this water quality improvement does not result in any additional revenue. The high reduction in pathogens, however, does offers the opportunity of a revenue source through the reuse of the digested solids. Studies have shown that farms operating solids separators in conjunction with anaerobic digesters have cost savings through the recycling of bedding material and increased revenue through the sale of soil amendments (Lusk, 1998; Lazarus and Rudstrom, 2007; Leuer et al., 2008; Bishop and Shumway, 2009).

Livestock waste is the 5th largest source of anthropogenic methane emissions (7.2%) in the U.S. (USEPA, 2011). Methane is a greenhouse gas with 21 times the global warming potential of carbon dioxide (Calandar, 1995). As concerns over global warming continue to rise, the ability of anaerobic digesters to capture and utilize methane, results in additional economic benefits through the carbon credit trading market (AgStar, 2010b; Gloy, 2011; Key and Sneeringer, 2011). On the Chicago Climate Exchange, carbon credits traded between $0.05/ton (Nov, 2010) - $7.40/ton (June, 2008) (CCX, 2011).

Another potential income source for small-scale operations is the inclusion of co-products. It has been reported that the addition of food waste, and resulting tipping fee, can be a key revenue source for digesters turning a non-economically feasible system into a profitable system (Wright, et. al., 2004; Stokes et al., 2008; Bishop and Shumway, 2009; Gloy and Dressler, 2010). There is some risk involved in accepting off-farm food waste as some wastes are not well-suited for anaerobic digestion and can decrease biogas production (Bishop and Shumway, 2009).

Some studies have included decreased weed seed germination/viability and fertilizer production as additional benefits (Lusk, 1998; Nelson and Lamb, 2002;

Yiridoe et al., 2009). However, studies investigating these claims have found conflicting results (Allan et al., 2003; Katovich and Becker, 2004).

Perhaps the greatest economic issue facing small-scale digestion is uncertainty of both traditional and non-market factors. Gloy and Dressler (2010) cited the main challenges facing AD financing is the lack of information regarding the initial capital investment, predicted biogas production, expected lifetime, future electricity prices, and operating costs. This sentiment is shared by Stokes et al. (2008), who highlighted the lack of quantified data on non-market benefits as being a major obstacle towards widespread digester adoption. The AgSTAR Program, an outreach program supported by the USEPA, USDA, and USDOE to encourage the use of anaerobic digesters in the U.S., has begun to address the lack of standardized digestion performance data by releasing the report, "*Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures*", but it will take years to collect a comprehensive database.

Previous analyses conducted on the feasibility of small-scale anaerobic digestion uniformly cited a need for improved designs, with less required maintenance, and increased efficiency (Scruton, et al., 2004; Garrison and Richard, 2005). Research groups are addressing this need with some success (Wilkie, 2000b; Goodrich, 2005; Lazarus, 2009)

The Minnesota Project, a group funded by AgSTAR, evaluated six anaerobic digestion systems designed for small dairies, 100-300 cows. The largest reduction in capital investment was achieved through the elimination of the electrical generation capabilities. The Minnesota Project concluded that the digester costs were still too high ($105,000 - $230,000) and additional research is needed to further decrease capital costs (Goodrich, 2005). The Minnesota Project continued their study by building a small scale digester (Minnesota Project, 2008). The up-flow tank system was designed for 160 milking cows at a cost of $460,000 (US) (Lazarus, 2009). The system, while an excellent first step, has run into problems common at most dairies: engine failure and issues with manure handling. (Lazarus, 2011).

Private companies are also taking an interest in small-scale anaerobic digesters. For example, Avatar, BioProcess, and Agreen Energy/Quasar are three companies focusing on anaerobic digestion for farms varying from <100 – 400 cows. These companies all bring different, sometimes proprietary designs to the industry, and have pilot plants operating or under construction. The goal of many of these companies is to create a modular design that can be easily adapted (Scruton, 2007).

3.2 Objectives

Of the 30 million-plus digesters operating around the world, the majority of the systems are low-cost and concentrated in the tropics where the ambient temperature is at or near the optimal digestion temperature (Chen et al., 2010; Rao et al., 2010). In this study, low-cost digestion models from the developing world were modified to transfer this technology to temperate climates. Digestion technology from the developing world to the U.S. had not been explored but could offer a substantial potential renewable energy opportunity for small and medium scale dairy farmers with abundant waste resources.

The goals of the research were to make anaerobic digestion of manure more readily available, cost effective, and manageable to small dairy farmers in the United

States. Specifically, the research objectives were to (1) perform an economic assessment of constructed low-cost, pilot-scale research digesters, (2) perform an economic assessment of a 100-cow scale-up of the research digester design, (3) create a small-scale digester database and perform cost analyses of these systems, (4) reevaluate the minimum size dairy farm needed for anaerobic digestion to be economically feasible.

3.3 Methods

3.3.1 Research Site

Research digesters (UMD research digesters) were constructed from a modified Taiwanese digester design developed by Raul Botero and T. R. Preston for tropical climates. The traditional Taiwanese digester is a simply designed plug-flow reactor constructed of a tubular polyethylene bag and PVC piping (Botero and Preston, 1987). Modifications to this design were necessitated by the sensitivity of methanogens to the lower temperatures inherent in the temperate climate of the U.S. There are nine plug-flow UMD research digesters located at the United States Department of Agriculture (USDA) dairy facility in Beltsville, Maryland. Each digester is 14.3 feet in length with a diameter of 3 feet and a total capacity of 700 gallons per digester. The digesters are fed 25 gallons of manure daily with a combined treatment volume of 225 gallons per day with a 21-day retention time.

The UMD research digesters were constructed of a PVC-based flexible material, laid in insulative foam beds surrounded by radiant barriers, and enclosed within 42 inch drainage culverts to both protect and help maintain the desired shape of the digesters.

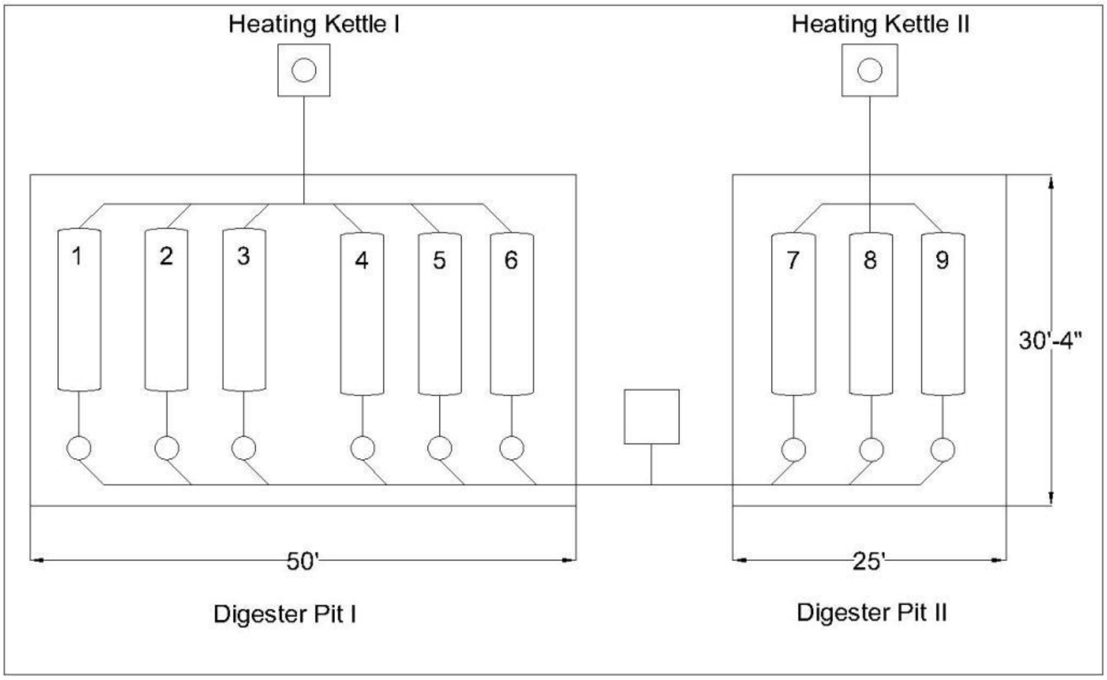
Figure 3.1 University of Maryland research digesters

Manure is pumped into a heating kettle and warmed to 35°C before draining into the digesters. Preheating of manure influent is a technique that has shown promise in past experiments but has not been tested as a modification to the Taiwanese design.

The heating kettle design was similar to that of a tempering tank in the confectionery food industry. The manure is stored in an inner vessel and surrounded by a water jacket. Utilizing a portion of the biogas produced from the digesters, the water bath surrounding the manure is heated. This method allowed for even heat distribution to the manure while also protecting the microorganisms from overheating. Once the manure reaches 35°C, it is released into the digester. The culverts are partially buried for added insulation and protected from the elements by a windshield structure.

The UMD research digesters are augmented with recirculation capabilities, allowing the effluent from the digesters to be reintroduced into the system through the heating kettle. Recirculation has been shown to aid in the distribution of the microorganisms and to keep warm material circulating through the system (Karmin et al., 2005). These modifications represent a departure for the original Taiwanese-model design in an effort to create a design that is compatible with a temperate climate. A schematic of the research system is shown in Figure 3.2.

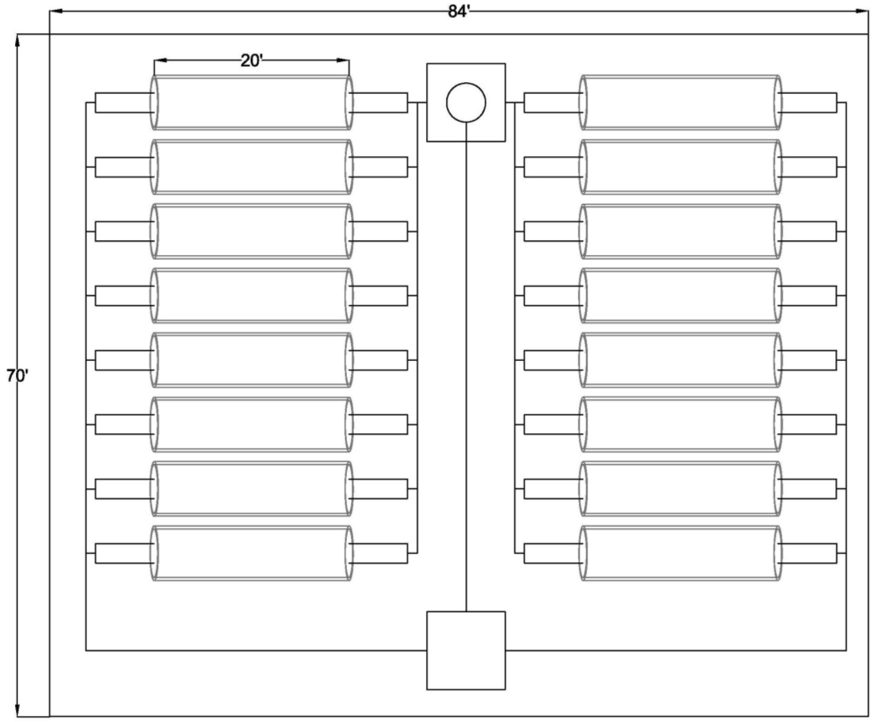
Figure 3.2 Schematic of research digestion system



The research system is located at the USDA's Beltsville Agricultural Research Center (BARC) located in Beltsville, Maryland. The farm uses a manure scraper system to remove the waste from its 120-cow facility. The manure is separated using a solid-squeezer separator. The solids are composted, while the liquid portion is treated by a mixed digester system installed in 1994 for $263,000 (Weeks, 2011). The digester effluent is stored in a lagoon and spray applied to the fields as fertilizer. The influent to the UMD research digesters is pumped from two locations. Six of the UMD research digesters receive un-separated manure pumped from the manure storage pit located before solid separation, and three UMD research digesters receive liquid manure pumped from a manure storage pit located after solid separation. The effluent from all the research digesters is pumped back into the storage lagoon. These connections were used as the boundary line for the economic analysis of the research digesters; thus, neither the solids separator nor the lagoon storage is included in the economic assessment.

The UMD research system was conceptually scaled up to supply a 100 cow dairy (referenced as UMD digester.) The scale up was performed on a component by component basis to most accurately represent real costs. This method, while more accurate, did present some disadvantages in form of limited scale up production. For example, the UMD research system consisted of nine research digesters for the purpose of replication during research. The 100 cow UMD system, however, consisted of 16, 60 inch diameter, digesters because the culverts used in the UMD research system are only manufactured up to a 60 inch diameter requiring multiple digesters in order to treat the expected volume of waste (37,500 gpd) for the 100 cow system. The culverts are manufactured in 20' lengths. The digesters were designed using one 20' culvert, as a 20' length has a diameter to length ratio of 1:4, which falls within the recommended 1:3.5 – 1:5 ratio (Lusk, 1998; Ogejo et al., 2009). In contrast, a two culvert digester with a length of 40' has a corresponding diameter to length ratio of 1:7.7, which is outside the recommended range. A schematic of the 100 cow system is shown in Figure 3.3.

Figure 3.3 Schematic of theoretical 100 cow digestion system



3.3.2 Digester Economic Comparisons

The UMD digester was evaluated with literature values obtained from existing and theoretical digesters for farms of 250 or less cows. The digester types include complete-mixed, plug-flow, covered lagoons, fixed film, and up-flow. Due to the lack of small-scale digesters currently in operation, there was limited data available on the costs of these systems. The cost data used in this study were compiled from conversations with providers and farmers for actual systems and projected costs for theoretical systems. For multiple existing systems the actual digester capital costs were greater than the original projected cost; therefore, the theoretical costs may be lower than the actual construction costs incurred if the system was constructed. The costs for the theoretical digesters were determined by extrapolating costs of existing components from other systems (Goodrich, 2011). Due to the limited number of 100-

cow digesters, digestion systems with less than 250 cows were included in the analysis. All the systems used in the comparison are listed in Table 3.1.

Table 3.1 Database of small-scale digester systems

Name	Type	Description	#cows	Items
UMD 1	Low Cost Plug Flow	UMD Beltsville, MD	100	digester, collection, excavation, gen-set
UMD 2	Low Cost Plug Flow	UMD Beltsville, MD	100	digester, collection, excavation
Theoretical 1	Covered Pond	-	100	digester, collection, boiler
Theoretical 2	Plug Flow	-	100	digester, collection, boiler
Theoretical 3	Upright	-	100	digester, separator, composter, boiler
Theoretical 4	Upright Mixed	-	100	digester, separator, boiler
Theoretical 5	Low Cost Plug Flow	-	100	digester, collection, boiler
Theoretical 6	Upright Mixed	WA State Dairy Farm, WA	200	digester, gen-set
Digester 1	Upright	USDA Beltsville, MD	220	digester, collection, separator, boiler
Digester 2	Plug Flow	Northeast IA CC Farm, IA	120	digester, gen-set
Digester 3	Upflow-tank	Jer-Lindy Farm, MN	160	digester, collection, building, labor, excavation, boiler, gen-set
Digester 4	Plug Flow	Freund Dairy, CT	250	digester, boiler
Digester 5	Fixed-Film	JJ Farber Dairy, NY	100	digester, boiler
Digester 6	Covered Pond	Spring Valley Dairy, NY	236	digester, gen-set, manure storage
Digester 7	Fixed-Film	Williston Cattle Co., VT	250	digester, extra research ports, boiler
Digester 8	Upright Mixed	WA State Dairy Farm, WA	200	digester, boiler

All the systems were compared when corrected for size and the UMD digester was evaluated under two scenarios: the first scenario was calculated without an electric generation system, the other system included the cost of an electric generation system and payback from utilities.

3.3.3 Conventional Manure Management Systems

Currently the most common means of manure management on small dairy operations is liquid/slurry storage and spread. In the United States, the majority of dairy farmers (62%) use liquid/slurry or daily spread for manure management (US EIIP, 1997; US NASS, 2009). It should be noted that due to the uniqueness of each farm, the cost of such systems, even for farms of the same, size farm will vary. For example, the University of Maryland Research and Education Center farm, Clarksville Farm, had to install a more expensive system in order to meet the approval of residential neighbors (Bassler, 2011).

A database of manure pit systems was collected with two types of manure systems dominating, the earthen pit and a lagoon with solid separation. The average capital cost for each type of system was used. The operation and maintenance of such a system was calculated based on farmers' records.

Table 3.2 Typical manure pit systems

Name	Type	Description	#cows
Manure Pit 1	Earthen Manure Pit	Pit, pumps, pipes	150
Manure Pit 2	Lagoon	Lagoon, solid separator, concrete pad, pumps, pipes	250

3.3.4 Cash Flow and NPV Analyses

In order to evaluate the economic viability of the proposed modified plug-flow system, a cash flow approach was used, as recommended by the EPA-AgSTAR *Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* (Eastern Research Group, 2011). The cash flow approach tabulates and compares all annual costs and revenues. Required assumptions described by the AgSTAR Protocol are as follows: (1) initial capital for the system is considered a combination of internal capital and borrowed capital, (2) the interest rate on borrowed capital is assumed to equal the rate of return on internal capital, (3) no cost-sharing assistance is included in the analysis, (4) payments for the total capital costs occur as a uniform series of annual payments over the useful life of the system, and (5) the useful life of the system is assumed to be 20 years and the replacement of system components with shorter lifetimes is accounted for in annual operation and maintenance costs. If records are not available on annual operation and maintenance costs, the EPA recommends assuming these costs to be 3% of the total capital costs (Eastern Research Group, 2011). Other studies have found operation and maintenance costs of 5% of capital cost for digesters with electrical generation to be more accurate (Martin, 2004; Beddoes et al., 2007; Lazarus, 2009). For this analysis, operation and maintenance costs totaling 3% of the capital cost were used for boiler systems and 5% of the capital cost was used for electrical generation systems. The cash flow analysis precludes income taxes. The boundary condition for all analysis includes only those components which are required solely by the digester system.

Operating costs for the manure pit options were based on the assumptions that a 100 cow dairy needs approximately 1 million gallons of storage annually (Erb, 2011). The operating cost to agitate and spread the slurry was assumed to be $0.01/gal of slurry (Erb, 2011).

Operating costs were calculated based on the methods presented except when more detailed operating costs were available (Digester 3, Digester 5, and Digester 6, as described below). To represent the best case scenario, all possible benefits were included: on-farm biogas utilization, electrical generation (where appropriate), recycling of bedding, and carbon credit offsets. Annual benefits for Digester 3, Digester 5, and Digester 6 were taken from existing published economic data for these systems.

A Net Present Value (NPV) analysis was also performed to determine the present worth and test the cost-effectiveness of the modified plug-flow system against other commonly used systems for manure treatment. NPV takes into account the system's annual cash flow discounted over the investment life to determine its net value. If NPV is positive, the investment provides a greater return than the alternate choice; if the NPV is negative, the alternate presents the better opportunity. When there is more than one competing investment, as was the case in this analysis, the higher NPV is preferred (Stermole and Stermole, 2000). The discount rate on borrowed capital is assumed to equal the average effective interest rate (7.8%) on non-real-estate farm loans (Federal Reserve, 2010).

3.3.5 Boundary Assumptions

When analyzing the costs of an anaerobic digestion system, setting the same boundaries for each system was needed for equal comparison. For this reason, it was assumed a slurry/storage and spread system was already installed and the digester was an additional component. In the description of each system, it was noted whether a solid separator was included in the system costs. If a solid separator was not included in the system costs, it was assumed the separator already existed as a component of the slurry/storage system. Without solid separation there cannot be an income from bedding reuse.

3.3.6 Annual Revenue

If there was not a generator installed, it was assumed that all biogas produced was utilized on the farm and was offsetting the cost of natural gas that would be purchased without the digester. If a generator was installed, it was assumed that the produced electricity offset electricity that would have been purchased by the farm.

If biogas production data was not provided, it was calculated by assuming each cow produced 5.70 kg of volatile solid per day and 0.35 L of biogas was produced from each gram of volatile solid (Van Horn et at., 1994). Using these assumptions, it was calculated that one cow produces 2.0 m^3 biogas/day, which is comparable to the 1.9 m^3 biogas/cow/day calculated more recently by the Natural Resources Conservation Service (NRCS) (Beddoes et al., 2007). It was also assumed that the produced biogas contained 60% methane and one-third of the biogas produced was used to heat the digester itself, leaving two-thirds for revenue considerations (Van Horn et al., 1994; Beddoes et al, 2007; Bracmort, 2008). The average price of natural gas (\$5.10/ft^3) paid in 2010-2011 by U.S. industrial consumers, which included agricultural consumers, was used in the analysis (EIA, 2011).

Systems with electrical generation capabilities were assumed to be receiving retail prices for their electricity production. If not given, the average retail price of electricity in the United States in 2009 of \$0.09/kWh was used (EIA, 2010), which is within the range of \$0.06-\$0.12/kWh used in previous economic evaluations of anaerobic digesters in the United States (Metha, 2002; Garrison and Richard, 2005; Giesy et al., 2009).

Bedding reuse values were calculated based on the assumption that a dairy cow produces approximately one cubic foot of fiber per day (Weeks, 2003; Kramer, 2009) and bedding costs average $10/cubic yard (Kramer, 2009; Kemp, 2011). Carbon emission reduction calculations were based on the EPA-AgSTAR Reporting Protocol (Section 6.0 Reductions in Methane Emissions), with the following correction: in Table 4 the Default Value of kg CH_4 emitted/10^6 Btu was corrected to kg CH_4 emitted/10^9 Btu (IPCC, 2006; Eastern Research Group, 2011). A carbon credit cost of \$5.70/metric ton CO_2 equivalent was used, which is within the range traded on the Chicago Climate Exchange between 2008-2011 and has been used in other economic assessments (Lazarus, 2008; CCX 2011). By using the same value as other reports, a more consistent comparison between the different systems is achieved. All costs were converted to 2010 U.S. dollars using the Engineering News Record (ENR) Construction Cost Index (Grogan, 2006; ENR, 2007-2011).

3.3.7 Sensitivity Analysis

The economic parameters used in the analysis include a discount rate of 8% and a lifetime expectancy of 20 years. These values are within the range used in the literature, with discount rates ranging from 4-14.25% and lifetime expectancies ranging from 10-20 years (Garrison and Richard, 2005; Lazarus and Rudstrom, 2007; Bracmort et al., 2008; Bishop and Shumway, 2009; Giesy et al., 2009; Eastern Research Group, 2011). To gauge the weight of each assumed value a sensitivity analysis was run using a project discount rate of 4% and 14% and a lifetime expectancy of 10 years and 15 years.

The sensitivity analysis was conducted on the cash flow analysis using six additional scenarios. A summary of each sensitivity test is shown in Table 3.3, where a 4% discount rate with a 20 year lifetime is the best case scenario and a 14% discount rate with a 10 year lifetime is the worst case scenario.

Table 3.3 Summary of sensitivity test scenarios

4%, 10 years	8%, 10 years	14%, 10 years
4%, 15 years	8%, 15 years	14%, 15 years
4%, 20 years	8%, 20 years	14%, 20 years

3.4 Results

3.4.1 Capital Costs

Upon completing the design and construction of the UMD research digesters, a complete economic assessment was performed on the system. The UMD research digester cost is shown in Table 3.4. The most expensive system components were the digester bags, culverts, and conveyance system (piping and pumps), resulting in a total capital cost of $83,970 (2010 US$) not including labor.

Table 3.4 Cost of research digesters by sub-system (2010 US$, rounded to $10)

Sub-system	per unit	Total
Digester	$2,100	$18,930
Recirculation	$260	$2,350
Subtotal:	**$2,360**	**$21,280**
Site Preparation		$10,380
Conveyance		$10,300
Heating		$5,340
Biogas System		$3,770
Automation		$14,670
Electric		$10,790
Other		$7,440
Total:		**$83,970**

Utilizing the same design but scaled up for a 100 cow facility, the resulting UMD system capital costs, both with and without electrical generation, are shown in Table 3.5.

Table 3.5 Cost of 100 cow digester by sub-system (2010 US$, rounded to $10)

Sub-system	per unit	Total
Digester	$4,890	$79,270
Recirculation	$421	$3,790
Subtotal:	**$5,311**	**$83,060**
Site Preparation		$10,000
Conveyance		$13,530
Heating		$38,035
Biogas System		$5,000
Automation		$8,520
Electric		$10,000
Other		$16,000
Total:		**$184,150**
Total with gen-set:		**$284,150**

The UMD system with electrical generation will be referred here in after as UMD1, while the UMD system without electrical generation will be referred to as UMD2. With the addition of a co-generator, the capital cost of the UMD1 was calculated to be $284,150 (2010 US$) for a 100-cow farm with the co-generator accounting for 36% of the total capital cost. The UMD2 capital costs without a generator totaled $184,150 (2010 US$).

When compared to the other digesters' capital costs, UMD2 was the 6th least expensive system, while UMD1 was the 3rd most expensive system (out of 16 systems), as shown in Table 3.6.

Table 3.6 Capital cost and capital cost/cow (2010 US$, rounded to $10)

Name	Capital Costs Total	Capital Costs per Cow
UMD 1	$284,150	$2,840
UMD 2	$184,150	$1,840
Theoretical 1	$217,480	$2,170
Theoretical 2	$192,650	$1,930
Theoretical 3	$189,110	$1,890
Theoretical 4	$163,110	$1,630
Theoretical 5	$124,100	$1,240
Theoretical 6	$176,450	$880
Digester 1	$427,990	$1,950
Digester 2	$266,930	$2,220
Digester 3	$487,160	$3,040
Digester 4	$349,890	$1,400
Digester 5	$176,140	$1,760
Digester 6	$188,830	$800
Digester 7	$371,070	$1,480
Digester 8	$164,520	$820
Manure Pit	$150,000	$1,000
Lagoon w/ SS	$600,000	$2,400

When capital costs per cow were considered, UMD2 was the 9th least expensive digester system, and UMD1 became the 2nd most expensive digester system.

3.4.2 Cash-Flow Analysis

The cash-flow analysis found only four systems had a positive cash flow without cost sharing when all possible revenue sources were included, Theoretical 5, Theoretical 6, Digester 4, and Digester 8 with Digester 7 having a $0.00 cash flow balance, as shown in Table 3.7. The cash-flow analysis using 25%, 50% and 87.5% cost sharing opportunities is shown in Table 3.8.

Table 3.7 Cash flow analysis results (2010 US$, rounded to $10)

System	Capital Costs ($2010)	Annual Capital Costs	Annual Operating Cost	Annual Income	Annual Net Cost	Annual Cost per Cow
UMD 1	$284,150	($28,940)	($14,210)	$18,890	($24,260)	($240)
UMD 2	$184,150	($18,760)	($5,520)	$19,480	($4,800)	($50)
Theoretical 1	$217,480	($22,150)	($6,520)	$19,480	($9,190)	($90)
Theoretical 2	$192,650	($19,620)	($5,780)	$19,480	($5,920)	($60)
Theoretical 3	$189,110	($19,260)	($5,670)	$19,480	($5,450)	($50)
Theoretical 4	$163,110	($16,610)	($4,890)	$19,480	($2,020)	($20)
Theoretical 5	$124,100	($12,640)	($3,720)	$19,480	$3,120	$30
Theoretical 6	$176,450	($17,970)	($8,820)	$37,790	$11,000	$60
Digester 1	$427,990	($43,590)	($12,840)	$42,850	($13,580)	($60)
Digester 2	$266,930	($27,190)	($13,350)	$22,670	($17,870)	($150)
Digester 3	$487,160	($49,620)	($13,390)	$28,790	($34,220)	($210)
Digester 4	$349,890	($35,640)	($10,500)	$48,700	$2,560	$10
Digester 5	$176,140	($17,940)	($31,550)	$17,090	($32,400)	($320)
Digester 6	$188,830	($19,230)	($10,550)	$22,680	($7,100)	($30)
Digester 7	$371,070	($37,790)	($11,130)	$48,700	($220)	$0
Digester 8	$164,520	($16,760)	($4,940)	$38,960	$17,260	$90
Manure Pit 1	$150,000	($15,280)	($15,000)	$0	($30,280)	($200)
Manure Pit 2	$600,000	($61,110)	($25,000)	$33,800	($52,310)	($210)

Table 3.8 Cash flow analysis results with cost sharing (2010 US$, rounded to $10)

	25%		50%		87.50%	
System	Annual Net Cost	Annual Cost/Cow	Annual Net Cost	Annual Cost/Cow	Annual Net Cost	Annual Net Cost
UMD 1	($17,030)	($170)	($9,790)	($100)	$1,060	$10
UMD 2	($110)	$0	$4,580	$50	$11,620	$120
Theoretical 1	($3,650)	($40)	$1,880	$20	$10,190	$100
Theoretical 2	($1,020)	($10)	$3,890	$40	$11,250	$110
Theoretical 3	($640)	($10)	$4,180	$40	$11,400	$110
Theoretical 4	$2,130	$20	$6,280	$60	$12,510	$130
Theoretical 5	$6,280	$60	$9,440	$90	$14,180	$140
Theoretical 6	$15,490	$80	$19,980	$100	$26,720	$130
Digester 1	($2,680)	($10)	$8,210	$40	$24,560	$110
Digester 2	($11,070)	($90)	($4,270)	($40)	$5,920	$50
Digester 3	($21,810)	($140)	($9,410)	($60)	($9,200)	$60
Digester 4	$11,470	$50	$20,380	$80	$33,750	$140
Digester 5	($27,920)	($280)	($23,430)	($230)	($16,700)	($170)
Digester 6	($2,290)	($10)	$2,510	$10	$9,730	$40
Digester 7	$9,230	$40	$18,670	$70	$32,850	$130
Digester 8	$21,450	$110	$25,640	$130	$31,920	$160
Manure Pit 1	($26,460)	($180)	($22,640)	($150)	($16,910)	($110)
Manure Pit 2	($37,030)	($150)	($21,760)	($90)	$1,160	$0

A breakdown of each system's annual revenue is shown in Table 3.9. Bedding reuse accounted for the greatest percentage of annual revenue.

Table 3.9 Annual revenue results (2010 US$, rounded to $10)

Name	Biogas	Electrical Generation	Bedding Reuse	CO2 Credits	Total Revenue
UMD 1	$0	$4,700	$13,520	$670	$18,890
UMD 2	$5,270	$0	$13,520	$690	$19,480
Theoretical 1	$5,270	$0	$13,520	$690	$19,480
Theoretical 2	$5,270	$0	$13,520	$690	$19,480
Theoretical 3	$5,270	$0	$13,520	$690	$19,480
Theoretical 4	$5,270	$0	$13,520	$690	$19,480
Theoretical 5	$5,270	$0	$13,520	$690	$19,480
Theoretical 6	$0	$9,400	$27,040	$1,350	$37,790
Digester 1	$11,590	$0	$29,740	$1,520	$42,850
Digester 2	$0	$5,640	$16,220	$810	$21,730
Digester 3	$0	$7,520	$21,630	$1,080	$27,410 ($28,789)[a]
Digester 4	$13,170	$0	$33,800	$1,730	$48,700
Digester 5	$5,270	$0	$13,520	$690	$19,480 ($17,089)[a]
Digester 6	$0	$11,090	$31,910	$1,590	$44,590 ($22,675)[a]
Digester 7	$13,170	$0	$33,800	$1,730	$48,700
Digester 8	$10,540	$0	$27,040	$1,380	$38,960
Manure Pit 1	$0	$0	$20,280	$0	$20,280
Manure Pit 2	$0	$0	$33,800	$0	$33,800

[a] Amounts in parenthesis is the total revenue used in the cash flow analysis and is based on case study data adjusted to 2010$.

When carbon credits and bedding reuse were excluded as annual benefits no systems had a positive cash-flow, as shown in Table 3.10.

Table 3.10 Cash flow analysis without bedding reuse or carbon credits (2010 US$, rounded to $10)

Name	Biogas	Electrical Generation	Total Revenue
UMD 1	$0	$4,700	$4,700
UMD 2	$5,270	$0	$5,270
Theoretical 1	$5,270	$0	$5,270
Theoretical 2	$5,270	$0	$5,270
Theoretical 3	$5,270	$0	$5,270
Theoretical 4	$5,270	$0	$5,270
Theoretical 5	$5,270	$0	$5,270
Theoretical 6	$0	$9,400	$9,400
Digester 1	$11,590	$0	$11,590
Digester 2	$0	$5,640	$5,640
Digester 3	$0	$7,520	$7,520 ($11,000)[a]
Digester 4	$13,170	$0	$13,170
Digester 5	$5,270	$0	$5,270 ($0)[a]
Digester 6	$0	$11,090	$11,090 ($17,750)[a]
Digester 7	$13,170	$0	$13,170
Digester 8	$10,540	$0	$10,540
Manure Pit 1	$0	$0	$0
Manure Pit 2	$0	$0	$0

[a] Amounts in parenthesis is the total biogas or electrical revenue based on case study data adjusted to 2010$.

3.4.3 NVP Analysis

As with the cash flow analysis, four systems had a positive net present value, Theoretical 5, Theoretical 6, Digester 4, and Digester 8, followed by Digester 7, Theoretical 4, and UMD1 as the 7th most cost effective digester system. All systems are shown in Table 3.11.

Table 3.11 NPV analysis results (2010 US$, rounded to $10)

Name	Capital Investment	Annual Operating Cost	Annual Income	NPV
UMD 1	($284,150)	($14,210)	$18,890	($238,200)
UMD 2	($184,150)	($5,520)	$19,480	($47,090)
Theoretical 1	($217,480)	($6,520)	$19,480	($90,240)
Theoretical 2	($192,650)	($5,780)	$19,480	($58,140)
Theoretical 3	($189,110)	($5,670)	$19,480	($53,520)
Theoretical 4	($163,110)	($4,890)	$19,480	($19,860)
Theoretical 5	($124,100)	($3,720)	$19,480	$30,630
Theoretical 6	($176,450)	($8,820)	$37,790	$107,980
Digester 1	($427,990)	($12,840)	$42,850	($133,350)
Digester 2	($266,930)	($13,350)	$22,670	($175,430)
Digester 3	($487,160)	($13,390)	$28,790	($335,960)
Digester 4	($349,890)	($10,500)	$48,700	$25,160
Digester 5	($176,140)	($31,550)	$17,090	($318,110)
Digester 6	($188,830)	($10,550)	$22,680	($69,740)
Digester 7	($371,070)	($11,130)	$48,700	($2,200)
Digester 8	($164,520)	($4,940)	$38,960	$169,490
Manure Pit 1	($150,000)	($15,000)	$0	($297,270)
Manure Pit 2	($600,000)	($25,000)	$33,800	($513,600)

The least cost effective system was Digester 3 with a negative $642,190 net present value.

3.4.4 Sensitivity Analysis

Digester 8 was the only systems with a positive cash flow for all nine sensitivity scenarios. Theoretical 6 had positive cash flow for a majority of the scenarios. UMD2 had a positive cash flow under the best case scenario of 4% interest over a 20 year life. A complete list of digester cash flow under all nine scenarios is shown in Table 3.12.

Table 3.12 Sensitivity analysis of cash flow results (2010 US$, rounded to $10)

Name	4%, 10	4%, 15	4%, 20	8%, 10	8%, 15	8%, 20	14%, 10	14%, 15	14%, 20
UMD 1	($30,360)	($20,870)	($16,230)	($37,670)	($28,520)	($24,260)	($49,800)	($41,580)	($38,220)
UMD 2	($8,750)	($2,600)	**$410**	($13,480)	($7,550)	($4,800)	($21,340)	($16,020)	($13,840)
Theoretical 1	($13,860)	($6,590)	($3,050)	($19,450)	($12,450)	($9,190)	($28,730)	($22,450)	($19,880)
Theoretical 2	($10,050)	($3,620)	($480)	($15,010)	($8,810)	($5,920)	($23,230)	($17,670)	($15,390)
Theoretical 3	($9,510)	($3,190)	($110)	($14,370)	($8,280)	($5,450)	($22,440)	($16,980)	($14,740)
Theoretical 4	($5,520)	($70)	**$2,590**	($9,720)	($4,470)	($2,020)	($16,680)	($11,970)	($10,040)
Theoretical 5	**$460**	**$4,600**	**$6,630**	($2,730)	**$1,260**	**$3,120**	($8,030)	($4,440)	($2,980)
Theoretical 6	**$7,210**	**$13,110**	**$15,980**	**$2,670**	**$8,360**	**$11,000**	($4,860)	**$240**	**$2,330**
Digester 1	($22,760)	($8,470)	($1,490)	($33,760)	($19,990)	($13,580)	($52,040)	($39,670)	($34,610)
Digester 2	($23,590)	($14,680)	($10,330)	($30,460)	($21,870)	($17,870)	($41,850)	($34,140)	($30,980)
Digester 3	($44,670)	($28,400)	($20,450)	($57,200)	($41,510)	($34,220)	($78,000)	($63,910)	($58,150)
Digester 4	($4,940)	**$6,740**	**$12,450**	($13,940)	($2,680)	**$2,560**	($28,880)	($18,770)	($14,630)
Digester 5	($36,180)	($30,290)	($27,420)	($40,710)	($35,040)	($32,400)	($48,230)	($43,230)	($41,050)
Digester 6	($11,150)	($4,850)	($1,770)	($16,010)	($9,930)	($7,100)	($24,070)	($18,610)	($16,380)
Digester 7	($8,180)	**$4,210**	**$10,260**	($17,730)	($5,780)	($220)	($33,570)	($22,840)	($18,460)
Digester 8	**$13,730**	**$19,230**	**$21,910**	**$9,500**	**$14,800**	**$17,260**	**$2,480**	**$7,230**	**$9,180**

3.5 Discussion

3.5.1 Comparing System Costs

The UMD system did not perform well with or without electrical generation capabilities. This is due to the high initial capital costs of both systems without sufficient revenue. The systems may perform better when actual operation and maintenance data are available as both systems were designed with automotive capabilities that could decrease the time requirement needed for operation.

Of the four systems with a positive cash flow, two were existing systems, Digester 4 (without electrical generation) and Digester 8 (without electrical generation), and two were theoretical systems Theoretical 5 (without electrical generation) and Theoretical 6 (with electrical generation). All four systems had lower initial capital costs, which was likely the greatest factor in determining their cost effectiveness. Digester 4 is a horizontal plug-flow digester located in New York. The original system cost $234,890 (2010$) but an additional $115,000 (2010$) of added insulation and heating components were added to increase digester performance. The greatest value-added product from the digester system was determined to be “cow pots”; a degradable seed started pot made of digested fiber.

Digester 8 was a complete mixed digester utilizing a boiler system that was installed in 1976 in Washington State with a 164,520 (2010$) initial cost (Coppinger et al., 1980). Given the age of the system, it is possible that the cost to build the same system today would be higher than is accounted for in this analysis as the construction cost index is used for general construction costs and is not an exact inflation rate for all the materials used in construction of the digester. Theoretical 6 is the Washington State digester (Digester 8) with electrical generation capabilities included and could have similar inflation error as Digester 8.

Theoretical 5, a low cost plug flow system, was designed using a plastic liner inside of steel culvert, similar to the UMD design. The estimated capital costs are $124,100 (2010$), $60,000 cheaper than UMD2. Theoretical 5 capital costs were based on lower estimated costs for conveyance, electrical, automation, and the digester tank, much of which is farm dependent and will vary for every digester. It is unclear if this system would be able to maintain mesophilic temperatures in the winter without the insulation, and subsequent cost, added in the UMD system.

Of the three least cost effective systems one was a theoretical system, UMD1 (with electrical generation), and two were existing systems, Digester 3 (with electrical generation) and Digester 5 (without electrical generation). UMD1 and Digester 3 had high initial capital costs, and therefore needed to generate greater annual revenues to have a positive cash flow. The inclusion of a generator to the UMD system added $100,000 of additional costs with no revenue, making this a poor economical option. Digester 3 is an upflow tank reactor while Digester 5 is a fixed-film digester. Digester 3 had a capital cost of $487,160 (2010$), which will be difficult to recuperate without cost sharing opportunities.

Digester 5 had a moderate capital cost of $176,150 (2010$) (not including liquid storage) but high operating costs. The operating cost used in this analysis came from a case study of the digester and are 18% of the capital costs and include insurance, reporting, and spreading costs (Wright and Ma, 2003b). When an operating cost of 3% is used, the system still has a negative cash flow but changes from the least economical system to the 5^{th} least economical system. The other two systems (Digester 3 and Digester 6) used existing operational costs of 3% - 6% of the capital costs.

Given the systems' limited ability to generate revenue, neither manure pits had a positive cash flow. It is assumed that this cost is already being absorbed by the farm before the installation of the digester. If the cost of the manure pit is added to the cost of the digester, none of the digester systems generate a positive cash flow.

The cash flow sensitivity analysis shows that the economic success of a digester system is dependent on the discount rate and life expectancy of the system. Under the worst case scenario presented, only Digester 8 maintained a positive cash flow likely due to its low initial capital costs.

Under the best-case scenario, three additional systems became positive, including the UMD2 system. An interesting observation is that the digester with the lowest capital cost per cow ratio, Digester 6, did not have a positive cash flow under any scenario. The system revenue was not great enough to offset the capital costs even with its electrical generation capabilities. Digester 6 was a manure activated digester installed on the Spring Valley Farm in New York (Wright and Ma, 2003a). The revenue used in this analysis, \$22,675 (2010\$), was taken from a case study of the digester and does not include bedding reuse because the dairy used sand bedding (Wright and Ma, 2003a). If bedding reuse was added in as a revenue source, total annual revenue would be \$44,590 (2010\$) and Digester 6 would have a positive cash flow, demonstrating how revenue intake affects the economic success of a digestion system.

3.5.2 Affects on Revenue

The financial benefits of using an anaerobic digester included in this analysis were on-farm biogas use, electrical generation (where applicable), bedding reuse, and carbon credits. Given the industrial market price of natural gas, \$5.10/cf (EIA, 2011), and the price of electricity, \$0.09/kWh (EIA, 2010), it was more cost effective to use the biogas directly than it was to convert it into electricity even without taking into account the higher capital cost and operating cost of an electrical generation system. This gave all systems only utilizing boilers a higher annual income per cow than those utilizing electrical generation. Other studies have also concluded the direct use of biogas in lieu of electrical production was economically feasible when the on farm heating requirements were high enough to regularly utilize all of the produced biogas (Bracmort, et al., 2008; Bishop and Shumway, 2009). Past studies have also demonstrated an increase in the price of electricity expanded the economic feasibility of anaerobic digesters to smaller farms (60 – 650) (Mehta, 2002; Garrison and Richard, 2005; Giesy et al., 2009).

When waste heat from the generator was assumed to heat the digester and 100% of the biogas produced went to electricity generation, electrical generation was more cost effective than direct biogas use. However, the increased revenue was not sufficiently high to change the cost effectiveness (from negative cash flow to positive cash flow) for any of the affected systems digesters.

The annual kWh/cow calculated in this analysis was 780 kWh/cow, which assumed each cow produced 5.70 kg of volatile solid per day and 0.35 L of biogas were produced from each gram of volatile solid and 1.0 kWh/.934 m^3 of biogas conversion efficiency from biogas to electricity (Van Horn et al, 1994). This is lower than values used in some economic analyses (1,071 – 3,884 kWh/cow) (Gloy, 2011) but higher than another analysis (385 kWh/year) (Cherosky et al., 2011). In conversations with farmers and experts in the field, systems often perform at a lower efficiency than originally predicted (Freund, 2011; Lazarus, 2011). Given this, and the risky nature of investment, using lower estimates for energy production is an appropriately conservative method for an economic analysis.

For the digesters analyzed, carbon emission reductions ranged from 121,000 – 303,000 kg CO_2/year varying based on the biogas produced from each system. When the trading cost of carbon is low, such as the \$0.05/ton CO_2 value on the Chicago Climate Exchange in 2010, the annual income for each system ranged from \$6 -\$15 (CCX, 2011). If the highest rate for CO_2 reduction was used (\$7.40/ton from June 2008), the maximum additional yearly income was \$2,240 for 250 cows. Therefore, carbon emission reduction created by installing a digester does not greatly increase the income of a small-scale dairy. This is in agreement with one study that predicted CO_2 credits could rival electrical production as the highest anaerobic digester revenue source when trading prices were above \$4/ton for large operations; however when small farms (<250 cows) were analyzed, a trading value of \$26/ton CO_2 was needed and then it was only cost affective for 3% of farms within the small farm size range (Key and Sneeringer, 2011).

Additional costs not accounted for in this assessment were annual carbon audits. Farmers wishing to utilize carbon emission offsets will incur an additional cost associated with initial and annual inspections and verification of their operations, ranging in cost from $3,000-$5,000 for the initial verification and $700-$1,000 for annual carbon audits (Powers et al., 2009), making carbon credit price neutral or cost prohibitive for smaller operations.

Bedding reuse was one of the highest income sources generated from digester use, ranging from $33,800 - $13,520 annually for the systems analyzed. This finding is in agreement with much of the literature, which found bedding recycling for on-farm use or for off-farm sale can be an important income source for farms with solid separator capabilities (Lusk, 1998; Weeks, 2003; Leuer et al., 2008; Bishop and Shumway, 2009). This analysis assumes all digestion systems are taking advantage of solid separation and reuse. For systems where the cost of the solid separator was not included in the capital costs, it was assumed the separator already existed on the farm. This assumption is seen in other economic evaluations of anaerobic digesters where the cost savings from bedding reuse are included without the capital cost of the solid separator, presumably because the separator existed as part of the farm infrastructure before the installation of the digester (Moser et al., 1998; Scott et al., 2010). In other economic analyses, the cost of separators, when adjusted to 2010$, ranged from $17,000 to $54,000 and the cost of separators plus building and related separator equipment ranged from $46,000 to $71,000 (Lusk, 1998; Wright and Ma, 2003b; Goodrich, 2005; Lazarus, 2009).

3.5.3 Food Waste and Tipping Fees

The negative cash flow observed in many of the analyzed systems could be offset by the addition of food waste and accompanying tipping fees. Multiple studies have found the inclusion of tipping fees as a key revenue source for anaerobic digesters making an otherwise non-economically sound investment profitable (Wright et al., 2004; Bishop and Shumway, 2009; Gloy and Dressler, 2010). To have a zero net cash flow, the UMD2 digester would need to bring in $400 monthly in tipping fees. The UMD1 digester would need to bring in $2,020 monthly in tipping fees. In New York, landfill tipping fees range from $55/ton to $125/ton (Scott and Ma, 2004). Taking food waste could also increase income beyond the tipping fee by being an additional source of volatile solids, thus increasing biogas production. However, in taking offsite food waste into an anaerobic digester, the farmer does incur increased risks for introducing a foreign substance that could adversely affect the system (Scott and Ma, 2004; Bishop and Shumway, 2009).

3.5.4 Options for Funding

All economic analyses were done assuming the farmer paid 100% of the investment; in reality there are multiple cost-sharing opportunities available to farmers for anaerobic digester projects. Federal sources for digester funding include the 2002 Farm Bill sections 9006 and 9007 grants and guaranteed loans, which cover up to 25% and 50% of the project costs (Lazarus, 2008; AgStar, 2011c). Additional Federal funding can be found in the Environmental Quality Incentives Program, Conservation Innovation Grants and Value Added Producer Grants (Lazarus, 2008; AgStar, 2011c). Various grants, loans, tax exemptions, and production incentives are also available on the State and local level (AgStar, 2011c). Giesy et al., (2009) found economic feasibility of digesters to be highly sensitive to cost-sharing opportunities. Without the inclusion of tipping fees, the UMD2 digester had a positive net cash flow when only 26% or more of the initial investment was paid for by outside funding;

while the UMD1 digester needed 84% of the capital costs to be covered by outside investment.

3.5.5 Net Metering

Net metering is a policy that allows creators of renewable energy to receive retail value for any excess electricity produced; when more energy is produced than used, the meter runs backwards and the user only gets charged the net of the usage (Scruton, 2007; Lazarus, 2008). As retail rates are better than wholesale rates, a policy of net metering allows the farmer to receive a higher rate for the produced electricity (Scruton, 2007). In the United States, net metering laws have been enacted in 46 States (DSIRE, 2011). However, these laws vary from State to State and do not always include biogas production as an energy source eligible for net metering. For this analysis net metering prices were utilized. Without net metering, the price received for electricity would have decreased from \$.09/kwh to \$.04/kwh (EIA, 2010; FERC, 2011). This change only affected systems utilizing electricity generation, and did not change which systems had a positive cash flow, but did lower the net cash flow of Theoretical 6 from \$11,000/year to \$5,780/year.

3.5.6 Electrical Generation verses Boiler System

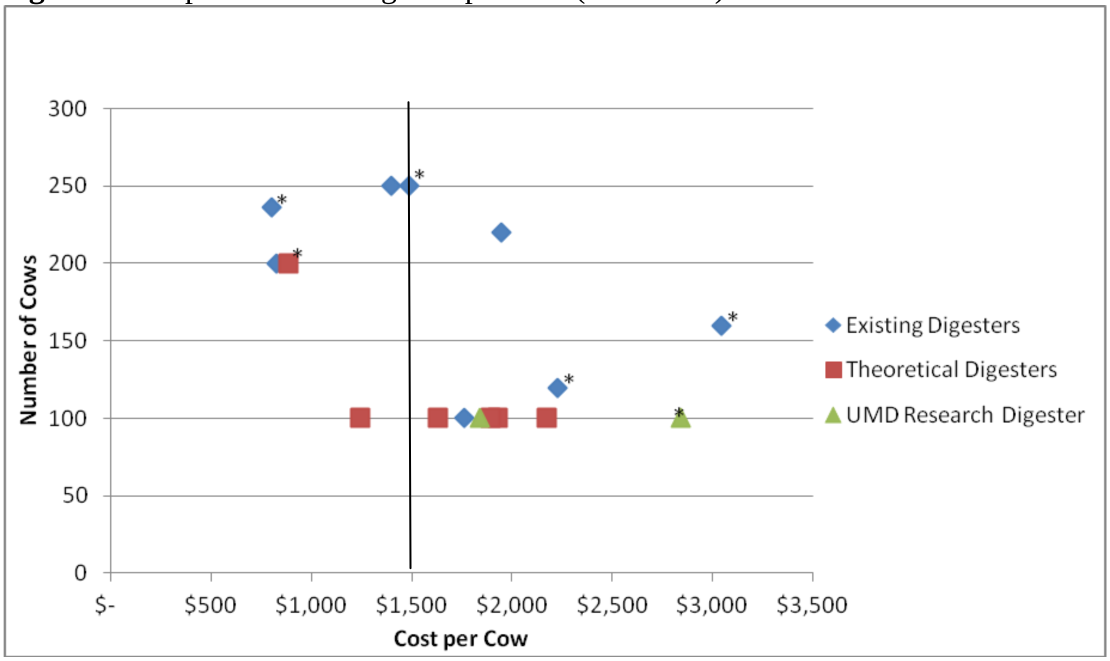
This study found the use of electrical generators to be cost effective for some systems but cost prohibitive for others. The UMD system was much more cost effective without the addition of electrical generation capabilities, which added \$100,000 in capital costs and an additional \$19,460 in net annual costs. This is in agreement with previous studies that also concluded the current price of electricity is too low to offset the high capital cost and additional maintenance cost of a co-generator (Bracmort et al., 2008; Bishop and Shumway, 2009).

Conversely, when analyzing the capital cost/cow, three of the six most cost-effective systems in the database had electrical generation capabilities. Demonstrating that while generators are a costly part of anaerobic digestion systems, they are not necessarily cost prohibitive. Millen (2008) also found small (130 and 70 cow) systems that were economically successful electricity producers. Thus, the use of co-generators on small farms should be analyzed on a case by case basis, and its economical viability will be related to the local price of electricity.

3.5.7 Minimum Size Dairy

Based on the results presented in this paper, a reevaluation of the minimum sized dairy needed for economically viable anaerobic digestion systems was conducted. Contrary to the AgSTAR general number of 500 cows, this study found theoretical systems with 100 cows and existing systems with 200 cows to be economically viable. Based on the published AgSTAR method for estimating the capital cost per cow of a plug flow anaerobic digester [$13,308*(\#cow)^{-0.3493}$], a 500 cow plug flow system costs $1,500/cow (AgStar, 2010a). Figure 3.3 represents the capital cost/cow for each system in the small scale database and shows that six of the sixteen systems were less expensive than $1,500/cow.

Figure 3.4 Capital costs of digester per cow (2010 US$)



(* represents systems with electrical generation capabilities.)

When the UMD digester is scaled-up to 200 cows, it decreases the cash flow of UMD1 from ($24,280) to ($24,760) however it increased the cash flow of UMD2 from ($4,820) to ($2,170). UMD2 as a 200 cow system almost meets the $1,500/cow threshold with a capital cost to cow ratio of $1,560/cow.

These results demonstrate that anaerobic digesters can be cost effective for small-scale systems although their viability must be analyzed on an individual basis as 63% of the systems analyzed were more expensive than the AgSTAR recommended capital cost of $1,500/cow. However, with an increase in revenue, such as an increase in the price of electricity or tipping fees, a greater capital cost could be afforded by the farmer.

3.5.8 Uncertainties

May of the uncertainties inherently found in economic assessments of anaerobic digesters have been well documented. The initial capital costs for systems of the same size vary significantly, as noted here and in previous research (Ghafoori et al., 2007). The lifetime, price of electricity and biogas, and discount rate are all variable and often necessitates the use of sensitivity analysis to determine the weight of each factor. As has been noted, the future price of electricity cannot be known for certain and will always be subject to uncertainties (Gloy and Dressler, 2010).

A less highlighted uncertainty is the variability in estimated biogas production. It has been noted that there are variations in methodology and a lack of published data on biogas output, electricity prices, and maintenance costs (Lazarus, 2008). As the production of biogas is dependent on microorganisms affected by their environment it is impossible to say with certainty what the biogas production will be for a given system. Although there are proven methods for estimating biogas production, the assumptions used throughout the literature vary, leading to an uneven comparison between theoretical designs or estimated future production. The publication of AgSTAR's *Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* will improve the normalization of biogas reporting for existing systems, but there still does not exist one agreed upon method for estimating future production. EPA's FarmWare software offers estimations of anaerobic digester costs (AgStar, 2011d). Using the FarmWare estimates, the UMD system would produce 1.6 times more biogas than what was calculated in this analysis.

Using the FarmWare calculated biogas production changes the economic feasibility of UMD1 from an annual cash flow of ($27,830) to ($20,662) and of the UMD2 system from ($6,919) to ($972). It should be noted that the FarmWare uses a digester operating temperature of 35°C while the design of the UMD system will likely not maintain a 35°C core temperature in the winter.

3.6 Conclusions and Future Research

Small scale anaerobic digestion can be economically viable in some instances. In an effort to design a more cost effective anaerobic digester for small scale dairy farms, a modified Taiwanese research digester was designed. A theoretical 100 cow system was designed with a capital cost of $184,150 (2010$) without electrical generation (UMD2) and $284,150 (2010$) with electrical generation (UMD1). When compared to other theoretical and existing small scale anaerobic digesters using a cash-flow analysis, UMD1 was the 2nd most expensive system while UMD2 was the 8th least expensive system out of 16 systems.

To make the UMD digester more cost effective, an investigation into cheaper materials should be done to try to lower the capital cost. With a 26% drop in capital costs, UMD2 would be cost neutral. If larger culverts are used as containment/insulation units, the number of digesters needed would decrease, decreasing the both the capital cost and operating costs of the system. Finding an alternative material to stainless steel for the heating kettle would also lower the capital cost.

The UMD digester design has multiple qualitative features that are not represented in the economic analysis. The system uses all PVC piping, which is readily available and easy to install and repair. The PVC-based digester bags are also easy to install and repair with readily available PVC primer and cement. The automation of pumping and heating added to the cost but will likely pay for itself with lower operation time requirements.

Actual operating costs and time will be vital to the success of this, as any, anaerobic digester. Detailed records need to be kept on the system over the course of its operation on operating costs, electrical demand, and time requirement.

Utilizing the complied database, a reevaluation of the minimum size dairy farm needed for anaerobic digestion to be economically set by AgSTAR should be reevaluated. It was determined that farms as small as 100-200 cows could generate a positive cash-flow from the installation of an anaerobic digester. The main factors affecting the analysis included initial capital costs and annual revenue. Very little economic data exists on the operation and maintenance costs of such systems, and there is a need for better data recording for existing systems.

Another area of uncertainty inherent in economic assessments is the range of assumptions made for volatile solids destruction and biogas production and variations in anaerobic digester reporting. AgSTAR's *Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures,* which was released in March 2011, will help to address the issue of anaerobic digester reporting inconsistencies, if the recommendations are followed by operators. However, there is still a need to improve reporting on theoretical systems in order to make even comparisons between designs.

Perhaps the most important question is whether this technology is ready for widespread implementation. The conclusions reached here show that while small-scale anaerobic digestion is economical in some cases, it is farm dependent and a majority of the systems analysis did not have a positive cash flow. In the AgSTAR digester database, of the 10 small scale digesters built, 6 have shut down (AgStar, 2011b). In this analysis, at least half of the existing digesters are now shutdown (4 out of 8). In three cases this was due to either the dairy closing or management changes and not due specifically to digester failure. The longest running small scale system has been operational for almost two decades, and there are four systems under construction, showing some success in the market. With the appearance of multiple private companies attempting to fill the niche of small scale anaerobic digestion with modular and proprietary designs, this technology could see much greater implementation in the coming years.

Chapter 4: Conclusions

The design and construction of research digesters is an important part of advancing anaerobic digester technology in the United States. By experimenting with new designs and different materials, the academic community can offer invaluable advice to farmers wishing to implement an anaerobic digester. While the effectiveness of the design has not yet been tested, the design and construction process of this research system have given valuable insight to its creators.

4.1 Successes

It is rare in a research project that each component will work correctly when tested the first time and this project was no exception. However, there are multiple components, which once troubleshot, worked very successfully. Once operational, the drainage and sump pump system worked effectively in preventing flooding and water damage to the site. When water tested, the conveyance system, both gravity and pressure, function at design specifications. The success of many components: the conveyance system when handling manure, the biogas collection system, the automation system, and the insulation and heating system, will not be known until the research digesters are completely online and operating for a continuous period of time.

4.2 Failures

As has been noted with other projects, one of the greatest material challenges with the construction of the research digesters was the digester bag material. The original bag specified in the design was made of a geo-membrane based material.

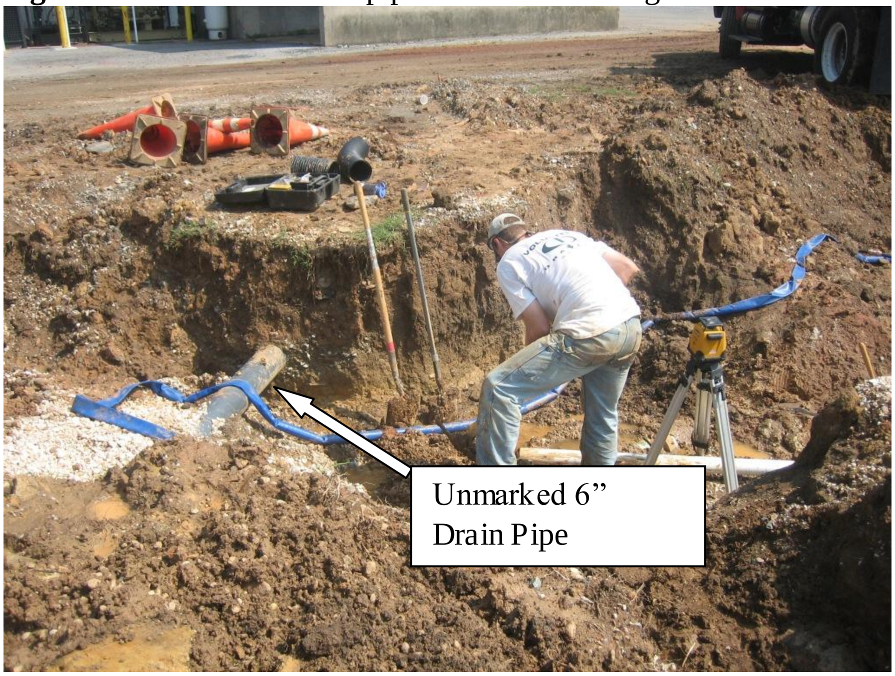
While this material appeared stronger and less likely to wear, it was difficult to create air-tight seals and when wearing did occur, it was difficult to repair. For these reasons, the geo-membrane material was replaced with a PVC-based material. The use of a PVC-based material makes creating air-tight seals with PVC piping simple and requires only PVC cement to create a chemical bond between the bag material and the pipe. Repairing holes is also simplified by the ability to chemically bond the bag material to itself with readily available PVC cement.

One of the main issues that occurred during construction was flooding. The water table at the site is 2.5-3.0 feet below ground level, and the soil is a Keyport Silt Loam with poor drainage. To prevent flooding of the digesters during rain events, additional measures to address flooding were designed. However, the addition of flood prevention measures did little to stop flooding until the electrical system was installed and the system was automated. Flooding caused both time delays and material waste. Figure 4.1 shows the site after a major rain event before the sump pump system was automated.

Figure 4.1 Flooding damage at research site

An additional issue experienced during construction was that of unmarked utilities. As on many older farms, the BARC farm has storm drains and drainage tiles that are not marked. Some conveyance pipes had to be re-directed and re-designed around unmarked drains. Another unforeseen issue involved the accidental redirecting of storm water from an 18 inch storm drain into the trench of the conveyance pressure pipes. This issue was corrected by mixing bentonite in the back fill and effectively creating a barrier around the pressure pipe and redirecting storm water to its original course along the 18-inch storm drain.

Figure 4.2 Unmarked drain pipe discovered during construction



4.3 Recommendations

Designing a research system is more complicated than that of a regular system due to the need for replication. Not only are multiple units and pathways required, but the system needs to be designed with minimal cross-contamination in an effort to create true duplication. Regardless of the number of replications desired, it is highly recommended that one digester be completely constructed and tested before being duplicated, although this is not a guaranteed way to insure success. The research digesters of this system were both air and water tested multiple times before leaks began to appear in the original bag material. Still, the principle of completing one digester before replicating is recommended as the best way to guard against lost time and money.

As is the case with many farm-scale digesters, conveying manure is one of the hardest operational challenges of a research digester. The system designed here, which utilizes holding tanks, multiple clean-outs, and gravity whenever possible, will hopefully address the need to move small volumes of manure through larger diameter pipe without sacrificing the minimum velocity needed to prevent sedimentation. As can be seen from the multiple type pumps used in manure management systems, there is no one correct way to deal with manure conveyance.

Finally, with a research project of this scale, it is important to schedule in advance the necessary design and construction time/sequencing. While construction timing and scheduling methods are well utilized by building contractors, this depth of project management is not often needed nor practiced in academia. However, depending on the magnitude of the project, borrowing from construction management methods can be beneficial. Some factors that should be considered in a research project construction timeline include: the contractor's ability to manage and coordinate the work force, the quality and completeness of the designs, the weather, labor availability, site conditions, and agency/government approval.

4.4 Next Step and Future Research

To bring the research system up to a completely operational level, troubleshooting will have to occur. Unfortunately, the trouble areas will likely be those not anticipated and thus sufficient time should be given for the system to be completely online. Once operational, energy production performance should be measured in terms of biogas production and composition, specifically the percent of CH_4 and H_2S, as these are indicators of substrate biodegradation and potential for energy production (Angelidaki and Sanders, 2004). Influent and effluent streams should be measured for water quality indicators including chemical oxygen demand

(COD), total solids (TS), turbidity, NH_4-N, pH, and TKN, which have been determined to be good indicators of digester performance (Lansing, 2008a; Eastern Research Group, 2011). Fixed solids (FS) and total phosphorus (TP) should also be measured to determine solids accumulation in the digesters (Eastern Research Group, 2011).

In addition to performance measures, a data log should be kept on all start-up, operation and maintenance activities. One component missing from the literature is detailed operation and maintenance data for anaerobic digesters. For this reason, keeping detailed records will be just as important as performance measurements. This log should record daily operation time as well as daily, monthly, and yearly maintenance time. Operation time should include the time mechanical components, such as pumps and mixers, are running in order to get a complete electrical demand for the system, as well as the daily time required from an operator. All maintenance activities should be recorded detailing time, cost of replacement part if appropriate, and whether the system operation was affected. Based on these logs, accurate operating costs can be calculated for the system.

Due to the complicated nature of research systems discussed above, there will be a limit to how much of an inference can be made from the operation logs to a farm scale digester. However, the data can be used to improve future designs and estimate the operation and maintenance of a digester. The data collected from this system could then be used to create an improved design for a farm scale digester. Detailed reports on the installation, start-up, operation, and maintenance of the farm scale digester will be valuable information that will aid in improving and promoting anaerobic digestion in United States.

Appendix A: Design Documents

A.1 Hydraulic Profile Calculations

Figure A.1 Hydraulic profile

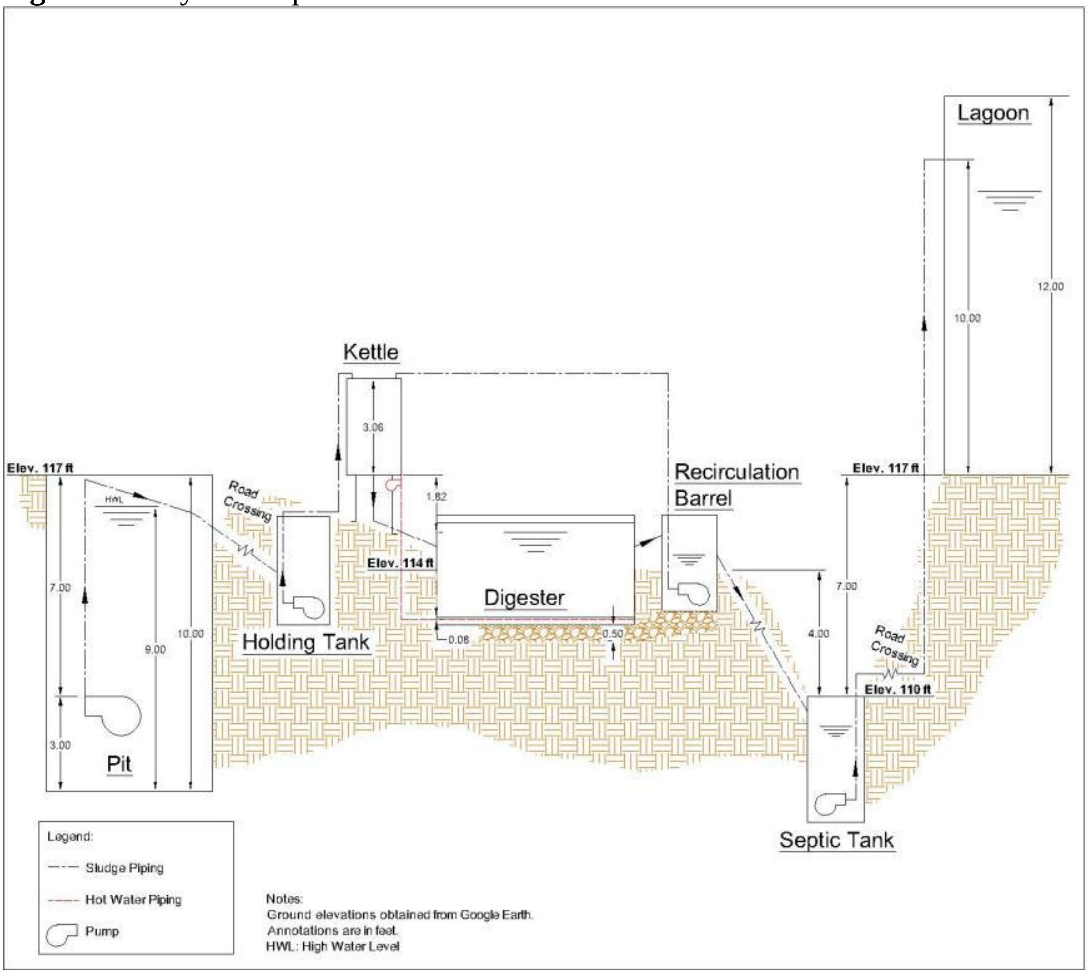


Table A.1 Hydraulic calculations: separator pit to holding tank

1.0 Piping from Separator Pit to Holding Tank	**3" diameter pipe**	**Comments**
Pipe Material	PVC	
Inlet invert elevation (ft)	110.00	see Hydraulic Profile
Discharge invert elevation (ft)	117.00	see Hydraulic Profile, not discharge elev. Highest pt in system
Losses assuming full pipe flow:		
Flow (gpm)	80.00	Total Flow = 152.27 gallons per day. See System Curve Tab

Pipe Diameter (in.)	3.00	
Hydraulic Radius (ft)	0.13	For circular pipe inside diameter
Velocity (ft/s)	3.63	V=QA (optimal min. velocity of 3.5)
C factor	120.00	
Pipe Length (ft)	120.00	Estimated (110 ft horiz. + 10 ft. vert.)
Major Losses (ft)	1.26	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Velocity Head (ft)	0.20	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)		K Coefficient 2" (Source: Cameron Hydr. Data, 1984)
Entrance	0.10	0.5
90 vert deg bend	0.06	0.3
90 horiz deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
Exit	0.20	1.0
Total Minor Losses (ft)	0.55	
Total Losses (ft)	1.81	
Open channel flow Calculations - Calculate depth of flow for a given discharge flow rate	-	-
Manning's n	0.011	roughness coefficient (for PVC 0.009-0.011)
velocity, (ft/s)	3.50	set to minimum
Flow (ft^3/s)	0.18	
Flow area, A (ft^2)	0.05	A = Q/V
($8*A/D^2$), calculated using set Q and V	6.52	$A = (1/8)*(\Theta-\sin(\Theta))*D^2$ or ($8*A/D^2$)
Angle, Θ (radians)	7.43	Calculate by goal seek: set following cell equal to above cell by changing cell Angle
($8*A/D^2$), calculated with goal seek	6.52	$A = (1/8)*(\Theta-\sin(\Theta))*D^2$ or $((8*A/D^2) = \Theta-\sin(\Theta))$
	-	
Wetted Perimeter, WP (ft)	0.93	WP = 0.5*Θ*D
Hydraulic Radius, R (ft)	0.05	R = A/WP
Minimum required slope (ft/ft)	0.03	Manning's Eqn.: $Q = 1.49/n*A*R^{2/3}*S^{1/2}$

Table A.2 Hydraulic calculations: holding tank to kettle

2.0 Piping from Holding Tank to Kettle	**2" diameter pipe**	**Comments**
Pipe Material	PVC	
Inlet invert elevation (ft)	110.00	see Hydraulic Profile
Discharge invert elevation (ft)	126.00	see Hydraulic Profile
Losses assuming full pipe flow:		
Flow (gpm)	15.00	Total Flow = 15 gallons per pumping cycle. See System Curve Tab
Pipe Diameter (in.)	2.00	
Hydraulic Radius (ft)	0.13	For circular pipe inside diameter
Velocity (ft/s)	0.68	V=QA (min. velocity of 3.5 required)
C factor	120.00	
Pipe Length (ft)	65.00	Estimated (55 ft horiz. + 10 ft. vert.)
Major Losses (ft)	0.03	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Volume in Pipe (gal)		
Velocity Head (ft)	0.01	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)		K Coefficient 2" (Source: Cameron Hydr. Data, 1984)
Entrance	0.10	0.5
90 vert deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
Exit	0.20	1.0
Total Minor Losses (ft)	0.55	
Total Losses (ft)	0.58	
Open channel flow Calculations - Calculate depth of flow for a given discharge flow rate	-	-
Manning's n	0.011	roughness coefficient (for PVC 0.009-0.011)
velocity, (ft/s)	3.50	set to minimum
Flow (ft^3/s)	0.03	
Flow area, A (ft^2)	0.01	A = Q/V
$(8*A/D^2)$, calculated using set Q and V	1.22	$A = (1/8)*(\Theta-\sin(\Theta))*D^2$ or $((8*A/D^2) = \Theta-\sin(\Theta))$
Angle, Θ (radians)	2.09	Calculate by goal seek: set following cell equal to above cell by changing cell Angle
Angle, Θ (degrees)	119.68	
$(8*A/D^2)$, calculated with goal seek	1.22	$A = (1/8)*(\Theta-\sin(\Theta))*D^2$ or $((8*A/D^2) = \Theta-\sin(\Theta))$

	-	
depth of flow (d)	-	
Wetted Perimeter, WP (ft)	0.26	WP = 0.5*Θ*D
Hydraulic Radius, R (ft)	0.04	R = A/WP
Minimum required slope (ft/ft)	0.06	Manning's Eqn.: Q = $1.49/n*A*R^{2/3}*S^{1/2}$ [$S = (Q*n/1.49/A/R^{2/3})^2$]

Table A.3 Hydraulic calculations: kettle to digesters

3.0 from Kettle to Digesters	**3rd Branch Digester**	**2nd Branch Digester**	**Closest (1st) Digester**	**Comments**
Pipe Material	PVC	PVC	PVC	
Inlet invert elevation (ft)	117.00	117.00	117.00	see Hydraulic Profile
Discharge invert elevation (ft)	115.15	115.18	115.18	see Hydraulic Profile
Flow (gpm)	25.38	25.38	25.38	variable, 25.38 equals total gallons per digester per day
Flow (ft^3/s)	0.06	0.06	0.06	
Manning's n	0.011	0.011	0.011	roughness coefficient (for PVC 0.009-0.011)
Pipe Diameter (in.)	2.00	2.00	2.00	
C factor	120.00	120.00	120.00	
Pipe Length (ft)	27.21	20.71	14.21	estimated from piping schematic
Given Slope* (ft/ft)	0.07	0.09	0.13	S (ft/ft) = difference elev./distance (*assuming constant slope, poor assumption)
Open channel flow Calculations - Calculate depth of flow for a given discharge flow rate	-	-	-	-
velocity, (ft/s)	2.55	2.55	2.55	set to minimum
Flow area, A (ft^2)	0.02	0.02	0.02	A = Q/V
($8*A/D^2$), calculated using set Q and V	6.39	6.39	6.39	$A = (1/8)*(Θ-\sin(Θ))*D^2$ or ($8*A/D^2$)
Angle, Θ (radians)	7.16	7.16	7.16	Calculate by goal seek: set cell 56 equal to cell 54 by changing cell Angle
($8*A/D^2$), calculated with goal seek	6.39	6.39	6.39	$A = (1/8)*(Θ-\sin(Θ))*D^2$ or (($8*A/D^2$) = Θ-sin(Θ))

	-	-	-	
Wetted Perimeter, WP (ft)	0.60	0.60	0.60	WP = 0.5*Θ*D
Hydraulic Radius, R (ft)	0.04	0.04	0.04	R = A/WP
Minimum required slope (ft/ft)	0.03	0.03	0.03	Manning's Eqn.: $Q = 1.49/n*A*R^{2/3}*S^{1/2}$
Losses assuming full pipe flow:				
Flow (gpm)	25.00	25.38	25.38	
Pipe Diameter (in.)	2.00	2.00	2.00	
Hydraulic Radius (ft)	0.08	0.08	0.08	For circular pipe inside diameter
Velocity (ft/s)	2.55	2.59	2.59	min velocity 3.50 ft/s
C factor	120.00	120.00	120.00	
Pipe Length (ft)	27.21	20.71	14.21	estimated from schematic
Major Losses (ft)	0.24	0.19	0.13	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Velocity Head (ft)	0.10	0.10	0.10	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)				K Coefficient (Source: Cameron Hydr. Data, 1984)
Entrance	0.05	0.05	0.05	0.5
45 horiz deg bend	0.03	0.03	0.03	0.3
Ball Valve	0.01	0.01	0.01	0.06
45 horiz deg bend	0.03	0.03	0.03	0.3
Tee, branch			0.12	1.14
Tee, flow	0.04	0.04		0.38
Ball Valve	0.01	0.01	0.01	0.06
Tee, branch		0.12		1.14
Tee, flow	0.04			0.38
Ball Valve	0.01	0.01		0.06
Tee, branch	0.12			1.14
Tee, flow				0.38
Ball Valve	0.01			0.06
90 horiz deg bend				0.57
Exit	0.10	0.10	0.10	1.0
Total Minor Losses (ft)	0.43	0.40	0.35	
Total Losses (ft)	0.67	0.58	0.48	

Table A.4 Hydraulic calculations: recirculation barrels to kettle

4.0 Recirculation Barrels to Kettle	**3rd Branch**	**2nd Branch**	**Closest (1st) Bag**	**Comments**
Pipe Material	PVC	PVC	PVC	
Inlet invert elevation (ft)	113.37	113.37	113.37	see Hydraulic Profile
Discharge invert elevation (ft)	126	126	126	see Hydraulic Profile
Losses assuming full pipe flow:				
Flow (gpm)	10.00	10.00	10.00	Total Flow = 35 gallons per pumping cycle. See System Curve Tab
Pipe Diameter (in.)	1.00	1.00	1.00	
Hydraulic Radius (ft)	0.04	0.04	0.04	For circular pipe inside diameter
Velocity (ft/s)	4.09	4.09	4.09	V=QA (min. velocity of 3.5 required)
C factor	120.00	120.00	120.00	
Pipe Length (ft)	60.00	53.00	46.00	estimated from piping schematic
Major Losses (ft)	2.81	2.49	2.16	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Velocity Head (ft)	0.26	0.26	0.26	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)				K Coefficient (Source: Cameron Hydr. Data, 1984)
Entrance	0.13	0.13	0.13	0.5
45 horiz. deg bend	0.10	0.10	0.10	0.37
45 horiz. deg bend	0.10	0.10	0.10	0.37
45 horiz. deg bend	0.10	0.10	0.10	0.37
45 horiz. deg bend	0.10	0.10	0.10	0.37
90 vert. deg bend			0.18	0.69
Tee, flow			0.12	0.46
Tee, branch	0.36	0.36		1.38
Tee, branch	0.36	0.36	0.36	1.38
45 vert deg bend	0.10	0.10	0.10	0.37
46 vert deg bend	0.10	0.10	0.10	0.37
45 vert deg bend	0.10	0.10	0.10	0.37
Exit	0.26	0.26	0.26	1.0
Total Minor Losses (ft)	1.78	1.78	1.72	
Total Losses (ft)	4.59	4.26	3.87	

Table A.5 Hydraulic calculations: digesters to septic tank

5.0 from Digesters to Septic Tank	**Farthest (1st) Digester**	**Comments**
Pipe Material	PVC	
Inlet invert elevation (ft)	115.18	see Hydraulic Profile
Discharge invert elevation (ft)	113.12	see Hydraulic Profile
Flow (gpm)	10.00	variable, 25.38 gallons total
Flow (ft^3/s)	0.02	
Manning's n	0.011	roughness coefficient (for PVC 0.009-0.011)
Pipe Diameter (in.)	3.00	
C factor	120.00	
Pipe Length (ft)	51.50	50' from farthest digesters plus 1' from each recirculation tank
Given Slope (ft/ft)	0.04	S (ft/ft) = difference elev./distance
Open channel flow Calculations - Calculate depth of flow for a given discharge flowrate	-	-
velocity, (ft/s)	2.00	set to minimum
Flow area, A (ft^2)	0.01	A = Q/V
($8*A/D^2$), calculated using set Q and V	1.43	$A = (1/8)*(\Theta-\sin(\Theta))*D^2$ or ($8*A/D^2$)
Angle, Θ (radians)	2.22	Calculate by goal seek: set cell 192 equal to cell 190 by changing cell Angle
($8*A/D^2$), calculated with goal seek	1.43	$A = (1/8)*(\Theta-\sin(\Theta))*D^2$ or $((8*A/D^2) = \Theta-\sin(\Theta))$
	-	
Wetted Perimeter, WP (ft)	0.28	WP = 0.5*Θ*D
Hydraulic Radius, R (ft)	0.04	R = A/WP
Required Slope (ft/ft), given Q and V	0.02	Manning's Eqn.: $Q = 1.49/n*A*R^{2/3}*S^{1/2}$
Losses assuming full pipe flow:		
Flow (gpm)	25	
Pipe Diameter (in.)	3.00	
Hydraulic Radius (ft)	0.13	For circular pipe inside diameter
Velocity (ft/s)	1.15	min velocity 3.50 ft/s
C factor	120.00	
Pipe Length (ft)	51.50	estimated from schematic
Major Losses (ft)	0.06	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Velocity Head (ft)	0.02	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)		K Coefficient (Source: Cameron Hydr. Data, 1984) (Tee, branch from manufact.)

Entrance	0.01	0.5
90 horiz deg bend	0.01	0.3
90 horiz deg bend	0.01	0.3
90 horiz deg bend	0.01	0.3
Tee, flow	0.00	0.06
Exit	0.02	1.0
Total Minor Losses (ft)	0.05	
Total Losses (ft)	0.12	

Table A.6 Hydraulic calculations: septic tank to storage lagoon

6.0 Piping from Septic Tank to Lagoon	**3" diameter pipe**	**Comments**
Pipe Material	PVC	
Inlet invert elevation (ft)	109.36	see Hydraulic Profile (2.06' loss from farthest digester + .5' inlet + 3.26' depth in septic tank)
Discharge invert elevation (ft)	129.00	see Hydraulic Profile
Losses assuming full pipe flow:		
Flow (gpm)	35.00	Total Flow = 35 gallons per pumping cycle. See System Curve Tab
Pipe Diameter (in.)	3.00	
Hydraulic Radius (ft)	0.13	For circular pipe inside diameter
Velocity (ft/s)	1.59	V=QA (min. velocity of 3.5 required)
C factor	120.00	
Pipe Length (ft)	240.00	Estimated from Google Earth (220 ft horiz. + 20 ft. vert.)
Major Losses (ft)	0.54	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Velocity Head (ft)	0.04	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)		K Coefficient 2" (Source: Cameron Hydr. Data, 1984)
Entrance	0.10	0.5
90 vert deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
90 vert deg bend	0.06	0.3
Exit	0.20	1.0
Total Minor Losses (ft)	0.49	
Total Losses (ft)	1.04	

Table A.7 Hydraulic calculations: water/ethylene glycol solution kettle to kettle

7.0 Water Piping from Kettle to Kettle	**Third Bag (Farthest)**	**Second Bag**	**First Bag (Closest)**	**Comments**
Pipe Material	Pex Tubing	Pex Tubing	Pex Tubing	
Inlet invert elevation (ft)	117.00	117.00	117.00	see Hydraulic Profile
Discharge invert elevation (ft)	112.42	112.42	112.42	see Hydraulic Profile
Losses assuming full pipe flow:				
Total Volume (gal)	4.18	3.61	2.99	Vol=L*(π*(D/12/2)^2)*7.48
Flow (gpm)	0.84	0.72	0.60	Total Flow = volume inside pipes. Here assuming 5 min pumping time
Pipe Diameter (in.)	1.00	1.00	1.00	
Hydraulic Radius (ft)	0.04	0.04	0.04	For circular pipe inside diameter
Velocity (ft/s)	0.34	0.30	0.24	V=QA (min. velocity of 3.5 required)
C factor	120.00	120.00	120.00	assuming same C Factor as PVC
Pipe Length (ft)	102.36	88.54	73.32	estimated (vertical and horizontal)
Major Losses (ft)	0.05	0.03	0.02	Hazen-Williams Eqn: $h_L = L*[V/(1.318*C*R^{0.63})]^{1.85}$
Velocity Head (ft)	0.002	0.001	0.001	$V^2/(2g)$
Minor Losses, $K*V^2/(2g)$ (ft)				K Coefficient (Source: Cameron Hydr. Data, 1984)
Entrance	0.001	0.001	0.000	0.5
90 horz deg bend	0.001	0.001	0.001	0.69
90 horz deg bend	0.001	0.001	0.001	0.69
90 horz deg bend	0.001	0.001	0.001	0.69
90 horz deg bend	0.001	0.001	0.001	0.69
close return bend	0.002	0.002	0.001	1.15
close return bend	0.002	0.002	0.001	1.15
close return bend	0.002	0.002	0.001	1.15
Tee, flow	0.001		0.000	0.46
Tee, flow	0.001		0.000	0.46
Tee, flow				0.46
Tee, flow				0.46
Tee, flow				0.46
Tee, branch	0.002	0.002		1.38
Tee, branch	0.002	0.002		1.38
Tee, branch	0.002	0.002		1.38
Tee, branch	0.002	0.002		1.38

Exit	0.002	0.001	0.001	1.0
Total Minor Losses (ft)	0.03	0.02	0.01	
Total Losses (ft)	0.07	0.05	0.03	

A.2 Gravity Slope Calculations

Figure A.2 Influent manure pipes (digesters 1-6)

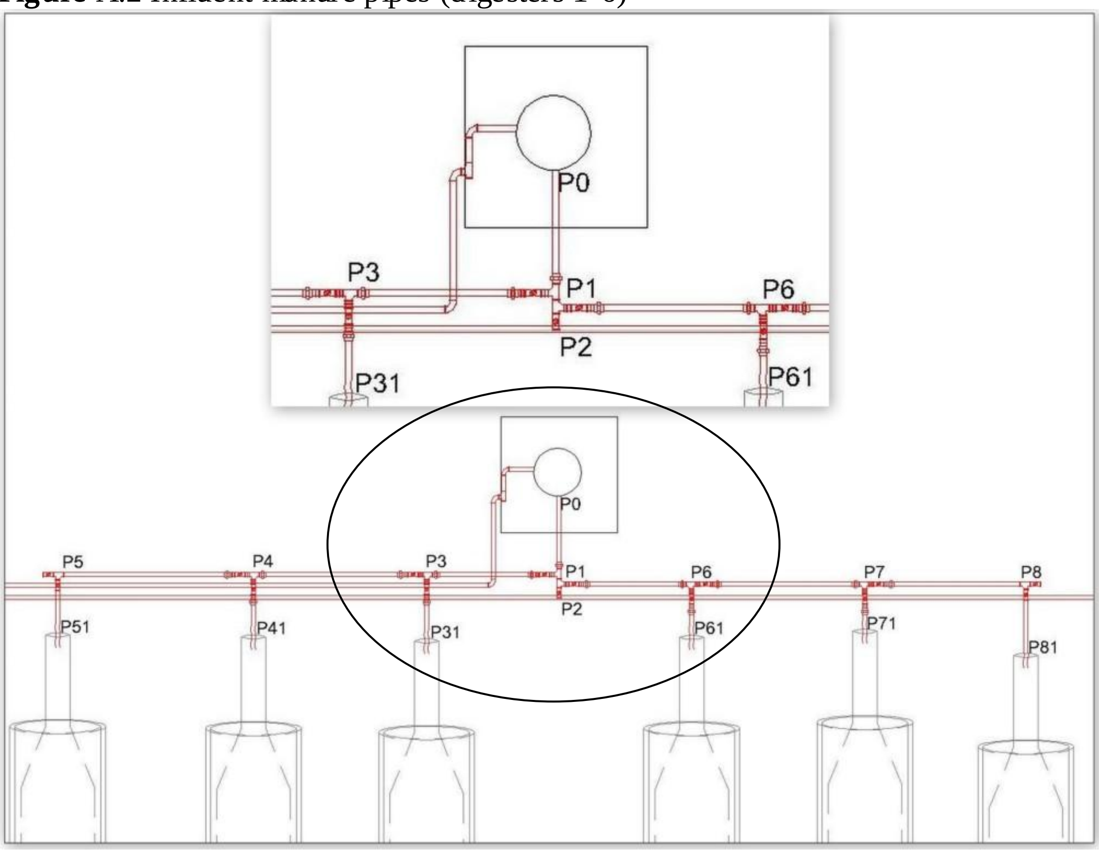


Table A.8 Influent manure pipes (digesters 1-6)

Start Node	End Node	Length (ft)	Start Elevation (ft)	End Elevation (ft)	Slope (ft/ft)	Degrees	Difference in Elevation (ft)
P0	P2	2.13	8.83	8.68	0.07	4.0	0.15
P0	P1	1.77	8.83	8.71	0.07	4.0	0.12
P1	P2	0.35	8.71	8.68	0.07	4.0	0.02
P1	P5	20.50	8.71	7.48	0.06	3.4	1.23
P1	P3	5.42	8.71	8.38	0.06	3.4	0.32
P3	P4	7.08	8.38	7.96	0.06	3.4	0.43
P4	P5	8.00	7.96	7.48	0.06	3.4	0.48
P3	P31	2.13	8.38	7.23	0.54	28.4	1.15
P4	P41	1.98	7.96	7.31	0.33	18.1	0.65
P5	P51	1.90	7.48	7.27	0.11	6.2	0.21
P2	P8	19.08	8.68	7.35	0.07	4.0	1.34
P2	P6	5.42	8.68	8.30	0.07	4.0	0.38
P6	P7	7.08	8.30	7.81	0.07	4.0	0.50
P7	P8	6.58	7.81	7.35	0.07	4.0	0.46
P6	P61	1.63	8.30	7.06	0.76	37.4	1.24
P7	P71	1.38	7.81	7.06	0.54	28.5	0.75
P8	P81	2.38	7.35	7.04	0.13	7.3	0.31

Figure A.3 Influent manure pipes (digesters 7-9)

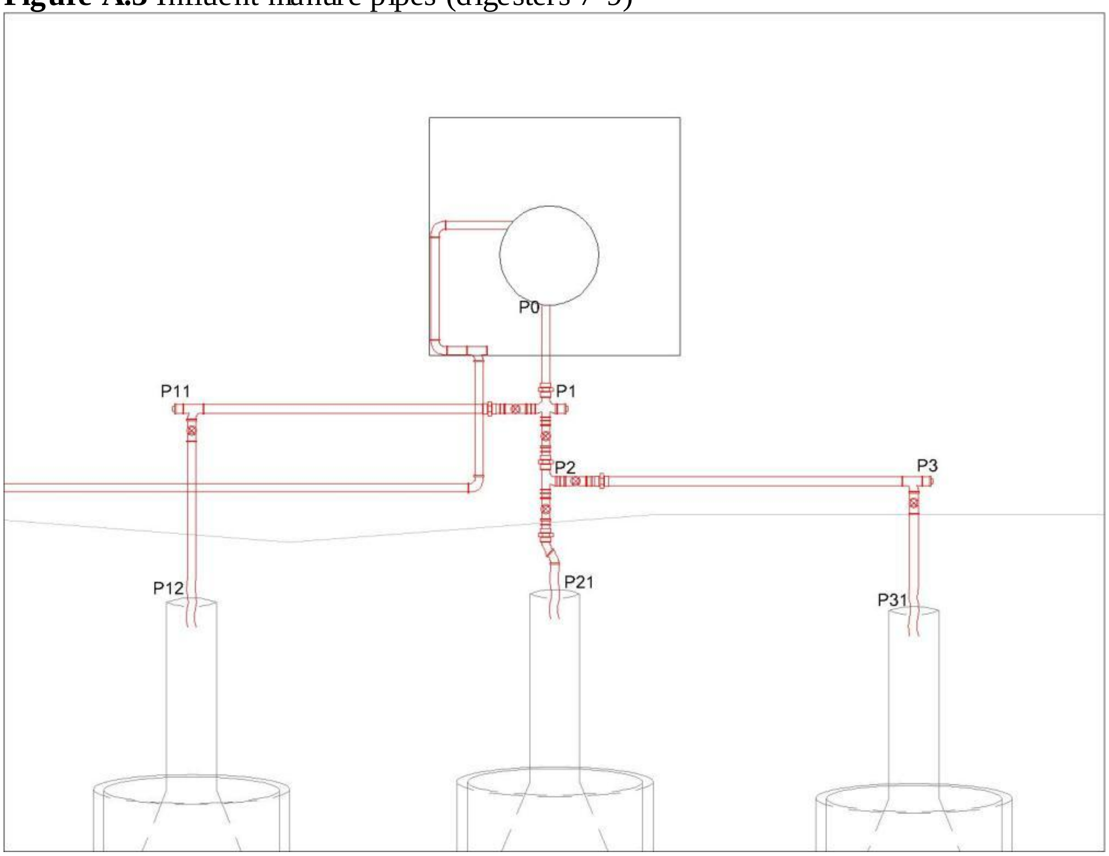


Table A.9 Influent manure pipes (digesters 7-9)

Start Node	End Node	Length (ft)	Start Elevation (ft)	End Elevation (ft)	Slope (ft/ft)	Degrees	Difference in Elevation (ft)
P0	P21	5.33	8.08	7.04	0.10/0.56	5.7/29.2	1.04
P0	P1	2.77	8.08	7.80	0.10	5.7	0.28
P1	P2	1.35	7.80	7.67	0.10	5.7	0.14
P2	P21	1.13	7.67	7.04	0.56	29.2	0.63
P1	P11	7.25	7.80	7.30	0.07	4.0	0.51
P11	P12	2.65	7.30	7.17	0.05	2.7	0.13
P2	P3	7.17	7.67	7.17	0.07	4.0	0.50
P3	P31	1.46	7.17	7.04	0.09	4.9	0.13

Figure A.4 Effluent manure pipes (digesters 1-9)

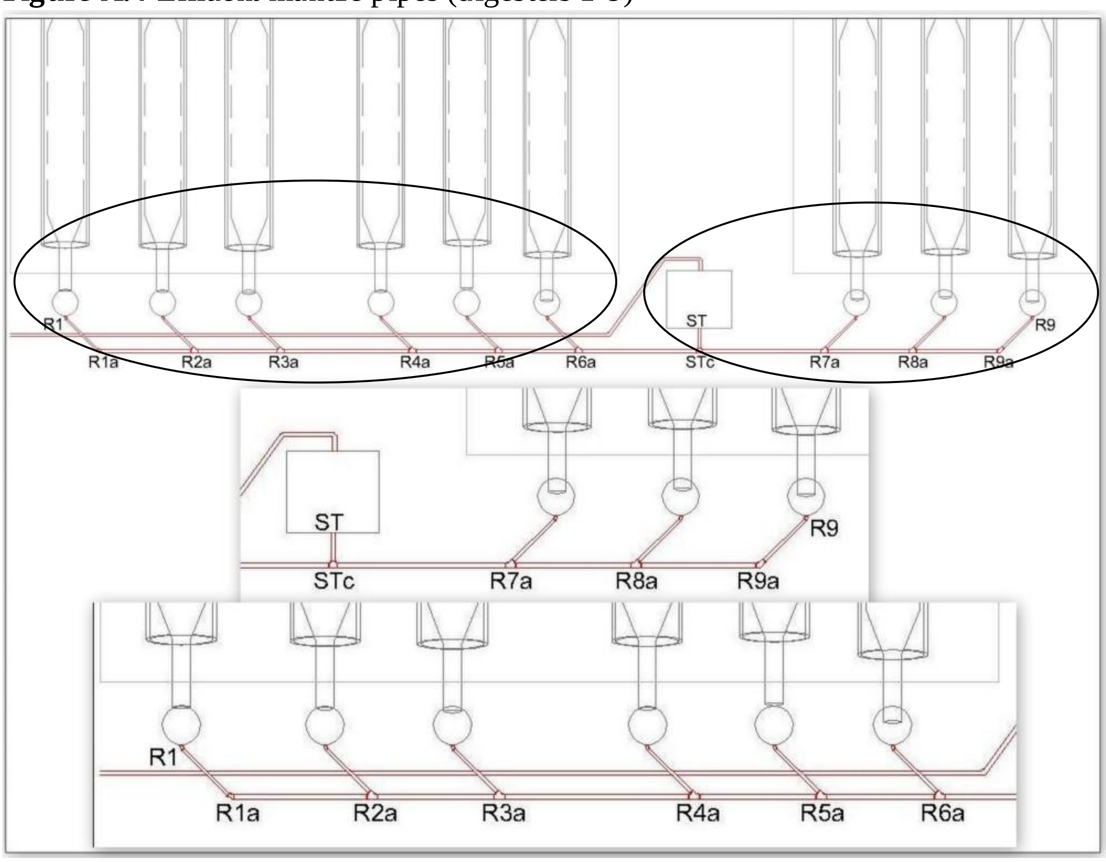


Table A.10 Effluent manure pipes (digesters 1-9)

Start Node	End Node	Length (ft)	Start Elevation (ft)	End Elevation (ft)	Slope (ft/ft)		Difference in Elevation (ft)
R1	R1a	4.24	9.00	8.83	0.04		0.17
R1a	R2a	6.50	8.83	8.57	0.04		0.26
R2a	R3a	6.50	8.57	8.31	0.04		0.26
R3a	R4a	13.50	8.31	7.77	0.04		0.54
R4a	R5a	6.50	7.77	7.51	0.04		0.26
R5a	R6a	6.50	7.51	7.25	0.04		0.26
R6a	STc	7.25	7.25	6.96	0.04		0.29
STc	ST	2.67	6.96	6.35	0.227		0.61
R9	R9a	4.24	8.24	8.07	0.04		0.17
R9a	R8a	7.25	8.07	7.72	0.048		0.35
R8a	R7a	7.25	7.72	7.37	0.048		0.35
R7a	STc	6.25	7.37	7.07	0.048		0.30
STc	ST	2.67	7.07	6.47	0.227		0.61
ST	ST_Inf	2.00	6.35	5.90	0.227		0.45

A.3 System and Pump Curves and Calculations

Table A.11 System curve calculations: manure pits to holding tanks

Static Height (feet)	Hs =	10			
Pipe Size Diameter (inches)	D =	3	K Value	K =	2.7
H-W Coefficient	C =	120	Length (feet)	L =	120

Q (gpm)	Static Hs	Velocity (V=Q/A)	Hv (Hv=V^2/(2g))	Hlm (Hlm=K*Hv)	Hl (Hl=L*(V/1.318 *C*R^0.63))^1.85)	Total Head (Hs+Hlm+Hl)
0	10	0.00	0.00	0.000	0.000	10.0
20	10	0.91	0.01	0.035	0.097	10.1
50	10	2.27	0.08	0.216	0.527	10.7
75	10	3.40	0.18	0.486	1.116	11.6
100	10	4.54	0.32	0.864	1.900	12.8
150	10	6.81	0.72	1.944	4.023	16.0
200	10	9.08	1.28	3.455	6.850	20.3

Figure A.5 System and pump curves: post-separated pit to holding tank

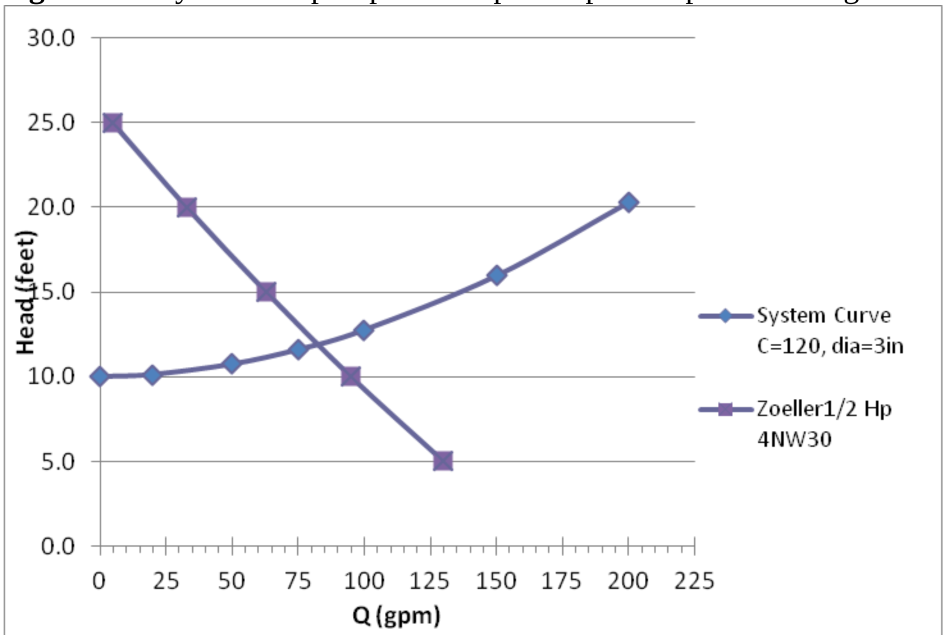


Figure A.6 System and pump curves: pre-separated pit to holding tank

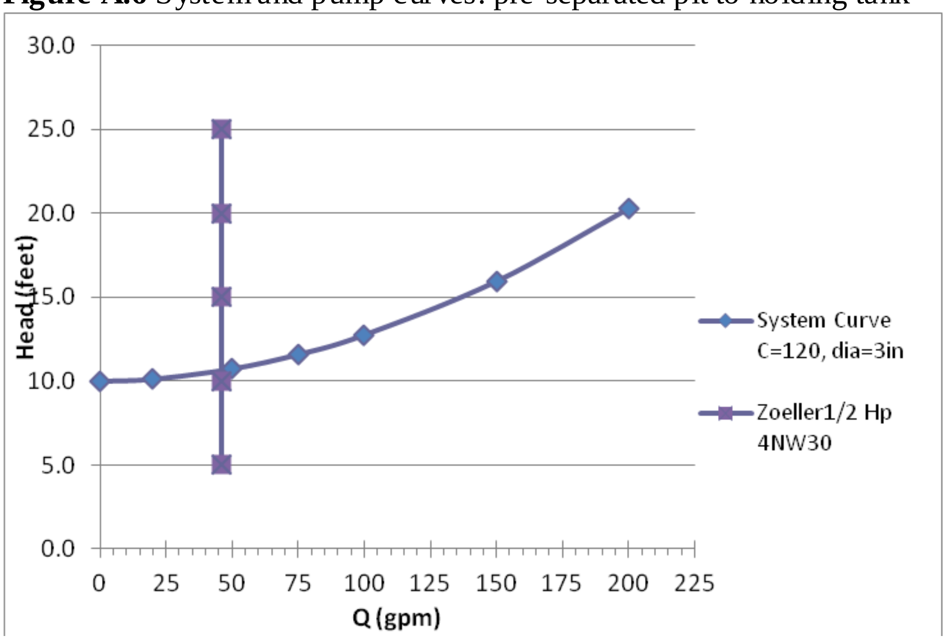


Table A.12 System curve calculations: holding tank to Pit I kettle

Static Height (feet)	Hs =	16			
Pipe Size Diameter (inches)	D =	2	K Value	K =	2.7
H-W Coefficient	C =	120	Length (feet)	L =	65

Q (gpm)	Static Hs	Velocity (V=Q/A)	Hv (Hv=V^2/(2g))	Hlm (Hlm=K*Hv)	Hl (Hl=L*(V/1.318 *C*R^0.63))^1.85)	Total Head (Hs+Hlm+Hl)
0	16	0.00	0.00	0.000	0.000	16.0
20	16	2.04	0.06	0.175	0.377	16.6
30	16	3.06	0.15	0.394	0.798	17.2
35	16	3.57	0.20	0.536	1.061	17.6
40	16	4.09	0.26	0.700	1.359	18.1
45	16	4.60	0.33	0.886	1.690	18.6
50	16	5.11	0.40	1.093	2.053	19.1

Figure A.7 System and pump curves: holding tank to Pit I kettle

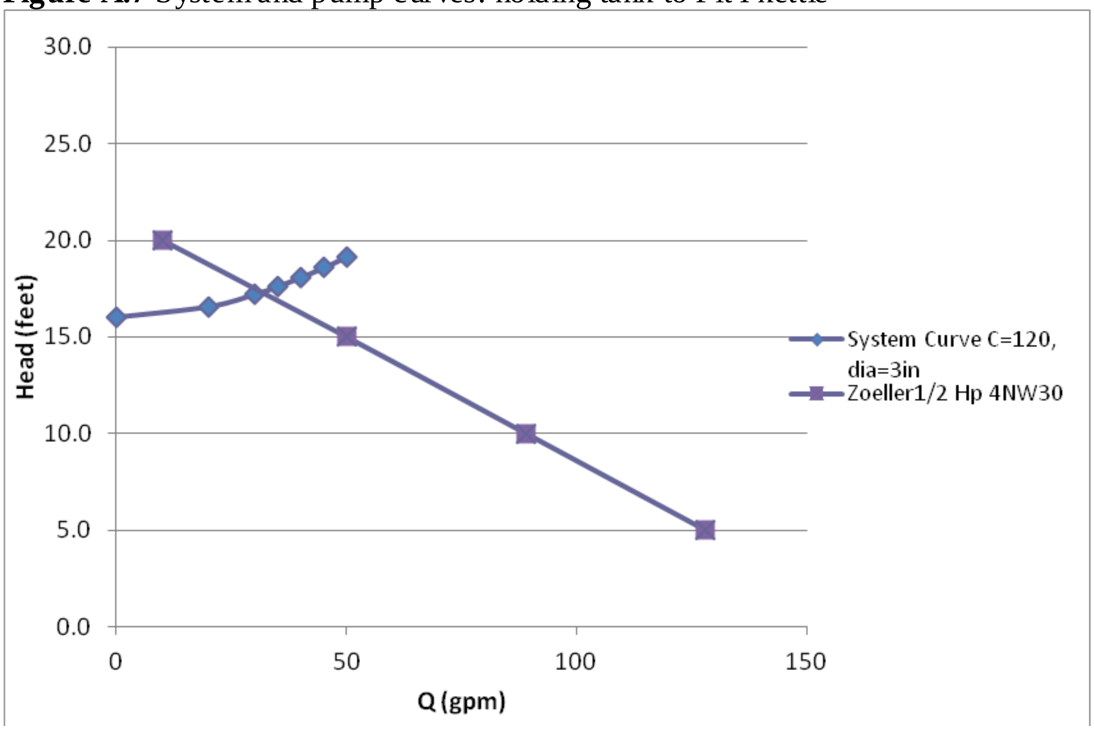


Table A.13 System curve calculations: holding tank to Pit II kettle

Static Height (feet)	Hs =	15.5			
Pipe Size Diameter (inches)	D =	2	K Value	K =	2.7
H-W Coefficient	C =	120	Length (feet)	L =	100

Q (gpm)	Static Hs	Velocity (V=Q/A)	Hv (Hv=V^2/(2g))	Hlm (Hlm=K*Hv)	Hl (Hl=L*(V/1.318 *C*R^0.63))^1.85)	Total Head (Hs+Hlm+Hl)
0	15.5	0.00	0.00	0.000	0.000	15.5
20	15.5	2.04	0.06	0.175	0.580	16.3
30	15.5	3.06	0.15	0.394	1.228	17.1
35	15.5	3.57	0.20	0.536	1.633	17.7
40	15.5	4.09	0.26	0.700	2.090	18.3
45	15.5	4.60	0.33	0.886	2.599	19.0
50	15.5	5.11	0.40	1.093	3.159	19.8

Figure A.8 System and pump curves: holding tank to Pit I kettle

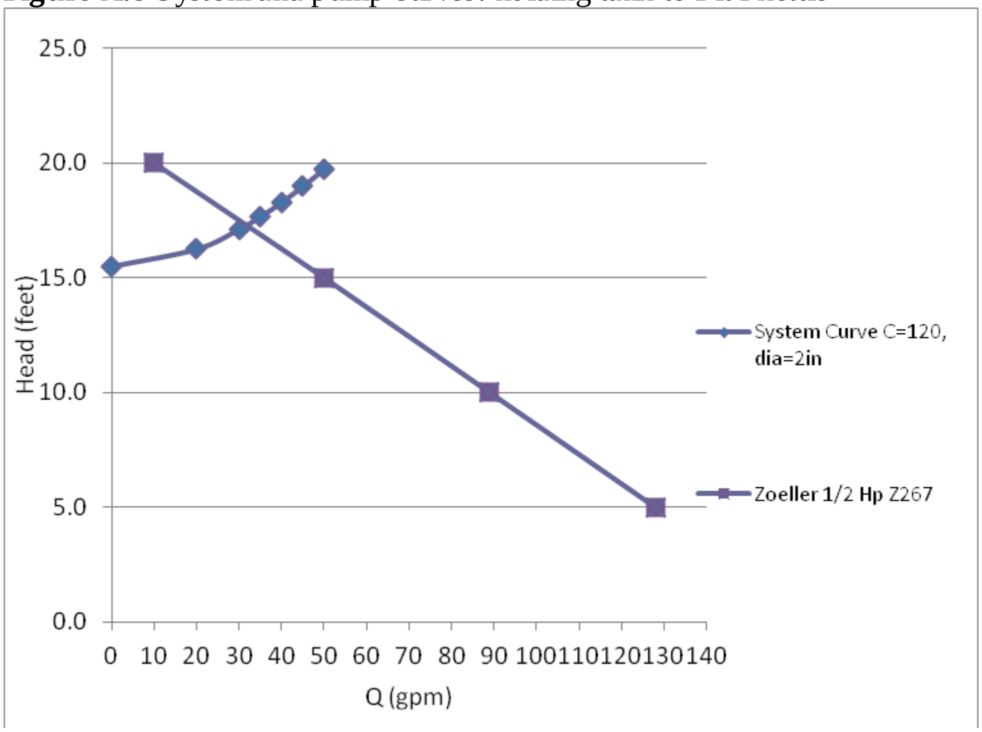


Table A.14 System curve calculations: recirculation barrels to kettle

Static Height (feet)	Hs =	12				
Pipe Size Diameter (inches)	D =	1		K Value	K =	6.62
H-W Coefficient	C =	120		Length (feet)	L =	40.63

Q (gpm)	Static Hs	Velocity (V=Q/A)	Hv (Hv=V^2/(2g))	Hlm (Hlm=K*Hv)	Hl (Hl=L*(V/1.318 *C*R^0.63))^1.85)	Total Head (Hs+Hlm+Hl)
0	12	0.00	0.00	0.000	0.000	12.0
5	12	2.04	0.06	0.429	0.528	13.0
10	12	4.09	0.26	1.716	1.905	15.6
15	12	6.13	0.58	3.860	4.033	19.9
20	12	8.17	1.04	6.862	6.868	25.7
25	12	10.21	1.62	10.722	10.378	33.1
30	12	12.26	2.33	15.440	14.541	42.0

Figure A.9 System and pump curves: recirculation to kettle

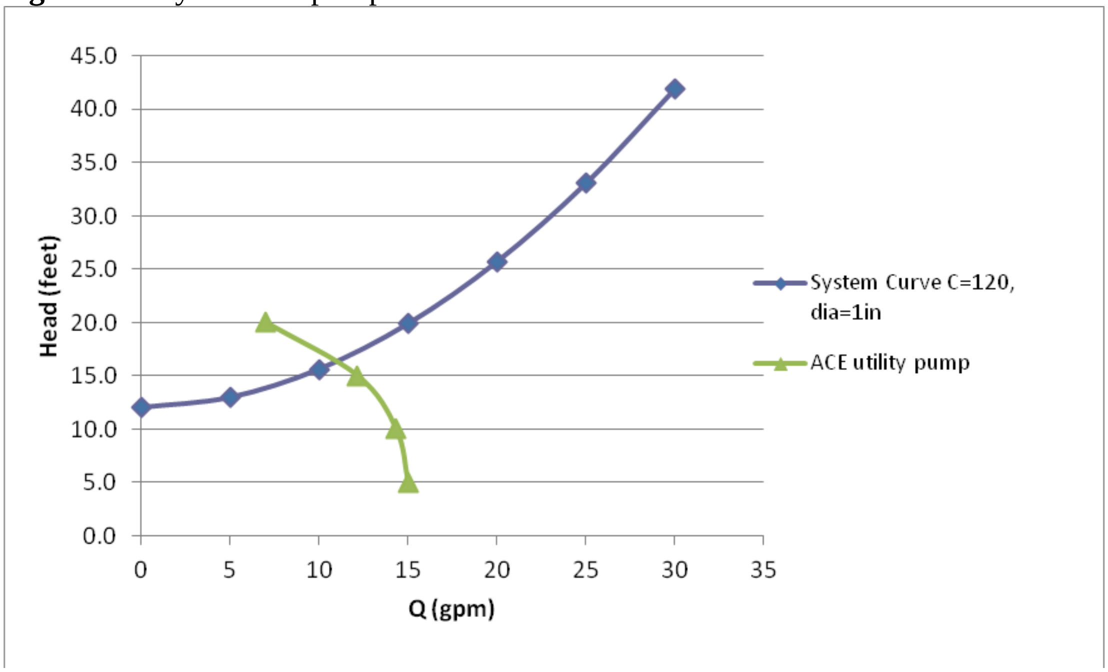


Table A.15 System curve calculations: septic tank to storage lagoon

Static Height (feet)	Hs =	19.64			
Pipe Size Diameter (inches)	D =	3	K Value	K =	2.4
H-W Coefficient	C =	120	Length (feet)	L =	240

Q (gpm)	Static Hs	Velocity (V=Q/A)	Hv (Hv=V^2/(2g))	Hlm (Hlm=K*Hv)	Hl (Hl=L*(V/1.318 *C*R^0.63))^1.85)	Total Head (Hs+Hlm+Hl)
0	19.64	0.00	0.00	0.000	0.000	19.6
20	19.64	0.91	0.01	0.031	0.194	19.9
30	19.64	1.36	0.03	0.069	0.410	20.1
35	19.64	1.59	0.04	0.094	0.545	20.3
40	19.64	1.82	0.05	0.123	0.698	20.5
45	19.64	2.04	0.06	0.155	0.868	20.7
50	19.64	2.27	0.08	0.192	1.054	20.9

Figure A.10 System and pump curves: septic tank to storage lagoon

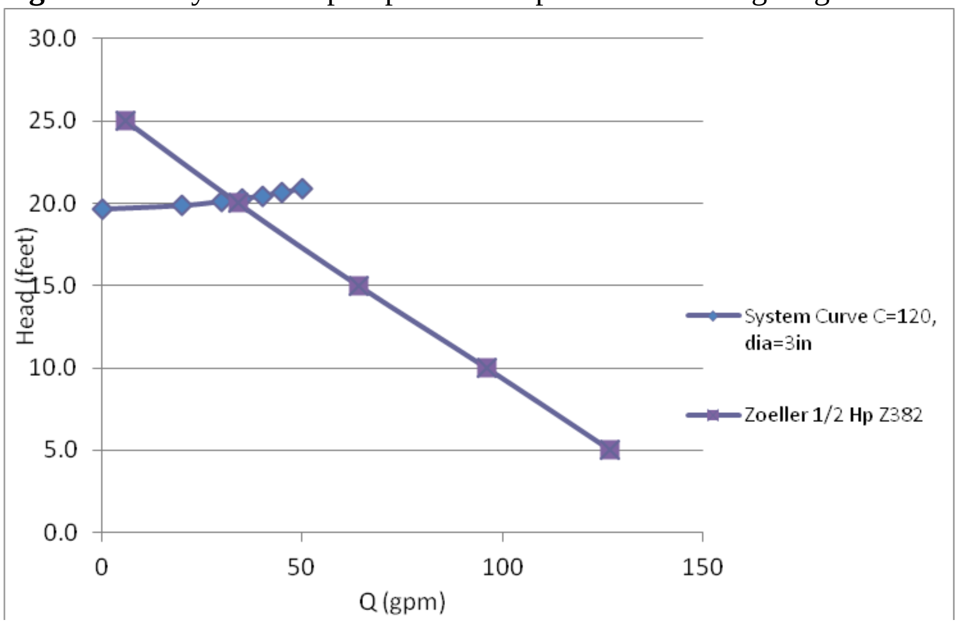
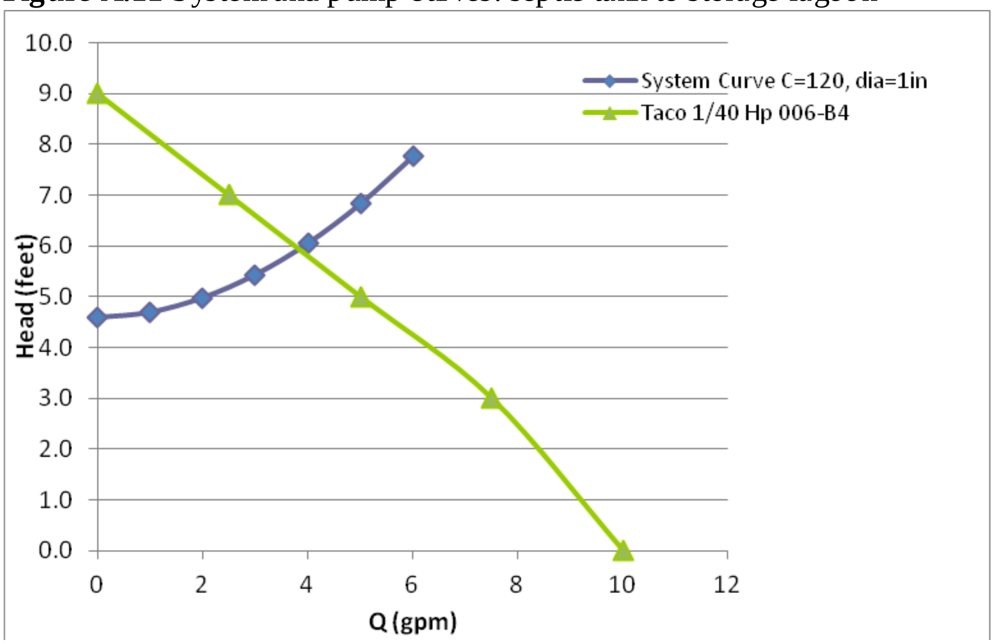


Table A.16 System curve calculations: water/ethylene glycol kettle to kettle

Static Height (feet)	Hs =	4.63			
Pipe Size Diameter (inches)	D =	1	K Value	K =	14.15
H-W Coefficient	C =	120	Length (feet)	L =	102.36

Q (gpm)	Static Hs	Velocity (V=Q/A)	Hv (Hv=V^2/(2g))	Hlm (Hlm=K*Hv)	Hl (Hl=L*(V/1.318 *C*R^0.63))^1.85)	Total Head (Hs+Hlm+Hl)
0	4.58	0.00	0.00	0.000	0.000	4.6
1	4.58	0.41	0.00	0.037	0.068	4.7
2	4.58	0.82	0.01	0.147	0.244	5.0
3	4.58	1.23	0.02	0.330	0.517	5.4
4	4.58	1.63	0.04	0.587	0.881	6.0
5	4.58	2.04	0.06	0.917	1.331	6.8
6	4.58	2.45	0.09	1.320	1.865	7.8

Figure A.11 System and pump curves: septic tank to storage lagoon

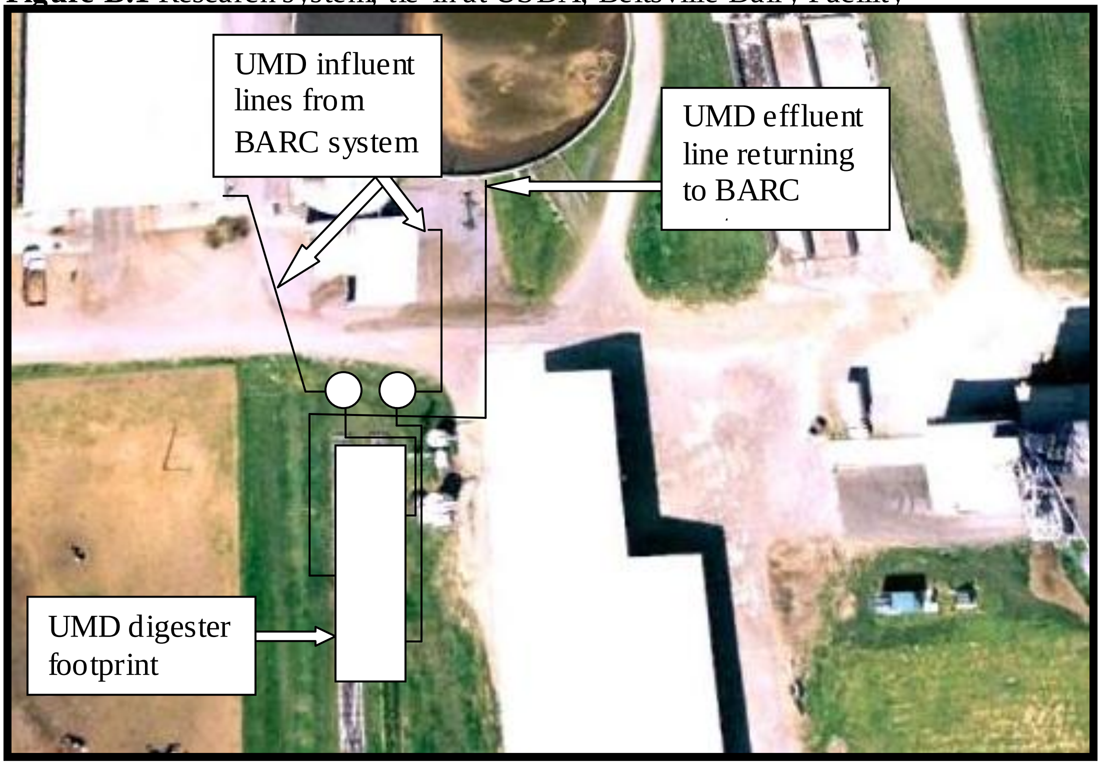


Appendix B: Construction Drawings and Descriptions

B.1 System Location and Connections

The research digester system was designed for minimal interference with the existing manure treatment system. The research system connects into the BARC system at three locations: an influent line from the un-separated manure holding pit, an influent line from the post-separated liquid manure holding pit, and a return line from the research digesters effluents to the lagoon, as shown in Figure B.1. Each influent line leads to a 500 gallon holding tank before being pumped to a heating kettle. Within the research system, the pre-separated and post-separated influent lines each have their own holding tank, heating kettle, and research digesters. The effluent from both the pre- and post-separated digesters is combined into one septic tank before being reintroduced into the BARC system via the storage lagoon.

Figure B.1 Research system, tie-in at USDA, Beltsville Dairy Facility



B.2 Hydraulic Design

As the conveyance of manure is one of the greatest challenges facing manure management systems, great detail was given to the design of the hydraulic system. Clogging, especially with un-separated manure, was a potential operating concern, and clean-out locations were included in the research system at distances not greater than 100 feet for a total of 15 clean-out locations (9 system clean-outs and 6 digester clean-outs). A schematic of the system hydraulics is shown in Figure B.2, while a schematic of the digesters hydraulics is shown in Figure B.3.

Figure B.2 Hydraulic schematic of system including clean-outs

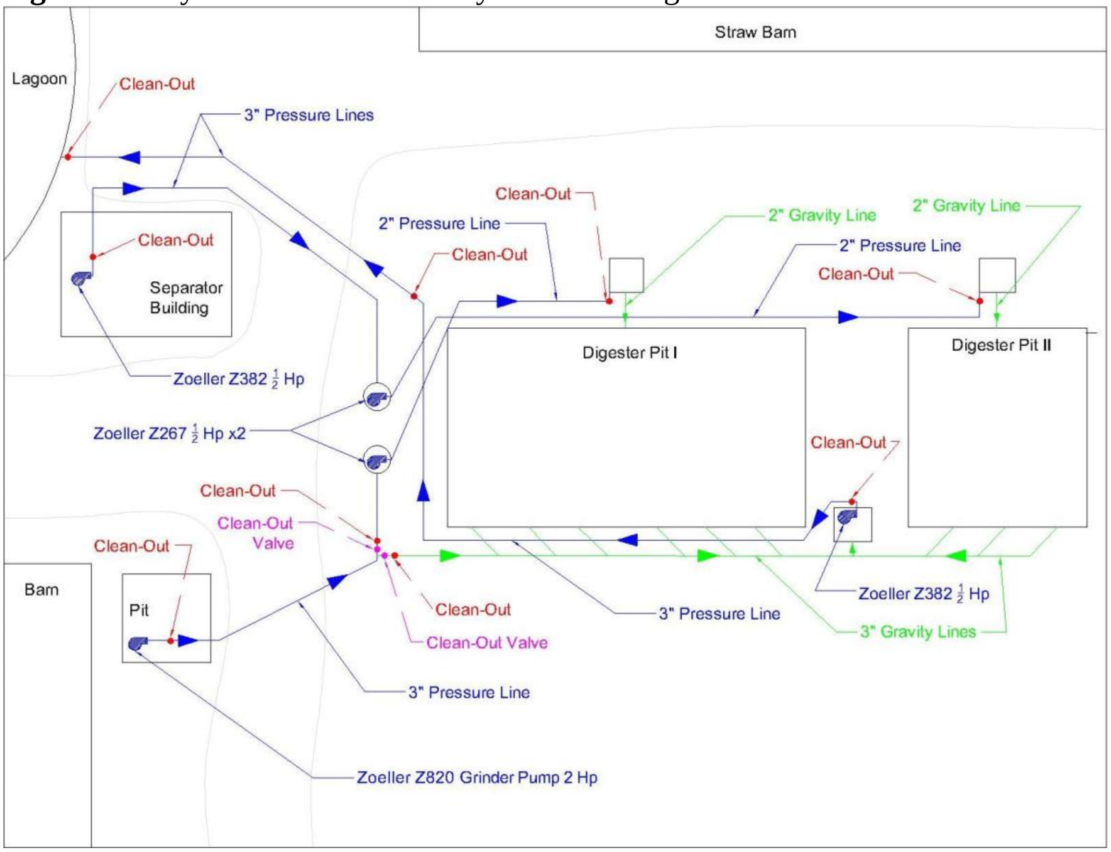
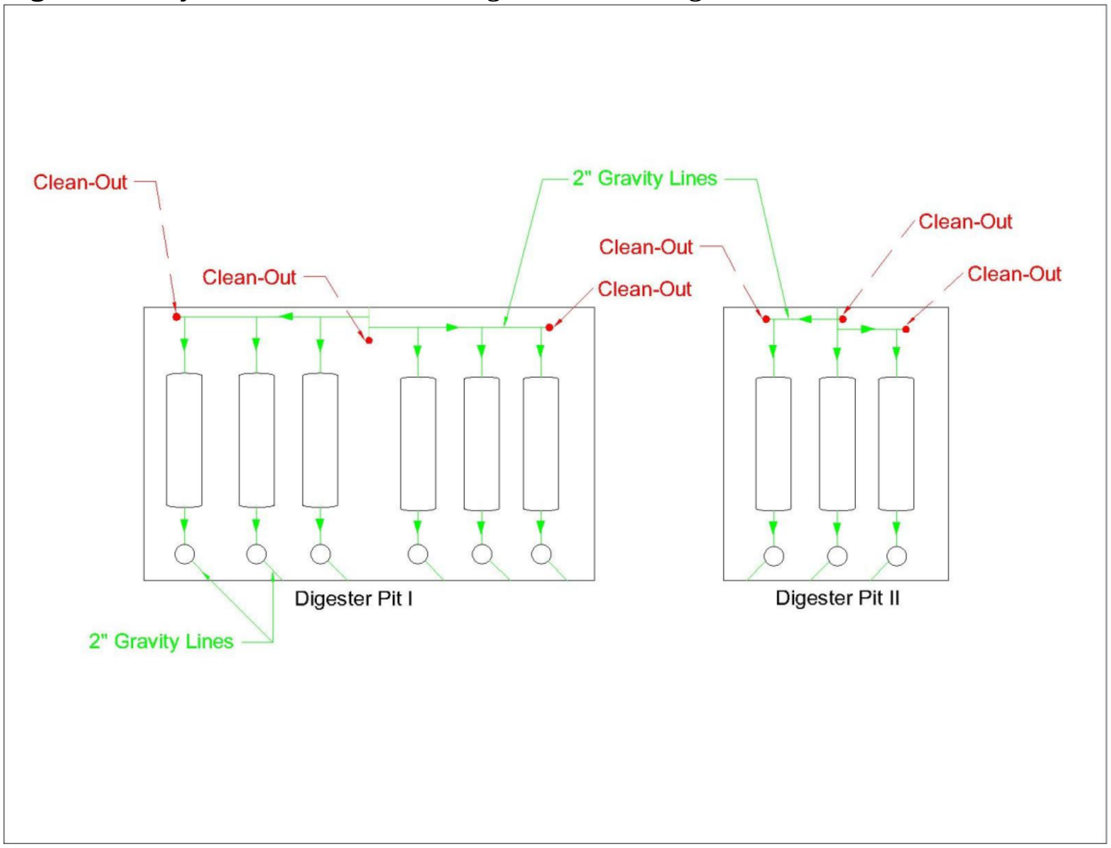


Figure B.3 Hydraulic schematic of digesters including clean-outs



Due to the flat terrain, pumps were required to convey the manure between the BARC system and the research system. The greatest conveyance design challenge involved designing for the minimum pipe diameter needed to prevent clogging and allow the passage of debris while maintaining a minimum velocity (3.50 ft/sec) of the relatively small volumes (25 – 225 gpd) needing to be conveyed. For passage below the road, the BARC operators insisted a minimum pipe diameter of 3” be used based on their operational experiences. To pump only 25 gallons from the BARC system through a 3” pipe to the kettle would have decreased the velocity in the post-separator line from the current 3.60 ft/sec to 1.50 ft/sec, below the target minimum velocity of 3.50 ft/sec. The pre-separator pump is over-sized for the system being the smallest grinder pump commercially available and changing the volume moved from 25 gallons to 150 gallons did little to change the pump time or velocity.

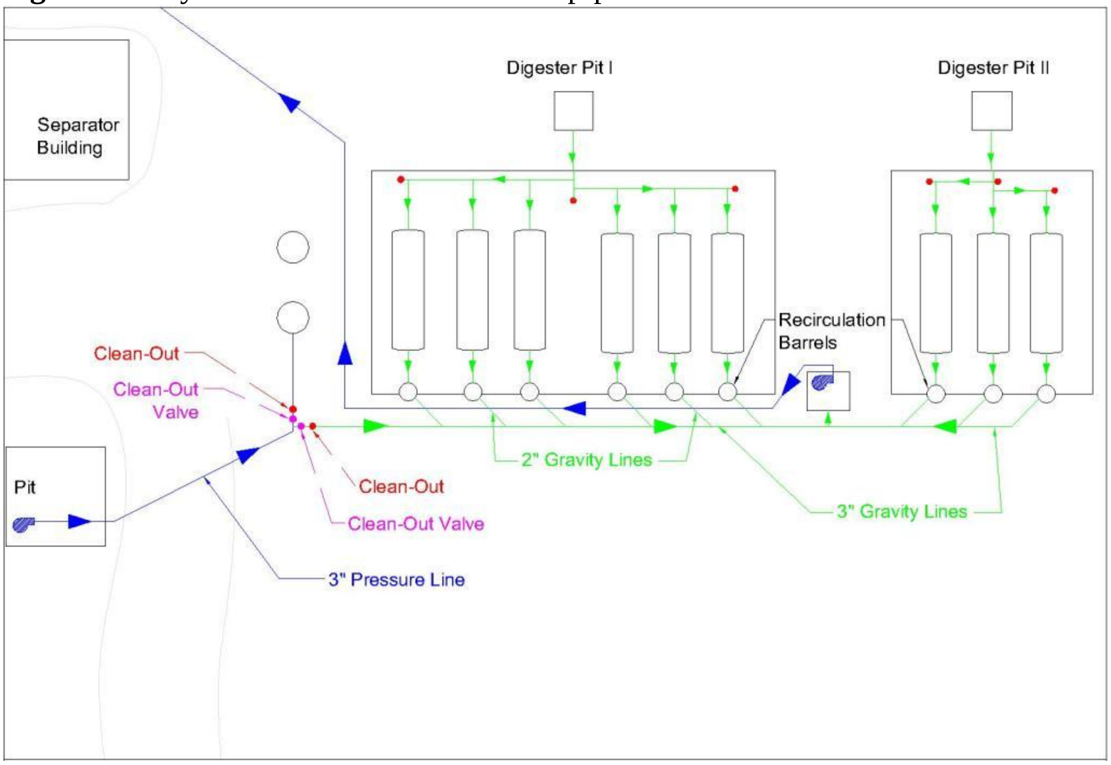
To keep the velocity in the system closer to the target minimum rate and to allow a location of additional substrate to be added to the system, both pre-separated and post-separated manure is pumped to 500 gallon holding tanks. From the holding tanks the manure is pumped in 25 gallons intervals to the heating kettle before being released into a digester. From both holding tanks, 2" diameter piping is used with an expected velocity of 3.00 ft/sec.

All digester effluent is conveyed by gravity and collected in a 500 gallon septic tank. The septic tank is emptied every 2-3 days through a 3" pipe to the BARC lagoon with an expected velocity of 1.50 ft/sec. Pump and system curves for all pumps are located in the Appendix A.

Gravity flow was utilized for the digester influent and effluent piping to simplify the design and decrease operational and maintenance costs. For the design, both full pipe and non-full pipe calculations were done. The majority of the influent flow was considered full pipe and the Hazen-Williams equation was used to determine the total losses in the system and thus the minimum height difference needed for flow to occur. Minimum velocity in the 2" influent pipes assuming 25 gpm was 2.55 ft/sec. This calculation was field-verified using a 5-gallon bucket of pre-separated manure and a stopwatch. To assure the majority of the manure leaving the heating kettle would reach the intended digester, partially-full pipe calculations were also performed using the Manning's Equation to determine a minimum slope required in this circumstance. Assuming a minimum velocity of 2.55 ft/sec and a flowrate of 25 gpd, the minimum slope required in the 2" pipe was 0.03 ft/ft. A safety factor of 2 was applied to all influent slopes. A detailed table of all calculation is shown in the Appendix A as well as final slopes and distances for construction.

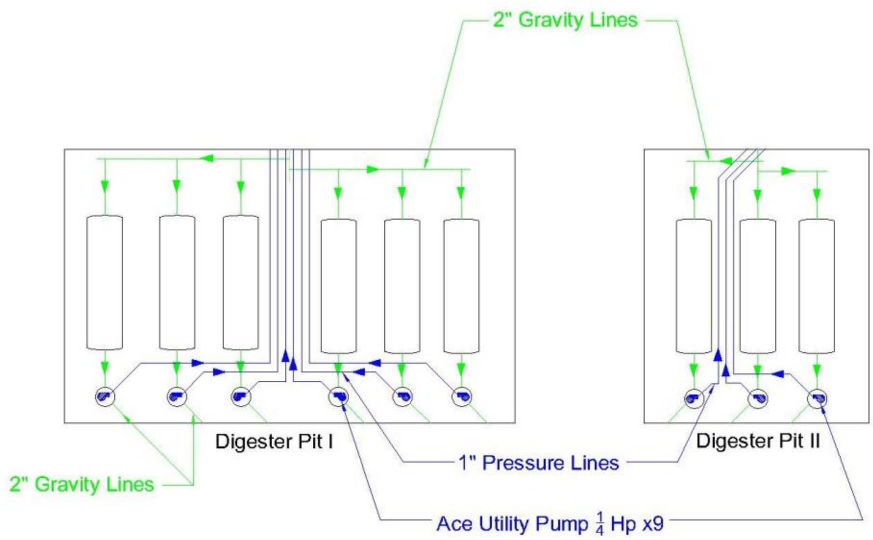
The effluent from each digester was collected in 50 gallon barrels. An overflow drain was placed at the 25 gallon mark so that 25 gallons of effluent is always stored for recirculation purposes. The overflow drain consists of a 2" pipe that connects into a main 3" drain for all the digesters. All overflow effluent drains to the 500 gallon septic tank where it is collected and eventually pumped to the BARC lagoon. A minimum slope of 0.04 ft/ft was used for the 3" drain pipe. This drain pipe can also be used as a clean-out pipe for the pressure line running between the pre-separated pit and the holding tank. This connection was installed with valves so in the event that the pre-separated pressure line needs to be cleaned-out, the wastewater can be washed directly to the septic tank and bypass the research system as shown in Figure B.4.

Figure B.4 Hydraulic schematic of effluent pipes and connections



Recirculation capabilities were installed for each digester. A ¼ Hp Ace sump pump was installed in each recirculation barrel. With a pipe diameter of 1", the flowrate is approximately 11 gpm from each recirculation barrel to its heating kettle. A system and pump curve for the recirculation system is given in the Appendix A.

Figure B.5 Hydraulic schematic of digesters including recirculation



B.3 Electrical, Automation, and Monitoring Systems

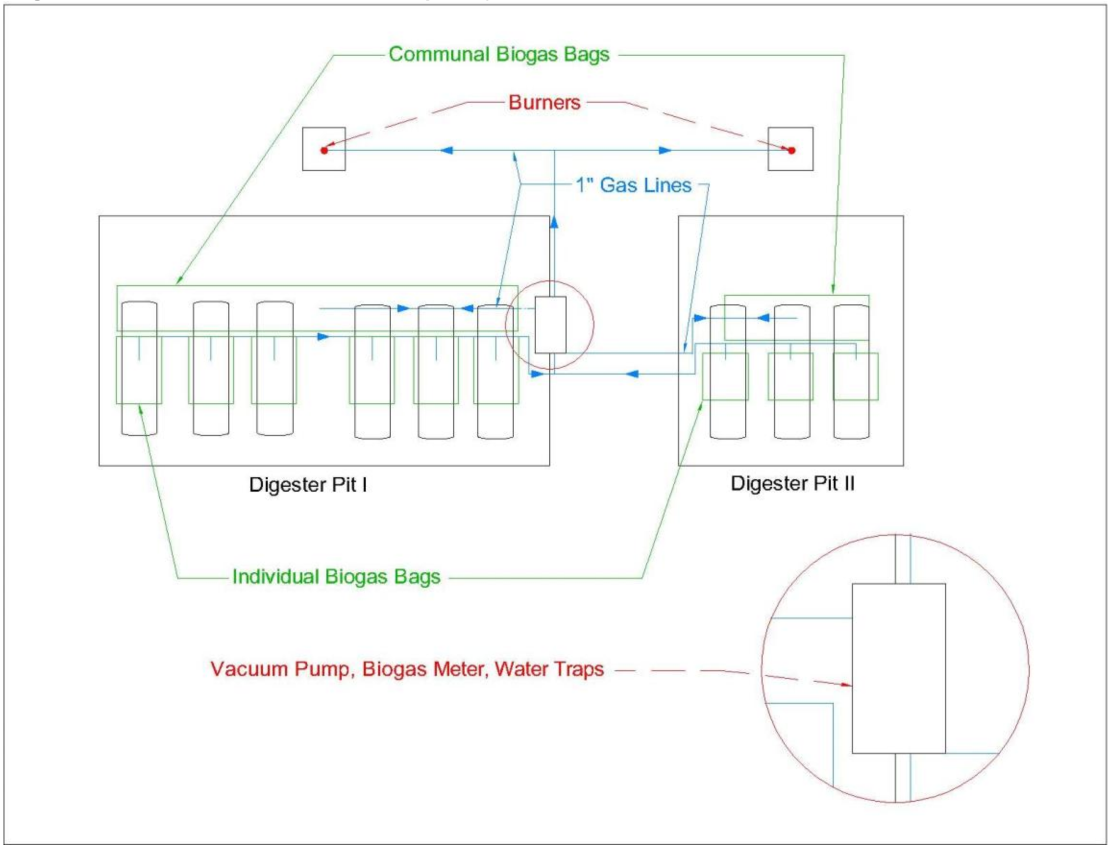
To decrease operating time requirements as well as monitor the system temperatures, an extensive automation and monitoring system, with accompanying electrical system, was designed by Andrew Moss. All valves, excluding clean-out valves and biogas valves, are Valbia electronic valves and actuators. All pumps, valves, heat ignition, and mixers are controlled electronically though the Labview software program. By installing such a system, an operator is not needed for daily operation.

In order to automate and monitor the system, both 110-120 volt wires to deliver power to the components and low voltage wire for the control system were installed. Temperature is continuously monitored within each digester, at the heating kettle, at the effluent, and in the soil around the digesters. By monitoring the temperature both within and around the digesters the effectiveness of the insulation can be calculated. Monitoring the internal temperature also aids in determining the frequency and effectiveness of recirculation/heating.

B.4 Biogas System

The biogas collection system, designed by Freddy Witarsa, was designed so that the gas production from each digester could be measured and sampled individually, before being collected and stored in a communal storage bag until needed for heating purposes. The biogas system required an operator every 2-3 days, depending on biogas production, to manually operate a vacuum pump to measure and convey the biogas from each individual storage unit to the communal storage unit. The biogas passes through a hydrogen sulfide scrubber and biogas meter before entering into the communal storage bags. Each kettle has its own communal storage bag. A plan view of the biogas system is shown in Figure B.6.

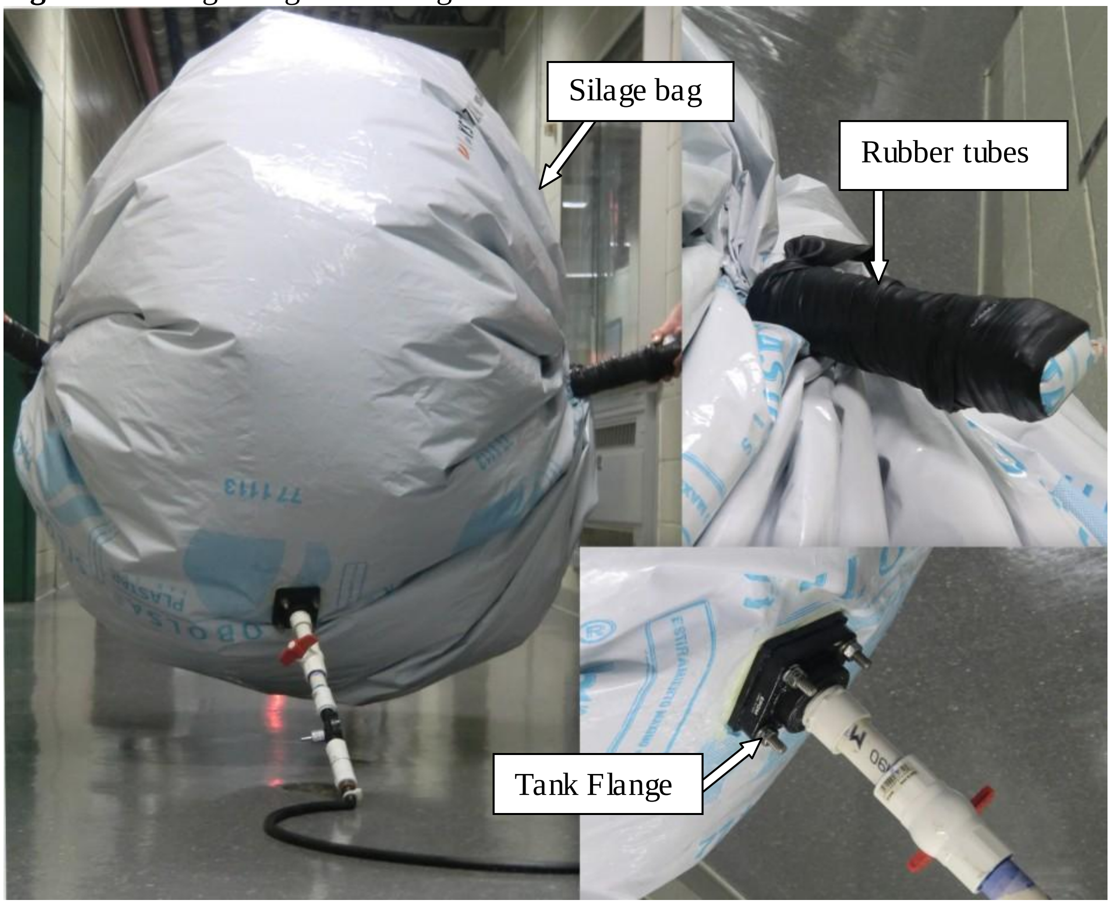
Figure B.6 Schematic of the biogas system



Designed by Freddy Witarsa

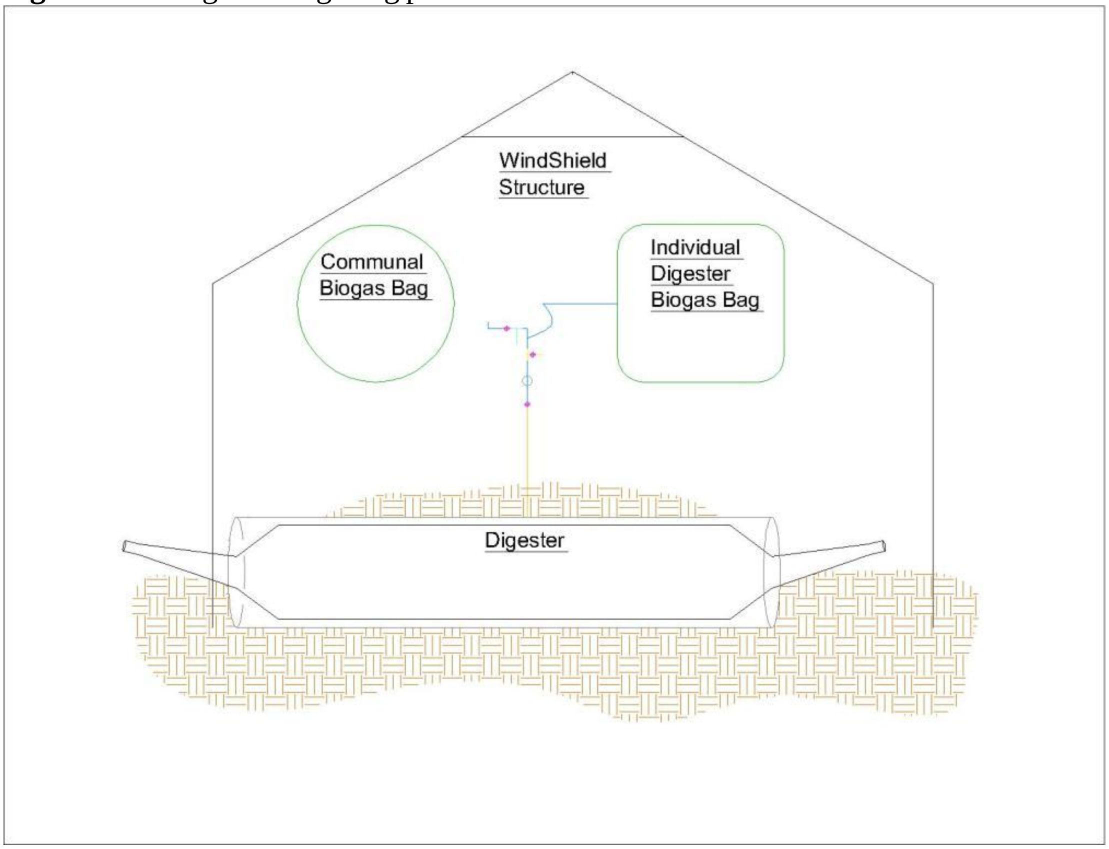
The biogas bags were made by double bagging silage bags, tying off each end with rubber tubes, and installing a 1" tank flange for connection of the gas piping as shown in Figure B.7.

Figure B.7 Biogas bags and fittings



The biogas bags were hung from the rafters of the windshield structure, as is shown in Figure B.8.

Figure B.8 Biogas storage bag profile



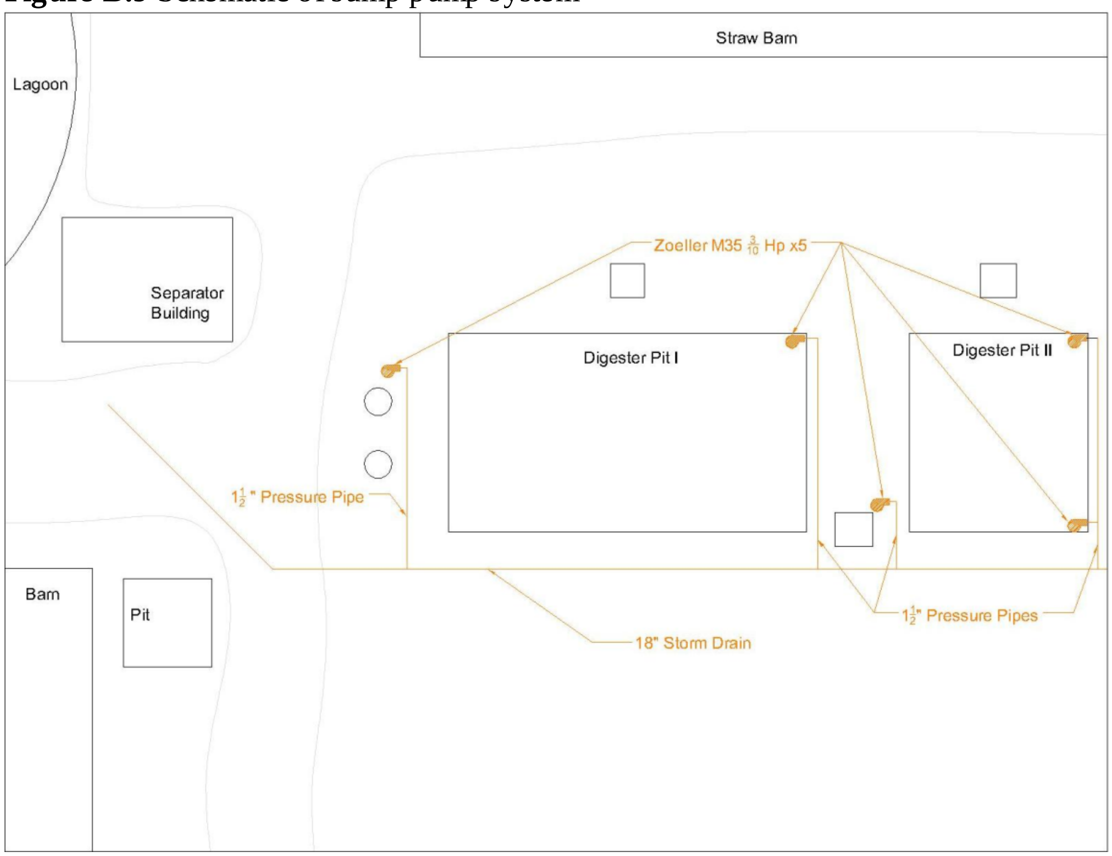
Once in the communal storage bags, the biogas is utilized automatically with the aid of the Labview system to open the valves allowing gas to flow from the communal biogas bags to the kettle burners and starting the ignition switch to heat incoming manure. All the components and cost of the biogas system is listed in Appendix C. The biogas collection system was designed with water traps to remove any condensation that forms in the gas pipes, and all biogas pipes are ½" PVC.

The heating system was designed for easy exchange of burner type from biogas to propane. Propane will be used as the fuel source during start-up and in the event the digesters are not producing sufficient biogas and supplemental fuel is required.

B.5 Flood Prevention

Both digester pits were excavated with 3' wide drainage channels along each side leading to a well and sump pump. The digesters were placed on top of 6" of crushed stone. The holding tanks were also placed on top of crushed stone with a well and sump pump. There are a total of 5 wells and sump pumps installed throughout the site as shown in Figure B.9. The sump pumps are all 3/10 Hp Zoeller M53, with automatic float switches and 1.5" diameter pipe, which tie into an existing 18" storm drain.

Figure B.9 Schematic of sump pump system



Appendix C: Material Costs Tables

The following tables list the materials and approximate costs (2010 US$, rounded to the 10$) for each of the research digester systems.

Table C.1 Digesters cost data

Item	**Description**	**Material Cost (2010 US$)**
Digesters		
Culverts	42" ADS dual wall HDPE	7,350
Foam bedding	Expanded polystyrene nests	2,650
Silicon glue	box of 12	50
Radiant barrier	polyethylene-core insulation	440
Metal glue	1/2 tube per digester	60
Metallic tape	1 roll	10
Digester bags	PVC-membrane tubular bag	4,140
Radiant tubing		
Pex tubing	55' per digester	640
Pex elbows	6 per digester	180
Pex unions	2 per digester	140
Pex adaptors	4 per digester	90
Pex rings	16 per digester	60
Rubber	-	440
Endcaps		
Mold	constructed in-house	-
Foam	Expanded polyurethane	1,360
PVC sheets	-	1,070
U-bolts	-	220
Ties	-	30
Total Cost		**18,930**

Table C.2 Heating system cost data

Item	Description	Material Cost (2010 US$)
Kettle	fabricated in house (~ $8,000 each)	-
Stirrer	1 per kettle	820
Kettle housing	1 per pit	2,520
Sub-Total:		**3,340**
Pex Outside Digesters[a]		
Pex tubing and fittings		1,570
Pex pumps	1 per kettle	200
Pex unions	26 total	230
Sub-Total:		**2,000**
Total:		**5,340**

[a]Pex inside the digesters included in the digesters cost estimate.

Table C.3 Conveyance system cost data

Item	Description	Material Cost (2010 US$)
Influent Piping	**Pits to Holding Tanks**	
pump (pre-separated)	1 x Zoeller 820	1,370
pump (post-separated)	1 x Zoeller 382	620
pump shipping costs		180
3" PVC pipe	240'	280
3" Fittings	couples, elbows, unions	460
PVC primer and cement	2 cans	20
Supports for pumps		50
Cage for pump		20
Stainless steel wire		10
Additional accessories		420
Influent Piping	**Holding Tanks to Kettles**	
Holding tanks	2 tanks and 2 risers	1,530
Holding tank plumbing	fittings	30
Anchors	anchors and washers	20
Pumps	2 Zoeller 267	650
2" PVC piping	150'	80
2" Fittings	unions and elbows	190
PVC glue and primer	2 cans	20
Connection pipe	metal flex tube	20
Additional accessories		420

Influent Piping	**Kettles to Digesters**	
2" PVC Pipe	60'	30
2" Fittings	elbows and tees	60
2" Ball valves	6	80
PVC glue and primer	3 cans	20
Additional accessories		420
Stands		60
Effluent Piping	**Digesters to Septic Tank**	
3" PVC piping	100'	100
3" PVC fittings	tees and elbows x14	50
2" PVC piping	18', 2 sticks	10
2" PVC fittings	elbows, wyes, and reducers	140
PVC glue and primer	2 cans	10
Additional accessories		420
Effluent Piping	**Septic Tank to Lagoon**	
Septic tank	500 gallon, concrete	990
Septic tank fittings	3" PVC	90
Pump	1 Zoeller 382	620
3" PVC piping	200'	210
3" PVC fittings	elbows, couplings, unions	220
Additional accessories		420
Recirculation		
Barrels	55 gallon drums (9 total)	90
Concrete slabs	1 per barrel	80
Pumps	1 per barrel	820
Effluent drain fittings	9 digesters	160
1" PVC piping	45'	180
1" fittings	pressure fittings	220
Manifold	pressure fittings and valves	370
Uniseals	1 1/2" uniseals (9 total)	20
Additional accessories		420
Total:		**12,650**

Table C.4 Electric, automation, and monitoring systems cost data

Item	Description	Material Cost (2010 US$)
Relays and Relay Boxes		
Relays		570
Fan and accessories		90
110V Lines		
Wire		2,780
Conduit, fittings, junction boxes		1,070
Low Voltage Lines		
Wire		520
Conduit and fittings		70
Other		
locknuts, plugs, paste, etc.		740
Cable		390
Outdoor Electrical Panel		4,560
Sub-Total		10,790
Automation		
Labview		4,780
Electronic Valves Influent		4,540
Electronic Valves Pex		2,570
Electronic Timer		190
Sub-Total		12,070
Monitoring		
Thermocouples		140
Data loggers		2,460
Sub-Total		**2,600**
Total		**25,460**

Table C.5: Biogas system cost data

Item	Description	Material Cost (2010 US$)
Biogas Ports in Digesters		
1.5" fittings	male and female adaptors	20
1.5" PVC piping	1 stick	-
1.5" Ball Valves	1 per digester	100
1.5" x 1/2" PVC Reducers	2 per digester	-
1/2" PVC Piping	3 sticks	10
1/2" PVC Tees	2 per digester	10
1/2" PVC Socket to Female	3 per digester	-
1/2" PVC Male to Barb	3 per digester	-
1/2" PVC Ball Valves	3 per digester	70
1/2" PVC Unions	1 per digester	20
1/2" Clear PVC tube	50 feet	30
PVC primer and cement	1	-
Biogas Collect Bags		
5 ft dia. silage bags	300 ft	270
Rubber tires	2 per bag (22 total)	-
1" x 1 1/2" tank gaskets	11 total	230
1 1/2" ball valves	11 total	120
Biogas Conveyance System		
1/2" PVC piping	280'	50
1/2" PVC ball valves	31 total	80
1/2" Unions	30 total	70
1/2" PVC Tees	26 total	10
1/2" PVC Elbows	19 total	10
1/2" PVC Couplings	9 total	-
1/2" PVC Cross	1 total	-
1/2" PVC Star	1 total	-
1.5" x 1/2" PVC Reducers	4 total	-
1.5" PVC clear pipe	5 feet	10
1/2" PVC Flexible tubing	10 feet	10
Biogas meter	-	1,620
Rubber Septums	bag of 100	100
Scrubber	brilopad for 12 months	40
Vacuum pump	1 total (borrowed, not purchased)	-
Biogas Utilization System		
Burner	2 per kettle	390
Electronic Igniter	includes electronic valves	510
Total		**3,770**

Table C.6: Additional system components cost data

Item	Description	Material Cost (2010 US$)
Additional Costs		
Windshield structure	Pit I	3,750
Windshield structure	Pit II	2,880
Anchors		800
Gravel		8,720
Sumps and Drainage		1,660
Total		**17,820**

Appendix D: Economic Calculations

D.1 Economic Calculations for Digester Systems

Table D.1 Digester general information

1.a Digester General Information	UMD 1	UMD 2	Theoretical 1	Theoretical 2	Comments
Type	Low Cost Plug Flow Digester	Low Cost Plug Flow Digester	Covered Pond Digester	Conventional Plug Flow Digester	
Description	UMD Beltsville, MD	UMD Beltsville, MD	-	-	
Items	digester, collection, excavation, gen-set	digester, collection, excavation	digester, collection, boiler	digester, collection, boiler	
# cows	100	100	100	100	
Year installed (year of estimate)	2010	2010	2005	2005	
ENR CCI Value	8801	8801	7446	7446	
Capital costs	$284,150	$184,150	$184,000	$163,000	
Source	-	-	(Goodrich, 2005)	(Goodrich, 2005)	
Cost (2010$) (ENR CCI 8800.66)	$284,150	$184,150	$217,480	$192,650	Cost (2010$) = 8800.66*(Capital Costs)/(ENR Value)
Capital cost per cow (2010$)	$2,840	$1,840	$2,170	$1,930	Cost/cow (2010$) = (Cost 2010$)/(#cows)

1.b Digester General Information	Theoretical 3	Theoretical 4	Theoretical 5	Theoretical 6	Comments
Type	Upright Digester	Upright Mixed Digester	Low Cost Plug Flow Digester	Complete Mixed	
Description	-	-	-	WA State Dairy Farm, WA	
Items	digester, separator, composter, boiler	digester, separator, boiler	digester, collection, boiler	digester, gen-set	
# cows	100	100	100	200	
Year installed (year of estimate)	2005	2005	2005	1980	
ENR CCI Value	7446	7446	7446	3237	
Capital costs	$160,000	$138,000	$105,000	$64,900	
Source	(Goodrich, 2005)	(Goodrich, 2005)	(Goodrich, 2005)	(Coppinger et al., 1980)	
Cost (2010$) (ENR CCI 8800.66)	$189,110	$163,110	$124,100	$176,450	Cost (2010$) = 8800.66*(Capital Costs)/(ENR Value)
Capital cost per cow (2010$)	$1,890	$1,630	$1,240	$880	Cost/cow (2010$) = (Cost 2010$)/(#cows)

1.c Digester General Information	Digester 1	Digester 2	Digester 3	Digester 4	Comments
Type	Upright Digester	Conventional Plug Flow Digester	Upflow-tank	Conventional Plug Flow Digester	
Description	USDA Beltsville, MD	Northeast IA CC Farm, IA	Jer-Lindy Farm, MN	Freund Dairy, CT	
Items	digester, collection, separator, boiler	digester, gen-set	digester, collection, building, labor, excavation, boiler, gen-set	digester, boiler	
# cows	220	120	160	250	
Year installed	1994	2006	2008	1996	
ENR CCI Value	5408	7751	8310	5620	
Capital costs	$263,000	$235,102	$460,000	$150,000	Plus $115,000 for additional insulation and heating
Source	(Weeks, 2011)	(Beddoes et al., 2007)	(Lazarus, 2009)	(Freund, 2011)	
Cost (2010$) (ENR CCI 8800.66)	$427,990	$266,930	$487,160	$349,890	Cost (2010$) = 8800.66*(Capital Costs)/(ENR Value)
Capital cost per cow (2010$)	$1,950	$2,220	$3,040	$1,400	Cost/cow (2010$) = (Cost 2010$)/(#cows)

1.d Digester General Information	Digester 5	Digester 6	Digester 7	Digester 8	Comments
Type	Fixed-film	Manure Activation/Covered Pond	Attached Growth	Upright Mixed Digester	
Description	JJ Farber Dairy, NY	Spring Valley Dairy, NY	Williston Cattle Co., VT	WA State Dairy Farm, WA	
Items	digester, boiler	digester, gen-set, manure storage	digester, extra research ports, boiler	digester, boiler	
# cows	100	236	250	200	
Year installed	2003	2003	2004	1980	
ENR CCI Value	6695	6695	7115	3237	
Capital costs	$134,000	$143,650	$300,000	$60,514	
Source	(Wright and Ma, 2003)	(Wright and Ma, 2003)	(Scruton and Whitcomb, 2005)	(Coppinger et al., 1980)	
Cost (2010$) (ENR CCI 8800.66)	$176,140	$188,830	$371,070	$164,520	Cost (2010$) = 8800.66*(Capital Costs)/(ENR Value)
Capital cost per cow (2010$)	$1,760	$800	$1,480	$820	Cost/cow (2010$) = (Cost 2010$)/(#cows)

Table D.2 Digesters biogas and electricity production

2.a Biogas and Electricity Production	**UMD 1**	**UMD 2**	**Theoretical 1**	**Theoretical 2**	**Comments**
Assumptions					
kg VS/d/cow	5.70	5.70	5.70	5.70	Source (Power et al., 1994)
L biogas/gram VS	0.35	0.35	0.35	0.35	Source (Power et al., 1994)
% remaining after heating digester	67%	67%	67%	67%	Source (Beddoes et al, 2007; Bracmort, 2008)
% CH4 in biogas	60%	60%	60%	60%	Source (Power et al., 1994; Beddoes et al, 2007)
kWh/m3 biogas (@ 60% Ch4)	1.07	1.07	1.07	1.07	Source (Power et al., 1994)
price of electricity ($/kWh)	0.09	0.09	0.09	0.09	Source (EIA, 2010)
Price of natural gas ($/m3)	0.18	0.18	0.18	0.18	Source (EIA, 2011)
Gross Annual Biogas (m3)	72,818	72,818	72,818	72,818	Gross Annual Biogas (m^3) = (#cows) * (kg VS/d/cow) * (365d/yr) * (1000g/kg) * (L biogas/gVS) / (1000m^3/L)
Net Annual Biogas (m3)	48,788	48,788	48,788	48,788	Net Annual Biogas (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating)
Net Annual CH4 (m3)	29,273	29,273	29,273	29,273	Net Annual CH4 (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating) * (%CH_4)
Annual Biogas Cost Savings ($)	~~$5,270~~	$5,270	$5,270	$5,270	Annual Biogas Cost Savings ($/yr) = (m3 CH4/yr)*($/m3)
Annual Electricity (kWh)	52,235	~~52,235~~	~~52,235~~	~~52,235~~	Annual Electricity (kWh) = (net biogas m3/yr)* (kWh/m3 biogas @60% CH4)
Annual Income Electricity ($)	$5,270	~~$5,270~~	~~$5,270~~	~~$5,270~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)

Annual Electricity (utilizing waste heat) (kWh)	77,963	~~77,963~~	~~77,963~~	~~77,963~~	Annual Electricity (kWh) = (gross biogas m3/yr)* (kWh/m3 biogas @60% CH4)
Annual Income Electricity (utilizing waste heat) ($)	$7,020	~~$7,020~~	~~$7,020~~	~~$7,020~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)

2.b Biogas and Electricity Production	**Theoretical 3**	**Theoretical 4**	**Theoretical 5**	**Theoretical 6**	**Comments**
Assumptions					
kg VS/d/cow	5.70	5.70	5.70	5.70	Source (Power et al., 1994)
L biogas/gram VS	0.35	0.35	0.35	0.35	Source (Power et al., 1994)
% remaining after heating digester	67%	67%	67%	67%	Source (Beddoes et al, 2007; Bracmort, 2008)
% CH4 in biogas	60%	60%	60%	60%	Source (Power et al., 1994; Beddoes et al, 2007)
kWh/m3 biogas (@ 60% Ch4)	1.07	1.07	1.07	1.07	Source (Power et al., 1994)
price of electricity ($/kWh)	0.09	0.09	0.09	0.09	Source (EIA, 2010)
Price of natural gas ($/m3)	0.18	0.18	0.18	0.18	Source (EIA, 2011)
Gross Annual Biogas (m3)	72,818	72,818	72,818	145,635	Gross Annual Biogas (m^3) = (#cows) * (kg VS/d/cow) * (365d/yr) * (1000g/kg) * (L biogas/gVS) / (1000m^3/L)
Net Annual Biogas (m3)	48,788	48,788	48,788	97,575	Net Annual Biogas (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating)
Net Annual CH4 (m3)	29,273	29,273	29,273	58,545	Net Annual CH4 (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating) * (%CH_4)
Annual Biogas Cost Savings ($)	$5,270	$5,270	$5,270	~~$10,540~~	Annual Biogas Cost Savings ($/yr) = (m3 CH4/yr)*($/m3)
Annual Electricity (kWh)	~~52,235~~	~~52,235~~	~~52,235~~	104,471	Annual Electricity (kWh) = (net biogas m3/yr)* (kWh/m3 biogas @60% CH4)

Annual Income Electricity ($)	~~$4,700~~	~~$4,700~~	~~$4,700~~	$9,400	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)
Annual Electricity (utilizing waste heat) (kWh)	77,963	~~77,963~~	~~77,963~~	~~155,926~~	Annual Electricity (kWh) = (gross biogas m3/yr)* (kWh/m3 biogas @60% CH4)
Annual Income Electricity (utilizing waste heat) ($)	$7,020	~~$7,020~~	~~$7,020~~	~~$14,030~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)

2.c Biogas and Electricity Production	**Digester 1**	**Digester 2**	**Digester 3**	**Digester 4**	**Comments**
Assumptions					
kg VS/d/cow	5.70	5.70	5.70	5.70	Source (Power et al., 1994)
L biogas/gram VS	0.35	0.35	0.35	0.35	Source (Power et al., 1994)
% remaining after heating digester	67%	67%	67%	67%	Source (Beddoes et al, 2007; Bracmort, 2008)
% CH4 in biogas	60%	60%	60%	60%	Source (Power et al., 1994; Beddoes et al, 2007)
kWh/m3 biogas (@ 60% Ch4)	1.07	1.07	1.07	1.07	Source (Power et al., 1994)
price of electricity ($/kWh)	0.09	0.09	0.09	0.09	Source (EIA, 2010)
Price of natural gas ($/m3)	0.18	0.18	0.18	0.18	Source (EIA, 2011)
Gross Annual Biogas (m3)	160,199	87,381	116,508	182,044	Gross Annual Biogas (m^3) = (#cows) * (kg VS/d/cow) * (365d/yr) * (1000g/kg) * (L biogas/gVS) / (1000m^3/L)
Net Annual Biogas (m3)	107,333	58,545	78,060	121,969	Net Annual Biogas (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating)
Net Annual CH4 (m3)	64,400	35,127	46,836	73,182	Net Annual CH4 (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating) * (%CH_4)
Annual Biogas Cost Savings ($)	$11,590	~~$6,320~~	~~$8,430~~	$13,170	Annual Biogas Cost Savings ($/yr) = (m3 CH4/yr)*($/m3)

Annual Electricity (kWh)	~~114,918~~	62,682	83,576	~~130,588~~	Annual Electricity (kWh) = (net biogas m3/yr)* (kWh/m3 biogas @60% CH4)
Annual Income Electricity ($)	~~$10,340~~	$5,640	$7,520	~~$11,750~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)
Annual Electricity (utilizing waste heat) (kWh)	171,519	~~93,556~~	~~124,741~~	~~194,908~~	Annual Electricity (kWh) = (gross biogas m3/yr)* (kWh/m3 biogas @60% CH4)
Annual Income Electricity (utilizing waste heat) ($)	$15,440	~~$8,420~~	~~$11,230~~	~~$17,540~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)

2.d Biogas and Electricity Production	**Digester 5**	**Digester 6**	**Digester 7**	**Digester 8**	**Comments**
Assumptions					
kg VS/d/cow	5.70	5.70	5.70	5.70	Source (Power et al., 1994)
L biogas/gram VS	0.35	0.35	0.35	0.35	Source (Power et al., 1994)
% remaining after heating digester	67%	67%	67%	67%	Source (Beddoes et al, 2007; Bracmort, 2008)
% CH4 in biogas	60%	60%	60%	60%	Source (Power et al., 1994; Beddoes et al, 2007)
kWh/m3 biogas (@ 60% Ch4)	1.07	1.07	1.07	1.07	Source (Power et al., 1994)
price of electricity ($/kWh)	0.09	0.09	0.09	0.09	Source (EIA, 2010)
Price of natural gas ($/m3)	0.18	0.18	0.18	0.18	Source (EIA, 2011)
Gross Annual Biogas (m3)	72,818	171,849	182,044	145,635	Gross Annual Biogas (m^3) = (#cows) * (kg VS/d/cow) * (365d/yr) * (1000g/kg) * (L biogas/gVS) / (1000m^3/L)
Net Annual Biogas (m3)	48,788	115,139	121,969	97,575	Net Annual Biogas (m3) = (gross biogas m^3/yr) * (%CH_4 remaining after heating)

Net Annual CH4 (m3)	29,273	69,083	73,182	58,545	Net Annual CH4 (m3) = (gross biogas m^3/yr) * (% CH_4 remaining after heating) * (% CH_4)
Annual Biogas Cost Savings ($)	$5,270	~~$12,440~~	$13,170	$10,540	Annual Biogas Cost Savings ($/yr) = (m3 CH4/yr)*($/m3)
Annual Electricity (kWh)	~~52,235~~	123,275	~~130,588~~	~~104,471~~	Annual Electricity (kWh) = (net biogas m3/yr)* (kWh/m3 biogas @60%CH4)
Annual Income Electricity ($)	~~$4,700~~	$11,090	~~$11,750~~	~~$9,400~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)
Annual Electricity (utilizing waste heat) (kWh)	77,963	~~183,993~~	~~194,908~~	~~155,926~~	Annual Electricity (kWh) = (gross biogas m3/yr)* (kWh/m3 biogas @60%CH4)
Annual Income Electricity (utilzing waste heat) ($)	$7,020	~~$16,560~~	~~$17,540~~	~~$14,030~~	Elect. Cost Savings ($/yr) = (Annual kWh)*($/kWh)

Table D.3 Digesters CO_2 reduction

3.a CO2 Reduction	UMD 1	UMD 2	Theoretical 1	Theoretical 2	Comments
Assumptions					
B0,t (for Dairy, from Appendix B) m3 CH4/kg VS	0.24	0.24	0.24	0.24	Source (Eastern Research Group, 2011)
MCFs,k (ave ambient T =20, liquid/slurry with crust)	26%	26%	26%	26%	Source (Eastern Research Group, 2011)
% CH4 in biogas (by volume)	60%	60%	60%	60%	Source (Eastern Research Group, 2011)
LKf (Projected Methane Leakage, %)	10%	10%	10%	10%	Source (Eastern Research Group, 2011)
CH4emitted boiler/furnace (kg CH4/10^6 BTU)	1.00	1.00	1.00	1.00	Source (Eastern Research Group, 2011); (IPCC, 2006)
CH4emitted internal combustion engine (kg CH4/10^6 BTU)	110	110	110	110	Source (Eastern Research Group, 2011); (IPCC, 2006)
CCX rate of CO2 reduction ($/metric ton CO2)	$5.70	$5.70	$5.70	$5.70	Source (CCX, 2011)
Gross Annual CH4 (m3)	43,691	43,691	43,691	43,691	Gross Annual CH4 (m3) = (net biogas m3/yr) *(%CH4)
EFm (kg CH4/year)	8,698	8,698	8,698	8,698	EFm (annual methane emissions from manure) (kg CH4/year) = [(kg VS/d/cow) * (#cow)*(365)] * [(B0t) * (.67 kg CH4/m3 CH4) * (MCF)
LKp (kg CH4/year)	2,927	2,927	2,927	2,927	LKp (Projected Methane Leak, kg CH4/year) = (Gross CH4 (m3/yr)) * (%leakage)*(.67)
Ceputil (kg CH4/year)	147	1	1	1	Ceputil (methane utilization related emissions, kg CH4/year) = [Gross CH4 m3/yr - (leaks kg/.67)] *(33,898)*(CH4 emitted)/(1x10^9)
Efp (kg CH4 per year)	5,624	5,770	5,770	5,770	Efp, Annual Net Methane Emission Reduction (kg CH4 per year) = Efm - (LKp+Ceputil)

Efpco2 (kg CO2 per year)	118,110	121,161	121,161	121,161	Efpco2, Annual Net Methane Emission Reduction (kg CO2 per year) = Efp*21
Annual Income CO2 credits ($)	$670	$690	$690	$690	Annual Income CO2 credits ($) = Efpco2/(1000kg/mton)*($/mton)

3.b CO2 Reduction	Theoretical 3	Theoretical 4	Theoretical 5	Theoretical 6	Comments
Assumptions					
B0,t (for Dairy, from Appendix B) m3 CH4/kg VS	0.24	0.24	0.24	0.24	Source (Eastern Research Group, 2011)
MCFs,k (ave ambient T =20, liquid/slurry with crust)	26%	26%	26%	26%	Source (Eastern Research Group, 2011)
% CH4 in biogas (by volume)	60%	60%	60%	60%	Source (Eastern Research Group, 2011)
LKf (Projected Methane Leakage, %)	10%	10%	10%	10%	Source (Eastern Research Group, 2011)
CH4emitted boiler/furnace (kg CH4/10^6 BTU)	1.00	1.00	1.00	1.00	Source (Eastern Research Group, 2011); (IPCC, 2006)
CH4emitted internal combustion engine (kg CH4/10^6 BTU)	110	110	110	110	Source (Eastern Research Group, 2011); (IPCC, 2006)
CCX rate of CO2 reduction ($/metric ton CO2)	$5.70	$5.70	$5.70	$5.70	Source (CCX, 2011)
Gross Annual CH4 (m3)	43,691	43,691	43,691	87,381	Gross Annual CH4 (m3) = (net biogas m3/yr) *(%CH4)
EFm (kg CH4/year)	8,698	8,698	8,698	17,396	EFm (annual methane emissions from manure) (kg CH4/year) = [(kg VS/d/cow) * (#cow)*(365)] * [(B0t) * (.67 kg CH4/m3 CH4) * (MCF)
LKp (kg CH4/year)	2,927	2,927	2,927	5,855	LKp (Projected Methane Leak, kg CH4/year) = (Gross CH4 (m3/yr)) * (%leakage)*(.67)
Ceputil (kg CH4/year)	1	1	1	293	Ceputil (methane utilization related emissions, kg CH4/year) = [Gross CH4 m3/yr - (leaks kg/.67)] *(33,898)*(CH4 emitted)/(1x10^9)

Efp (kg CH4 per year)	5,770	5,770	5,770	11,249	Efp, Annual Net Methane Emission Reduction (kg CH4 per year) = Efm - (LKp+Ceputil)
Efpco2 (kg CO2 per year)	121,161	121,161	121,161	236,219	Efpco2, Annual Net Methane Emission Reduction (kg CO2 per year) = Efp*21
Annual Income CO2 credits ($)	$690	$690	$690	$1,350	Annual Income CO2 credits ($) = Efpco2/(1000kg/mton)*($/mton)

3.c CO2 Reduction	Digester 1	Digester 2	Digester 3	Digester 4	Comments
Assumptions					
B0,t (for Dairy, from Appendix B) m3 CH4/kg VS	0.24	0.24	0.24	0.24	Source (Eastern Research Group, 2011)
MCFs,k (ave ambient T =20, liquid/slurry with crust)	26%	26%	26%	26%	Source (Eastern Research Group, 2011)
% CH4 in biogas (by volume)	60%	60%	60%	60%	Source (Eastern Research Group, 2011)
LKf (Projected Methane Leakage, %)	10%	10%	10%	10%	Source (Eastern Research Group, 2011)
CH4emitted boiler/furnace (kg CH4/10^6 BTU)	1.00	1.00	1.00	1.00	Source (Eastern Research Group, 2011); (IPCC, 2006)
CH4emitted internal combustion engine (kg CH4/10^6 BTU)	110	110	110	110	Source (Eastern Research Group, 2011); (IPCC, 2006)
CCX rate of CO2 reduction ($/metric ton CO2)	$5.70	$5.70	$5.70	$5.70	Source (CCX, 2011)
Gross Annual CH4 (m3)	96,119	52,429	69,905	109,226	Gross Annual CH4 (m3) = (net biogas m3/yr) *(%CH4)
EFm (kg CH4/year)	19,136	10,438	13,917	21,745	EFm (annual methane emissions from manure) (kg CH4/year) = [(kg VS/d/cow) * (#cow)*(365)] * [(B0t) * (.67 kg CH4/m3 CH4) * (MCF)
LKp (kg CH4/year)	6,440	3,513	4,684	7,318	LKp (Projected Methane Leak, kg CH4/year) = (Gross CH4 (m3/yr)) * (%leakage)*(.67)

Ceputil (kg CH4/year)	3	176	235	3	Ceputil (methane utilization related emissions, kg CH4/year) = [Gross CH4 m3/yr - (leaks kg/.67)] *(33,898)*(CH4 emitted)/(1x10^9)
Efp (kg CH4 per year)	12,693	6,749	8,999	14,424	Efp, Annual Net Methane Emission Reduction (kg CH4 per year) = Efm - (LKp+Ceputil)
Efpco2 (kg CO2 per year)	266,554	141,732	188,975	302,902	Efpco2, Annual Net Methane Emission Reduction (kg CO2 per year) = Efp*21
Annual Income CO2 credits ($)	$1,520	$810	$1,080	$1,730	Annual Income CO2 credits ($) = Efpco2/(1000kg/mton)*($/mton)

3.d CO2 Reduction	**Digester 5**	**Digester 6**	**Digester 7**	**Digester 8**	**Comments**
Assumptions					
B0,t (for Dairy, from Appendix B) m3 CH4/kg VS	0.24	0.24	0.24	0.24	Source (Eastern Research Group, 2011)
MCFs,k (ave ambient T =20, liquid/slurry with crust)	26%	26%	26%	26%	Source (Eastern Research Group, 2011)
% CH4 in biogas (by volume)	60%	60%	60%	60%	Source (Eastern Research Group, 2011)
LKf (Projected Methane Leakage, %)	10%	10%	10%	10%	Source (Eastern Research Group, 2011)
CH4emitted boiler/furnace (kg CH4/10^6 BTU)	1.00	1.00	1.00	1.00	Source (Eastern Research Group, 2011); (IPCC, 2006)
CH4emitted internal combustion engine (kg CH4/10^6 BTU)	110	110	110	110	Source (Eastern Research Group, 2011); (IPCC, 2006)
CCX rate of CO2 reduction ($/metric ton CO2)	$5.70	$5.70	$5.70	$5.70	Source (CCX, 2011)
Gross Annual CH4 (m3)	43,691	103,110	109,226	87,381	Gross Annual CH4 (m3) = (net biogas m3/yr) *(%CH4)
EFm (kg CH4/year)	8,698	20,528	21,745	17,396	EFm (annual methane emissions from manure) (kg CH4/year) = [(kg VS/d/cow) * (#cow)*(365)] * [(B0t) * (.67 kg CH4/m3 CH4) * (MCF)

LKp (kg CH4/year)	2,927	6,908	7,318	5,855	LKp (Projected Methane Leak, kg CH4/year) = (Gross CH4 (m3/yr)) * (%leakage)*(.67)
Ceputil (kg CH4/year)	1	346	3	3	Ceputil (methane utilization related emissions, kg CH4/year) = [Gross CH4 m3/yr - (leaks kg/.67)] *(33,898)*(CH4 emitted)/(1x10^9)
Efp (kg CH4 per year)	5,770	13,273	14,424	11,539	Efp, Annual Net Methane Emission Reduction (kg CH4 per year) = Efm - (LKp+Ceputil)
Efpco2 (kg CO2 per year)	121,161	278,739	302,902	242,321	Efpco2, Annual Net Methane Emission Reduction (kg CO2 per year) = Efp*21
Annual Income CO2 credits ($)	$690	$1,590	$1,730	$1,380	Annual Income CO2 credits ($) = Efpco2/(1000kg/mton)*($/mton)

Table D.4 Digesters bedding reuse

4.a Bedding Reuse	UMD 1	UMD 2	Theoretical 1	Theoretical 2	Comments
Assumptions					
bedding (cf/cow/day)	1	1	1	1	Source (Weeks, 2003; Kramer, 2009)
cost of bedding ($/cy)	$10	$10	$10	$10	Source (Kramer, 2009; Kemp, 2011)
Annual Produced Bedding (cy)	1,352	1,352	1,352	1,352	Annual Produced Bedding (cy) = (cf/cow/day)*(#cows) *(365)*(1cy/27cf)
Annual Income Bedding ($)	$13,520	$13,520	$13,520	$13,520	Annual Income Bedding ($) = (cy/year)*($/cy)

4.b Bedding Reuse	Theoretical 3	Theoretical 4	Theoretical 5	Theoretical 6	Comments
Assumptions					
bedding (cf/cow/day)	1	1	1	1	Source (Weeks, 2003; Kramer, 2009)
cost of bedding ($/cy)	$10	$10	$10	$10	Source (Kramer, 2009; Kemp, 2011)

Annual Produced Bedding (cy)	1,352	1,352	1,352	2,704	Annual Produced Bedding (cy) = (cf/cow/day)*(#cows) *(365)*(1cy/27cf)
Annual Income Bedding ($)	$13,520	$13,520	$13,520	$27,040	Annual Income Bedding ($) = (cy/year)*($/cy)

4.c Bedding Reuse	**Digester 1**	**Digester 2**	**Digester 3**	**Digester 4**	**Comments**
Assumptions					
bedding (cf/cow/day)	1	1	1	1	Source (Weeks, 2003; Kramer, 2009)
cost of bedding ($/cy)	$10	$10	$10	$10	Source (Kramer, 2009; Kemp, 2011)
Annual Produced Bedding (cy)	2,974	1,622	2,163	3,380	Annual Produced Bedding (cy) = (cf/cow/day)*(#cows) *(365)*(1cy/27cf)
Annual Income Bedding ($)	$29,740	$16,220	$21,630	$33,800	Annual Income Bedding ($) = (cy/year)*($/cy)

4.d Bedding Reuse	**Digester 5**	**Digester 6**	**Digester 7**	**Digester 8**	**Comments**
Assumptions					
bedding (cf/cow/day)	1	1	1	1	Source (Weeks, 2003; Kramer, 2009)
cost of bedding ($/cy)	$10	$10	$10	$10	Source (Kramer, 2009; Kemp, 2011)
Annual Produced Bedding (cy)	1,352	3,190	3,380	2,704	Annual Produced Bedding (cy) = (cf/cow/day)*(#cows) *(365)*(1cy/27cf)
Annual Income Bedding ($)	$13,520	$31,900	$33,800	$27,040	Annual Income Bedding ($) = (cy/year)*($/cy)

Table D.5 Digesters cash flow analysis

5.a Cash Flow Analysis	UMD 1	UMD 2	Theoretical 1	Theoretical 2	Comments
Assumptions					
lifetime	20	20	20	20	
discount rate	8%	8%	8%	8%	
A/P, 8%,20	-0.10185	-0.10185	-0.10185	-0.10185	Source (Stermole and Stermole, 2000)
O&M with elec. gen.	5%	5%	5%	5%	
O&M without elec. gen.	3%	3%	3%	3%	
Annual Capital Costs	($28,940)	($18,760)	($22,150)	($19,620)	Annual Capital Cost = (Capital Cost)*(A/P,i,n)
Annual Operating Cost	($14,210)	($5,520)	($6,520)	($5,780)	Annual Operating Cost = (Capital Cost)*(O&M)
Annual Income	$18,890	$19,480	$19,480	$19,480	∑ Annual Incomes (biogas/elec., CO2 credit, bedding reuse)
Annual Net Cost	($24,260)	($4,800)	($9,190)	($5,920)	Annual Net Cost = ∑ Annual Capital, Operating, Income
Annual Cost/Cow	($240)	($50)	($90)	($60)	Annual cost/cow = (Annual net cost)/(#cows)

5.b Cash Flow Analysis	Theoretical 3	Theoretical 4	Theoretical 5	Theoretical 6	Comments
Assumptions					
lifetime	20	20	20	20	
discount rate	8%	8%	8%	8%	
A/P, 8%,20	-0.10185	-0.10185	-0.10185	-0.10185	Source (Stermole and Stermole, 2000)
O&M with elec. gen.	5%	5%	5%	5%	
O&M without elec. gen.	3%	3%	3%	3%	
Annual Capital Costs	($19,260)	($16,610)	($12,640)	($17,970)	Annual Capital Cost = (Capital

					Cost)*(A/P,i,n)
Annual Operating Cost	($5,670)	($4,890)	($3,720)	($8,820)	Annual Operating Cost = (Capital Cost)*(O&M)
Annual Income	$19,480	$19,480	$19,480	$37,790	∑ Annual Incomes (biogas/elec., CO2 credit, bedding reuse)
Annual Net Cost	($5,450)	($2,020)	$3,120	$11,000	Annual Net Cost = ∑ Annual Capital, Operating, Income
Annual Cost/Cow	($50)	($20)	$30	$60	Annual cost/cow = (Annual net cost)/(#cows)

5.c Cash Flow Analysis	**Digester 1**	**Digester 2**	**Digester 3**	**Digester 4**	**Comments**
Assumptions					
lifetime	20	20	20	20	
discount rate	8%	8%	8%	8%	
A/P, 8%,20	-0.10185	-0.10185	-0.10185	-0.10185	Source (Stermole and Stermole, 2000)
O&M with elec. gen.	5%	5%	5%	5%	
O&M without elec. gen.	3%	3%	3%	3%	
Annual Capital Costs	($43,590)	($27,190)	($49,620)	($35,640)	Annual Capital Cost = (Capital Cost)*(A/P,i,n)
Annual Operating Cost Calculated	($12,840)	($13,350)	($24,360)	($10,500)	Annual Operating Cost = (Capital Cost)*(O&M)
Annual Operating Cost from Source	-	-	($13,390)	-	from Source, adjusted to 2010$ using ENR CCI#
Annual Income Calculated	$42,850	$22,670	$30,230	$48,700	∑ Annual Incomes (biogas/elec., CO2 credit, bedding reuse)
Annual Income from Source	-	-	$28,790	-	from Source, adjusted to 2010$ using ENR CCI#
Annual Net Cost	($13,580)	($17,870)	($34,220)	$2,560	Annual Net Cost = ∑ Annual Capital, Operating, Income
Annual Cost/Cow	($60)	($150)	($210)	$10	Annual cost/cow = (Annual net cost)/(#cows)

5.d Cash Flow Analysis	Digester 5	Digester 6	Digester 7	Digester 8	Comments
Assumptions					
lifetime	20	20	20	20	
discount rate	8%	8%	8%	8%	
A/P, 8%,20	-0.10185	-0.10185	-0.10185	-0.10185	Source (Stermole and Stermole, 2000)
O&M with elec. gen.	5%	5%	5%	5%	
O&M without elec. gen.	3%	3%	3%	3%	
Annual Capital Costs	($17,940)	($19,230)	($37,790)	($16,760)	Annual Capital Cost = (Capital Cost)*(A/P,i,n)
Annual Operating Cost Calculated	($5,280)	($9,440)	($11,130)	($4,940)	Annual Operating Cost = (Capital Cost)*(O&M)
Annual Operating Cost from Source	($31,550)	($10,550)	-	-	from Source, adjusted to 2010$ using ENR CCI#
Annual Income Calculated	$17,090	$44,580	$48,700	$38,960	∑ Annual Incomes (biogas/elec., CO2 credit, bedding reuse)
Annual Income from Source	$17,090	$22,680	-	-	from Source, adjusted to 2010$ using ENR CCI#
Annual Net Cost	($32,400)	($7,100)	($220)	$17,260	Annual Net Cost = ∑ Annual Capital, Operating, Income
Annual Cost/Cow	($320)	($30)	$0	$90	Annual cost/cow = (Annual net cost)/(#cows)

Table D.6 Digesters net present value analysis

6.a Net Present Value Analysis	UMD 1	UMD 2	Theoretical 1	Theoretical 2	Comments
Assumptions					
discount rate	8%	8%	8%	8%	
lifetime	20	20	20	20	
P/A, 8%,20	9.8181	9.8181	9.8181	9.8181	Source (Stermole and Stermole, 2000)
Capital Investment	($284,150)	($184,150)	($217,480)	($192,650)	see section 1.0 Digester General Information
Annual Operating Costs	($14,210)	($5,520)	($6,520)	($5,780)	see section 5.0 Cash Flow Analysis
Annual Income	$18,890	$19,480	$19,480	$19,480	see section 5.0 Cash Flow Analysis
NPV	($238,200)	($47,090)	($90,240)	($58,140)	NPV = (Capital Investment)+(Annual Operating Costs*(P/A,i,n))+(Annual Income*(P/A,i,n))

6.b Net Present Value Analysis	Theoretical 3	Theoretical 4	Theoretical 5	Theoretical 6	Comments
Assumptions					
discount rate	8%	8%	8%	8%	
lifetime	20	20	20	20	
P/A, 8%,20	9.8181	9.8181	9.8181	9.8181	Source (Stermole and Stermole, 2000)
Capital Investment	($189,110)	($163,110)	($124,100)	($176,450)	see section 1.0 Digester General Information
Annual Operating Costs	($5,670)	($4,890)	($3,720)	($8,820)	see section 5.0 Cash Flow Analysis
Annual Income	$19,480	$19,480	$19,480	$37,790	see section 5.0 Cash Flow Analysis
NPV	($53,520)	($19,860)	$30,630	$107,980	NPV = (Capital Investment)+(Annual Operating Costs*(P/A,i,n))+(Annual Income*(P/A,i,n))

6.c Net Present Value Analysis	Digester 1	Digester 2	Digester 3	Digester 4	Comments
Assumptions					
discount rate	8%	8%	8%	8%	
lifetime	20	20	20	20	
P/A, 8%,20	9.8181	9.8181	9.8181	9.8181	Source (Stermole and Stermole, 2000)
Capital Investment	($427,990)	($266,930)	($487,160)	($349,890)	see section 1.0 Digester General Information
Annual Operating Cost	($12,840)	($13,350)	($24,360)	($10,500)	see section 5.0 Cash Flow Analysis
Annual Operating Cost from Source	-	-	($13,390)	-	see section 5.0 Cash Flow Analysis
Annual Income Calculated	$42,850	$22,670	$30,230	$48,700	see section 5.0 Cash Flow Analysis
Annual Income from Source	-	-	$28,790	-	see section 5.0 Cash Flow Analysis
NPV	($133,350)	($175,430)	($335,960)	$25,160	NPV = (Capital Investment)+(Annual Operating Costs*(P/A,i,n))+(Annual Income*(P/A,i,n))

6.d Net Present Value Analysis	Digester 5	Digester 6	Digester 7	Digester 8	Comments
Assumptions					
discount rate	8%	8%	8%	8%	
lifetime	20	20	20	20	
P/A, 8%,20	9.8181	9.8181	9.8181	9.8181	Source (Stermole and Stermole, 2000)
Capital Investment	($176,140)	($188,830)	($371,070)	($164,520)	see section 1.0 Digester General Information
Annual Operating Cost	($5,280)	($9,440)	($11,130)	($4,940)	see section 5.0 Cash Flow Analysis
Annual Operating Cost from Source	($31,550)	($10,550)	-	-	see section 5.0 Cash Flow Analysis
Annual Income Calculated	$19,480	$44,580	$48,700	$38,960	see section 5.0 Cash Flow Analysis
Annual Income from Source	$17,090	$22,680	-	-	see section 5.0 Cash Flow Analysis
NPV	($318,110)	($69,740)	($2,200)	$169,490	NPV = (Capital Investment)+(Annual Operating Costs*(P/A,i,n))+(Annual Income*(P/A,i,n))

Table D.7 Digesters sensitivity analysis

7.a Sensitivity Analysis	UMD 1	UMD 2	Theoretical 1	Theoretical 2	Comments
Assumptions					
A/P, 4%, 10	-0.1233	-0.1233	-0.1233	-0.1233	Source (Stermole and Stermole, 2000)
A/P, 4%, 15	-0.0899	-0.0899	-0.0899	-0.0899	Source (Stermole and Stermole, 2000)
A/P, 4%, 20	-0.0736	-0.0736	-0.0736	-0.0736	Source (Stermole and Stermole, 2000)
A/P, 8%, 10	-0.1490	-0.1490	-0.1490	-0.1490	Source (Stermole and Stermole, 2000)
A/P, 8%, 15	-0.1168	-0.1168	-0.1168	-0.1168	Source (Stermole and Stermole, 2000)
A/P, 8%, 20	-0.1019	-0.1019	-0.1019	-0.1019	Source (Stermole and Stermole, 2000)
A/P, 14%, 10	-0.1917	-0.1917	-0.1917	-0.1917	Source (Stermole and Stermole, 2000)
A/P, 14%, 15	-0.1628	-0.1628	-0.1628	-0.1628	Source (Stermole and Stermole, 2000)
A/P, 14%, 20	-0.1510	-0.1510	-0.1510	-0.1510	Source (Stermole and Stermole, 2000)
Capital Cost	$284,150	$184,150	$217,480	$192,650	see section 1.0 Digester General Information
Annual Operating Costs	($14,210)	($5,520)	($6,520)	($5,780)	see section 5.0 Cash Flow Analysis
Annual Income	$18,890	$19,480	$19,480	$19,480	see section 5.0 Cash Flow Analysis
Cash Flow (4%, 10)	($30,360)	($8,750)	($13,860)	($10,050)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 15)	($20,870)	($2,600)	($6,590)	($3,620)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 20)	($16,230)	$410	($3,050)	($480)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 10)	($37,670)	($13,480)	($19,450)	($15,010)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 15)	($28,520)	($7,550)	($12,450)	($8,810)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 20)	($24,260)	($4,800)	($9,190)	($5,920)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income

Cash Flow (14%, 10)	($49,800)	($21,340)	($28,730)	($23,230)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 15)	($41,580)	($16,020)	($22,450)	($17,670)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 20)	($38,220)	($13,840)	($19,880)	($15,390)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income

7.b Sensitivity Analysis	**Theoretical 3**	**Theoretical 4**	**Theoretical 5**	**Theoretical 6**	**Comments**
Assumptions					
A/P, 4%, 10	-0.1233	-0.1233	-0.1233	-0.1233	Source (Stermole and Stermole, 2000)
A/P, 4%, 15	-0.0899	-0.0899	-0.0899	-0.0899	Source (Stermole and Stermole, 2000)
A/P, 4%, 20	-0.0736	-0.0736	-0.0736	-0.0736	Source (Stermole and Stermole, 2000)
A/P, 8%, 10	-0.1490	-0.1490	-0.1490	-0.1490	Source (Stermole and Stermole, 2000)
A/P, 8%, 15	-0.1168	-0.1168	-0.1168	-0.1168	Source (Stermole and Stermole, 2000)
A/P, 8%, 20	-0.1019	-0.1019	-0.1019	-0.1019	Source (Stermole and Stermole, 2000)
A/P, 14%, 10	-0.1917	-0.1917	-0.1917	-0.1917	Source (Stermole and Stermole, 2000)
A/P, 14%, 15	-0.1628	-0.1628	-0.1628	-0.1628	Source (Stermole and Stermole, 2000)
A/P, 14%, 20	-0.1510	-0.1510	-0.1510	-0.1510	Source (Stermole and Stermole, 2000)
Capital Cost	$189,110	$163,110	$124,100	$176,450	see section 1.0 Digester General Information
Annual Operating Costs	($5,670)	($4,890)	($3,720)	($8,820)	see section 5.0 Cash Flow Analysis
Annual Income	$19,480	$19,480	$19,480	$37,790	see section 5.0 Cash Flow Analysis
Cash Flow (4%, 10)	($9,510)	($5,520)	$460	$7,210	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 15)	($3,190)	($70)	$4,600	$13,110	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 20)	($110)	$2,590	$6,630	$15,980	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income

Cash Flow (8%, 10)	($14,370)	($9,720)	($2,730)	$2,670	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 15)	($8,280)	($4,470)	$1,260	$8,360	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 20)	($5,450)	($2,020)	$3,120	$11,000	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 10)	($22,440)	($16,680)	($8,030)	($4,860)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 15)	($16,980)	($11,970)	($4,440)	$240	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 20)	($14,740)	($10,040)	($2,980)	$2,330	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income

7.c Sensitivity Analysis	Digester 1	Digester 2	Digester 3	Digester 4	Comments
Assumptions					
A/P, 4%, 10	-0.1233	-0.1233	-0.1233	-0.1233	Source (Stermole and Stermole, 2000)
A/P, 4%, 15	-0.0899	-0.0899	-0.0899	-0.0899	Source (Stermole and Stermole, 2000)
A/P, 4%, 20	-0.0736	-0.0736	-0.0736	-0.0736	Source (Stermole and Stermole, 2000)
A/P, 8%, 10	-0.1490	-0.1490	-0.1490	-0.1490	Source (Stermole and Stermole, 2000)
A/P, 8%, 15	-0.1168	-0.1168	-0.1168	-0.1168	Source (Stermole and Stermole, 2000)
A/P, 8%, 20	-0.1019	-0.1019	-0.1019	-0.1019	Source (Stermole and Stermole, 2000)
A/P, 14%, 10	-0.1917	-0.1917	-0.1917	-0.1917	Source (Stermole and Stermole, 2000)
A/P, 14%, 15	-0.1628	-0.1628	-0.1628	-0.1628	Source (Stermole and Stermole, 2000)
A/P, 14%, 20	-0.1510	-0.1510	-0.1510	-0.1510	Source (Stermole and Stermole, 2000)
Capital Cost	$427,990	$266,930	$487,160	$349,890	see section 1.0 Digester General Information
Annual Operating Costs	($12,840)	($13,350)	($13,390)	($10,500)	see section 5.0 Cash Flow Analysis
Annual Income	$42,850	$22,670	$28,790	$48,700	see section 5.0 Cash Flow Analysis

Cash Flow (4%, 10)	($22,760)	($23,590)	($44,670)	($4,940)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 15)	($8,470)	($14,680)	($28,400)	$6,740	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 20)	($1,490)	($10,330)	($20,450)	$12,450	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 10)	($33,770)	($30,460)	($57,200)	($13,940)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 15)	($19,990)	($21,870)	($41,510)	($2,680)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 20)	($13,580)	($17,870)	($34,220)	$2,560	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 10)	($52,040)	($41,850)	($78,000)	($28,880)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 15)	($39,670)	($34,140)	($63,910)	($18,770)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 20)	($34,610)	($30,980)	($58,150)	($14,630)	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income

7.d Sensitivity Analysis	**Digester 5**	**Digester 6**	**Digester 7**	**Digester 8**	**Comments**
Assumptions					
A/P, 4%, 10	-0.1233	-0.1233	-0.1233	-0.1233	Source (Stermole and Stermole, 2000)
A/P, 4%, 15	-0.0899	-0.0899	-0.0899	-0.0899	Source (Stermole and Stermole, 2000)
A/P, 4%, 20	-0.0736	-0.0736	-0.0736	-0.0736	Source (Stermole and Stermole, 2000)
A/P, 8%, 10	-0.1490	-0.1490	-0.1490	-0.1490	Source (Stermole and Stermole, 2000)
A/P, 8%, 15	-0.1168	-0.1168	-0.1168	-0.1168	Source (Stermole and Stermole, 2000)
A/P, 8%, 20	-0.1019	-0.1019	-0.1019	-0.1019	Source (Stermole and Stermole, 2000)
A/P, 14%, 10	-0.1917	-0.1917	-0.1917	-0.1917	Source (Stermole and Stermole, 2000)
A/P, 14%, 15	-0.1628	-0.1628	-0.1628	-0.1628	Source (Stermole and Stermole, 2000)
A/P, 14%, 20	-0.1510	-0.1510	-0.1510	-0.1510	Source (Stermole and Stermole, 2000)

Capital Cost	$176,140	$188,830	$371,070	$164,520	see section 1.0 Digester General Information
Annual Operating Costs	($31,550)	($10,550)	($11,130)	($4,940)	see section 5.0 Cash Flow Analysis
Annual Income	$17,090	$22,680	$48,700	$38,960	see section 5.0 Cash Flow Analysis
Cash Flow (4%, 10)	($36,180)	($11,150)	($8,180)	$13,730	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 15)	($30,290)	($4,850)	$4,210	$19,230	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (4%, 20)	($27,420)	($1,770)	$10,260	$21,910	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 10)	($40,710)	($16,010)	($17,730)	$9,500	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 15)	($35,040)	($9,930)	($5,780)	$14,800	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (8%, 20)	($32,400)	($7,100)	($220)	$17,260	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 10)	($48,230)	($24,070)	($33,570)	$2,480	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 15)	($43,140)	($18,610)	($22,840)	$7,230	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income
Cash Flow (14%, 20)	($41,050)	($16,380)	($18,460)	$9,180	Annual Net Cost = ∑ (Capital Cost)*(A/P,i,n), Operating, Income

D.2 Economic Calculations for Manure Pit Systems

Table D.8 Manure pit general information

8 Manure Pit General Information			**Manure Pit 2**			**Manure Pit 1**	**Comments**
Storage Type	Slurry storage	Lagoon	Lagoon (average)	Manure pit	Manure pit	Manure pit (typical)	
Description	tank, concrete pad, holding pit, piping	lagoon, solid separator, pumps, piping	lagoon, solid separator, pumps, piping	pit	pit	pit, pumps, piping	
# cows	200	320	250	70	160	150	
Year installed (year of estimate)	2009	1997	-	2000	1965	2011	
ENR CCI Value	8671	5826	-	6221	-	8801	
Capital costs	$600,000	$400,000	-	$87,000	unknown	$150,000	
Source	(Wiles, 2011)	(Tucker, 2011)	-	(Kolholtz, 2011)	(Anderson, 2011)	(Johnson-NRCS, 2011)	owners
Cost (2010$) (ENR CCI 8800.66)	$608,970	$604,230	$600,000	$123,080	-	$149,990	Cost (2010$) = 8800.66*(Capital Costs)/(ENR Value)
Capital cost per cow (2010$)	$3,040	$1,890	$2,400	$1,760	-	$1,000	Cost/cow (2010$) = (Cost 2010$)/(#cows)

Table D.9 Manure pit operating costs

9 Operating Costs			**Manure Pit 2**			**Manure Pit 1**	**Comments**
Description	pit 1-2 years, slurry storage 6 mo., pump every couple days/wks	empty lagoon 6 mo. (wk process), pump 1 d/mo.	empty every 6 mo.	empty pit 6 mo. ($5,000/empty)	portable pump used, clean out every 6 wks ($680/clean-out)	empty pit 6 mo.	description by owner
O&M costs by owner	-	-	-	$10,000	$5,893	-	
O&M costs calculated	$20,000	$32,000	$25,000	$7,000	$16,000	$15,000	$100/cow/year (Erb, 2011)

Table D.10 Manure pit bedding reuse

10 Bedding Reuse			**Manure Pit 2**			**Manure Pit 1**	**Comments**
Assumptions							
bedding (cf/cow/day)	1	1	1	1	1		Source (Weeks, 2003; Kramer, 2009)
cost of bedding ($/cy)	$10	$10	$10	$10	$10		Source (Kramer, 2009; Kemp, 2011)
Annual Produced Bedding (cy)	2,704	4,326	3,380	-	-	-	Annual Produced Bedding (cy) = (cf/cow/day)*(#cows) *(365)*(1cy/27cf)
Annual Income Bedding ($)	$27,040	$43,260	$33,800	-	-	-	Annual Income Bedding ($) = (cy/year)*($/cy)

Table D.11 Manure pit cash flow analysis

4.0 Cash Flow Analysis			**Manure Pit 2**			**Manure Pit 1**	**Comments**
Assumptions							
lifetime	20	20	20	20	20	20	
discount rate	8%	8%	8%	8%	8%	8%	
A/P, 8%,20	-0.10185	-0.10185	-0.10185	-0.10185	-0.10185	-0.10185	Source (Stermole and Stermole, 2000)
Annual Capital Costs	($62,020)	($61,540)	($61,110)	($12,540)	-	($15,280)	Annual Capital Cost = (Capital Cost)*(A/P,i,n)
Annual Operating Cost Calculated	($20,000)	($32,000)	($25,000)	($7,000)	($16,000)	($15,000)	Annual Operating Cost = (Capital Cost)*(O&M)
Annual Income Calculated	$27,040	$43,260	$33,800	$0	$0	$0	∑ Annual Incomes (biogas/elec., CO2 credit, bedding reuse)
Annual Net Cost	($54,980)	($50,280)	($52,310)	($19,540)	-	($30,280)	Annual Net Cost = ∑ Annual Capital, Operating, Income
Annual Cost/Cow	($270)	($160)	($210)	($280)	-	($200)	Annual cost/cow = (Annual net cost)/(#cows)

Table D.12 Manure pit net present value analysis

12 Net Present Value Analysis			Manure Pit 2			Manure Pit 1	Comments
Assumptions							
discount rate	8%	8%	8%	8%	8%	8%	
lifetime	20	20	20	20	20	20	
P/A, 8%,20	9.8181	9.8181	9.8181	9.8181	9.8181	9.8181	Source (Stermole and Stermole, 2000)
Capital Investment	($608,970)	($604,230)	($600,000)	($123,080)	-	($149,990)	see section 1.0 Digester General Information
Annual Operating Cost	($20,000)	($32,000)	($25,000)	($7,000)	($16,000)	($15,000)	see section 5.0 Cash Flow Analysis
Annual Income Calculated	$27,040	$43,260	$33,800	$0	$0	$0	see section 5.0 Cash Flow Analysis
NPV	($539,850)	($493,680)	($513,600)	($191,810)	-	($297,260)	NPV = (Capital Investment)+(Annual Operating Costs*(P/A,i,n))+(Annual Income*(P/A,i,n))

Appendix E: Contacts

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Bibliography

AGreen Energy, L., 2011. http://www.agreenenergyllc.com/ (Accessed 10/20/2011).

AgStar, 2006. Market Opportunities for Biogas Recovery Systems: A Guide to Identifying Candidates for On-Farm and Centralized Systems. EPA-430-8-06-004. U. S. Environmental Protection Agency, Office of Environmental Information, Washington D. C.

AgStar, 2010a. Anaerobic Digestion Capital Costs for Dairy Farms. United States Environmental Protection Agency. Available at: http://www.epa.gov/agstar/documents/digester_cost_fs.pdf

AgStar, 2010b. Market opportunities for biogas recovery systems at U.S. livestock facilities. U.S. Environmental Protection Agency, Office of Environmental Information, Washington, D.C. Available at: http://www.epa.gov/agstar/documents/biogas_recovery_systems_screenres.pdf

AgStar, 2010c. U.S. Anaerobic Digester Status Report. In: U.S. Environmental Protection Agency (Ed), Washington D.C. Available at: http://www.epa.gov/agstar/documents/digester_status_report2010.pdf

AgStar, 2011a. AgStar: An EPA Partnership Program. Available at: http://www.epa.gov/agstar/

AgStar, 2011b. Anaerobic Digester Database. Available at: http://www.epa.gov/agstar/projects/index.html

AgStar, 2011c. Farmware. Available at: http://www.epa.gov/agstar/tools/project-dev/farmware.html

AgStar, 2011d. Funding Programs for Developing Anaerobic Digestion Systems. United States Department of Agriculture. Available at: http://www.epa.gov/agstar/documents/agstar_federal_incentives.pdf

Akinbami, J.F.K., M.O. Ilori, T.O. Oyebisi, I.O. Akinwumi and O. Adeoti, 2001. Biogas energy use in Nigeria: current status, future prospects and policy implications. Renewable & Sustainable Energy Reviews, 5: 97-112.

Allan, D., E. Katovich and C. Nelson, 2003. Fertilizer Value and Weed Seed Destruction Potential of Digested Manure. Anaerobic Digester Technology Applications in Animal Agriculture: A National Summit, Raleigh, North Carolina.

Amani, T., M. Nosrati and T.R. Sreekrishnan, 2010. Anaerobic digestion from the viewpoint of microbiological, chemical, and operational aspects - a review. Environmental Reviews, 18: 255-278.

An, B.X., T.R. Preston and F. Dolberg, 1997. The Introduction of low-cost Polyethylene Tube Biodigesters on Small Scale Farms in Vietnam. Livestock Research for Rural Development, 9.

Anderson, J.L., 1982. Economic Assessment of Anaerobic Digestion Systems for Dairy Waste Disposal and Energy Recovery - Effect of Selected Institutional and Technological Changes. Resources and Conservation, 8: 131-146.

Angelidaki, I. and Sanders, W., 2004. Assessment of the anaerobic biodegradability of macropollutants. Reviews in Environmental Science and Bio/Technology, 3: 117-129.

AVATAR Energy, 2011. http://www.avatarenergy.com/ (Accessed 10/20/2011).

Bassler, R., 2011. personal communication, June 27, 2011.

Beddoes, J.C., K.S. Bracmort, R.T. Burns and W.F. Lazarus, 2007. An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities. In: USDA (Ed), Vol. Technical Note No. 1, Washington D.C. Available at: http://policy.nrcs.usda.gov/OpenNonWebContent.aspx?content=18476.wba

BioProcessH2O, 2008. Pilot Project Program North Williston Cattle Company Final Report. BioProcessH2O, LLC, Portsmouth, RI. Available at: http://www.fppcinc.org/pdf/reports_bioprocesstechnologies.pdf

Bishop, C.P. and C.R. Shumway, 2009. The Economics of Dairy Anaerobic Digestion with Coproduct Marketing. Review of Agricultural Economics, 31: 394-410.

Bohn, I., L. Bjornsson and B. Mattiasson, 2007. The energy balance in farm scale anaerobic digestion of crop residues at 11-37 degrees C. Process Biochemistry, 42: 57-64.

Botero, R. and T.R. Preston, 1987. Biodigestor de bajo costo para la produccion de combustible y fertilizante a partir de excretas. CIPAV, Cali, Colombia.

Bracmort, K., R.T. Burns, J. Beddoes and W. Lazarus, 2008. An analysis of anaerobic digestion system costs on U.S. livestock production systems. ASABE Annual International Meeting, Providence, Rhode Island.

Buxton, D. and B. Reed, 2010. Disposal of Latrine waste: Is Biogas the Answer? A Review of Literature. EWB-UK National Research Conference, Leicestershire, UK.

Calander, B., 1995. Scientific Aspects of the Framework Convention on Climate Change and National Greenhouse Inventories. Environmental Monitoring and Assessment, 38: 129-140.

CCX, 2011. Chicago Climate Exchange, Market Info: Historical Data. Intercontinental Exchange, Inc., Chicago, IL. Available at: https://www.theice.com/ccx.jhtml

Chae, K.J., A. Jang, S.K. Yim and I.S. Kim, 2008. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Bioresource Technology, 99: 1-6.

Chen, Y., G.H. Yang, S. Sweeney and Y.Z. Feng, 2010. Household biogas use in rural China: A study of opportunities and constraints. Renewable & Sustainable Energy Reviews, 14: 545-549.

Cheng, J., S. Liehr and C. Lyerly, 2003. Swine Wastewater Treatment in an Integrated System of Anaerobic Digestion and Duckweed Nutrient Removal. ASAE Annual International Meeting, Paper Number: 034151, Las Vegas, NV.

Cherosky, P., Y. Li and K. Mancl, 2011. Manure to Energy Through Anaerobic Digestion. In: The Ohio State University (Ed), Vol. AEX-653.1-11, Ohio State University Extension, Columbus, OH. Available at: http://ohioline.osu.edu/aex-fact/pdf/AEX-653.1-11.pdf

Colleran, E., M. Barry, A. Wilkie and P.J. Newell, 1982. Anaerobic Digestion of Agricultural Wastes Using the Upflow Anaerobic Filter Design. Process Biochemistry, 17: 12-17.

Coppinger, E., D. Baylon and J. Lenart, 1980. Economic and Operational Experience of Full-Scale Anaerobic Diary Manure Digester. Biogas and Alcohol Fuels Production: 220-233.

CWNS, 2008. 2008 Clean Watersheds Needs Survey. USEPA Office of Water Management, Washington DC. Available at: http://water.epa.gov/scitech/datait/databases/cwns/

DSIRE, 2011. Database of State Incentives for Renewables & Efficiency. Available at: http://www.dsireusa.org/incentives/index.cfm?EE=1&RE=1&SPV=0&ST=0&searchtype=Net&sh=1

Eastern Research Group, Inc., 2011. Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures. USEPA AgStar Program. Available at: http://www.epa.gov/agstar/documents/protocol.pdf

El-Mashad, H. M., van Loon, W.K.P., and Zeeman, G., 2003. A Model of Solar Energy Utilisation in the Anaerobic Digestion of Cattle Manure. Biosystems Engineering, 84 (2): 231-238

El-Mashad, H.M., van Loon, W.K.P., Zeeman, G. and Bot, G.P.A., 2005. Rheological properties of dairy cattle manure. Bioresource Technology, 96: 531-535.

Erb, K., 2011. personal communication, June 24, 2011.

Federal Reserve, 2010. Agricultural Finance Databook. Division of Research and Statistics and Board of Governors of the Federal Reserve System, E-15. Washington D. C. Available at: http://www.federalreserve.gov/releases/e15/default_2010.htm

FERC, 2011. Electric Power Markets: National Overview. Federal Energy Regulatory Commission. Available at: http://www.ferc.gov/market-oversight/mkt-electric/overview.asp

Freund, M., 2011. personal communication, July 13, 2011.

Garrison, A.V. and T.L. Richard, 2005. Methane and manure: Feasibility analysis of price and policy alternatives. Transactions of the ASAE, 48: 1287-1294.

Gerardi, M.H., 2003. The Microbiology of Anaerobic Digesters. Wiley-Interscience, Hoboken, NJ.

Ghafoori, E. and P.C. Flynn, 2007. Optimizing the size of anaerobic digesters. Transactions of the ASABE, 50: 1029-1036.

Giesy, R., Wilkie, A. C., de Vries, A., and Nordstedt, R. A., 2009. Economic Feasibility of Anaerobic Digestion to Produce Electricity on Florida Dairy Farms. AN159. Department of Animal Science, Florida Cooperative Extension Services, Institute of Food and Agricultural Sciences, University of Florida. Available at: http://edis.ifas.ufl.edu/an159

Gloy, B.A., 2011. The Potential Supply of Carbon Dioxide Offsets from the Anaerobic Digestion of Dairy Waste in the United States. Applied Economic Perspectives and Policy, 33: 59-78.

Gloy, B.A. and J.B. Dressler, 2010. Financial barriers to the adoption of anaerobic digestion on US livestock operations. Agricultural Finance Review, 70: 157-168.

Goodrich, P., 2011. personal communication, July 12, 2011.

Goodrich, P.R., 2005. Anaerobic Digester Systems for Mid-Sized Dairy Farms. The Minnesota Project. Available at: http://www.mnproject.org/pdf/agstar%20report%20full%20update.pdf

Grogan, T., 2006. Construction Cost Index History (1918-2006). Vol. 256, McGraw-Hill Companies, Inc., pp. 43-43.

Gunnerson, C.G. and D.C. Stuckey, 1986. Anaerobic Digestion: Principles and Practices for Biogas Systems. Vol. Technical Paper No. 49, The World Bank, Washington D. C. Available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/1999/11/19/000178830_98101904164835/Rendered/PDF/multi_page.pdf

Inglis, S.F., C.A. Gooch, L.R. Jones and D. Aneshansley, 2007. Cleanout of a Plug-Flow Anaerobic Digester after Five Years of Continuous Operation. International Symposium on Air Quality and Waste Management for Agriculture, Vol. Paper No. 701P0907cd, ASABE, Broomsfield, CO.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

Karim, K., K.T. Klasson, R. Hoffmann, S.R. Drescher, D.W. DePaoli and M.H. Al-Dahhan, 2005. Anaerobic digestion of animal waste: Effect of mixing. Bioresource Technology, 96: 1607-1612.

Katovich, E.J. and R.L. Becker, 2004. Weed Seed Survival in Anaerobic Digesters. The Minnesota Project. Available at: http://www.mnproject.org/pdf/Weed%20Seed%20long%20-%20web%20cx.pdf

Kemp, M., 2011. personal communication, August 31, 2011.

Key, N. and S. Sneeringer, 2011. Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations. ERR-111. In: USDA, Economic Research Service, Washington D.C. Available at: http://www.ers.usda.gov/publications/err111/

Koutrouli, E.C., H. Kalfas, H.N. Gavala, I.V. Skiadas, K. Stamatelatou and G. Lyberatos, 2009. Hydrogen and methane production through two-stage mesophilic anaerobic digestion of olive pulp. Bioresource Technology, 100: 3718-3723.

Kramer, J., 2009. Wisconsin Agricultural Biogas Handbook. Wisconsin Focus on Energy – Renewables Program, Madison, WI. Available at: http://www.focusonenergy.com/files/document_management_system/renewables/biogas08_casestudy.pdf

Krich, K., D. Augenstein, J. Batmale, J. Benemann, B. Rutledge and D. Salour, 2005. Biomethane from Dairy Waste: A Sourcebook for the Production and Use of Renewable Natural Gas in California. Western United Dairymen. Available at: http://www.suscon.org/cowpower/biomethaneSourcebook/Full_Report.pdf

Kumar, K. V. and Bia, R. K., 2008. Solar Greenhouse Assisted Biogas Plant in Hilly Region – A Field Study. Solar Energy, 82 (10): 911-917.

Lansing, S., R.B. Botero and J.F. Martin, 2008a. Waste treatment and biogas quality in small-scale agricultural digesters. Bioresource Technology, 99: 5881-5890.

Lansing, S., J.F. Martin, R.B. Botero, T.N. da Silva and E.D. da Silva, 2010. Wastewater transformations and fertilizer value when co-digesting differing ratios of swine manure and used cooking grease in low-cost digesters. Biomass & Bioenergy, 34: 1711-1720.

Lansing, S., J. Viquez, H. Martinez, R. Botero and J. Martin, 2008b. Quantifying electricity generation and waste transformations in a low-cost, plug-flow anaerobic digestion system. Ecological Engineering, 34: 332-348.

Lazarus, W., 2008. Farm-Based Anaerobic Digesters as an Energy and Odor Control Technology: Background and Policy Issues. In: USDA Vol. AER-843, Office of Energy Policy and New Users, Washington D. C. Available at: http://www.usda.gov/oce/reports/energy/AnerobicDigesters0308.pdf

Lazarus, W., 2011. personal communication, August 1, 2011.

Lazarus, W.F., 2009. Economic Analysis of the Jer-Lindy Farms Anaerobic Digester. Methane Digester Pilot Project: Implementing Cutting Edge Technology. The Minnesota Project. Available at: http://www.mnproject.org/pdf/LCMR_Digester_factsheet_economics.pdf

Lazarus, W.F. and M. Rudstrom, 2007. The economics of anaerobic digester operation on a Minnesota dairy farm. Review of Agricultural Economics, 29: 349-364.

Lettinga, G., S. Rebac, S. Parshina, A. Nozhevnikova, J.B. van Lier and A.J.M. Stams, 1999. High-rate anaerobic treatment of wastewater at low temperatures. Applied and Environmental Microbiology, 65: 1696-1702.

Leuer, E.R., J. Hyde and T.L. Richard, 2008. Investing in Methane Digester on Pennsylvania Dairy Farms: Implication of Scale Economies and Environmental Programs. Agricultural and Resource Economics Review, 37: 188-203.

Li, J.F., Y.H. Wan and J.M. Ohi, 1997. Renewable energy development in China: Resource assessment, technology status, and greenhouse gas mitigation potential. Applied Energy, 56: 381-394.

Loomis, A. W. and Westaway, C. R., 1984. Cameron Hydraulic Data, 16th Edition. Ingersoll-Rand, Woodcliff Lake, NJ.

Lusk, P. and National Renewable Energy Laboratory (U.S.), 1998. Methane Recovery from Animal Manures the Current Opportunities Casebook. NREL/SR-580-25145, National Renewable Energy Laboratory, Golden, CO. Available at: http://www.nrel.gov/docs/fy99osti/25145.pdf

Martin, J.H., 2004. A Comparison of Dairy Manure Management with and without Anaerobic Digestion and Biogas Utilization. In: USEPA, Eastern Research Group, Inc., Boston, MA. Available at: http://www.epa.gov/agstar/documents/nydairy2003.pdf

Masse, D.I., F. Croteau and L. Masse, 2007. The fate of crop nutrients during digestion of swine manure in psychrophilic anaerobic sequencing batch reactors. Bioresource Technology, 98: 2819-2823.

Metha, A., 2002. The Economics and Feasibility of Electricity Generation Using Manure Digesters on Small and Mid-Sixed Dairy Farms. Department of Agricultural and Applied Economics. Energy Analysis and Policy Program, University of Wisconsin, Madison, WI. Available at: http://www.mrec.org/pubs/Biogas_Economics_Metha.pdf

Millen, G., 2008. Small-scale digester boosts farm economics. BioCycle, 49: 46-47.

Moser, M.A., 2005. Is a Digester Right for Your Farm? , W. D. Hoard & Sons Company, Fort Arkinson, WI. Available at: http://www.rcmdigester.com/publications/HoardsDairyman.pdf

Moser, M.A., R.P. Mattocks, S. Gettier and K. Roos, 1998. Benefits, Costs, and Operating Experience at Seven New Agricultural Anaerobic Digesters. Technical Articles and Reports, AgSTAR. Available at: http://www.mnproject.org/pdf/costbenefits.pdf

Mulbry, W., S. Kondrad, C. Pizarro and E. Kebede-Westhead, 2008. Treatment of dairy manure effluent using freshwater algae: Algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresource Technology, 99: 8137-8142.

Nelson, C. and J. Lamb, 2002. Haubenschild farms anaerobic digester. Final report, The Minnesota Project., St. Paul, MN, USA. Available at: http://www.mnproject.org/pdf/Haubyrptupdated.pdf

ENR, 2007-2011. Engineering News-Record, Construction Cost Index. 266 (18), 266 (1), 263 (1), 258/259 (24/1).

Ogejo, J. A., Wen, Z., Ignosh, J., Bendfeldt, E., Collins, Jr., E. R., 2009. Biomethane Technology. Pub 442-881. Virginia Cooperative Extension. College of Agriculture and Life Science, Virginia Tech. Available at: http://pubs.ext.vt.edu/442/442-881/442-881_pdf.pdf

Olsen, J.E. and H.E. Larsen, 1987. Bacterial Decimation Times in Anaerobic Digestions of Animal Slurries. Biological Wastes, 21: 153-168.

Pain, B.F., T.H. Misselbrook, C.R. Clarkson and Y.J. Rees, 1990. Odor and Ammonia Emissions Following the Spreading of Anaerobically-Digested Pig Slurry on Grassland. Biological Wastes, 34: 259-267.

Powers, C.A., D.D. Schulte and R.R. Stowell, 2009. Carbon Credits from Livestock Production. In: University of Nebraska-Lincoln, Vol. G1962, University of Nebraska-Lincoln Extension, Lincoln, NE. Available at: http://www.ianrpubs.unl.edu/live/g1962/build/g1962.pdf

Powers, W.J., H.H. Van Horn, A.C. Wilkie, C.J. Wilcox and R.A. Nordstedt, 1999. Effects of anaerobic digestion and additives to effluent or cattle feed on odor and odorant concentrations. Journal of Animal Science, 77: 1412-1421.

Purohit, P., A. Kumar, S. Rana and T.C. Kandpal, 2002. Using renewable energy technologies for domestic cooking in India: a methodology for potential estimation. Renewable Energy, 26: 235-246.

Rao, P.V., S.S. Baral, R. Dey and S. Mutnuri, 2010. Biogas generation potential by anaerobic digestion for sustainable energy development in India. Renewable & Sustainable Energy Reviews, 14: 2086-2094.

Ravindranath, N.H. and R. Balachandra, 2009. Sustainable bioenergy for India: Technical, economic and policy analysis. Energy, 34: 1003-1013.

Rodriguez, L. and T.R. Preston, undated. Biodigester Installation Manual. In: University of Tropical Agriculture Foundation Finca Ecologica, University of Agriculture and Forestry, Ho Chi Minh City, Vietnam. Available at: http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGA/AGAP/FRG/Recycle/biodig/manual.htm

Roos, K.F., J.B. Martin and M.A. Moser, 2004. AgStar Handbook: A Manual for Developing Biogas Systems at Commercial Farms in the United States. EPA-430-B-97-015 In: USEPA, Washington DC. Available at: http://www.epa.gov/agstar/documents/AgSTAR-handbook.pdf

Rubio-Loza, L.A. and A. Noyola, 2010. Two-phase (acidogenic-methanogenic) anaerobic thermophilic/mesophilic digestion system for producing Class A biosolids from municipal sludge. Bioresource Technology, 101: 576-585.

Sahlstrom, L., 2003. A review of survival of pathogenic bacteria in organic waste used in biogas plants. Bioresource Technology, 87: 161-166.

SERCC, 2011. Historical Climate Summaries for Maryland. Southeast Regional Climate Center, The University of North Carolina, Chapel Hill, NC. Available at: http://www.sercc.com/cgi-bin/sercc/cliMAIN.pl?md0700

Scott, N. and J. Ma, 2004. A Guideline for Co-Digestion of Food Wastes in Farm-based Anaerobic Digesters. In: Cornell University, Department of Biological and Environmental Engineering, Vol. Fact Sheet FW-2, Cornell Cooperative Extension. Available at: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Fact_Sheets/Codigestion_factsheet.pdf

Scott, N., J. Pronto and C. Gooch, 2010. Biogas Casebook: NYS On-farm Anaerobic Digesters. Department of Biological and Environmental Engineering Cornell University, Ithaca, NY. Available at: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Case_Studies/Northeast_Biogas_Case_Study_Book.pdf

Scruton, D., 2007. Vermont's Experience with the Adoption of Anaerobic Digestion on Farms. AgStar National Conference, Sacramento, CA.

Scruton, D. and O. Whitcomb, 2005. Manure Digesters for Energy - What's Happening on Vermont Farms? , Alternative Energy on the Farm Forum, University of Vermont Extension, Burlington, VT. Available at: http://www.uvm.edu/~cmorriso/AltEnergy/manuredigest.pdf

Scruton, D.L., S.A. Weeks and R.S. Achilles, 2004. Strategic Hurdles to Widespread Adoption of On-Farm Anaerobic Digesters. Dairy Manure Management Systems, Vol. Paper Number: 044164, ASAE/CSAE, Ottawa, Canada.

Stermole, F.J. and J.M. Stermole, 2000. Economic Evaluation and Investment Decision Making. Investment Evaluations Corporation, Lakewood, CO.

Stokes, J.R., R.M. Rajagopalan and S.E. Stefanou, 2008. Investment in a Methane Digester: An Application of Capital Budgeting and Real Options. Review of Agricultural Economics, 30: 664-676.

Tchobanoglous, G., F.L. Burton, and H.D. Stensel, 2003. Wastewater engineering: treatment and reuse. McGraw-Hill, Boston, MA.

Trivett, A. and M. Hall, 2009. Feasibility of Biogas Production on Small Livestock Farms. In: Department of Engineering, University of Prince Edward Island, Charlottetown, PEI. Available at: http://ecopei.ca/Final-biogas_report_2008.pdf

United Nations, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Framework Convention on Climate Change. Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf

US EIA, 2010. Annual Energy Review 2009. Energy Information Administration, Office of Energy Markets and End Use, DOE/EIA-0384. Washington, DC. Available at: http://www.eia.gov/totalenergy/data/annual/index.cfm

US EIA, 2011. Natural Gas Industrial Prices. U.S. Department of Energy, Energy Information Administration, Washington, DC. Available at: http://www.eia.gov/dnav/ng/hist/n3035us3m.htm

US EIIP, 1997. EIIP Emission Inventory Improvement Program. Vol. VIII chapter 7, USEPA, Office of Air Quality Planning and Standards, Research Triangle Park, NC. Available at: http://www.epa.gov/ttn/chief/eiip/techreport/

USEPA, 2010. EPA Helps Launch Global Methane Initiative to Cut Greenhouse Gases/Countries to Fight Climate Change While Developing Clean Energy and Stronger Economies. 2010 News Release, United States Environmental Protection Agency, Newsroom. Available at: http://yosemite.epa.gov/opa/admpress.nsf/2010%20Press%20Releases?OpenView

USEPA, 2011. Inventory of U.S. Greenhouse Gases Emissions and Sinks: 1990 - 2009. EPA 430-R-11-005. USEPA, Washington DC. Available at: http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Complete_Report.pdf

US NASS, 1999. 1997 Census of Agriculture. USDA, National Agricultural Statistics Service, Washington, DC. Available at: http://www.agcensus.usda.gov/Publications/1997/index.asp

US NASS, 2009. 2007 Census of Agriculture. Volume 1, Geographic area series. Part 51, United States summary and state data. USDA, National Agricultural Statistics Service, Washington, DC. Available at: http://www.agcensus.usda.gov/Publications/2007/Full_Report/usv1.pdf

van Nes, W.J., 2006. Asia hits the Gas: Biogas from Anaerobic Digestion Rolls out Across Asia. Renewable Energy World, January-February 2006: p. 102 - 111.

Vanhorn, H.H., A.C. Wilkie, W.J. Powers and R.A. Nordstedt, 1994. Components of Dairy Manure Management Systems. Journal of Dairy Science, 77: 2008-2030.

Ward, A.J., P.J. Hobbs, P.J. Holliman and D.L. Jones, 2008. Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology, 99: 7928-7940.

Weeks, S., 2003. Anaerobic Fixed-Film Digester System for Dairy Manure. Northeast Agricultural & Biological Engineering Conference, Vol. Paper # 03-023, Storrs, CT.

Weeks, S., 2011. personal communication, June 6, 2011.

Wilkie, A.C., 2000a. Anaerobic Digestion: Holistic Bioprocessing of Animal Manures. Animal Residuals Management Conference, Water Environmental Federation, Alexandria, VA, pp. p. 1-12.

Wilkie, A.C., 2000b. Reducing dairy manure odor and producing energy. Biocycle, 41: 48-50.

Wilkinson, K.G., 2011. A comparison of the drivers influencing adoption of on-farm anaerobic digestion in Germany and Australia. Biomass & Bioenergy, 35: 1613-1622.

Wright, P. and S. Inglis, 2003. An Economic Comparison of Two Anaerobic Digestion Systems on Dairy Farms. ASAE Annual International Meeting, Vol. Paper Number: 034154, ASAE, Las Vegas, NV.

Wright, P., S. Inglis, J. Ma, C. Gooch, B. Aldrich, A. Meister and N. Scott, 2004. Comparison of Five Anaerobic Digestion Systems on Dairy Farms. ASAE/CSAE Annual International Meeting, Vol. Paper No. 044032, ASAE/CSAE, Ottawa, Ontario.

Wright, P. and J. Ma, 2003a. Anaerobic Digester at Spring Valley Dairy: Case Study. In: Cornell University Manure Management Program, Case Study AD-6. Available at: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Case_Studies/Spring_Valley_Case_Study.pdf

Wright, P. and J. Ma, 2003b. Fixed Film Digester at Farber Dairy Farm: Case Study. In: Cornell University Manure Management Program, Case Study AD-3. Available at: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Case_Studies/Farber_Case_Study.pdf

Yiridoe, E.K., R. Gordon and B.B. Brown, 2009. Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. Energy Policy, 37: 1170-1179