

The Pennsylvania State University

The Graduate School

College of Engineering

COMPUTER OPERATION AND MONITORING FOR A DAIRY MANURE

ANAEROBIC DIGESTER

A Thesis in

Agricultural and Biological Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2009

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Abstract

The dairy industry is an important part of Pennsylvania's agricultural industry. One of the challenges in dairy farming is properly managing manure. Manure can be used as a fertilizer but also has environmental concerns. Anaerobic digesters offer farmers the opportunity to gain more benefits from their manure. Anaerobic digesters produce biogas which is approximately 60% methane. The methane can be burned in an engine generator set to produce electricity and heat. Both the electricity and heat can be used to help offset some of the farm's costs.

However, farmers have little knowledge and time to devote to digester operation. For that reason, problems can be difficult to correct and uncorrected problems can lead to digester failure. A computerized monitoring and operation system could alert the farmer to problems sooner and allow the farmer to remotely operate the digester, and thus save the farmer time and reduce the risks of digester failure. The pilot-scale experiments described in this thesis provide the basis for further development and commercial implementation of computerized dairy digester operation and monitoring systems.

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1.0 Introduction and Justification

Technology has helped to reduce management requirements and performance variability in many industries, including farming. One aspect of livestock production that could benefit from improved technology is manure utilization. Manure accumulation is a problem facing every dairy farmer. Uncontrolled manure land application can have damaging consequences for both nearby waterways and the land itself. The land can become over fertilized and waterways can begin to accumulate algae, which reduce the oxygen in the water and kill fish and other aquatic life (Morse, 1995). While a natural byproduct of dairy production, manure accumulation requires environmental and economical solutions. The manure must be stored until it can be spread, and then generally provides the farm with only one benefit, the nutrients to fertilize crops.

One potential solution utilizes microorganisms to both reduce the environmental impact of manure and also provide additional benefits to the farm. Microorganisms are used in a large number of food and pharmaceutical manufacturing processes. With dairy manure, microorganisms utilized in an anaerobic digester can help reduce the volume of waste and lessen the dairy herd's environmental impact through the reduction of greenhouse gas emissions and odors.

Anaerobic digesters can be used to help dairy farms manage their manure, while offering a number of benefits over traditional manure management systems, including electricity and heat generation, odor control, and pathogen reduction. However, anaerobic digesters do not make the manure disappear and do not eliminate the need for manure storage. They are merely a part of the manure management system. Current anaerobic digesters require significant time and expertise of the farmer or an operator. Remote monitoring systems could reduce the required time and expertise, and potentially shift the responsibility of digester management from the farmer to a third party operator.

This project developed a monitoring system that could be used to automate data collection and then potentially transmit that data to the farm office or a remote location. To test the sensors and data acquisition system, a lab-scale anaerobic digester was constructed, instrumented, and monitored with a computer. Following lab-scale monitoring, a fully operational digester was instrumented and prepared for remote monitoring. This work lays the groundwork for remote operation of a digester by third-

party contractors, and also for automated computer control. The goal was to demonstrate how computers can provide operators with more information on digester conditions, quickly and in one place, which would reduce time spent on digester management and monitoring. Through the use of third party operators, manure management could be contracted out and thus relieve the farmer of that responsibility.

1.1 Dairy Industry Background and Potential for Anaerobic Digestion

In 2008 Pennsylvania was the fifth largest milk producing state, with production exceeding 4.7 billion kg (10.5 billion pounds) of milk (USDA-NASS, 2009). Economically, the dairy industry has the highest economic value of any Pennsylvania agricultural production sector, at approximately \$2.2 billion in 2005 (USDA-NASS, 2009).

Dairy cows produce about 68 kg (150 lbs) of manure a day (ASABE, 2005). In 2005 there were 550,000 dairy cows in Pennsylvania (USDA-NASS, 2009) which correlates to approximately 37 million kg (over 82 million lbs) of manure a day. If not properly managed, manure can have detrimental environmental impacts on both soil and water systems. It is therefore important for a farmer to implement good management practices when dealing with the storage and disposal of manure.

Anaerobic digesters have the ability to help improve manure management. While digesters do not make manure disappear, they reduce the release of greenhouse gases and retain the nutrients for fertilizing fields. Biogas from the digestion process can be combusted in an engine generator set to create electricity. Waste heat from the combustion process may also be captured and used for barn heating in the winter months or to provide hot water for the dairy year round. By separating solids from the digester effluent, farmers can produce their own bedding material. Odor and greenhouse gas reductions are two other benefits from anaerobic digestion; however, it is difficult to place a value on these benefits. The value a neighbor would place on the reduction of odor has more than monetary dimensions. Similarly the value of a reduction in nuisance complaints to the farmer might translate to the ability to stay in business or get approval for an expansion. Livestock operations often have a distinct odor which many people consider a nuisance. A digester can help to greatly reduce and limit the area exposed to

odors. Digested manure has little odor, and once manure enters the sealed digester it is contained and can not be smelled. The reduction in greenhouse gases is another advantage of a digester which has limited monetary value in the US today, but is a major incentive for digesters in other developed countries.

1.2 Digester Economics

In 2007 the NRCS performed an analysis of anaerobic digesters for livestock production facilities. Since electricity and heat are the two most desirable products from anaerobic digestion, that study compared the cost of these digester-generated energy outputs with standard commercial costs. In this analysis, electricity and heat provided farms with the largest revenue stream from anaerobic digestion. Typically, electrical generation equipment makes up the largest capital cost for a digester project (NRCS, 2007). This large capital investment contributes to average retail electrical cost being less than dairy digester electrical production cost on a \$/kWh basis (NRCS, 2007). However, producing heat from anaerobic digesters is cheaper than purchasing heating fuels (natural gas, diesel fuel, propane, heating oil, and gasoline) on \$/GJ basis.

In 1999 a dairy farm in Minnesota began operation of an anaerobic digester with 425 cows (Nelson and Lamb, 2002). During the study the herd size was increased to 700 cows. The farm was able to receive grants and technical assistance covering 36% of the project cost. In addition, a no-interest loan was provided covering 42% of the project cost. This left 22% of the project to be paid directly by the farm (Nelson and Lamb, 2002). A financial analysis was performed assuming the farm had to payback the entire digester cost, which was not the actual case. Under the four scenarios examined the payback period ranges from 5-11 years (Nelson and Lamb, 2002). The farm was able to receive a favorable buyback rate from the utility at the full retail rate. The farm has benefited financially from the digester with a total electrical value of approximately \$80,000 in 2001 (Nelson and Lamb, 2002).

Another case study at a Wisconsin dairy farm shows the digester generating \$101 per cow-year following a 6.3 year payback period (Martin, 2005). During the study the herd size was increased from 750 to 860 cows. The farm separates the digested solids for its own bedding. They have also been able to sell excess solids as bedding for another

farm. This provides an additional revenue stream to the farm. In this case the engine-generator set is owned and operated by Alliant Energy, the local power company (Martin, 2005). The farm currently receives \$0.015 per kWh because Alliant owns the engine-generator set. If the farm owned the set they would receive \$0.06 per kWh (Martin, 2005). The primary economic benefit to the farm comes in the form of avoided bedding costs. This is estimated at \$60,000 a year and the selling of solids provides an estimated \$8,600 a year. Electricity generation provides approximately \$18,000 a year. This provides the farm with a total income of just under \$87,000 a year (Martin, 2005).

A study performed by Garrison and Richard (2005) examined the financial viability of digesters under various scenarios. They found that with favorable electricity rates, the break-even dairy herd size supported by a digester could be reduced from 330 head to between 148-234 head of cattle. Pennsylvania had 330 farms with 200+ head of cattle in 2005 (USDA-NASS, 2006c).

1.3 Overview of the Anaerobic Digestion Process

Anaerobic digestion is a biological process where manure and other organic residues are converted into methane and carbon dioxide gas by microorganisms. Conceptually, the process has three distinct parts: hydrolysis, acid formation, and methane formation. Hydrolysis breaks down large molecules such as protein and carbohydrates into their constituents. In the acid formation stage, two distinct fermentations occur. The first fermentation converts the organic material into volatile fatty acids (VFA) and hydrogen gas by microorganisms called acetogens. A secondary fermentation takes place converting a number of these acids into acetic acid. During methanogenesis, methane producing microorganisms, methanogens, use the VFAs, primarily acetic acid, and hydrogen to form biogas, a gas mixture composed of methane and carbon dioxide.

Like all living things, microorganisms within the anaerobic digestion process have certain conditions that they need in order to survive and continue their metabolic processes. Methanogens are particularly sensitive compared to their VFA producing counterparts, requiring a pH between 6 and 8 and a temperature in either the mesophilic (30-40 C) or thermophilic (50-60 C) regions for favorable growth rates, which even under

optimum conditions are relatively slow. The slow growth rate may result in the methanogenic community being unable to grow as quickly as they are leaving the system with digested manure, a condition known as washout.

One common limiting factor to anaerobic digestion is an imbalance between the acid formation and methane formation stages. This imbalance has two potential limiting effects. Hydrogen gas is produced by the acid formation stage and used in the methane formation stage. If the hydrogen gas builds up, it changes the chemistry of the digester environment and the energetics for some of the microorganisms become unfavorable. This can then halt hydrolysis and some of the acid formers. A second consequence of acid formation outpacing methane formation is the build up of organic acids lowering the pH. By lowering the pH, the methanogens can become inhibited. Once the methanogens are inhibited, they will no longer destroy the VFAs and produce methane. Since any inhibition of the methanogens results in a buildup of VFAs, this problem may begin to compound. The buildup of VFAs causes the pH to drop further, increasing the inhibition of methanogens. Quickly, the point will be reached where the digester must be shut down and restarted with new feedstock. The typical solution to this problem is to either stop feeding the digester or slow down the feeding. This solution relies on slowing the VFA production by providing less substrate for the acetogens. This also places one more burden on the operator to determine the necessary feeding rate, and how long to slow/stop feeding. Given the potential for pH “upsets”, pH monitoring and control within a digester is important to ensure continuous and steady operation.

Temperature monitoring and regulation is another important factor. As mentioned earlier, methanogens grow best in the mesophilic or thermophilic temperature regions. If a digester is not operated within one of these ranges, methanogenic growth slows. This slower growth increases the possibility of washout, and also the possibility of the acetogens outpacing the methanogens and reducing digester pH. A reduction in digester pH creates a compounded problem with the temperature problem. It is necessary to maintain strict temperature regulation to ensure the best conditions for methanogenic growth, which helps maintain digester stability.

Since the acetogens have a faster growth rate than the methanogens, it is also important to try and manage the substrate concentration within the digester to maintain a

quasi-steady-state condition. This can be done through altering the digester loading rate through the use of dilution water. Using the previous day's biogas production, a control system could determine the proportion of water and manure for the current day's feeding, with any excess manure going to temporary storage. By controlling the substrate concentration, biogas can be produced at a steady rate and with consistent levels of methane. Consistent methane production is both an indicator of good management and a desired outcome for most on-farm digesters.

1.4 Need for Remote Monitoring

In 1998 Lusk reported there were 28 operating anaerobic digesters and 10 under construction/planning phases in the United States. Lusk (1998) found that 29 digesters were no longer operating, primarily because of the difficulty in managing the digester.

In the previous section, some key and easily measurable parameters to ensure steady biogas production were identified. Monitoring these key parameters could help make digesters a more consistent and manageable farm resource.

One of the main disadvantages of implementing an anaerobic digester currently is the need to physically monitor the digester. Farmers do not have much time to spend on a digester project that requires regular on-site attention, especially if problems arise. Remote monitoring could allow the farmer to periodically check a computer screen. The farmer would not have to visit the digester every day to know what is occurring. The farmer could also quickly see a problem with the digester and begin to take action or formulate a plan to address the problem before complete failure occurs. With a remote monitoring system, these same functions could also be accomplished by a third party operator, with the expertise to monitor and maintain many digesters within a region.

2.0 Literature Review

As stated previously, it is estimated that more than 38 million kg (84 million lbs) of manure are produced daily in Pennsylvania. Morse (1995) documented a number of environmental problems associated with mismanagement of manure such as eutrophication of waterways, water pH, and salt build up in soils. Anaerobic digesters provide odor reduction and aid in the reduction of green house gas emissions. Research has shown that under certain conditions, anaerobic digesters can be a financially viable manure management practice (Garrison and Richard, 2003; Nelson and Lamb, 2002; Martin, 2005). However, a large number of previously built digesters have failed due to improper management (Lusk, 1998). Computer monitoring and operation could help ease a number of management problems. Through the addition of remote monitoring, it becomes possible to establish a central monitoring station where trained operators can monitor and correct digester operational problems for many individual farms, further easing the burden of manure management on the farmer. While such a station is still in the future, the intent of this research is to help make it a possibility. Even without such stations, remote monitoring has value for on-farm implementation. By allowing the farmer to evaluate his or her digester from the main office area, the digester's condition can be checked faster and more frequently. This may also help farmers to identify digester problems earlier.

This literature review will begin with a discussion of anaerobic digestion including the biological process as well as an overview of the differing digester types. From there it will be necessary to explore the state of sensor technology and remote monitoring. This information provides a starting point for digester instrumentation and control.

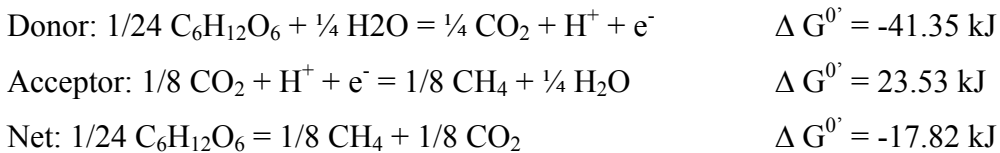
The next section will discuss the application of control systems to anaerobic digesters. Eventually controls should be folded into a whole digester automation package. Effective automatic controls will further reduce problems and the management time associated with digester operations. This should provide a complete picture of the state of anaerobic digestion technology with respect to operations, monitoring, and control.

2.1 Anaerobic Digestion Conditions

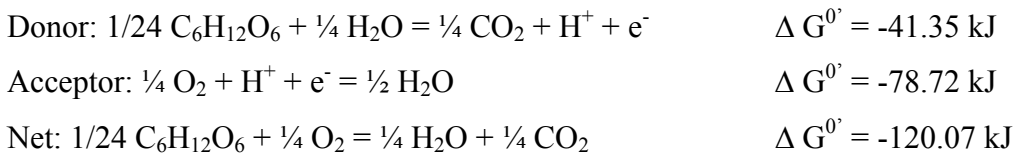
Anaerobic digestion as a way to treat wastes is not a new idea. It has been implemented in wastewater treatment for a long time. McCarty wrote a series of articles in 1964 which describe the fundamentals about the microorganisms and the necessary conditions for anaerobic digestion.

From a bioenergetics perspective, anaerobic digestion does not provide as much energy to the microorganisms as an aerobic treatment process (McCarty, 1964; Rittman and McCarty, 2001). This results in slower microbial growth and reduced biomass production (McCarty, 1964; Rittman and McCarty, 2001). The reason for this is that oxygen, which is used in aerobic systems, is a much better electron acceptor than carbon dioxide. Because of this, more energy can be generated from the use of oxygen than from carbon dioxide. A comparison of the energetics for both an aerobic and anaerobic system is provided below.

Methanogenesis of Glucose:



Aerobic Oxidation of Glucose:



(Rittman and McCarty, 2001)

The results show the aerobic system generates 120 kJ of energy compared to the nearly 18 kJ from the anaerobic system. The anaerobic system provides the microorganisms with only 14.8% of the energy in the aerobic system. However the stoichiometry in the aerobic system produces water and carbon dioxide as the primary products. Neither of these are useful fuels for heating or electrical generation. The anaerobic system creates methane gas, which, as the primary constituent of natural gas, is

a very attractive renewable energy resource. For both of these sets of reactions a certain amount of the energy available to the microorganisms will be used for growth. In anaerobic reactions, the microbes access a smaller fraction of the energy in the wastes, so they produce less microbial biomass, and the difference is available as methane in the biogas.

It has been mentioned earlier that anaerobic digestion has two optimal temperature ranges. The first, around 35 C, is mesophilic, and the second, around 55 C, is thermophilic. It should be noted that the temperature ranges do not overlap, as there are different microbial populations involved. For both temperature ranges, there is a limit above which increasing the temperature starts to result in lower gas production.

Anaerobic digestion also has an optimal pH range, from pH 6.6 to 7.6. Because of the organic acids generated by acetogenesis, it is important to ensure the feedstock has the necessary buffering capacity to minimize upsets during digestion. Dairy manure does provide some buffering capacity to help maintain the necessary pH while still allowing the acetogens to decompose the organic material into volatile fatty acids (VFAs). In addition to the manures' buffering capacity, anaerobic digestion also produces ammonia, whose alkalinity can counteract some of the acidity associated with VFAs. Angelidaki (1993) studied the effects of ammonia, which can become inhibitory to anaerobic digestion; however, a high ammonia content feedstock is necessary for ammonia toxicity to become a serious problem. Ammonia toxicity is not a common problem for dairy manure digesters.

The anaerobic digestion process occurs in three phases. Figure 2.1 provides a flow chart for the process (Brock, 2006). The first phase is the hydrolytic stage where large organic molecules are broken down into their constituents. The second stage is the acid formation stage. This stage consists of two distinct fermentation processes. The first fermentation takes the simpler organic molecules created by hydrolysis and converts them into an array of organic acids (Brock, 2006). Since the methanogens cannot utilize many of the organic acids created by the primary fermentation, a second fermentation is necessary, which converts many of the unusable organic acids into acetic acid (Brock, 2006). The final stage is methane formation. The three primary VFA's produced are acetic, butyric, and propionic acids (McCarty, 1964).

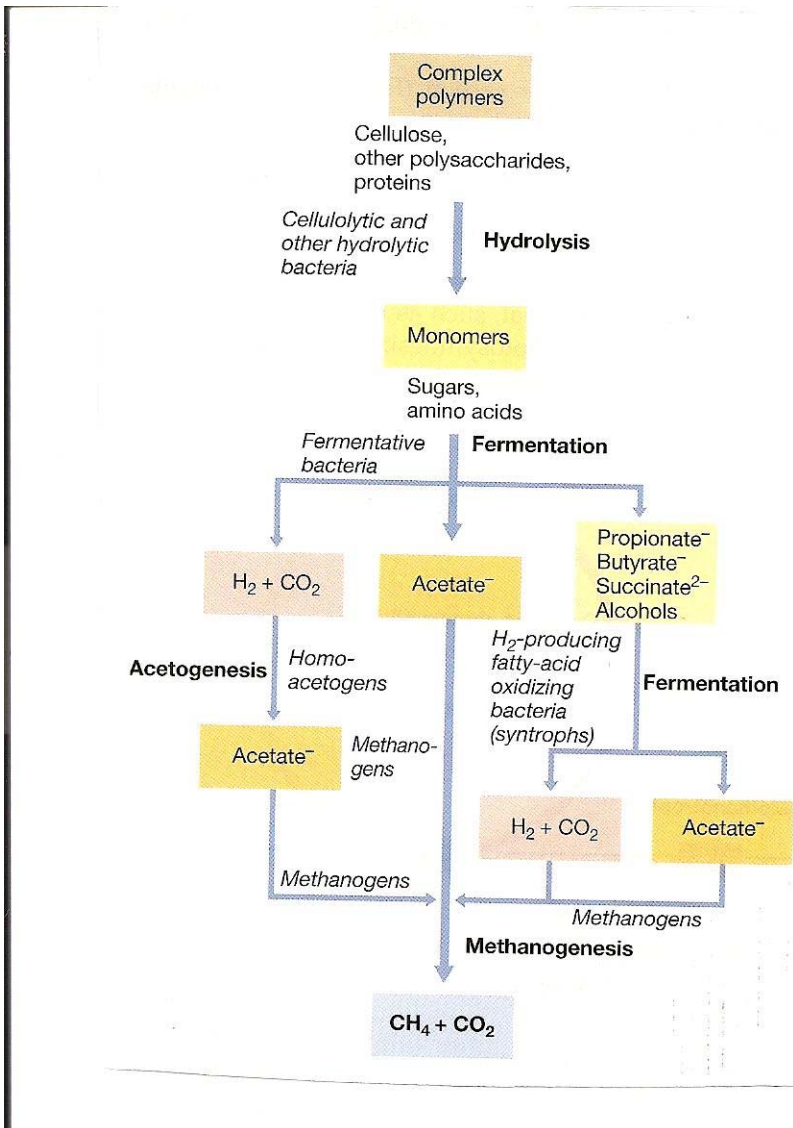


Figure 2.1: Anaerobic Food Web (Brock, 2006)

The final phase involves the methanogenic microorganisms converting the VFA's and hydrogen into methane and carbon dioxide gas. The methane gas makes up approximately 65% of the gas produced. The remainder of the gas is primarily carbon dioxide with traces of hydrogen sulfide and ammonia (Brock, 2006). The exact stoichiometry is determined by the composition of the feedstock being decomposed during the digestion process.

The anaerobic digestion process is accomplished by a consortium of microorganisms. These microorganisms have a syntrophic relationship (Brock, 2006). If one group becomes inhibited, it can result in the instability of the entire process. An example is hydrogen gas production and usage. If hydrogen gas, a product of the fermentation steps, builds up, it begins to inhibit some of the fermenters (Brock, 2006). Therefore, it is important the methanogens utilize the hydrogen gas quickly.

2.1.1 Digester Models

When operating a process, it is important to understand its limits. Amorim et al. (2005) performed research to model an anaerobic digester's reaction to increasing influent concentrations and to shock loads. The goal was to examine the reactor's stability in response to varying influent concentrations. The authors also wanted to quantify the system's limitations. The system used was a horizontal-flow anaerobic immobilized biomass (HAIB) reactor. The reactor was 100 cm long with a diameter of 5 cm giving the reactor a length to width ratio of 20. Polyurethane foam made up an inert matrix for biofilm growth and biomass utilization (Amorim et al., 2005). The researchers used a synthetic substrate for their experiments rather than wastewater (Amorim et al., 2005). They concluded that the shock load did not cause any process inhibition. This load was three times the organic loading rate for one hydraulic retention time. This was performed after the reactor reached stability at the base organic loading rate. While the shock loads did cause an increase in effluent chemical oxygen demand (COD) and total volatile acids (TVA) concentrations, the system recovered in 17 hours (Amorim et al., 2005). The authors conclude the maximum capacity of the anaerobic digester was not reached because the digester was able to recover. An interesting observation from this research is the COD profile. The profile shows a gradual decrease in COD along the length of the digester (Amorim et al., 2005). They also observed "the most active biomass was formed in the inlet zone" (Amorim et al., 2005). Even though the maximum capacity of the digester was not characterized, the study still provides information which is valuable about the conditions within an anaerobic digester. This information is important in order to understand how the digester is working and what areas are most critical to monitor.

Blumensaat and Keller (2005) applied the International Water Association's (IWA) Anaerobic Digestion Model No. 1 (ADM1) to a two-stage anaerobic digester with a thermophilic first stage and a mesophilic second stage. A 'benchmark implementation' was performed where the authors' model was compared with AQUASIM 2.0. The authors' model was also tested against a pilot-scale plant. The two reactors were continuously mixed, and partial control was achieved through a programmable logic controller (PLC). Constant temperatures (55 C for the thermophilic pre-treatment stage and 35 C second stage) were maintained within the two reactors. The model accurately predicted biogas volume and flow, both low and medium loads. Blumensaat and Keller (2005) also found that as loading increased, model accuracy decreased.

The effect of mixing on anaerobic digester production has been modeled by Keshtkar et al. (2003). Their reactor was assumed to consist of two regions: a flow-through region and a retention region. The amount of mixing in their simulation was based on information found in literature (Keshtkar et al., 2003). The experimental conditions were a temperature at 35 C, 15-day hydraulic retention time (HRT), atmospheric gas pressure, and also a gas to liquid volume ratio of 1:10. Three different mixing conditions were simulated. Methane yield was found to increase with both retention time and amount of mixing (Keshtkar et al., 2003). The model was compared with previously published results, including from a two-stage anaerobic sequencing batch reactor which used dairy manure as a substrate (Keshtkar et al., 2003). This research provides further understanding about manure digestion that could be valuable when making decisions about features to place on a digester being built.

All these models aid in the understanding of the processes occurring within an anaerobic digester. This understanding aids in identifying the necessary parameters to monitor, which spurs research for better sensors as well as understanding what information a computer requires for digester operation.

2.1.2 Digester Types

There are many different digester designs and types. This section serves to provide an overview of some designs that have been used in on-farm systems. The discussion includes some key parameters and typical operating conditions.

2.1.2.1 Plug Flow

The first type of digester to be discussed is the plug flow design. This design has been attractive to dairy farms in the past because of its ability to handle high solids content. Figure 2.2 below provides an illustration for a plug flow design.

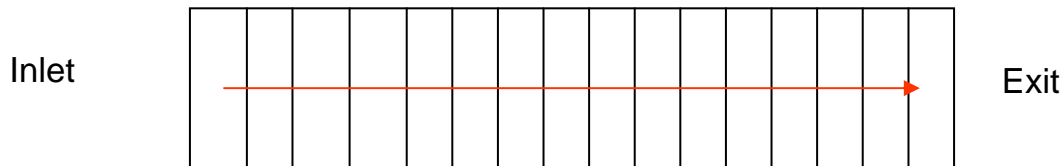


Figure 2.2: Plug flow diagram illustration

In this design, the digester has no mixing system. As material is loaded into one end of the digester, an equal volume is displaced out of the digester at the other end (Rittman and McCarty, 2001). Everything in front of the recently loaded material is pushed down the digester. Each of these loadings can be thought of as a plug, with later plug loads forcing previous plugs through the digester. Each plug will start with a low concentration of microorganisms and a high concentration of substrate. As it continues down the digester this situation reverses, and when the plug exits it should have a low concentration of substrate and a high concentration of microorganisms (Rittman and McCarty, 2001).

2.1.2.2 Complete Mix

The second major type of digester is referred to as a complete mix system. This design uses mixing to obtain an equal concentration of both micro-organisms and substrate throughout the entire digester (Rittman and McCarty, 2001). Mixing can be achieved in a number of ways: gas can be recirculated, a mechanical stirrer can be used, the digester's material itself can be recirculated, and there are yet other methods (Rittman and McCarty, 2001; Metcalf and Eddy, 2003). Figure 2.3 provides an illustration of this type of system.

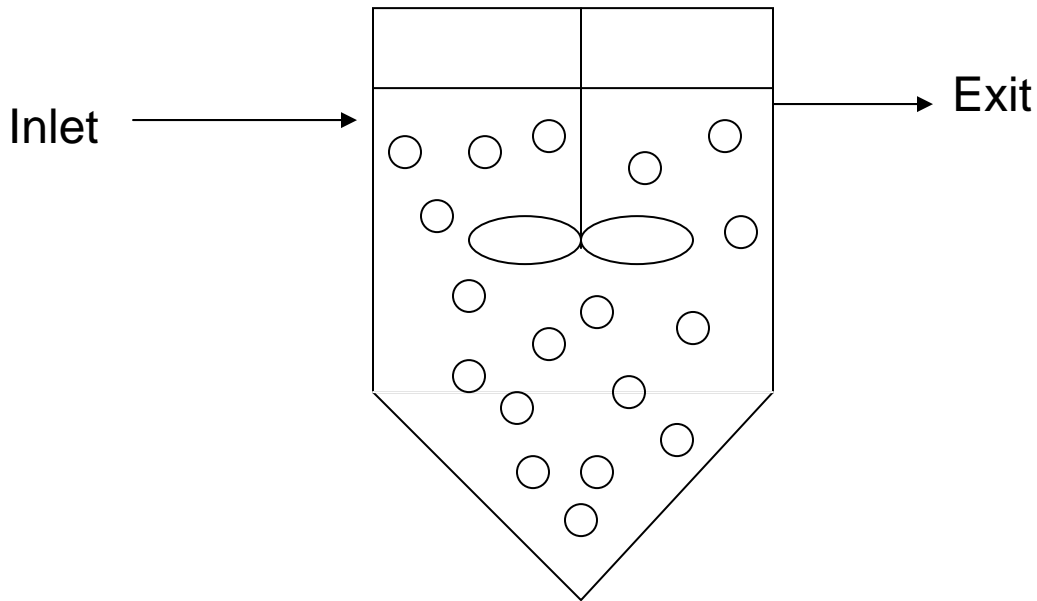


Figure 2.3: Complete Mix digester illustration

2.1.2.3 Other Designs

There are many other types of digester systems, some of which will be touched on here. There are multiple types of phased reactor systems. This type of system consists of two tanks with each tank operating under differing conditions. The two broad classifications of this type are temperature-phased and acid-phased. In temperature phased digestion, one reactor is operated at the mesophilic temperature range while the other reactor is operated in the thermophilic region (Metcalf and Eddy, 2003). For acid phased digestion, the first phase is where acetogenesis occurs and methanogenesis occurs in the second reactor (Rittman and McCarty, 2001; Metcalf and Eddy, 2003).

Another anaerobic storage and treatment system common in the livestock farming industry is a lagoon system. For this type of digester, a manure lagoon is created and then covered (Metcalf and Eddy, 2003). The cover prevents oxygen from reaching the manure and digestion can occur. Also a pipe must be used to move gas from the digester to the point of utilization.

There is also a fluidized bed system. For this type of design, some media is placed within the digester to give the microorganisms a surface to grow on (Rittman and McCarty, 2001). With this type of system the influent can be moved through the digester

faster. There are also many designs that include upflow and downflow sludge blankets (Rittman and McCarty, 2001).

The number of digester designs is large, but the microbiological process is the same for every design. To have a successful digester, the organic material must be broken down, and in order to achieve that result, the necessary growth conditions for microorganisms must be maintained.

2.2 Sensing Technology for Anaerobic Digesters

Sensors are often cited as the primary limitation to the control of anaerobic digesters. Spanjers and van Lier (2006) provided an overview of current sensing technology. They conclude that “the majority of in-line measuring techniques is still under development and applied on a laboratory scale.” (Spanjers and van Lier, 2006). They also conclude that anaerobic processes are still largely dependent upon “manual laboratory analysis” and the adaptation of the system by a “qualified operator.”

Chromatography, electrochemistry, spectrometric, titrimetric, observers, and some other principles have all been explored as sensing options for anaerobic digestion (Spanjers and van Lier, 2006). Part of this exploration included determining the capabilities of these sensing styles as applied to an anaerobic digester. The research focused on the sensors’ ability to provide quick, online data.

Spanjers et al. (2006) investigated the use of infrared monitoring as an inline sensing option to increase the ability to apply controls to a wastewater anaerobic digester. There was some difficulty performing the onsite sensor calibration because of the low concentrations. However, the measurements were found to agree with measurements taken in a lab. The authors noted the need for improved hardware, but otherwise obtained good agreement from the sensor system compared with conventional lab analysis.

Steyer et al. (2004) performed work to look at the use of software sensors to improve sensor fault recognition. In addition to fault recognition, they combined conventional sensors with some more advanced sensors. A TOCmeter, titrimetric sensor for measuring alkalinity, VFAs and bicarbonate, and finally an infra-red spectrometer to measure alkalinity, VFAs, total organic carbon, and dissolved CO₂ (Steyer et al, 2004).

These developments provide more reliable sensors for anaerobic digesters and help to overcome current challenges in sensing systems. Part of this system works by comparing measurements from multiple sensors. If the measurements do not agree, then at least one of the two sensors must be faulty. Steyer et al. (2004) implemented their system on a working digester. However, some faults did occur with various sensors, and some drawbacks of the proposed system were noted. The system would require a lot of computing power, and the authors conclude that to avoid this problem, the sensors should be divided into small computing blocks. Using the smaller computing blocks would also increase the speed of fault recognition.

Sensing technology is improving rapidly, and that allows for more accurate and faster control. By improving sensing capabilities, more can also be learned about anaerobic digestion which can help with the design of digesters as well as in the aspect of control. Improved sensors allow a control system to control more of the parameters and maintain a digester at peak operating conditions.

2.3 Proportional and Integral Control in Anaerobic Digesters

In applying controls to anaerobic digesters, lack of appropriate sensors and the complexity of the biological process pose significant problems. In order to overcome these problems, various control strategies have been attempted. The primary current limitations are the need for a human operator, the lag time involved in deciding upon a control action, a lack of testing, or some combination of the three.

There are a number of types of control systems. Bateson (2002) presents the general characteristics of different types of control strategies. Proportional (P) and integral (I) are two broad control theories that are usually present within a control system (Bateson, 2002). The two theories can be combined to form a PI controller.

Due to limitations in sensing technology, a PI controller will have difficulty providing proper control of an anaerobic digester. Adaptive controls are designed to adapt to the process over time (Bateson, 2002). Within adaptive control, Bateson (2002) presents two broad categories: process-based tuning and pattern recognition using stored knowledge. Process-based tuning is a process of refining the set point with the conditions. The longer the process runs, the closer the set point gets to the actual

conditions, with an improved set point improving the system's response. Pattern recognition works by remembering previous trends. The past trends can then be used to help anticipate future problems. If the system begins to approach a past problem, then the controller will anticipate the problem and take corrective action before the problem occurs.

Most control literature for anaerobic digesters has centered on wastewater treatment. While a number of the measured variables are the same as would be appropriate for manure, for wastewater treatment the dilution rate is usually the chosen controlled variable (Renard et al., 1988; Alvarez-Ramirez et al., 1996; Alcaraz-Gonzalez et al., 2001; Alvarez-Ramirez et al., 2002).

Renard et al. (1988) and Alvarez-Ramirez et al. (1996) came up with adaptive control systems for anaerobic digesters. However, these control systems have been somewhat limited by their reliance on COD measurements that take hours. Renard et al. (1988) had to wait two hours before any adjustments could be made, while Alvarez-Ramirez et al. (1996) had to wait 12 hours. While both research groups' controls showed good results, their systems have two limitations that should be considered. The first limitation is the reliance on someone to manually perform the COD measurements. This condition prevents full automation because the system relies on a human chemical analyst. Most farmers will not have the time or money to devote to performing regular COD analysis on their manure. The second limitation is the lag experienced in the experiments. If conditions inside a farm digester become unstable, the potential for failure increases the longer it takes to recognize and correct the problem. Twelve, and even two, hours could be too long a time period to wait for a control system to respond to a problem.

Alatqi et al. (1990) attempted to overcome the time delay by measuring total organic carbon (TOC) instead of COD. TOC measurements could be available in three to seven minutes (Alatqi et al., 1990), and would greatly reduce the time delay introduced by COD measurements. Alvarez-Ramirez et al. (2002) also used indirect measurement techniques as an indication of COD concentration to reduce the response time. Volatile fatty acids (VFA) measurements can be made within 10 minutes (Alvarez-Ramirez et al., 2002). VFAs are an intermediate product in the anaerobic digestion process. For these

reasons, Alvarez-Ramirez chose to use this measurement to control the process rather than a direct COD measurement. Alcaraz-Gonzalez et al. (2001) used an interval observer, which is a software process, to deal with the testing problem. The observer does not attempt to reconstruct the unmeasured variables. Instead, the measured variables are used to provide an interval for a function containing both the yield coefficient for COD degradation, along with the concentration of acidogenic bacteria. By using VFA concentration to regulate COD concentration, the controller anticipates the conditions within the digester and reacts before problems occur.

As a preliminary step to physically test a control system, simulations can be run to assess the system's stability. Mendez-Acosta et al. (2005) designed a control system that implemented both feed-forward and feedback control. However, their system was only tested in simulation and not applied to an operating digester. Alatiqi et al. (1990) also provided a control scheme which has only been developed through control theory. Without testing on a physical system, the control system is relying on assumptions about the biological processes that may not hold within an operating digester.

Mailleret et al. (2004) performed simulations before testing the control scheme on a physical system. Alvarez-Ramirez et al. (2002) also provided simulation results before evaluating actual test results. Simulations demonstrate the controller's theoretical ability to maintain stability within the digester. However, as mentioned earlier, anaerobic digestion is a complex biological process. Lab or pilot-scale experiments provide more confidence in the control scheme to achieve effective results. Alvarez-Ramirez et al. (2002) provided data from a much longer testing period than Mailleret et al. (2004). Alvarez-Ramirez et al. (2002) showed the ability of a PI system to provide stability, and they also show the improved stability of their cascade control system.

The previous control research on anaerobic digesters has focused on a reduction of COD. This parameter is of primary importance to the application of anaerobic digesters that perform a wastewater treatment function. A farm manure digester will also benefit from the reduction of COD, but for different reasons. The parameter of primary interest in a farm-based digester is the production of methane. Methane will be related to COD concentration; however, the reduction of COD is not the primary concern in a farm-based digester.

2.4 Fuzzy Control for Anaerobic Digesters

Fuzzy controls are based on the vague descriptions people give situations (Bateson, 2002). For example, hot and cold have no set temperature. Rather, they are an individual approximation of how one feels. In fuzzy logic, these terms are grouped into a set with varying degrees of membership (Bateson, 2002). Fuzzy control consists of three steps: fuzzification, application of fuzzy rules, and defuzzification (Bateson, 2002). The degree of membership is used by the fuzzy rules to determine the degree of response necessary (Bateson, 2002). Defuzzification then converts this mathematical response into a physical change in the system (Bateson, 2002).

Fuzzy control rules are desirable because past experiences are incorporated into the control system. Estaben et al. (1997) worked to make their digester control system flexible, with the result that the system is programmed to follow evolutionary tendencies. The lack of accuracy of the model for the initial conditions of the system is actually seen as an advantage. Gaseous flow rate, along with pH, were the chosen control parameters (Estaben et al., 1997). A set point was also used to ensure a certain level of COD reduction (80%). Some additional restrictions were put into place to prevent complete system failure. To test their system, Estaben et al. (1997) applied different disturbances to both the influent substrate concentration and also to the input liquid flow rate. After performing simulations on the controller, it was tested in a 15 L fluidized bed reactor (Estaben et al., 1997). The disturbances lowered the influent concentration while maintaining the biogas output. COD was always reduced by 80% (Estaben et al., 1997).

Genovesi et al. (1999) used fuzzy controls to characterize sensor faults for anaerobic digestion. The system determines the level and nature of the fault. The research explores sensor fault, subprocess fault, and also process fault. This type of information isolates a fault. The system shows the ability to warn and identify potential errors, which allow appropriate preventative action to be taken and help reduce the risk of a larger digester failure.

2.5 Recording Digester Conditions

Remote monitoring is another way in which technology can be applied to a farm-based digester. Remote monitoring would allow data from the digester to be sent and used off the farm, and in future research would allow universities or other third parties to collect data about digesters. An effective remote monitoring system would also be instrumental to the development of a central monitoring station for multiple anaerobic digesters.

Bernard et al. (2005) performed research on the application of remote monitoring to anaerobic digesters. While this is a rare example of remote monitoring specifically of digesters, remote monitoring of other processes is well-documented. Microcontrollers and PLCs both have the ability to send information over a local area network (LAN). They can also be hooked up to a wireless router and have the information sent over the Internet. In this particular implementation, information could not only be sent to the central monitoring station, but, depending on how urgent the message was, it could also be sent to the operator's cell phone. For their research, Bernard et al. had the algorithms they used to control the system located in a central monitoring station.

While a good level of communication was demonstrated and definitely showed that the technological capability exists for remote monitoring and control, the components of the system located on-site at the digester had autonomy and provided depollution control. The digester could also be controlled remotely and in the event of a problem the system would request expert assistance. In this way, even with a loss of communication, the system would still be attempting to maintain the necessary anaerobic digestion conditions. This arrangement would help to minimize the amount of time the digester is not operating optimally.

Information was gathered from the system and sent to the remote databases, where analysis was performed using an XML language that was developed for wastewater treatment (Bernard et al., 2005). The overall program also controlled the pumps and electrovalves used within the system. The research clearly demonstrated the feasibility of remote monitoring and operation.

2.6 State of the art

The first step to designing a control system is to understand the process being controlled. The research literature on anaerobic digestion is comprehensive, and many parameters have been identified that can be monitored and controlled. However, sensing technology continues to provide challenges to achieving the desired level of monitoring and thus control of an anaerobic digester. Also some of the control schemes that have showed promising results *in silico* are not yet suitable for on-farm implementation.

While the research is encouraging and indicates that control can be accomplished, control systems for actual operation should first be tested experimentally. Some of the previous research has only been carried out in simulation (Alatqi et al., 1990 and Mendez-Acosta et al., 2005). Although simulations can show a controller's ability to stabilize a disturbance quickly, they are still only simulations and are limited by the mathematical models. Because of the nature of anaerobic digestion, simulations alone cannot prove a control strategy's effectiveness. They can only provide encouragement for the potential of the idea behind the control strategy. Blumensaat and Keller (2005) demonstrated some deficiencies in the current knowledge of the anaerobic digestion process, thus exposing limitations to any mathematical model used for simulation purposes.

A second set of limitations to most current and prior research have been measurement systems that have relied on data that has to be manually collected and/or analyzed, and therefore is comparatively old (Alvarez-Ramirez et al., 1996 and Renard et al., 1988). The COD analysis takes a relatively long time to conduct (hours) and that translates to high system lag. In the cases previously mentioned, the COD measurements have been performed by hand. In addition to the collection time, the control system is relying on human input that takes away from the automation of the process. In short, there are still limitations to the control process that need to be overcome.

Fuzzy controllers have also been developed to try and break away from complex control design. Classic controls have to find ways to program around a wide range of unknown variables, such as the growth kinetics of multiple microbial populations. Fuzzy systems take operator experience from the already functioning digester and use it to create a controller that would react in a similar manner to the operator. A limitation to

this design for dairy manure is its ability to work for any digester, since feed type and bedding can vary significantly from farm to farm. The controller, once developed, becomes dependent on the micro-organisms to act in a similar manner on all these farms, and that is unlikely. Fuzzy controllers at present are also still relying on COD analysis rather than biogas production, although the later can be measured in real time.

A number of researchers have worked to overcome the previously mentioned limitations by using mathematical schemes to eliminate the unknown biological components. COD concentration and growth kinetics have been mathematically removed from the equations used to govern the controller. Improved sensing technology is also being investigated which can help with this problem. Although sensors cannot provide direct information about growth kinetics, they may be capable of providing information about the rate of biomass increase or COD reduction based on other indicators such as biogas production rates. Such rates could then be used to provide a real-time picture of the conditions within the digester. Research is being conducted to try and allow for real time COD data that would help with control scheme design.

In contrast to the control aspect, work in remote monitoring is quite thorough at this point. The TELEMAT project has implemented a remote monitoring system which can provide information to an operator's cell phone. Remote monitoring is a well established technology that has been successfully implemented for many different applications. However, it has not been used for on farm anaerobic digestion. Therefore, applying remote monitoring should be a straightforward but novel task. The remote monitoring portion of the research actually takes this technology to the farm level.

Ultimately, all the previous research suggests that a remote monitoring and control system can be created and used on an anaerobic digester. This would then make anaerobic digestion a more viable on-farm practice, providing environmental benefits by preventing the release of greenhouse gases, and offsetting farm operation costs by providing both heat and electricity to the farm. Microorganisms cannot be directly controlled; however, some key conditions that affect their performance can be monitored cheaply and remotely. This information can aid human operators today, as well as automated controllers in the future, to make better decisions quickly to keep digesters running near their optimum.

This research will demonstrate the use of computer technology for digester operation and data collection. It will also provide an evaluation of a sensor system exposed to a manure feedstock to simulate on farm conditions. Finally the research will apply remote monitoring to a full scale operating digester.

3.0 Goals, Objectives, and Hypotheses

The goal for this research was to demonstrate the operation and monitoring of an anaerobic digester through the use of a computer. The steps involved in achieving this goal ranged from the design and construction of a lab scale digester to writing a software program for long term monitoring and operation. There was also the need to select and test the necessary sensors to monitor digester conditions and integrate them with the computer to achieve the monitoring portion. Finally, the remote monitoring system was implemented on a currently functioning full-scale digester.

Through achieving this goal, anaerobic digestion becomes a more viable option as part of a farm's manure management strategy. Checking the digester becomes as simple as opening a webpage. Digester management can then be simplified and to some extent automated. This type of system could also lead to the development of a central monitoring station where remote operators could manage multiple anaerobic digesters.

Hypothesis 1: Commercially available sensors can provide measurements within 5% of the actual value in a corrosive environment for 6 months.

This hypothesis will deal with whether affordable sensors are available which can provide accurate measurements with a minimal amount of maintenance. This helps to evaluate whether computer sensing is appropriate at the farm level.

Hypothesis 2: A computer can maintain the temperature of a lab-scale anaerobic digester within +/- 3 C for 6 months.

This hypothesis helps to establish the computer can maintain the necessary conditions for microbial growth so that digestion can occur.

Hypothesis 3: A proportional control can be used to achieve pH recovery of 1 pH unit in an abiotic lab-scale, anaerobic digester within 2 hours.

The final hypothesis focuses on using computer control to recover from an acid shockload. It also helps to understand the recovery time for an extreme condition. This helps to understand whether computer control can react to the event fast enough to compensate for acid production in an upset.

Objective 1: Construct a lab scale digester for experiments.

Before experimentation can begin, it is necessary to have an apparatus to perform the experiments. In this study a lab-scale digester fulfills this role. In addition, a lab-scale digester would help to show proof-of-concept for the monitoring system. The lab-scale system allows the monitoring system to be subjected to various conditions and determine any effects of long-term use or extreme conditions on the sensors. Proof-of-concept of automated computer operation could also be demonstrated with the lab-scale system.

Objective 2: Establish data collection and calibrate sensors.

Before anything else can be done, the control system must be able to collect data. Without data collection, the sensors cannot be calibrated and information about an anaerobic digester cannot be obtained to determine whether or not the hypothesis is true or false. The data will be collected over established wired means by a group of National Instruments DAQ boards that will send the data to a laptop. To further the research, objective 4 explores transmitting the data from the laptop to the internet. This will allow the data to be viewed from anywhere in the world.

Calibration is another important step in the preliminary phase of the research. Measurements reported by the sensors through the control system will be compared with standard lab instruments and measurement techniques. Calibration is necessary to ensure the operator and control system is getting accurate measurements. Without accurate measurements, an operator or automated control system could potentially create an upset in the anaerobic digester rather than prevent it.

Objective 3: Evaluate long term data collection from a manure-based feedstock in the lab scale digester.

Manure from the Penn State freestall barn was collected and used as the feedstock for the digester's operation. This exposed the monitoring system to manure-based

digester conditions. This helped demonstrate that the monitoring system can provide long term data collection capability.

In addition the digester was operated from the computer. This would show that a computer system can be used for digester operation.

3.1 Summary of Research Goals

By accomplishing the above objectives, the hypotheses could either be proven or indicate the system requires further development and better testing. The successful testing of these hypotheses would demonstrate proof-of-concept about the potential value of automation in this area of farm management. Furthermore, with increased reliability and less time spent monitoring, anaerobic digesters could become more attractive to farms which are still deciding on whether or not to make the investment.

4.0 Lab-Scale Digester Design

A lab scale anaerobic digester was designed and constructed. The digester was designed with a volume of approximately 20 L (5 gallons) for a 20-day hydraulic retention time. The digester system was also designed to act as a complete mix reactor. To achieve mixing, manure was recirculated from the bottom of the digester and back through a draft tube extending into the top of the digester. The following section serves to both chronicle and justify the decisions made in digester design. Detailed drawings for the main digester reactor can be viewed in Appendix A. Figure 4.1 is a picture of the final assembly.

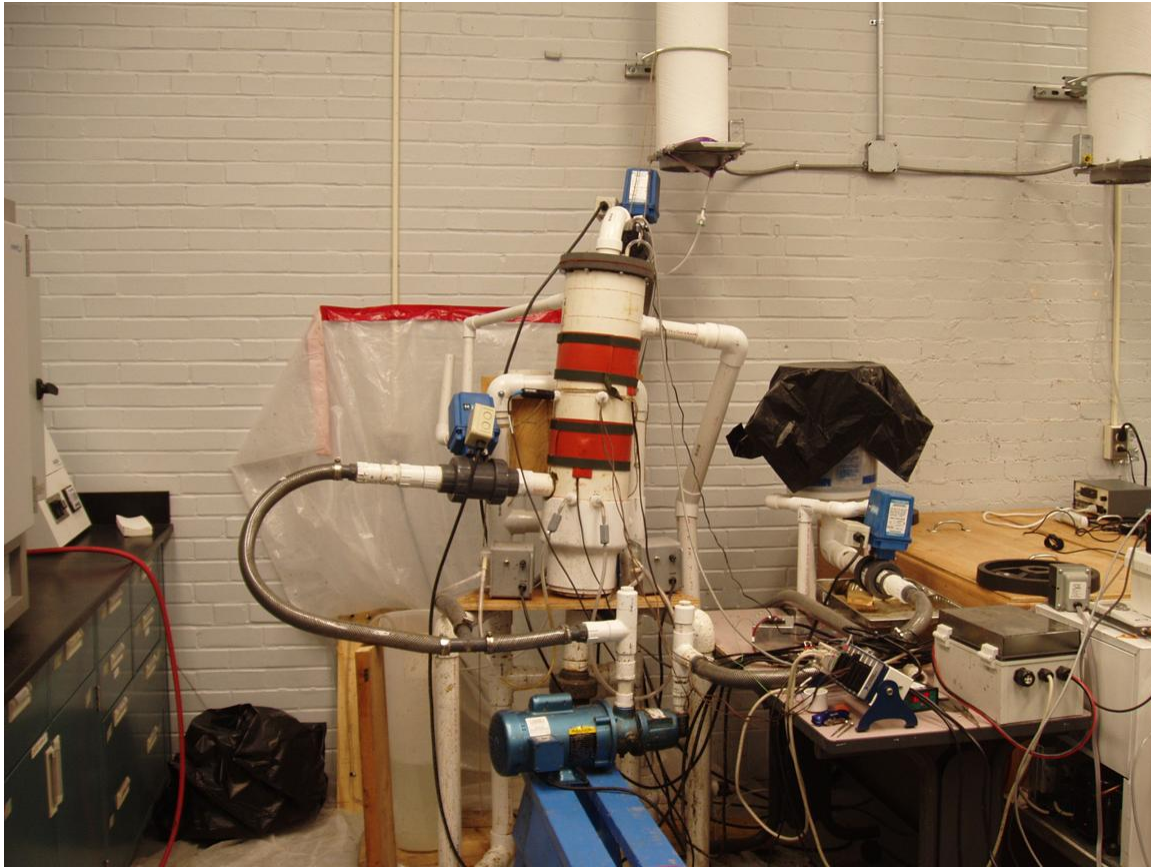


Figure 4.1 Picture of Final Digester System

4.1 Main Reactor

The digester was constructed from PVC pipe. Eight inch PVC pipe was cut to approximately 76.2 cm (30 inches) in length and used for the main body of the reactor.

Approximately 61.0 cm (24 inches) from the bottom a two inch hole was cut in the tank to connect the overflow line. The first 61.0 cm (24 inches) contain liquid volume and the upper 15.2 cm (6 inches) provide head space for the biogas. Using reducer fittings, the bottom of the digester reduces from the 8 inch pipe down to 2 inch pipe. The 2 inch pipe connects to a Tee fitting that has a manual valve located vertically inline with the reactor body. This valve works to ensure the digester can be completely emptied quickly, if necessary.

4.2 Lid and Recirculation Tube

The lid and connecting seal on the main reactor tank were cut using a water jet from a local machine shop (Skytop Machinery, State College/PA). The lid has a 2 inch hole, a 1/2 inch hole, and 8 1/4 inch holes on a 9 inch bolt circle. A silicon gasket was cut to match the bolt pattern and line up with the bolt holes. The gasket would ensure a tight seal to prevent air from leaking in the top of the reactor.

A piece of 2 inch PVC pipe was placed in the 2 inch diameter hole and plastic welded into place. A tube was constructed out of 2 inch PVC pipe to run into the center of the main reactor. Two rectangular slots were cut on opposing sides of the tube. These slots are both 1 inch wide and 3 inches tall. A restriction was also added to the central tube. The restriction was made from cutting fiberglass with a hole saw. A 2 inch coupling with the fiberglass ring reduced the diameter from 2 inches to 1.5 inches, and was glued to connect the reactor section of the tube with the inlet section. Figure 4.2 shows the full tube assembly.

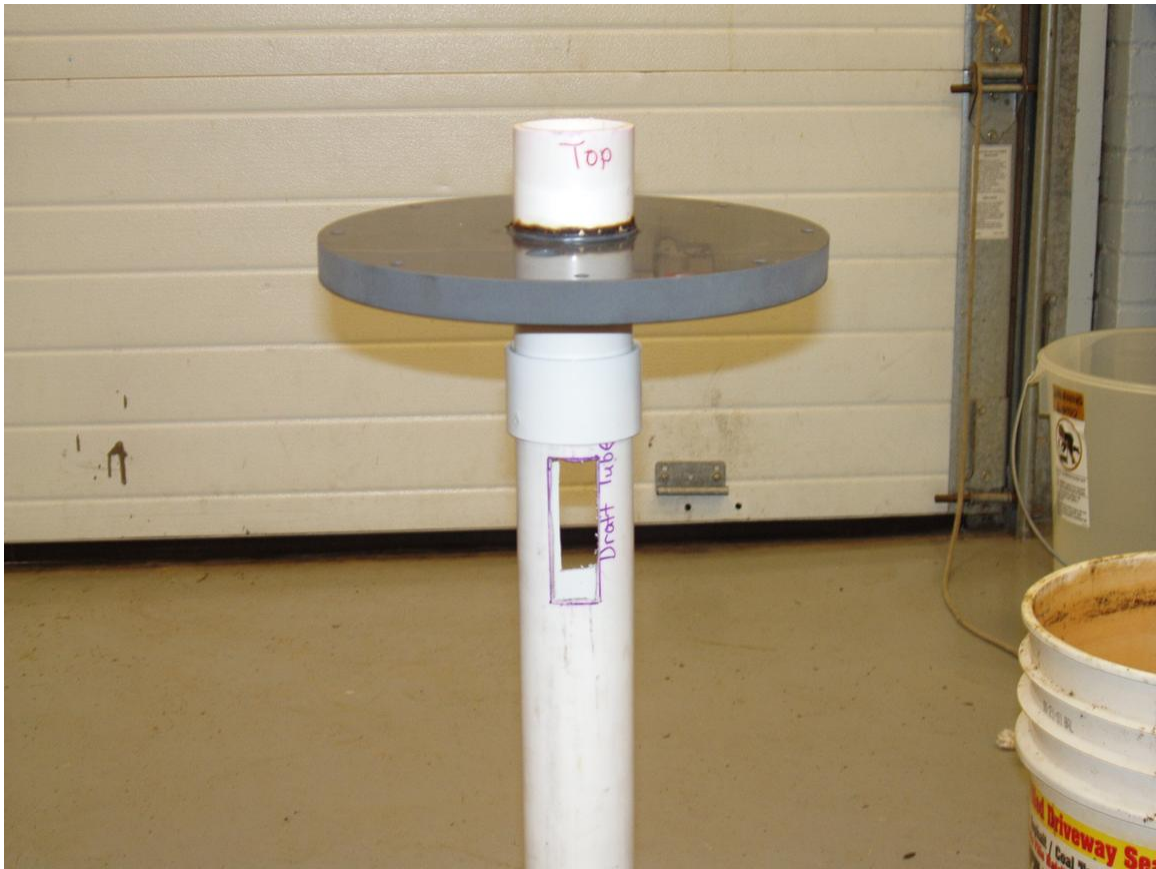


Figure 4.2: Picture of recirculation tube assembly

4.3 Feeding

To feed the digester, material is pumped in near the main reactor's base. An overflow line is located 24 inches above the inlet line. As manure is pumped into the digester, the liquid level will rise until it spills into the overflow line. Once filled, the feed volume displaces previously mixed digester contents that then leave the main digester tank. During routine operation this creates a situation where the fresh manure volume entering the reactor is equal to the digestate volume leaving the reactor.

A Moyno model 330 progressive cavity pump (Springfield, Ohio) (Figure 4.3) is used for both feeding and recirculation of material within the digester. One inch outside diameter tubing was used initially to connect all of the lines. The tubing was later enlarged to 1¼ inch tubing after repeated clogging of the ¾ inch lines. The detailed reasons for this change are discussed in Chapter 5. Four electronically controlled valves

are used to ensure proper material flow once the pump is activated. Two of these valves are 2 inches in diameter while the other two are 1½ inches in diameter.

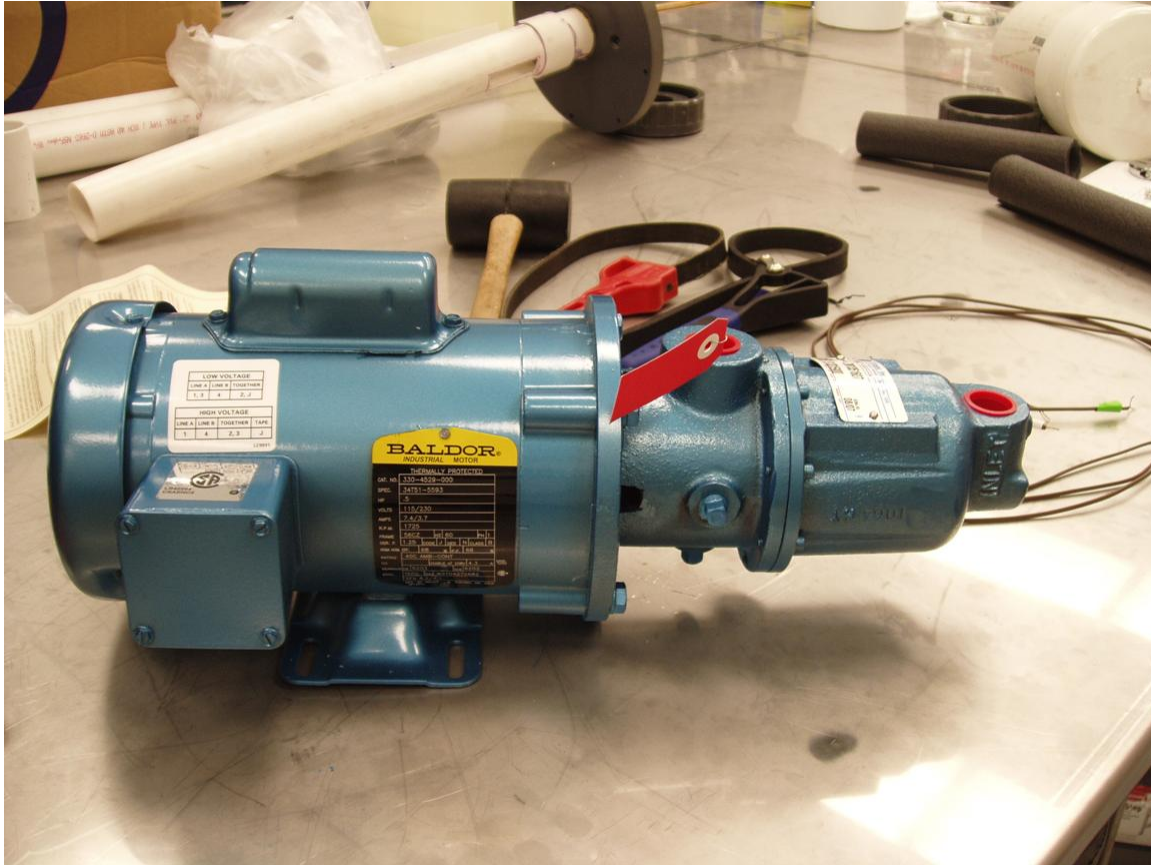


Figure 4.3: Moyno pump used to pump feed in and recirculate

4.4 System Exit

An overflow line was used to remove digestate from the digester. As new feed is pumped into the digester, the liquid level inside the digester rises. Once it reaches the overflow line, the liquid will then begin to run down the overflow line. To prevent biogas from leaking out the overflow line, a water seal was placed between the overflow and the collection bucket. Figure 4.4 shows a schematic for this design.

The effluent would then push the material in the seal out. This initial effluent had thus been removed from the digester for one day before being collected and analyzed.

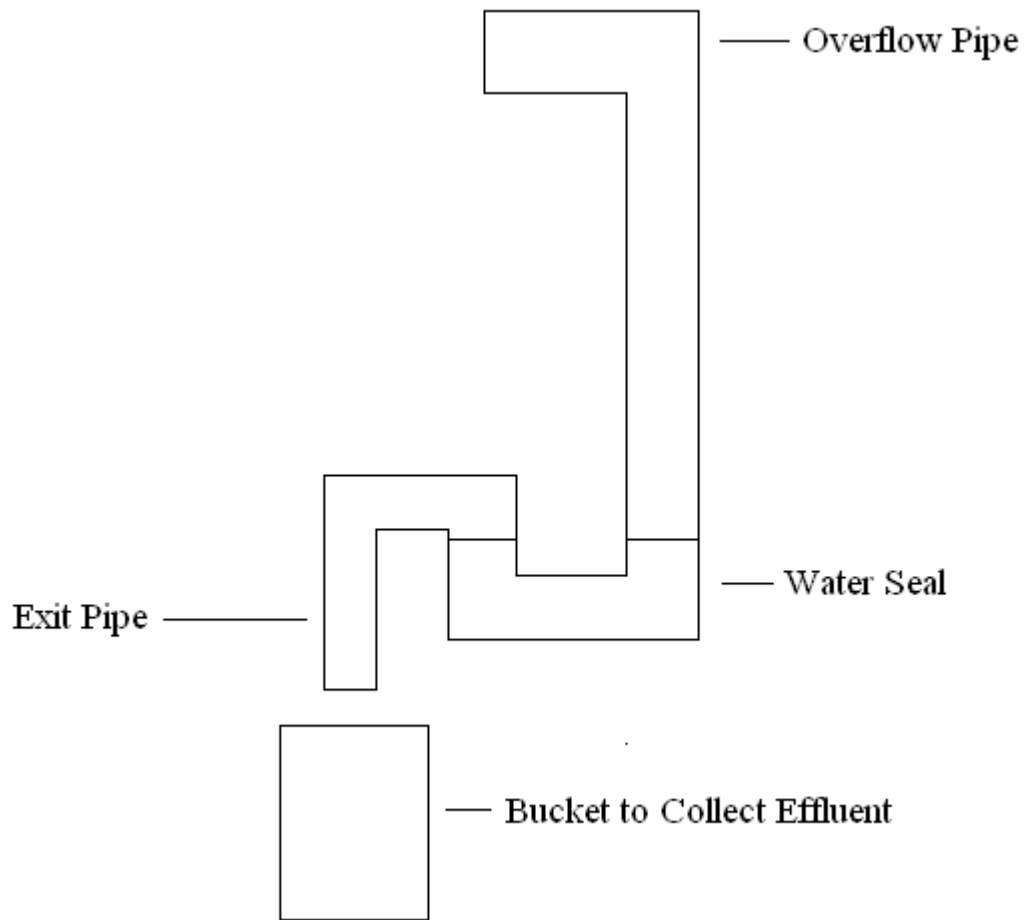


Figure 4.4: Digester Overflow Schematic

4.5 Valve Placement

Four electronic valves (Figure 4.5) were used in constructing the digester. These valves are controlled electronically from the laptop computer through the use of solid state relays. Two solid state relays were needed per valve. One energized the valve to open and the other to close. Rather than rotating only 90° , these valves turn 360° . Therefore, it took four 90° turns of the valve (OFF-ON-OFF-ON) for it to travel an entire cycle.

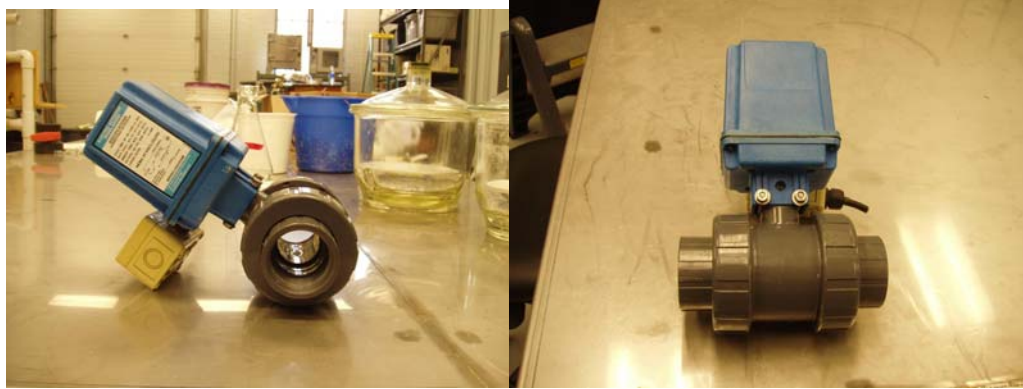


Figure 4.5: Electronic valve

Since one pump was used to perform both feeding and recirculation, two valves fed into the pump's inlet and two others received flow from the pump outlet. Only one valve on the inlet and outlet sides is open at any given time ensuring that the material flow follows the proper path. Valves 1 and 2 are placed along the feed line, while valves 3 and 4 are placed along the recirculation line. Thus Valves 1 and 2 are opened together during feeding and valves 3 and 4 are opened together for recirculation and mixing. Figure 4.6 provides a flow schematic for the valves. Valve 1 is located between the feed tank and the pump inlet, while Valve 2 is located between the pump outlet and the main reactor. Valve 3 is located between the bottom of the digester and the pump inlet, while Valve 4 is located between the pump outlet and the top of the digester.

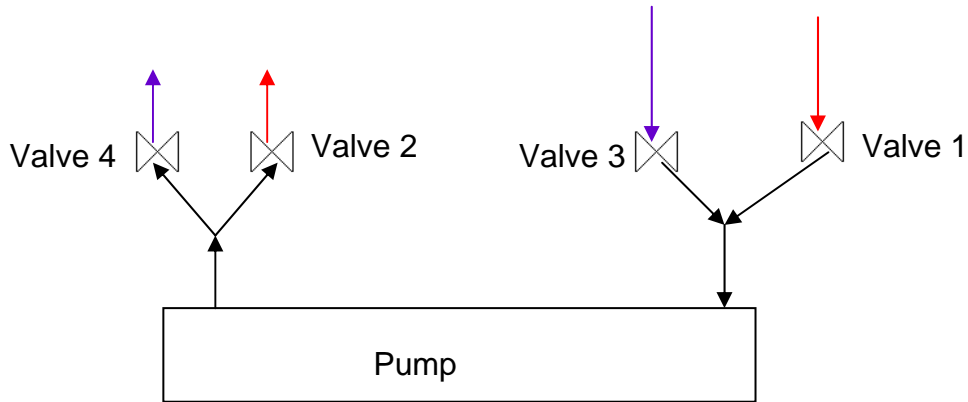
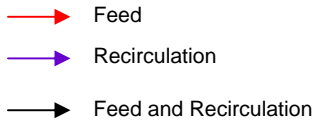


Figure 4.6: Valve flow schematic

4.6 Heating

In order to heat the main reactor, two strip heaters were purchased. They are 5 inches wide and can vary in length. The heaters are held on by Velcro. When energized, an electrical current flows through the heaters causing them to heat up. For these strip heaters, the current can not be varied, so the heaters are either on or off.

The first heater was wrapped around the lower part of the main reactor body between the feed inlet and the pH and thermocouple ports. The second heater was placed on the upper reactor body between the pH and thermocouple ports and the overflow line (Figure 4.7).



Figure 4.7: Heater placement on the Digester

4.7 Supplemental Tanks

For pH and VS concentration control, two additional tanks were constructed to hold additives for the digester. Both were made out of 6 inch PVC pipe and 6 inch PVC caps. Each piece of pipe was cut to 9 inches in length. The cap added approximately 2 inches to the overall tank height. A 1/2 inch hole was drilled out of the caps using a lathe and the caps were then threaded with 1/2 inch NPT threads. A fitting with 1/2 inch NPT threads on one end was screwed into the tapped caps. The other end of the fitting was a 1/4 inch barb fitting. The tanks have a volume of approximately 1.33 gallons. 1/4 inch Tygon tubing was run from the fitting to one of two Mityflex peristaltic pumps (Model 907, Anko Product, Bradenton, Florida) from each of these two supplemental tanks (Figure 4.8). The same tubing continues to a check valve, and then enters the main reactor at the same level as the feed.

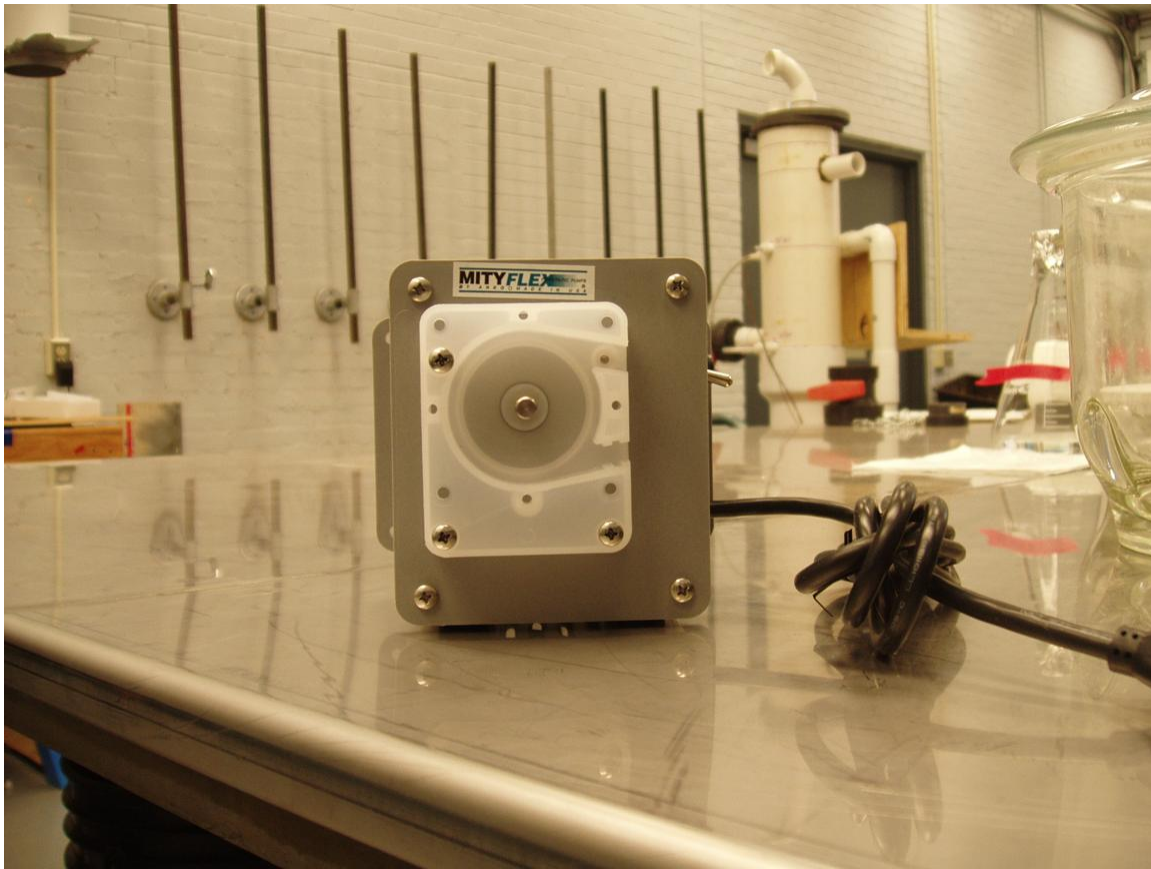


Figure 4.8: Peristaltic pump

The entrances were placed at the bottom of the reactor to keep them below liquid level. Since it is more difficult to make something gas tight than liquid tight, most threaded openings were kept below liquid level.

The check valves were added after testing the feed and overflow system. When testing the system, water was pumped into the digester. During the filling process, it was observed that the additive tanks began filling with water before the digester was full. The two additive tanks were completely filled. A check valve was necessary in order to prevent the manure mixture from flowing up these lines and back into the additive tanks.

4.8 Feedtank

A 5 gallon bucket was modified to construct the feed tank. A 3 inch hole was placed in the bottom of the 5 gallon tank. A shower drain was then placed in the hole to create a flush seal with the bottom. The metal grating on top of the drain was removed.

The drain is of a standard design for use with 2 inch PVC pipe. Therefore, off the shelf PVC parts could be bought and used. A short piece of PVC pipe connected the shower drain to a PVC elbow. From the elbow a 2 inch threaded PVC pipe was screwed into one end of Valve 1.

4.9 Sensors

A pH probe, a gas flow meter, and three T-type thermocouples were used to sense the conditions within the digester. The pH probe (model 27001-70, Cole-Palmer, Vernon Hills, Illinois) was connected to a transmitter (alpha 200, Eutech Instruments, Vernon Hills, Illinois). The transmitter was then wired to the data acquisition board an NI cDAQ-9172 chassis containing eight data acquisition cards (National Instruments, Austin, Texas). The gas flow meter (M-20SCCM-D, Alicat Scientific, Tucson, Arizona) was calibrated for a gas mixture of 65% methane and 35% carbon dioxide. The flow meter was also wired to the data acquisition board. The data acquisition board has a connection which hooks up to the laptop computer (Latitude D520, Dell Computers, Round Rock, Texas) through the USB port. The laptop ran the Windows XP Professional operating system and LabView (Versions 8.2 and 8.6, National Instruments, Austin, Texas) data acquisition and control software.

The data acquisition board contained eight data acquisition cards (Figure 4.9), all also from National Instruments: two cards for digital input/output signals (NI 9401), two cards for analog output signals (NI 9263), one card for analog input signals (NI 9205), and three cards for temperature sensor inputs (NI 9211). The three thermocouples were each wired to one of the temperature sensor cards. Both the pH transmitter and the gas flow meter were wired to the analog input card. The analog output card was not used. The two digital input/output cards were only used for sending signals to the relays which activated the valves, pumps, or heaters.

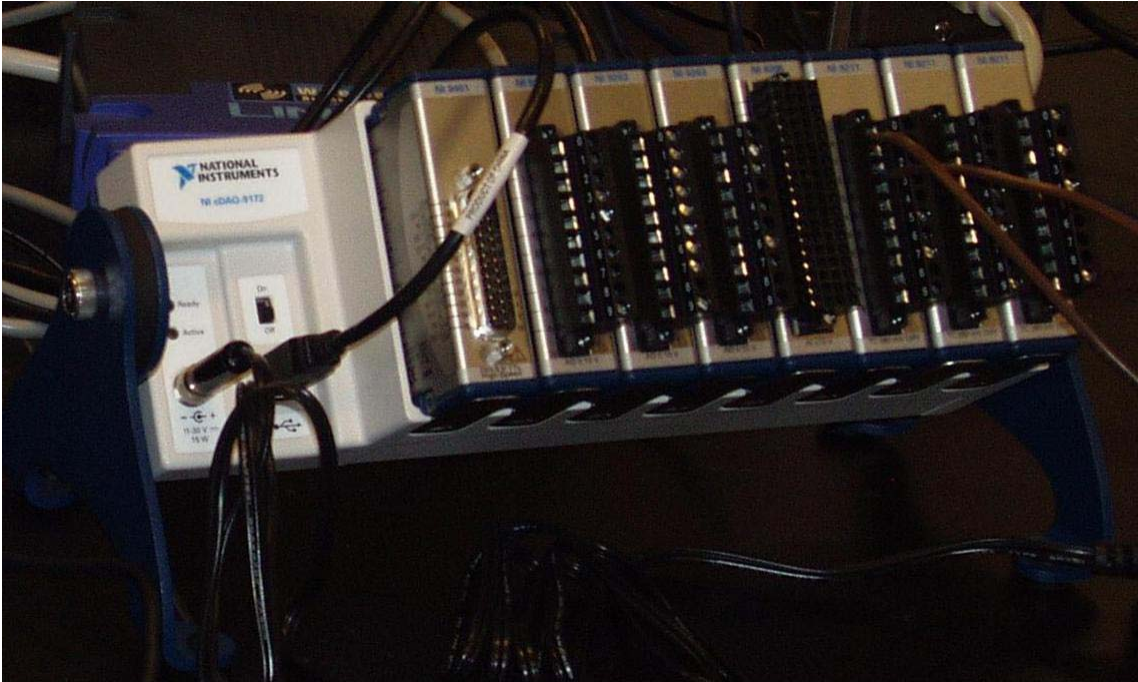


Figure 4.9: Data Acquisition Board

To communicate from the laptop to the various pieces of electronic equipment, wires run from the data acquisition board to a bank of solid state relays. All the output signals are digital signals, and the relays are either turned on or off. If activated, the relay allows current to flow to the device, which then performs the necessary function.

4.10 Adapters

Because the Moyno pump's inlet and outlet are only 3/4 inch NPT, 2 inch tubing could not be used for the whole system. At first 3/4 inch tubing was used. Using 3/4 inch tubing, a barb fitting was screwed into the pump. The tubing was connected to the fitting and secured with a hose clamp. However, due to problems that will be discussed in more depth in Chapter 5, this tubing size proved to be insufficient for the system's needs. The tubing was upgraded to 1 1/4 inch tubing.

Because the tubing had a smaller diameter than the valves, adapters had to be made for the tubing to fit with the electronic valves (for both sizes of tubing). A piece of PVC pipe either 2 inches or 1 1/2, depending on the valve size, was cut to approximately three inches. On one end, a threaded adapter was glued so it could be screwed into the

valve. For the other end, a PVC endcap was modified on a lathe in the ABE machine shop. First a center hole was drilled in the middle of the cap. Then a hole of the correct size was drilled in two steps. First a smaller hole was drilled, then the appropriately sized hole for the required tap. Finally the proper size tap was threaded into the hole. To ensure the hole was properly threaded to the correct depth, a barb connection was tested until it properly fit into the hole. When the tubing was enlarged, this process was repeated with a larger barb fitting.

With the larger tubing, two adapters had to be constructed for the pump, one for the pump inlet and one for the pump outlet. A barb fitting was placed in an inch and a half end cap following the method previously described. The end cap was connected to an 1 ½ inch PVC which was connected to a Tee fitting. The bottom of the Tee was reduced to the ¾ inch NPT pump fitting. The top had a small piece of PVC which connected to an end cap. The end cap was tapped as above for a ¾ inch plug. The plug was screwed in and could be removed to help deal with inlet clogs. Figure 4.10 provides a schematic for the pump adapter.

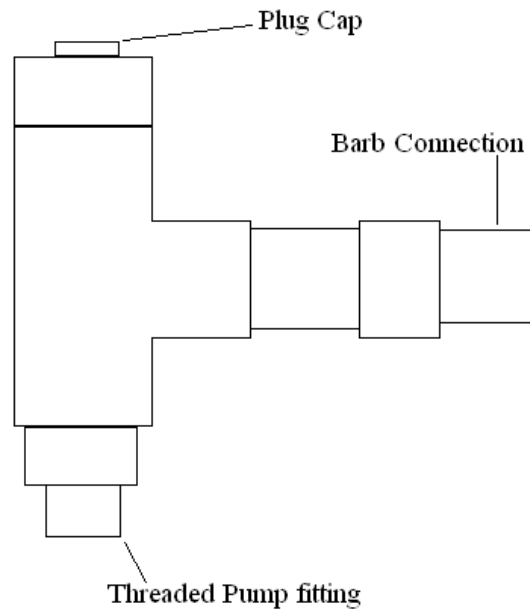


Figure 4.10: Pump adapter piece

4.11 Wiring

In order to control the digester from the computer, 12 solid state relays were used to activate the pumps, valves, and heaters. The two digital input/output DAQ cards previously described were used to send all the signals, with the first card dedicated to controlling the valves. Each of the four valves required the use of two solid-state relays, one for opening the valve and the other to close the valve. Each of the three pumps used a single solid state relay, while the final solid-state relay was used to control the heaters. All the solid-state relays were housed in a Fibox to prevent liquid from spilling on them.

Each relay had the input end wired to the computer output cable. The other end was connected to a power cord. A single power cord was run into the box and acted as the sole power source for all the devices.

4.12 Digester Program

All data acquisition programs written for this project were written in National Instruments' (Austin, Texas) LabVIEW software. The labscale programs were coded using version 8.2, and the remote monitoring program was coded using version 8.6. Version 8.6 was chosen for the remote monitoring because it has the added feature of website publishing. LabVIEW was chosen because it provides relatively inexpensive and flexible hardware and software. LabVIEW has a number of pre-made functions which reduce programming time and complexity. These functions allow the National Instruments hardware to directly communicate with the laptop without having to write code setting up and initializing communications.

Figure 4.11 provides a screenshot for the front panel of the digester operational program. The program is Digester V3.vi, which was created by Scott Shore using LabVIEW 8.2. This program is the operator interface with the digester. All valve and pump action is controlled through the program. The graph shows the three temperatures being recorded from the digester. Two sets of LEDs indicate whether the recirculation line for the feed line is open. The set at the top of the screen (lit in the figure) shows which direction is open. The other set, located next to the toggle switch, indicates which direction the switch is pointing. The box located under Feeding Time was added as a user input. The operator could input a time and the digester would automatically feed

itself. This feature was not fully implemented and never tested. A concern with automatic feeding in the laboratory scale reactor was the possibility of the operator walking away from the digester, when feeding occurred. Due to the clogging problems, the operator needed to be present during feeding to stop the pump in the event of a clog. This prevented the pump from damaging itself by running dry, in the event the clog was on the inlet side of the pump, or the pump being unable to run and causing the power strip to reset, in the event the pump housing was clogged. It also helped reduce the possibility of pressure buildup resulting in a hose popping off and pumping manure into the lab. The Feed/Recirculation toggle switch was used to change which line is open between the feed line and the recirculation line.

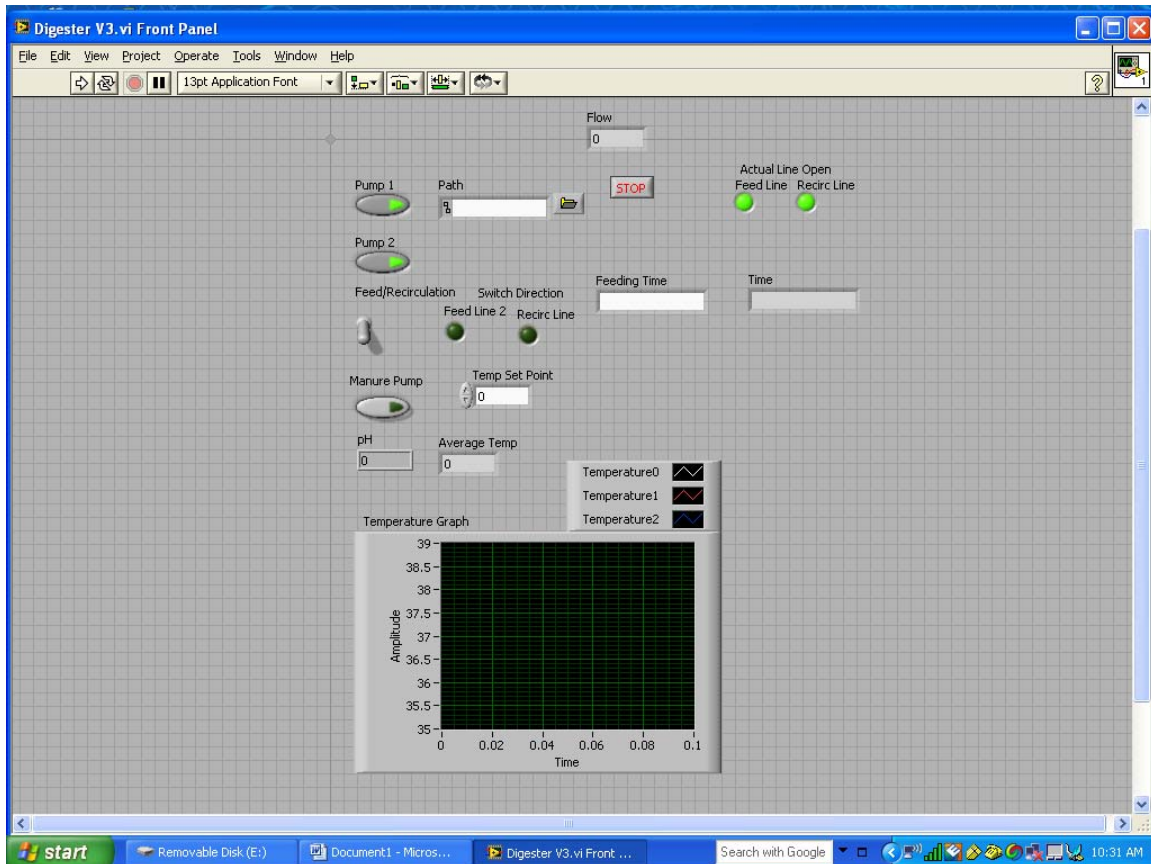


Figure 4.11: Digester control program Front Panel

The box labeled “Path” with the folder next to it is where the operator would enter or browse for a filename to save the data. By clicking on the folder, the operator can select the file where data will be saved. The switch labeled Pump 1 was used to operate

the added water pump, while the Pump 2 switch was used to operate the base addition pump. Both of these two switches were operator-controlled. The water tank was not used during testing due to the inability to obtain stable digester conditions. Pump 2 was used on multiple occasions to try and maintain the necessary pH conditions within the digester and later to perform the pH shock load tests. When used to perform the pH shock load tests, Pump 2 was computer controlled.

The switch located under the box labeled Manure pump controlled the progressive cavity pump, used for feeding and recirculation. To the right of the Manure pump switch is a box labeled Temp Set Point. This is where the desired internal temperature for the digester is input by the operator. As mentioned in the previous section, one limitation of proportional control is steady-state error below the set point. Therefore, it was necessary to set the desired temperature a couple of degrees high. The desired internal temperature was 37 C, so the set point was placed at 39 C to compensate for the steady-state error at the higher temperature.

5.0 Methods and Procedures

This section serves to document the methods and procedures followed in performing all the experimental work with this research project. This documentation should be adequate to allow someone else to replicate the work performed, or to verify the calculations and results.

5.1 Measuring Moisture Content and Volatile Solids Content

The moisture content and volatile solids (VS) content were determined by standard wastewater methods 2540 B 2-72 and 2540 E 2-77 (Clesceri et al., 1989). First a ceramic crucible was oven dried or stored in a dessicator, then weighed. The crucibles used for this study typically weighed between 40 and 55 grams. A sample was then scooped out of a bucket. Samples were taken from either the bucket where fresh dairy manure had been collected or the bucket where the digester effluent ran into or the bucket where the feed for the digester had been mixed. Each sample was typically 40 to 50 grams.

Next the weight of the crucible with the sample was recorded. The crucible was then placed within the drying oven for twenty four hours at 105 C. Early work was performed at 82 C because of fear the sample might splatter at 105. This was seen to not be a problem so 105 was used for the remainder of the work. Preliminary testing was also done to ensure that 24 hours was enough drying time to achieve constant weight. Some samples were weighed every six hours to watch the weight change. Little change was observed between 18 and 24 hours.

After 24 hours, the crucibles were placed in a desiccator for 30 minutes. Following the 30 minute cool down period, the crucibles were re-weighed and the values recorded. The samples were then placed in the furnace for VS analysis.

For VS analysis, these previously dried and weighed samples were heated in a muffle furnace to combust the organic fraction. A program was run on the furnace which held the samples at 550 C for 5 hours. This is the temperature recommended by the Water Environment Federation standard methods manual (Clesceri et al., 1989). Following 5 hours at 550 C, the furnace cooled down to 105 C. For safety reasons, the samples were removed after the furnace had returned to 105, rather than attempting to

remove them at 550. The samples were placed in a desiccator for 30 minutes again and re-weighed. The recorded mass was then used to determine the VS content of the sample.

5.2 Manure Collection

Manure was collected on an as-needed basis from the Penn State Freestall Dairy Barn in Centre County, PA. The barn has five aisles with the center aisle being the largest; the center aisle also serves as a feed alley. The two outside aisles contain sand bedding and the second and fourth aisles contain no bedding, just concrete floor.

Manure was collected from the second and fourth aisles. To try and avoid sand collection, manure towards the middle alley was collected first and when possible. Typically the manure was collected around 10 o'clock in the morning. This provided sufficient time for the cows to have deposited manure on the floor following the morning scraping.

Two five gallon buckets were filled with manure. The job was also typically done by two people. One person used a pusher to shove the manure into a pile. The second person then used a shovel to scoop up the manure and place it in the buckets.

Prior to going to the barn, the buckets were weighed. Upon returning the buckets were reweighed to determine the quantity of manure collected. Three replicate subsamples from each manure bucket were then analyzed for both moisture content and VS analysis.

5.3 Feed Creation

After dairy manure was collected, subsamples were dried in the drying oven and ashed in the muffle furnace to determine the moisture content and the volatile solids content. This analysis was performed in triplicate and the data indicated a volatile solids content of approximately 12% on a wet basis (w.b.). The average VS concentration (w.b.) of the manure taken from the barn was 12.9% with a standard deviation of 0.63. This is in keeping with the ASABE Standard D384.2. The feed was prepared to a desired volatile solids concentration which was less than the 12% in normal dairy manure.

Two different volatile solids contents were used as the basis for preparing the feed. In the initial experiments, manure was diluted to an 9% VS concentration (w.b.). The amount of water to be added to the manure was calculated from equation 5.1. The manure was assumed to have a VS concentration of 12%. Table 5.1 shows the all the VS data for the manure collected from the barn.

$$0.09 = 0.12 / (1+x)$$

$$0.09 * x + 0.09 = 0.12$$

$$0.09 * x = 0.03$$

$$x = 0.333$$

Equation 5.1: Water addition to manure for feedstock creation

Table 5.1: VS data from Penn State Freestall Dairy Barn

Date Manure Collected	Bucket Sample Came From	Sample	VS (%)
3/10/08	1	1	11.9
3/10/08	1	2	11.7
3/10/08	1	3	11.9
4/29/08	1	1	13.1
4/29/08	1	2	12.4
4/29/08	1	3	12.7
4/29/08	2	1	13.8
4/29/08	2	2	13.4
4/29/08	2	3	13.4
8/11/08	1	1	13.4
8/11/08	1	2	13.0
8/11/08	1	3	13.0
8/11/08	2	1	13.2
8/11/08	2	2	13.0
8/11/08	2	3	13.1

Since manure is primarily water, a density of 1g/cm³ was assumed. In order to achieve the necessary VS content, 0.5 kg of water was added for every 1.0 kg of manure. By using the density of water, this translates into 500 cm³ H₂O for every kg of manure. Since 1 cm³ = 1mL, it was necessary to add 500 mL of water for every kg of manure to achieve the desired feed strength.

During later experiments the VS content goal was 6% VS (w.b.) to minimize the repeated clogging problems discussed below. Going through the same calculation as for the 8% VS, the result was a 1 to 1 ratio of water to manure if the fresh manure was 12% VS (w.b.).

The manure was also homogenized before feeding. For homogenization, an empty bucket first had its mass recorded. The mass of the empty blender was also recorded. To prepare the feedstock 0.3-0.5 kg was scooped into the blender and massed. The proper amount of water was then added. This mixture was blended until it freely turned in the blender. The mixture was then poured into the bucket. This process was repeated until the approximately 3 to 5 kg was within the bucket. The feedstock was then poured into the feed tank.

Later, following repeated clogging of the pump and also the inlet valve, manure was screened prior to feed creation. This introduced an additional step following the blending operation. Simply stated, the blended feed was poured through a colander to screen out the larger particles. A metal mixing bowl slightly smaller than the colander was used to press the feed through the colander. Screening greatly reduced the VS level of the feed. In order to try and solve this problem and maintain VS, sugar was added to the feed. However, sugar addition was not continued long as it resulted in interesting but non-ideal outcomes for the digester's performance, with the highly degradable substrate encouraging acid upset conditions.

5.4 Digester Operation Narrative

To begin operation and testing, the digester was filled to capacity with regular tap water. No inoculum was used for the startup of Trial 1. The heating control was activated and brought the water up to the necessary operating temperature and maintained it. Over the next twenty days, feed was added at a loading rate 0.95 L/day (0.25 gallons/day). At the end of 20 days, the digester was filled with manure. This manure was prepared as mentioned in section 5.3. Initially the feedstock had a VS concentration of 9% on a total mass basis.

Initially the digester pH was 7.0, consistent with the building tap water. With the addition of feed, the pH within the digester began to drop. While some reduction of pH

was expected with the onset of acetogenesis, in this case, the pH rapidly dropped to 6.2 (Figure 5.1). The large drop in pH can be noticed over the first five days of digester operation with the largest drop occurring between day two and three.

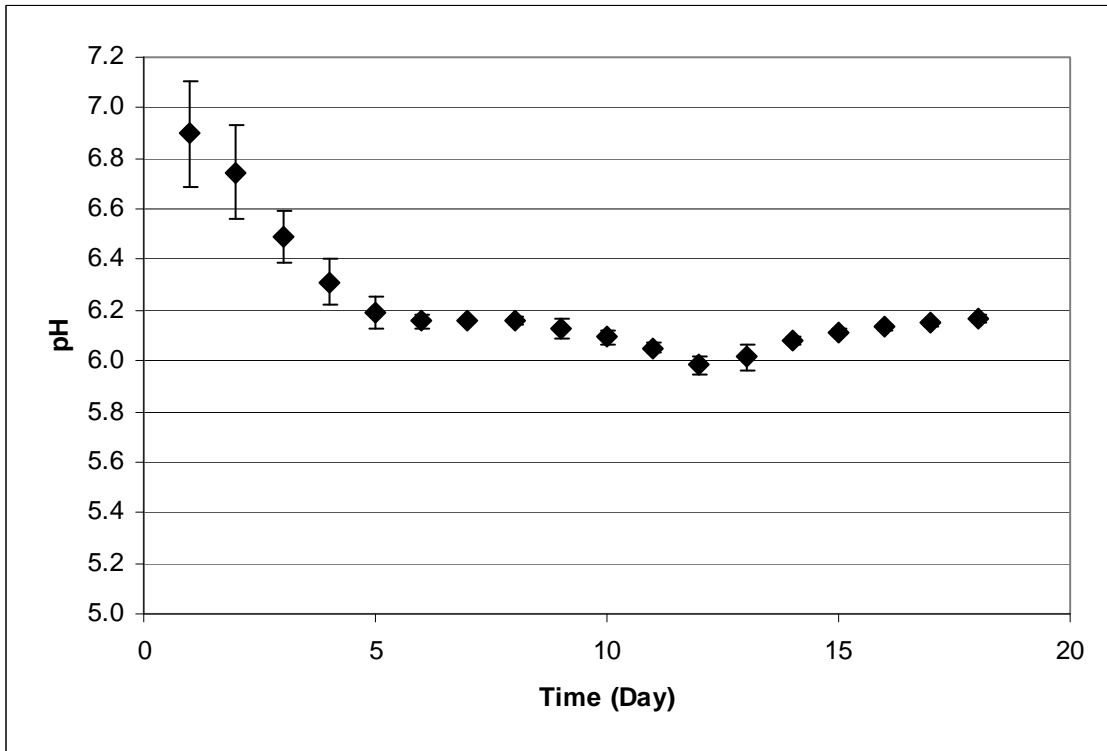


Figure 5.1: Average Daily pH value over the first 18 days of Trial 1

Since the pH did not rebound, feeding was stopped for 4 days from day 8 to day 12. No buffering agents were added, instead observing whether the methanogenic community could correct the problem by consuming the built-up acid. This was the first indication of what would be an ongoing problem. The methanogenic community in dairy manure obtained from the farm was never strong enough to establish and populate the digester. After 45 days, still at low pH, the first trial was stopped.

Towards the end of the first trial, problems began to occur with clogging. The primary mechanical operating problem with the digester was related to clogging. Initially the tubing used for feeding and recirculation was $\frac{3}{4}$ inch inside diameter. The problem was initially thought to be localized to the recirculation line, and the first time this was solved by reversing the inlet and outlet lines to the pump. Running the pump backwards, the clog was pushed back into the digester. However, clogs occurred at the pump inlet

and also on the Tee fitting on the inlet side. These problems continued to occur and also moved to the pump inlet. One strategy tried was to increase the mixing frequency. It was felt that if the solids did not have the opportunity to settle then there would be fewer problems with the digester. However, this strategy only worked for a day before clogging resumed. To solve the clogging problem, the tubing was changed to 1 ¼ inch diameter. A second trial was conducted for 30 days following the change in tubing.

While larger tubing resolved the problem of clogs occurring at the Tee, some clogs still occurred in the pump inlet. The solution implemented was to lower the feed concentration from 9% VS to 6% VS. Even lowering the feed concentration was not a perfect solution as will be discussed below.

To change the tubing, new adapters had to be constructed for both the valves and the pump. The new adapters were made using PVC. The end caps for the pump adapters had smaller end caps screwed on top to allow easier access to the pump inlet and outlet in case of clogs. While changing the tubing, the overflow line was broken. Rewelding the piece was not a practical solution. The digester was emptied utilizing the manure valve at the digester's bottom to ensure digestate did not spill out through the overflow hole on the side. The first solution tested was to machine down some PVC pipe to fit in the hole and glue it in place with some rubber to help seal it up. This proved a very fragile and temporary solution as the overflow line once again broke. Once this second break occurred, a bulkhead fitting was constructed using a metal plate, rubber and threaded PVC pipe fitting. Below is a schematic of the fitting (Figure 5.2). Figure 5.3 includes two photos looking into the draft tube through the hole sealed with the bulkhead fitting. The threaded connection provides compression of the rubber gasket against the digester wall to seal the digester and prevent biogas from leaking out.

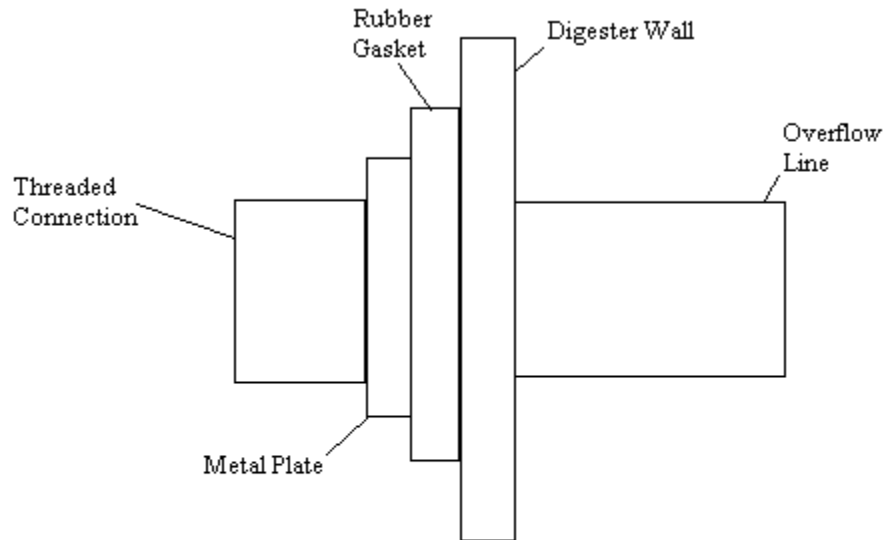


Figure 5.2: Diagram of Bulk Head Fitting to attach Overflow Line



Figure 5.3: Picture through Overflow Line Hole

The picture on the left shows the hole while water was being recirculated. That is the reflection you can see in the back of the draft tube. This photo was taken to try and determine whether fluid was flowing back out through the windows cut in the draft tube or not. Due to the difference in the sizing of the pump inlet/outlet and the diameter sizing for all the line, the system did not run full and so the windows seemed to be unnecessary. As will be discussed in Chapter 7 it would be worthwhile to try and fix this problem.

Trial 2 was begun with inoculum from the University Park wastewater treatment plant. After 30 days from the beginning of trial 2, a clog occurred in the digester. The pump inlet was checked and found to be clear. The housing to the pump was then removed. After removing the housing, it was observed that the interior of the pump had clogged. This was the result of a gradual build up of larger solids. The primary culprits in this build up were corn kernels that, due to their shape, were able sit in the grooves around the central screw in the pump. The kernels eventually managed to collect other pieces of solid material, mostly larger pieces of straw, and form a type of solid semi-porous matrix within the housing. At first the pump was able to continue to push water through the obstruction, but over time the void space decreased where water could no longer be pumped. Following this discovery it was decided that in the future the manure would be screened to remove these large particles, so the digester would be tested with a primarily liquid manure fraction. This would greatly reduce the opportunity for clogging and help ensure long-term operation. Since this screening would result in the loss of a large proportion of VS, it was decided that sugar would be added to the mixture to increase the VS content.

During this time biogas production had been negligible, if it was occurring, as no measurable gas was observed. It was decided to restart the digester with inoculum from Penn England. Penn England had an active dairy manure digester at the time. In addition to this no sugar would be added at the beginning in order to try and achieve a stable level of performance before adding more stress to the system. Instead, the VS concentration would gradually be increased to the desired level.

At the startup of trial 3, another problem occurred, which was a clogged inlet valve of the digester. When trying to pump material into the digester with the valve clogged, pressure built up in the system and popped a hose loose. The PVC connector between the pump outlet and hose also broke, with the break occurring at the pump outlet. The photo below (Figure 5.4) shows the condition of the valve following its removal from the system to be cleaned and fixed. Sand build up can be clearly seen along the ball of the valve. Upon taking the valve apart to clean it, it was seen that some other solids as well had built up and were also part of the problem. None of the other valves ever had this problem occur.



Figure 5.4: Clogged Valve

The picture on the left shows the connection on the pump side of the valve and the valve itself. The picture on the right shows the valve. The area where sand has gotten into the valve is highlighted. This is after initial cleaning but before taking the valve apart to completely clean.

Problems also occurred in the electrical system. During trial 2, the gas flow meter was obtained and installed. Following installation of the flow meter to the system, the pH transmission and the flow meter transmission interfered with each other, resulting in meaningless data. The temperature data came in through a different DAQ card and was unaffected. The flow meter was unplugged to allow pH to be monitored, and temperature was still recorded during this time. Dr. Rod Thomas helped to fix this interference problem. At first an isolation amp was placed into the system; however, it did not solve the problem. The isolation amp was left inline with the pH transmitter, and a transformer was added to the flow meter. In addition a common ground was connected and the settings in the DAQ were changed from differential to root single error. This solved the problem and allowed proper data transmissions.

Despite the above mentioned setbacks, some encouraging results were seen from the first three months of operation. The first was that the temperature was capable of being controlled within a narrow band. Figure 5.5 shows the average daily temperature for trial 1. The standard deviations are graphed as well. The average daily temperature is between 37 and 38 C most days. The standard deviation is also less than a degree for most days as well, with the exception of days where digester maintenance, such as clearing of clogs and fixing the overflow line, was necessary. This shows that

proportional control for temperature was more than adequate to reach and maintain the temperature necessary for digestion.

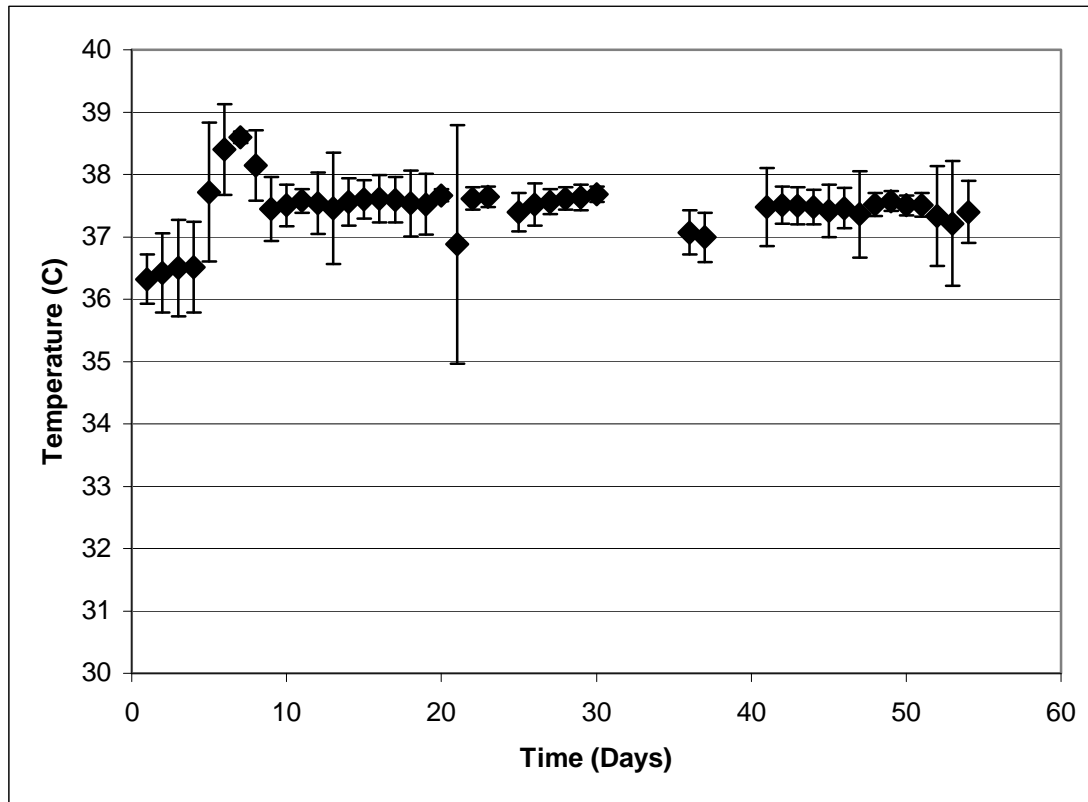


Figure 5.5: Trial 1 daily average temperature

The addition of inoculum to the digester during start-up also resulted in improved pH within the system. The flow meter displayed readings indicating a small amount of biogas; however, it was within the error limit of 0. Although full operation was not achieved, the experience has helped to understand the start-up process to a digester as well as digester behavior.

Volatile Solids destruction was also observed to be around 66%. This is probably a bit high from what actually occurred because some solids would have settled out onto some of the flat surfaces within the digester and feed/recirculation lines. It was also later observed towards the end of the digester's operation that the effluent VS content was higher than the influent VS. This suggests that solids had settled within the digester system and were being pushed out. However, the data still suggests that considerable VS

destruction was occurring over the course of the trials. This shows the presence of active microorganisms, with the digester helping to treat the manure for spreading purposes.

In mid October the digester was stopped so that the sensors could be evaluated and full-scale implementation begun. Since they had been exposed to a harsher than usual digester environment for many months it was important to see what kind of effect this had on them. Figures 5.6 and 5.7 show what the sensors looked like upon removal from the digester. As can be seen, there was significant solids build-up over the sensors. This is not expected to have affected the thermocouples very much in terms of accuracy, although it may have reduced the response time. However, the pH probe relies on having its glass junction open for ion exchange, and this solids build up could have prevented that. While it may seem that all this information should just be available from looking at the spec sheets and obtained from manufacturers when discussing applications. But when buying sensors for a digester, this experience has shown digesters and manure are slightly different beasts, and the system has to be able to tolerate both. The pump should have had no problems handling digester solids at the 6% VS ratio and was not expected to clog at the 9% VS rate. However, the way the solids in the manure interacted resulted in clogs nonetheless. The valves should also have been more than adequate for handling the job with the manure. Yet one still clogged. Operating conditions were also extreme with a pH in the 5's, accumulation of organic acids, the possible presence of hydrogen sulfide, and an average operating temperature set at 37 C. This combination creates an extremely stressful environment that may damage many sensors. The observed solids accumulation in various parts of the reactor only adds to the potential problems that could result. Even if the pH probe's calibration had not been found to be off, the accumulation of solids on it may have an impact on the probes ability to get proper ion exchange. This could result in misleading information, leading to operators either ignoring a real problem or trying to fix a problem that does not exist.



Figure 5.6: pH Probe upon removal from Digester



Figure 5.7: Thermocouples before and after cleaning off

The lack of significant biogas production may have had several causes. The manure was stored in the refrigerator prior to feeding, and this cold may have been a shock to the manure microbial community. With no inoculation in the first trial, the methanogen population would originally be coming from the manure. Even once the

digester was stable and fully operational, it was expected the methanogens in the manure would help to bolster the already working population.

Despite these challenges, the computer was capable of handling the digester operation and working as a monitoring and command center. The computer was able to record the data transmitted from the digester and store it within a single text file capable of storing multiple days of data, even when recorded every 5-6 seconds. Thus a large amount of information on the time the digester was operating is available for analysis, which will be discussed further in the Chapter 6. Unfortunately this is true for only the pH and temperatures, as biogas production never reached a high enough level. Nevertheless, it has been demonstrated that long term sensor operation and data logging can be accomplished with a computer for an anaerobic digester.

5.5 Thermocouple Test

A digester environment is warm, wet, and often corrosive, all of which can destroy sensors over time. To evaluate the tolerance of thermocouples to these conditions, a calibration was completed after the previously described series of trials. After removing the thermocouples from the anaerobic digester, they were washed in water and then tested to determine how well the thermocouples were working. An ice bath and a hot water bath were used to generate consistent, defined temperatures.

For the ice bath, a beaker was packed with ice and then water was added to fill the void spaces. Three glass thermometers were placed in the container. The thermometers were checked with all reading within the range [-1, 1] C.

The “digester aged” thermocouples were then placed in the ice bath along with three new thermocouples. Data was sampled once a second, and the average temperatures over the previous five minute interval were recorded using the computer data acquisition system for all six thermocouples. The glass thermometer temperatures were hand recorded every five minutes. This was continued for one hour.

Following the ice bath, a hot water bath was used to check thermocouple performance at higher temperatures. For this test, the water bath was set to boiling and the temperature first checked using the glass thermometers. The temperatures were all within the range [99, 101] C. All six thermocouples were added to the boiling water.

Data was recorded in five minute intervals. The glass thermometers were recorded every five minutes as well. This was performed for 25 minutes.

5.6 pH Probe Test

The pH probe was evaluated with a 24 hour test. The probe was calibrated with a two-point calibration using a pH 7 buffer solution and a pH 4 buffer solution. The calibration was performed using the pH transmitter and sensor coupled as had been the case during the digester trials.

Following calibration the pH probe was left immersed in the pH 7.00 buffer solution for 24 hours. The laptop data acquisition system recorded the pH readings every 5 to 6 seconds.

The data then had 0.13 added to the pH readings to compensate for the difference between the transmitter and laptop readings, as determined by manual calibration. Sampling from the same minute every hour, all the data recorded during that minute were averaged and graphed. This data was used to determine whether the pH probe drifted over 24 hours.

5.7 pH Shock Load Test

An acid shock test was performed in an abiotic environment. This helps to minimize external factors and ensure the controller is responsible for the pH recovery. To perform this test approximately 20 L buffer solution was created with a buffering capacity of approximately 6 g/L, which was estimated to be similar to manure. The mixture consisted of 5 g/L of baking soda and 7.5 g/L of sodium phosphate dibasic. The buffering capacity was found using standard wastewater methods 2320 B Titration method (Clesceri et al., 1989).

This solution was pumped into the digester until it began to spill out the overflow line. The pH setpoint input into the computer was 6.8. Vinegar was then used to provide the acid shock to the system. 2 L of vinegar was pumped into the digester, corresponding to two days feeding. A base solution of baking soda at a concentration 50 g/L was then pumped into the digester under computer control. Every 5 minutes the digester was

mixed for 1 minute. The test was run until the digester pH reached 6.8 or a sustained level of 6.77 for more than 10 minutes.

6.0 Results and Discussion

This section serves to chronicle the experimental process, the resulting data, and provide an interpretation of the data. The research targeted the demonstration of a computerized data acquisition system to operate and record data from an anaerobic digester. Following the digester's operation for 7 months under both typical and extreme conditions, the monitoring system was evaluated to determine how it held up under the conditions within the digester.

6.1 Temperature Control

Temperature is perhaps the most common control variable in anaerobic digesters, normally managed via a simple thermostat and hot water recirculation system in dairy digesters in the U.S. In order to demonstrate computerized operation of digester temperature control, a heating system needed to be implemented. Section 4.6 discusses the heaters chosen; however, this is only part of the heating system. The other necessary components included the thermocouple sensors and incorporating temperature control strategies into the digester control program.

To test different temperature control strategies, the digester was filled with water. A program was written that allowed for multiple strategies to be tested, and each strategy was allowed to run for 2 hours while the temperature data was recorded. The two hour time frame allowed the control to reach steady-state, generating data which was examined. The setpoint used for testing the control scheme was 30 C. This temperature was chosen because it was close to the desired operating level of 37 C; however, it was close enough to room temperature to allow the water to cool quickly and perform multiple tests.

First a simple on/off control was tested. If the average temperature was below the setpoint, the heaters were on. If the average temperature was above the setpoint, the heaters were off. Due to the dramatic overshoot of the setpoint, it was apparent that a simple average would not be a good approach. The strategy was changed to a weighted average. The temperature with the highest temperature was weighted by a factor of 2X, while the other two sensors had a weighting function of 1X. The heaters were turned on if the weighted average temperature was below the desired setpoint, i.e. the digester was

too cold. The heaters would then be turned off once the weighted average temperature was greater than the setpoint, i.e. the digester was too hot. Figure 6.1 shows the results from this strategy. After 2000 seconds, a cycle can be seen to develop. The heating phase is 600 seconds and the cooling phase is 1000 seconds.

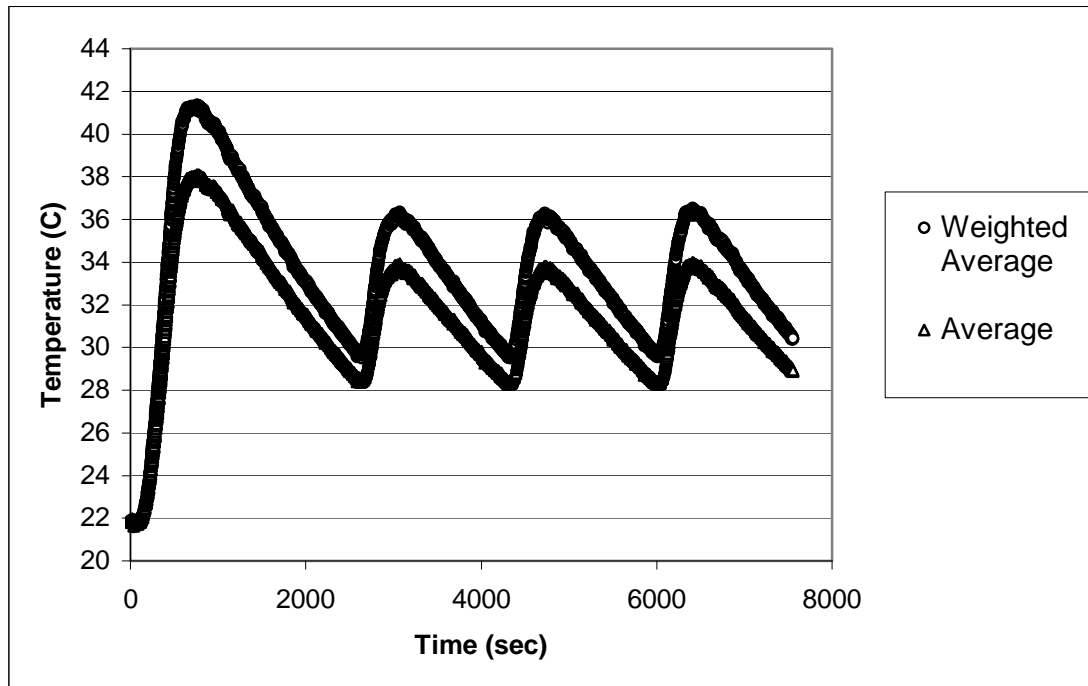


Figure 6.1: Weighted average Test 1

After the first weighted average was conducted, the concern was over the amount of time the digester spent above the desired setpoint. It was noticed that heating could be achieved faster than cooling. To compensate for this a new weighted average was used, this time the lagging temperature was not included in the control temperature calculation, only the higher two thermocouple readings were included (Figure 6.2). The amount of overshoot was still a concern. There were two reasons for this concern. The first is that at the higher temperature the overshoot would be increased as well as the cycle period. The second reason was the observation that heating was easier to achieve than cooling. If the temperature dropped below the desired temperature, it could be raised faster than waiting for the digester to cool.

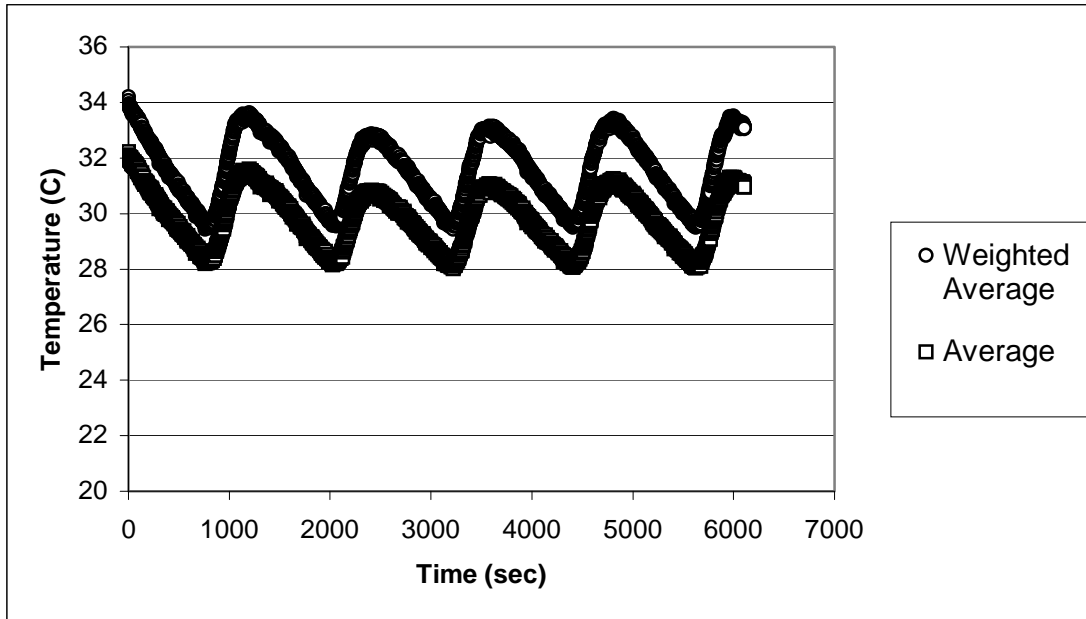


Figure 6.2: Two thermocouple weighted average temperature control

Finally a proportional control was tested which divided heating into 5 second intervals. Depending on the difference between the setpoint and the average temperature, the heater would be on for a proportional amount of the 5 second interval. Figure 6.3 displays these results. Equation 6.1 shows the heating equations, including the LabVIEW timers function in milliseconds. The overshoot was less than 3 degrees. After 2000 seconds, the controller maintains a steady temperature.

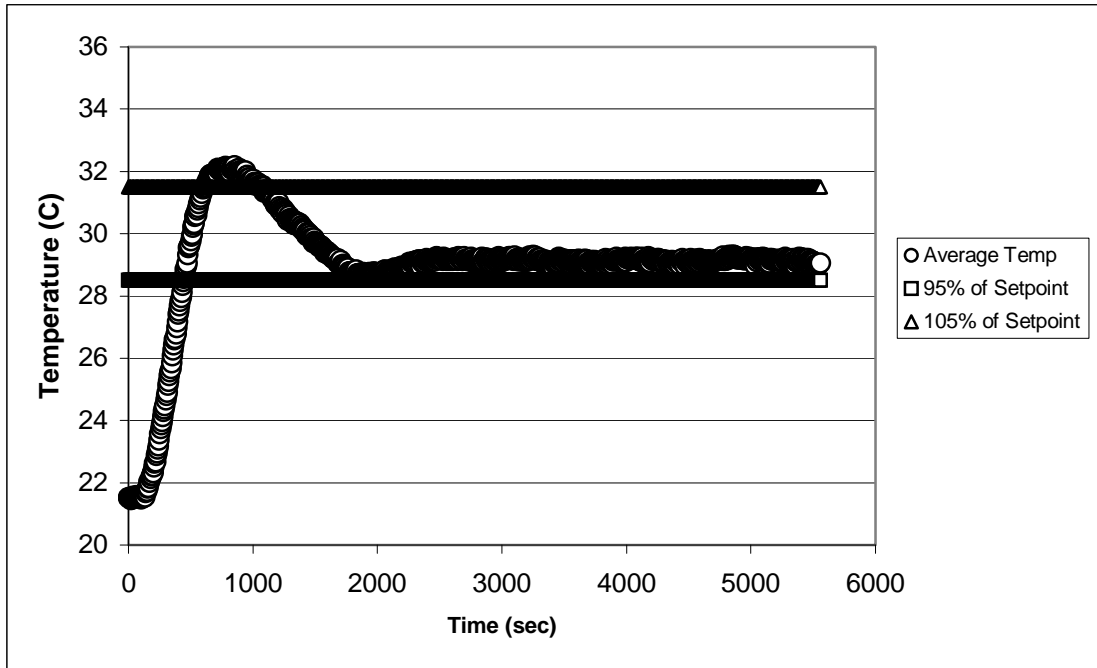


Figure 6.3: Proportional control graph with setpoint of 30 C

Error = setpoint-average temperature

Heaters On = Error * 400

Heaters Off = 5000 – Heaters On

Equation 6.1: Heating Algorithm

It was decided to go with a proportional control for the digester. However, proportional control typically has a steady-state error associated with it (Bateson, 2002). This means that this control strategy will have some error associated with its operation. Figure 6.3 shows this steady-state error to be on the order of 1 degree below the desired setpoint. By increasing the setpoint, the steady-state error would also increase. In order to compensate for this, the setpoint used for digester operation was 39 C rather than the desired 37 C.

6.2 Temperature and pH Results for Digester Operation

During the seven months the digester was in operation, data was collected on temperature, pH, and gas flow. As previously mentioned, biogas flow was minimal and pH fell to acidic levels. A proportional control was used to maintain the desired temperature within the digester. The preliminary controller testing has already been described. However the results of how the controller managed to maintain the digester conditions have not been explored in detail.

The digester tests can be divided into three distinct trials. The first trial consisted of no seed material and unscreened manure. The second trial consisted of seed material and unscreened manure. The third trial consisted of seed material and screened manure. The controller showed good effects at maintaining the necessary temperature conditions for digestion to occur (Figures 6.4-6.6).

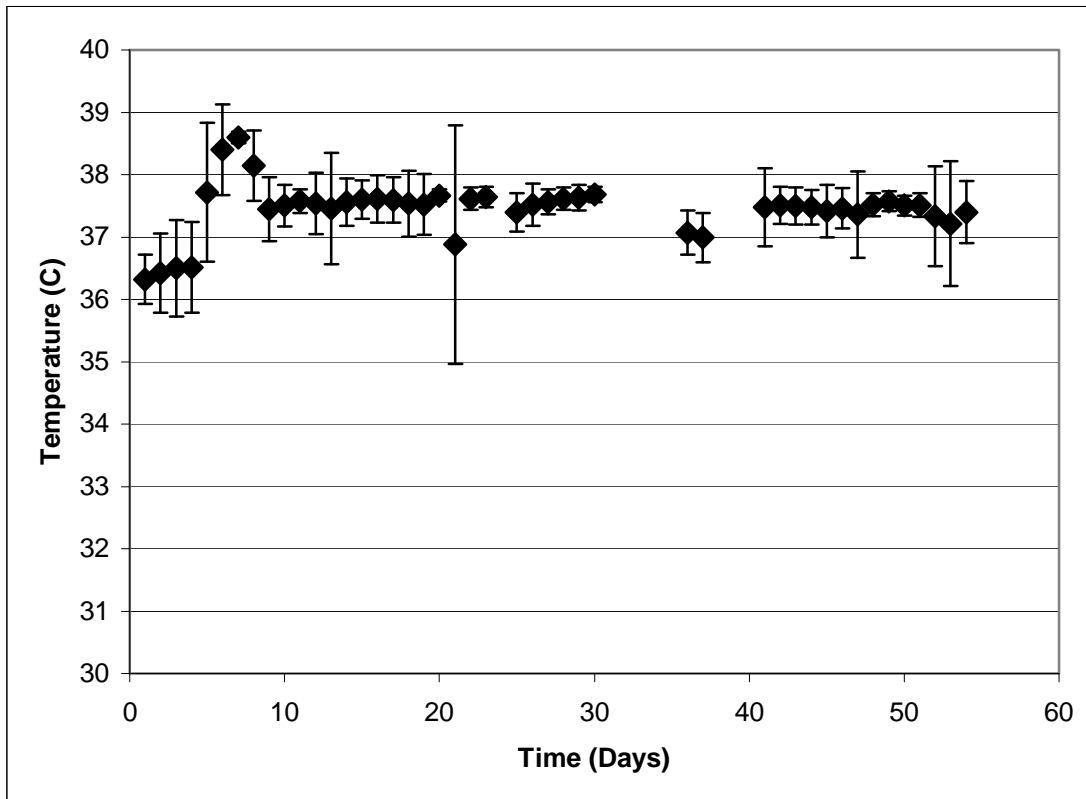


Figure 6.4: Trial 1 Average Daily Temperature

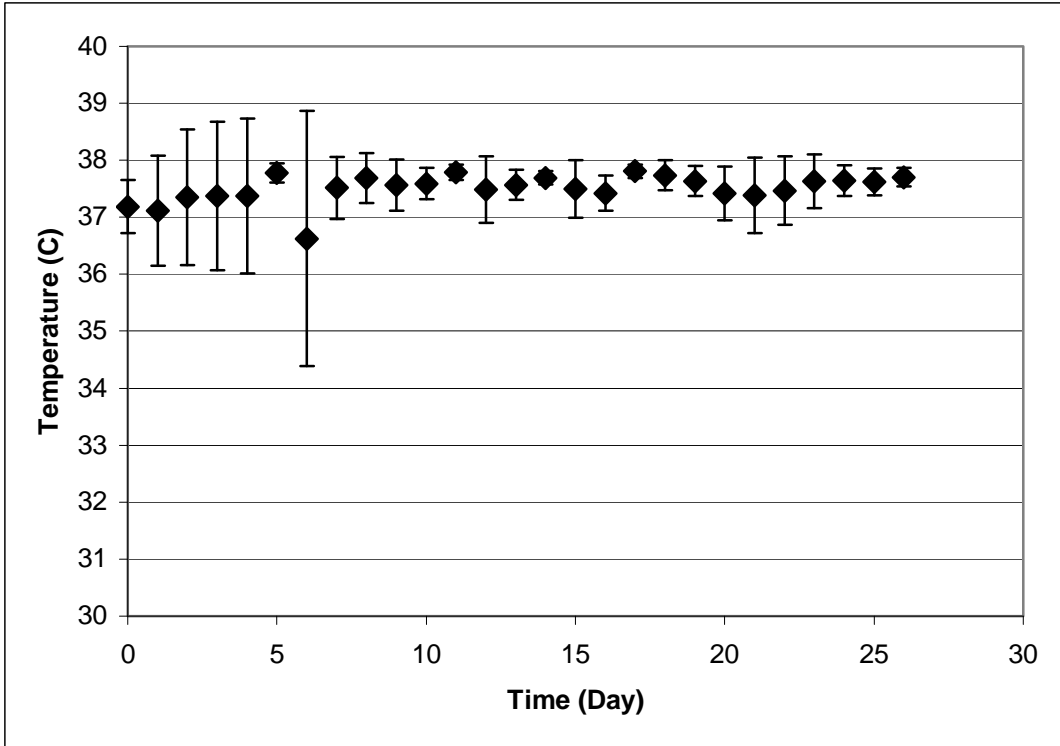


Figure 6.5: Trial 2 Average Daily Temperature

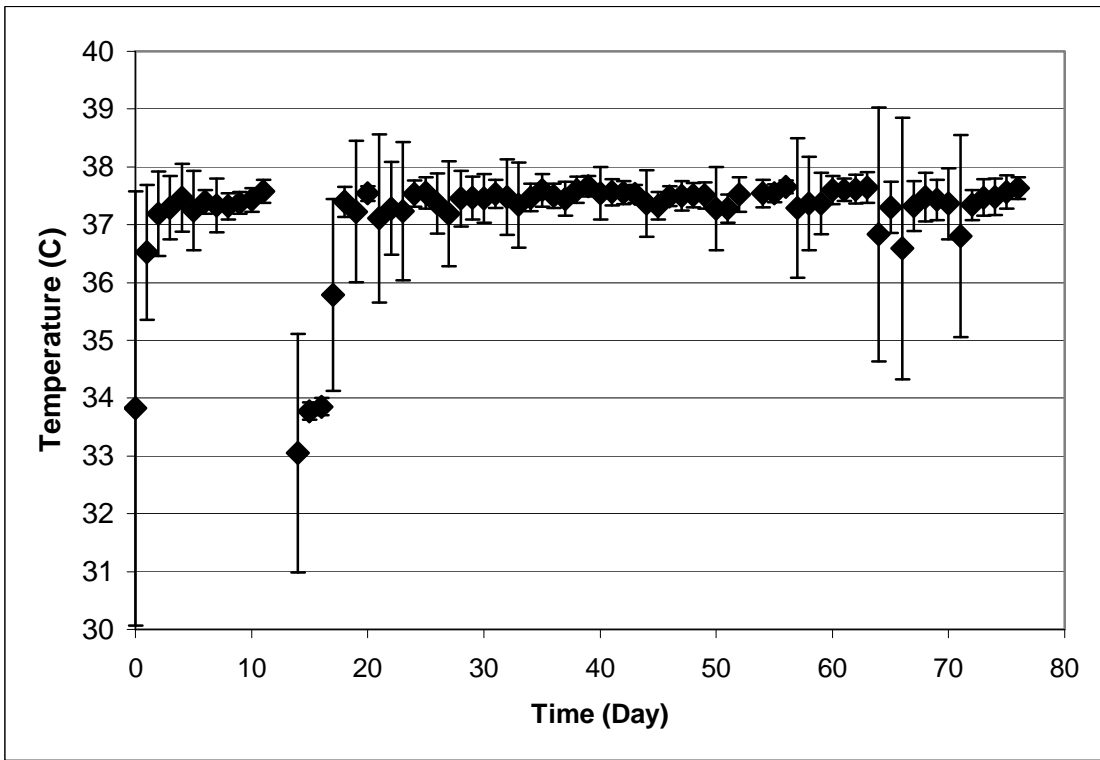


Figure 6.6: Trial 3 Average Daily Temperature

In the cases of trial 1 and 2, the average daily digester temperature did not fall below 36 C. Even for the final trial this only occurred 4 times out 76 days. The error bars on the three graphs show a standard deviation above and below the average temperature for that day. Most days this standard deviation is less than 0.5 C. The more extreme deviations are on the order of 2 C, and those occurred on days where computer operation had to be halted for digester maintenance.

Data was also recorded about the pH within the digester. The average daily pH is presented in figures 6.7 to 6.9, with error bars showing one standard deviation both above and below the average daily value. It should be noted that some of this data is suspect as the pH sensor at the end of the trials was out of calibration (see section 6.4.1). Trial 1 is missing data because once the flow meter was first connected to the system it caused erroneous pH readings. For the last part of trial one the flow meter was unhooked so pH could be recorded. At the beginning of trial 2 the problem with the flow meter and pH meter persisted until about half way through the trial. This problem and its solution have been previously described in greater detail.

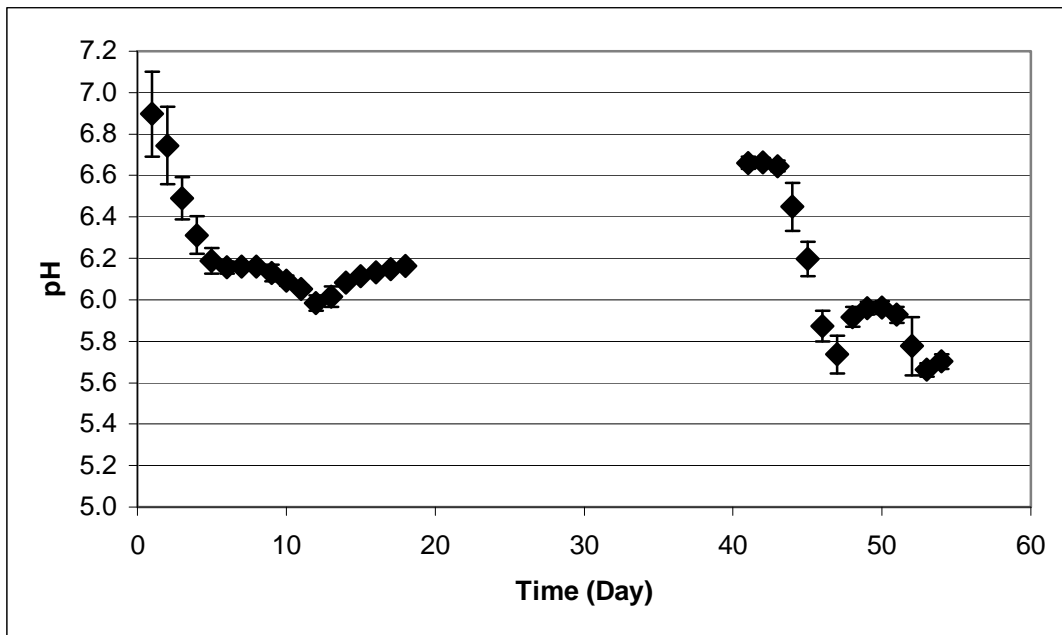


Figure 6.7: Trial 1 Average Daily pH

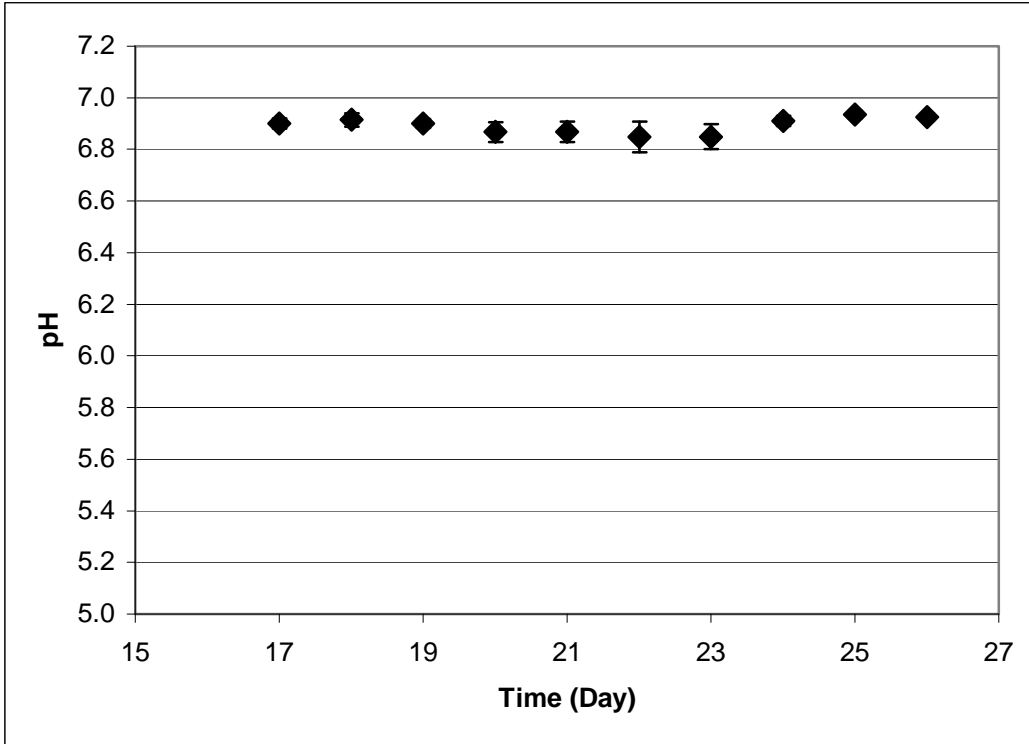


Figure 6.8: Trial 2 Average Daily pH

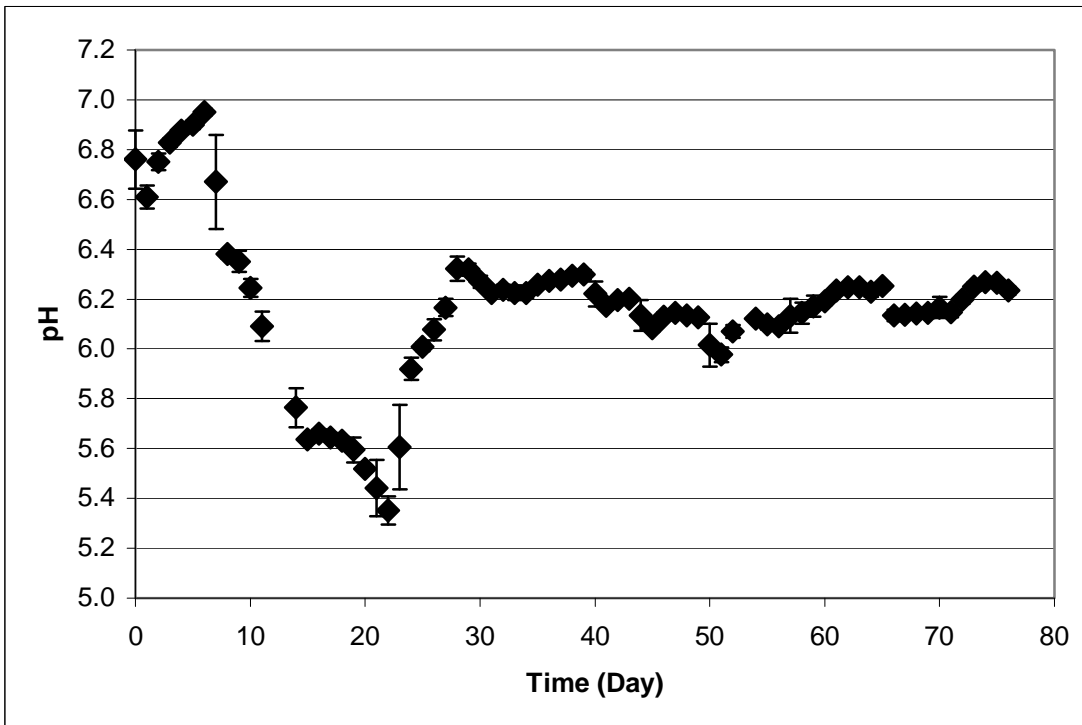


Figure 6.9: Trial 3 Average Daily pH

The end of trial 2 showed the best pH results maintaining the pH within a band of 6.8 and 7.0. In Trial 1a, a slow steady descent for pH can be observed at the outset of the trial. In part 1b, despite a brief recovery, the pH is once again descending to a level of approximately 6.0 and below. This environment puts a great deal of stress on the microbiological system. The result is an unstable system which finds alternative metabolic pathways to the methanogenic one.

The rapid drop occurring in Trial 3 is the result of adding sugar to the strained manure. Upon straining the manure, a large portion of the VS were removed from the feed. In order to increase the VS concentration, sugar was added to the manure. However by adding raw sugar, the hydrolysis step in the digestion process was skipped. This contributed to the unstable conditions within the digester and resulted in a large pH upset.

6.3 Digester Sensor Evaluation

Following the operation of the anaerobic digester for 7 months, the lab-scale experimental phase was stopped and the sensors were evaluated. This sensor evaluation portion of the research served to demonstrate whether the sensors needed calibration and/or cleaning along with determining if the sensors were damaged.

6.3.1 pH Probe Evaluation

As previously indicated, the pH probe was subjected to low pH, elevated temperature, and solids build-up during the seven months of digester operation. To see what had happened to the pH probe during that time, it was first gently cleaned and placed in some pH 7 buffer solution to see what it read. The initial reading was down at 6.2 showing that the pH probe was not accurately reading the solution pH. It is unknown at what point during the trials the probe fell out of calibration. The probe's inaccurate readings may explain why attempts to regulate pH during trial 3, through manual addition of baking soda, sodium bicarbonate, and even sodium hydroxide appeared to be ineffective. The attempts to regulate the pH could only be as good as the data. Since the data was incorrect, it was not possible to properly regulate the pH. Although the pH was never controlled through the computer, even if it was, the incorrectly low sensor data

would have had the pump constantly running. Even a computer can only make a decision based on the information available. If the information is flawed, whether the operator is human or a computer, the proper action cannot be taken. In order to check the pH probe, the pH of the daily effluent could be taken with a bench top probe. This value could be compared with the digester's pH probe. When the difference between the two probes is greater than 0.15, the digester probe could be removed and recalibrated.

The next question asked with regards to the pH probe was whether or not it could be calibrated. This question sought to answer whether regular maintenance would be enough to allow for accurate pH measurements, or if probes need to be replaced on a regular basis. The probe was calibrated and then placed in a pH 7 buffer solution, then left for 20+ hours to check the drift that occurred. The pH data for the same minute every hour was averaged and the standard deviation was also taken. The results are displayed in Figures 6.10 and 6.11.

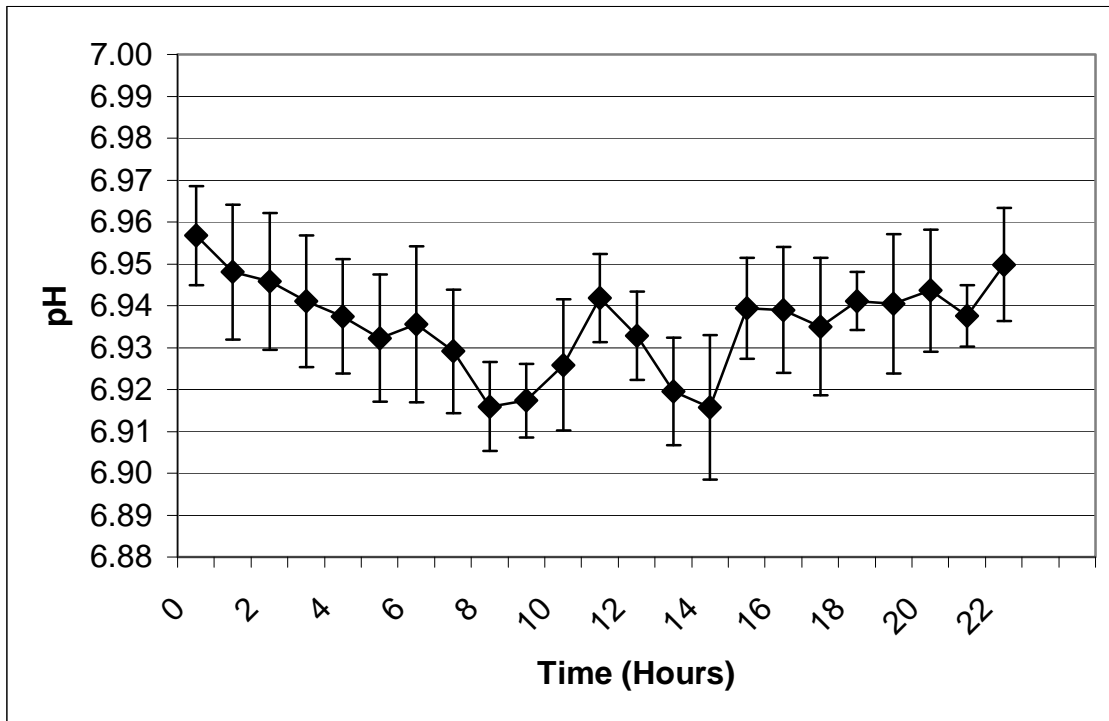


Figure 6.10: pH Drift Test 1 results

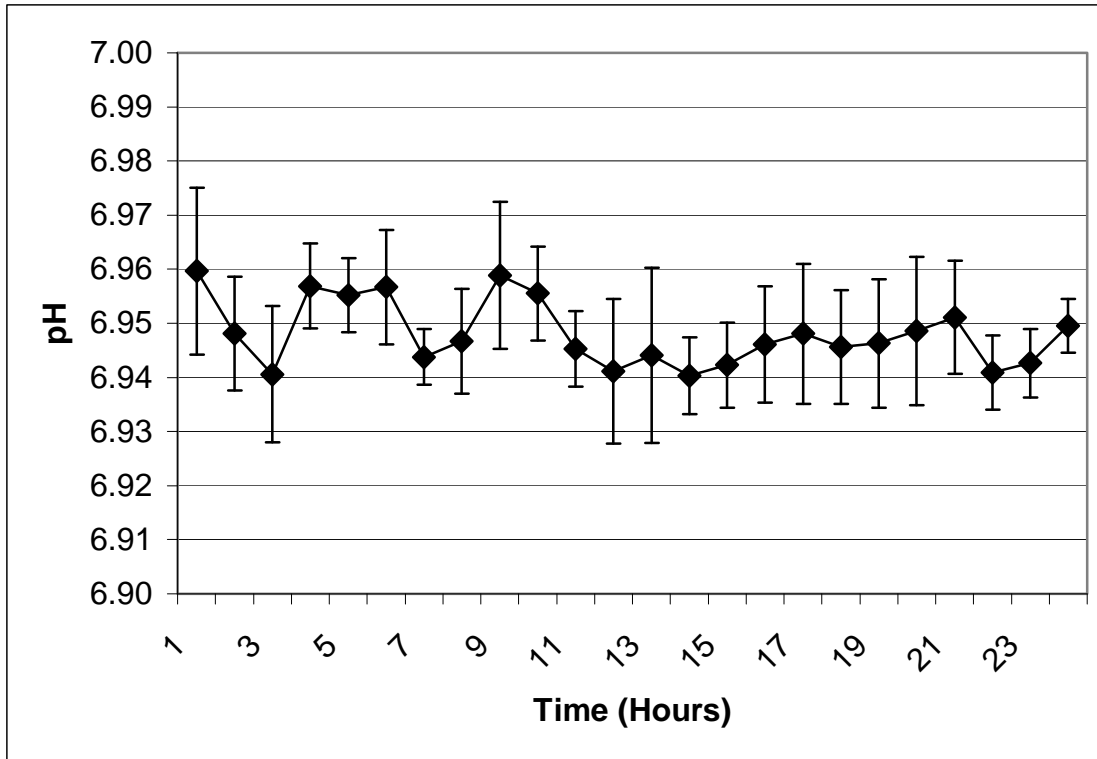


Figure 6.11: pH Drift Test 2 results

Over a 24 hour period the readings drifted approximately 0.06 pH units from the initial pH 7 at the moment of calibration. This correlates to an error of 0.9%. A one sample t-test was performed using Minitab software to determine whether there was a significant difference from 7. The result was a p of 0.00 for both. Therefore, at a 95% confidence interval the null hypothesis, that the average value over the 24 hour tested was from 7, can be rejected. This shows being held in the digester for 7 months had a slight effect on the probe. This reinforces the need for regular sensor maintenance.

6.3.2 Thermocouple Evaluation

The thermocouples were tested under an ice bath and a hot water bath. The ice bath and hot water bath were used to calibrate the temperature sensors.

Thermocouple testing and re-calibration in the ice bath and hot water bath were similar. For the ice bath test a large bowl was filled approximately a third full with ice. Tap water was then added to fill up to the ice level and take up the void space within the ice. The entire thermocouple assembly was placed in the beaker along with three glass

thermometers. The thermometers came from McMaster-Carr and came with certificates of calibration. However, to reduce the possibility a single thermometer was damaged or miscalibrated, three were used. Three new Type-T copper-constantin thermocouples were also made to compare with the older thermocouples that had been placed in the digester. All the probes were placed in the same region of the container. A program was written to average the temperatures and record them every 5 minutes. The program was started and the temperature data from the thermocouples was recorded approximately every 5 minutes the thermometers. Data was collected over a 60 minute period for the ice bath. Data collection from the hot water bath was similar, except the bath temperature was set to boil water at 100 C, and only continued for 25 minutes due to the loss of water as it boiled off.

The results of the ice bath tests are presented below in Figures 6.12 and 6.13. In the first test one of the thermocouples created to compare with the digester thermocouples fell out of the ice bath; therefore all of its readings showed room temperature. This was not discovered until the experiment ended and so that data was not used. The thermometers had markings of 1 degree C. For that reason the thermometers were read to the nearest degree C.

The highest temperature seen during either of the two tests was at the start of the first test when one of the digester probes recorded a temperature of 1.6 C, suggesting that the thermocouple was still equilibrating. The three digester probes reported higher readings. However these were still within 1 degree C of the other readings, and it is not believed that these differences are significant.

A two sample t-test was conducted on the data. For both tests, the probes that had spent 7 months in the digester were compared to the new probes and the glass thermometers. The glass thermometers were also compared to the new probes. A two sample t-test was conducted on whether the difference between the average of any two was less than 1 degree. The results show that at a 95% confidence interval the null hypothesis can be rejected and the difference between any two groups is less than 1 degree.

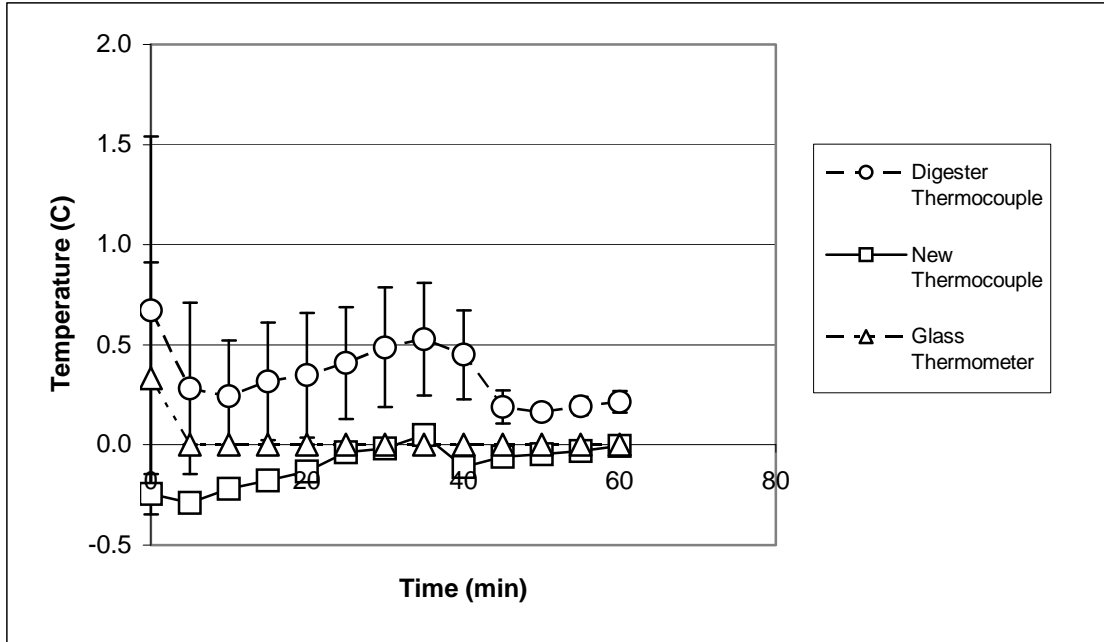


Figure 6.12: Ice bath temperature test 1 results

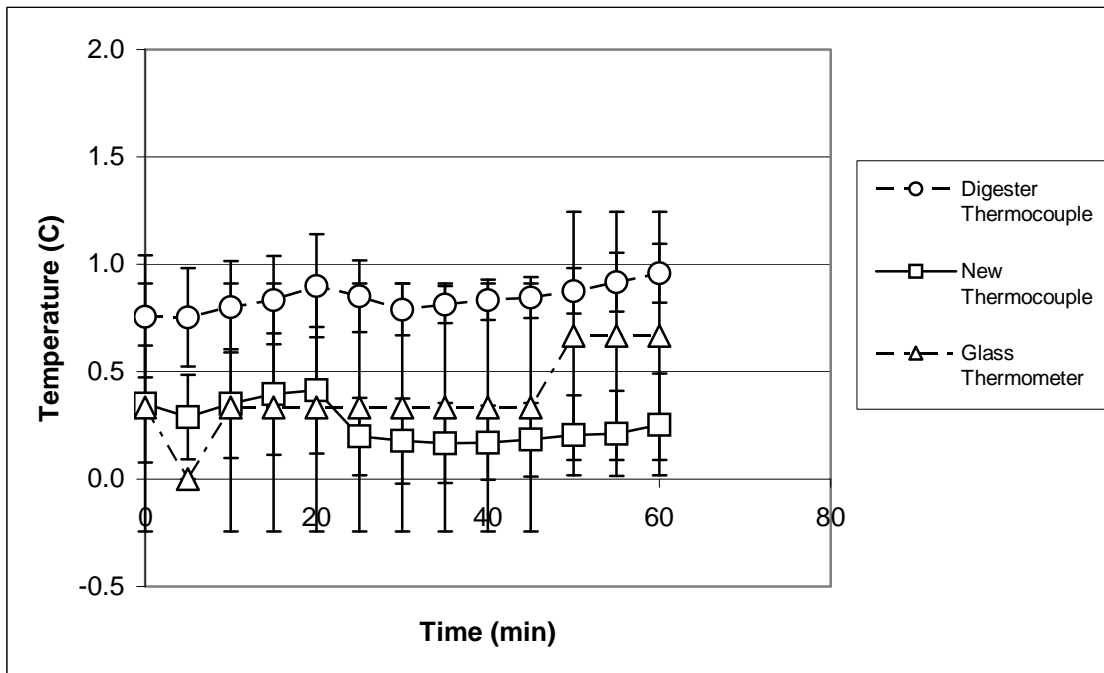


Figure 6.13: Ice bath temperature test 2 results

The hot water bath results are shown in Figures 6.14 and 6.15. The only test where the average temperature recorded by the thermocouples placed in the digester was not the highest was in the final hot water test. However, in this test it is believed that one

of the thermocouples was not adequately submerged because it provided readings of 97.5 C while all the other probes recorded 98 C or higher. This probe was removed and an average of the other two thermocouples was added to Figure 6.15. For the first 10 minutes, the new probes record the highest average reading. After 10 minutes, the digester thermocouples read the highest.

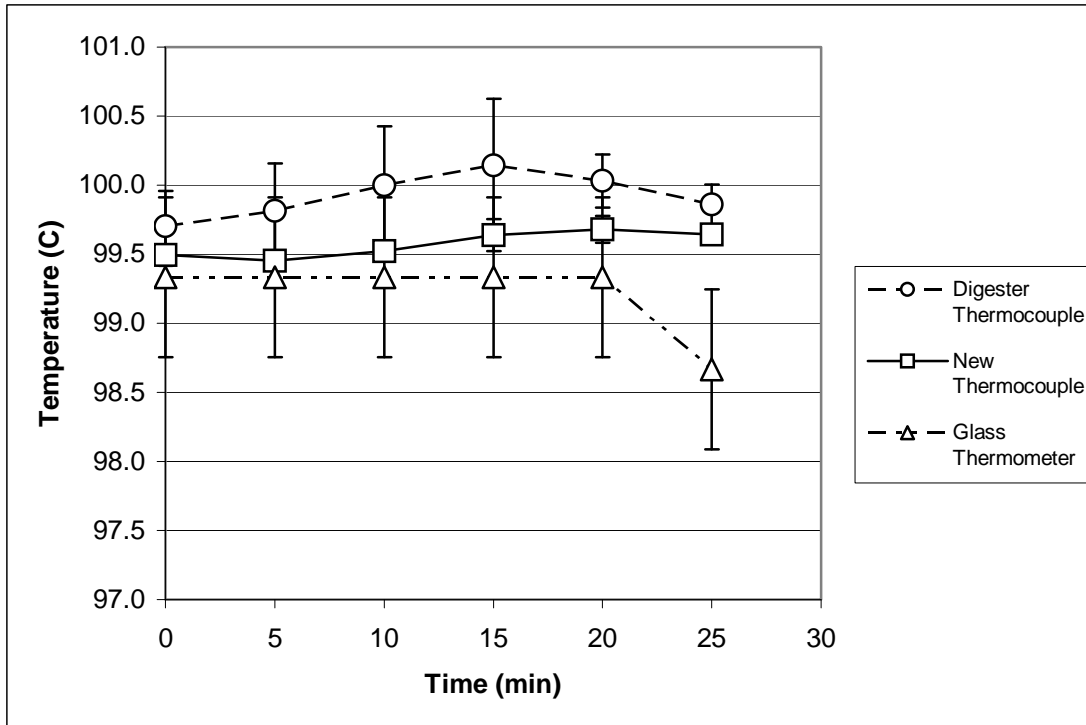


Figure 6.14: Hot Water Bath temperature test 1 results

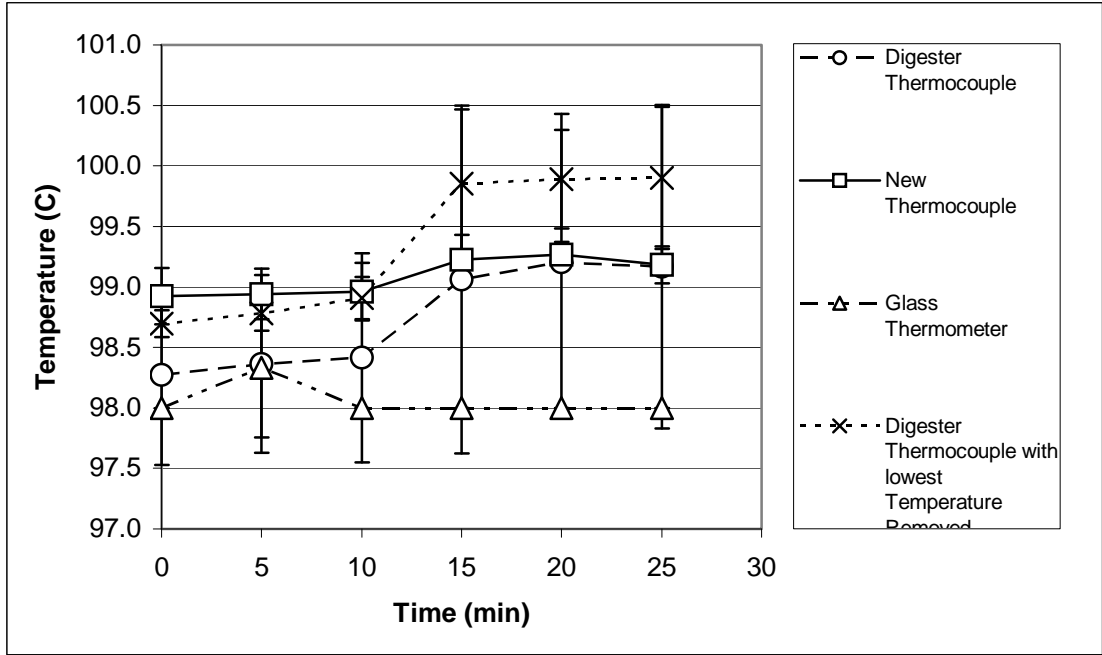


Figure 6.15: Hot Water Bath temperature test 2 results

The average readings of the digester thermocouples were compared to both the newly created thermocouples and also to the thermometers. A two sample t-test was used to test whether the average temperature difference for the two hot water bath tests was less than 2 degrees. At a 95% confidence level the null hypothesis that the average between any two categories is greater than 2 can be rejected. These tests included the outlying data in the second hot water test. For this reason, it is believed that the thermocouples used in the digester are still operating properly.

6.3.3 Flow Meter Evaluation

In order to test the flow meter, it was sent back to Alicat to be checked for re-calibration. The company tested the flow meter at five different points (Alicat Calibration Data Sheet). Four of the five calibration points were outside the tolerance range, with the sensor overpredicting flow by approximately 20%. The one point still meeting the tolerance criteria was at 0 flow. Table 6.1 shows the results of the re-calibration test. Table 6.2 shows the results of the flow meter leaving Alicat after re-calibration (Alicat Calibration Data Sheet). The flow meter was re-calibrated to an uncertainty of 0.8% of the reading and 0.2% of the Full Scale.

Table 6.1 Flow Meter Re-calibration

Device Reading (SCCM)	Actual (SCCM)
0.00	0.00
5.90	4.99
12.04	9.98
18.38	14.98
24.91	19.99

Table 6.2 Post Calibration Results

Device Reading (SCCM)	Actual (SCCM)
0.00	0.00
4.99	4.99
10.00	9.98
14.98	14.98
19.95	19.99

It was noted that a flaky, crystalline substance was found inside the flow meter (Alicat Repair Note). This was thought to be the cause of the problem. Two possible causes are water vapor entering the flow meter or hydrogen sulfide. Since biogas was produced in negligible amounts, hydrogen sulfide seems an unlikely source. Water vapor seems the most likely cause. Some moisture was viewed in the tubing from the digester to the flow meter. When picking a flow meter, water vapor was not expected to be a large component. However, condensation can be a concern with the gas stream coming from a warm, wet digester. One recommendation from this experience is that flow meter installations be downstream of a condenser that should include hydrogen sulfide removal.

6.3.4 Sensor Evaluation Results Summary

The results show that commercially available sensors are available to handle digester conditions for extended periods. However, these sensors do require regular maintenance to ensure proper long term operation. Both pH probe and flow meter were out of calibration when first removed from the system. Both were able to be recalibrated. However the pH probe showed it read too low and should be replaced. For pH probes, easy access should be provided for removal, cleaning, and replacement. Flow meters should be positioned downstream of gas-cleanup systems that remove hydrogen sulfide

and water vapor. The thermocouples were shown to still be within calibration and also operational.

6.4 pH Shock Load Results

A proportional pH control (Equation 6.2) was programmed and tested against an acid shock load. This was performed to examine the effectiveness of a simple and cheap system as well as exploring the necessary amount of sodium bicarbonate base (NaHCO_3) required to counteract the buildup of organic acids. A buffer solution consisting of 5 g/L of baking soda and 7.5 g/L of sodium phosphate dibasic was first created and filled the digester. This solution had a buffering capacity of approximately 6.0 g/L. Following this vinegar was added to the digester. The vinegar addition corresponded to a two day feeding of the lab-scale digester. This simulates if a strong acid were fed to the digester for two days. The NaHCO_3 solution was created by dissolving commercial baking soda in water and this solution was used as the base addition. Baking soda was chosen to demonstrate an option already available to farmers as opposed to a specially ordered chemical. Lime would be another option as well.

Error = setpoint-pH measurement

Pump On = Error * 4000

Pump Off = 5000 – Pump On

Equation 6.2: pH Algorithm

Table 6.3: pH Shock Test Summary

	Min pH	Base (mL)	Time to reach 6.75 (min)	Time to reach 6.80 (min)
Test 1	5.73	6063	72	89
Test 2	5.23	6562	90	110
Test 3	5.80	6238	78	90

Table 6.3 shows this acid addition caused the pH to drop to around 5.7-5.8 at the start of the tests. The table also shows the system was able to recover in approximately 90 minutes with between 6.0 and 6.5 L of base. In all cases, the system recovered in under 2 hours. Based on the concentration of base this is between 300-325 g of baking

soda. Figure 6.16 shows how base addition changed with time. At first a nearly linear increase in pH is observed, followed by the curve leveling as it approached the setpoint.

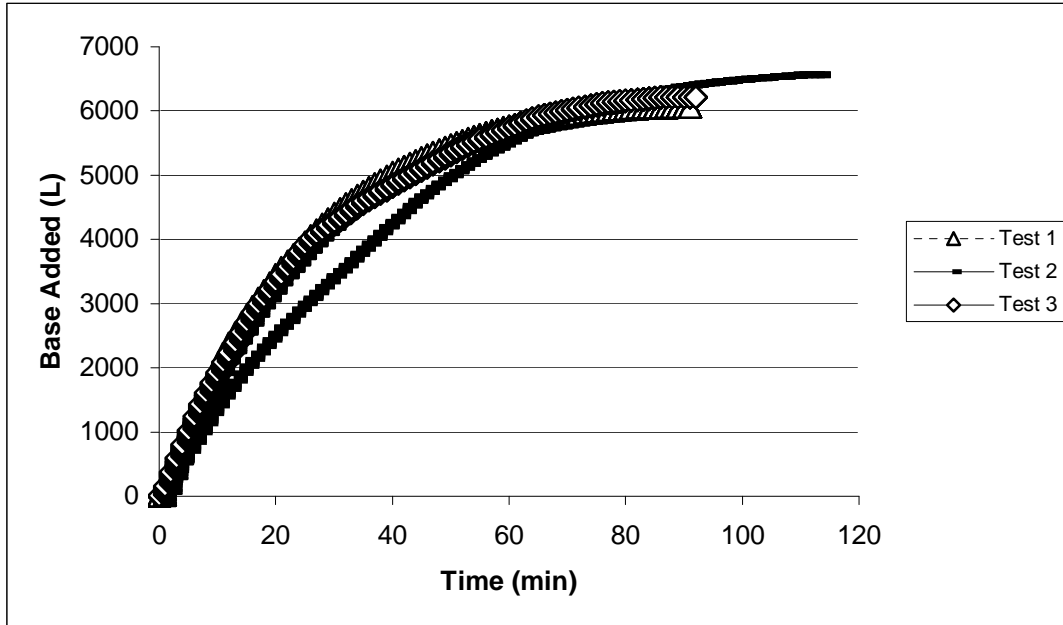


Figure 6.16: Total Base Addition for pH Shock Tests

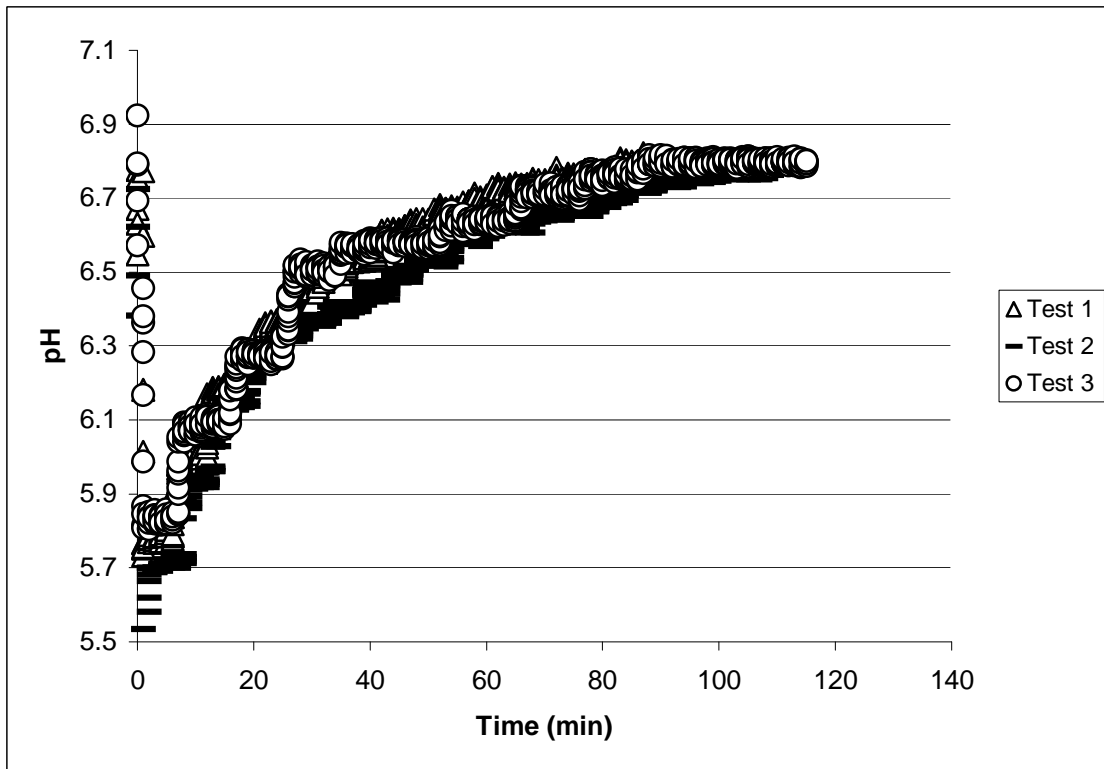


Figure 6.17: pH Response for pH Shock Tests

A similar curve is seen in Figure 6.17 as pH changed with time. The system was frequently mixed in order to maintain an accurate reflection of the pH within the system. Noise along the y-axis occurred just after the acid shock was added. The acid was still being mixed into the system. Test 2 takes longer to reach the stable point than the other two tests. This can be explained because temperature control was also turned on during the test. This resulted in two five second loops operating at the same time. This produced a lag in the system that was not part of tests 1 and 3.

The results show that the control system worked and was able to recover the system. A one-sample t test showed that at a 95% confidence interval the average recovery time was less than 120 minutes. This system resembles a worst-case scenario situation. The lab-scale digester also only monitored at a single point, which was fine because the lab digester is not very large and was mixed frequently. A full scale digester would want to include pH measurements of the influent, effluent, and at least one other spot in the digester depending on the mixing configuration.

6.5 Remote Monitoring on an Operating Dairy Farm

Following the work with the lab scale digester and sensor evaluation, the next objective was to begin full scale monitoring remotely via the internet. This would not only allow us to obtain data on an actual, operational on-farm digester, it would also allow others to observe the data coming in from a digester, either for verification of data or as an educational tool. This data could be used by third party certifiers of greenhouse gas credits or renewable energy credits to document a reduction in greenhouse gases or an offset to electricity production. In short, remote monitoring and data access through the internet can be a tool to show case Pennsylvania's commitment to green energy as well as provide important data about the operation of an anaerobic digester.

The farm chosen for this part of the project is the Penn England dairy. Figure 6.18 below shows a picture of the digester. A case study for the farm performed by Pat and Deb Topper of Penn State Agricultural and Biological Engineering is provided in Appendix B. The farm has 800 milking cows, and the digester design is a mixed loop design. The mixed loop is somewhere between a complete mix and plug flow. Some mixing does occur in the two main zones of the digester, but it does not mix the entire

system. The digester is operated in the mesophilic temperature range, at approximately 38 C (100 F). Several thermisters and a gas flow meter were already in place, and are being used as sensors for this project. In addition, pH probes are being placed in both the influent and effluent tanks, which provide temperatures for those two additional locations. Thermocouples will also be used to determine the heat savings generated from the digester, and to record the ambient air temperature. Figure 6.19 provides the digester layout on the farm.



Figure 6.18: Penn England Digester

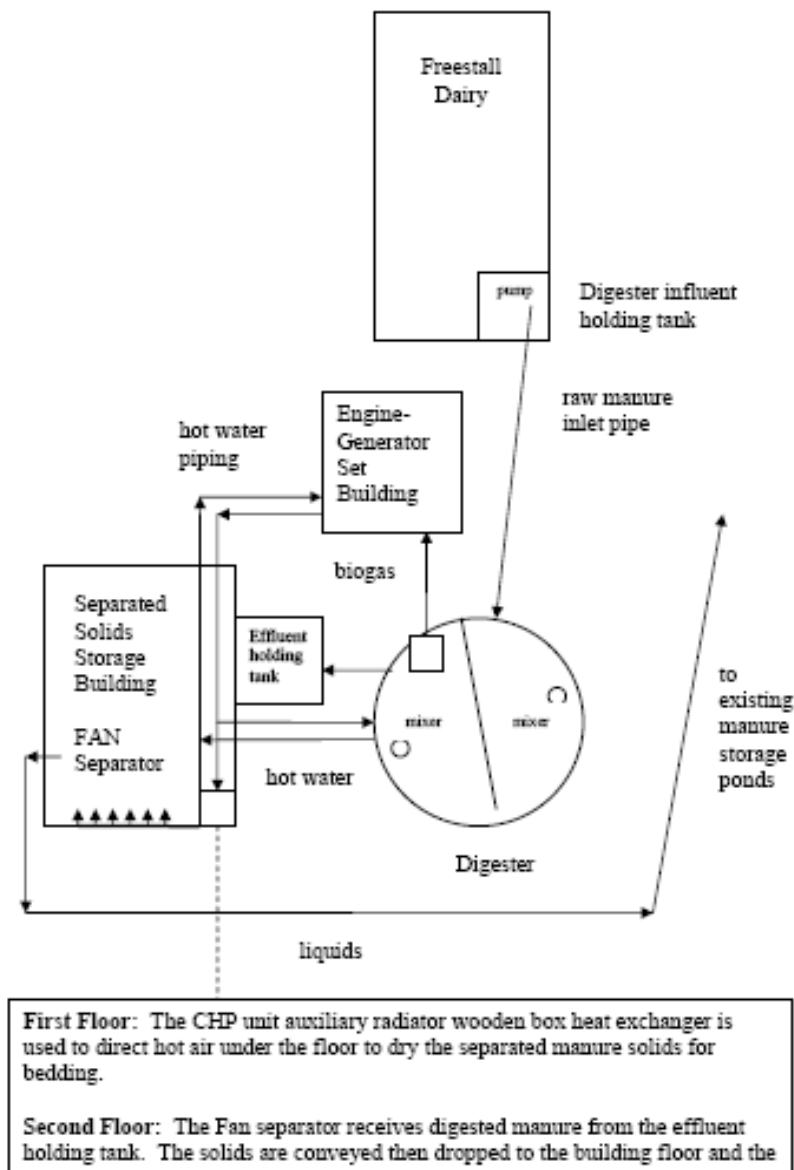


Figure 6.19: Penn England Manure Flow Layout (Topper, 2007)

The initial LabVIEW monitoring screen for the Penn England digester monitoring program can be seen below in Figure 6.20. The program stores the data in a text file every 5 minutes. The stored data will be the average of the data from the previous five minute interval for parameters such as pH and temperature. Data cells for parameters such as gas, electricity, and heat production will store cumulative values for each day. A lot of information can be gathered from the 5 minute averages.

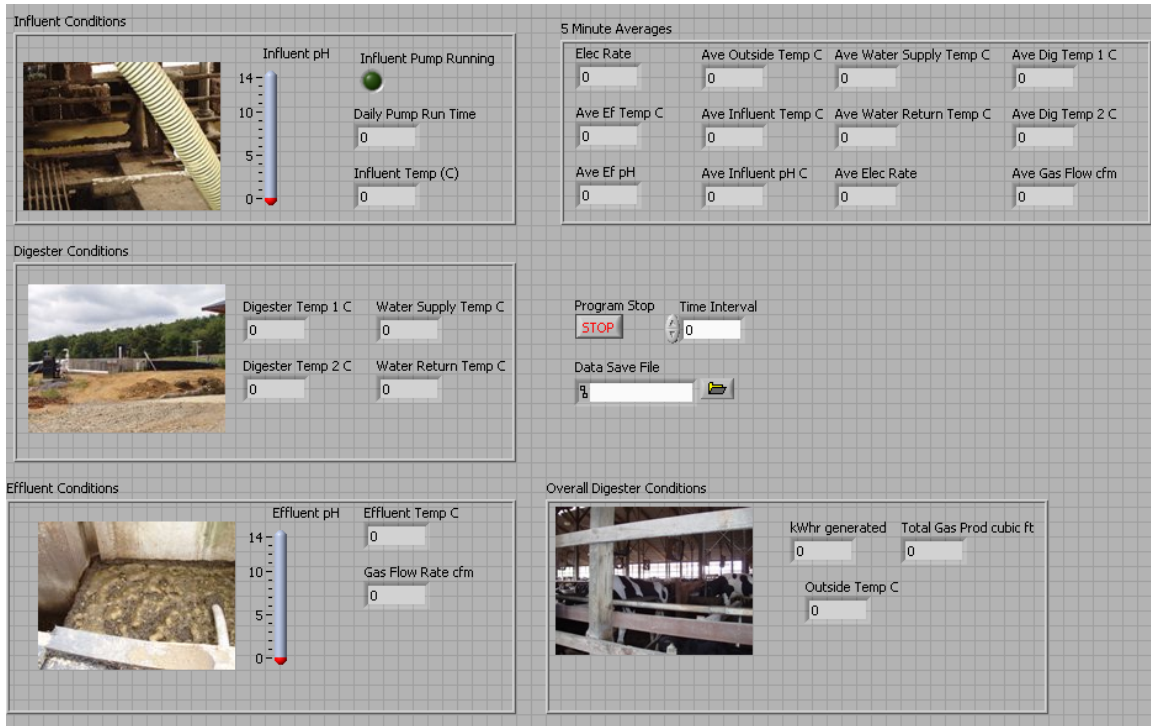


Figure 6.20: Tentative Front Panel for Remote Monitoring Program

Currently the remote monitoring project is in the final stages of installation and implementation. One sensor remains to be installed and the programming for uploading data to the internet is in place. The final programming for the connection between the laptop computer at the farm and the server is all that remains.

6.6 Summary

Although extensive research on controlling digesters has previously been performed, this prior work has looked at the digester from the perspective of treating wastewater and settled sludge. This is generally a dilute waste stream, and is also far more uniform than dairy manure which may contain corn kernels or pieces of straw. A farm scale digester will also have to deal with whatever may be present on the floor when scraping occurs, and does not benefit from the trash-screens and primary settling systems that clean the inflow of most wastewater treatment plants. In addition to these differences in the influent stream, a farm-scale digester must be profitable as part of the farm's overall operation. A municipal digester does not have this same problem as they are in the business of merely providing clean, safe effluent water, which residents pay for

and a digester can help achieve. So where a wastewater plant has as its primary concern the levels of COD, BOD, and nutrients in the effluent water, the farmer is primarily concerned with the level of biogas production as an indicator of both odor reduction and income generation.

In this study, the observed pH reduction in pilot-scale trials certainly indicates that the first of the two metabolic pathways, acetogenesis, was occurring. However, it seems that the second metabolic pathway, methanogenesis, was not as effective. Perhaps a small oxygen leak may have allowed for facultative growth, as many methanogens are obligate anaerobes. Or it may be simply a problem that insufficient inoculum or excessively cold feedstock prevented methanogenic growth.

This project has had many components that demonstrated the important role that computers can play in farm-scale anaerobic digesters. While there are a number of things which may seem to be common sense, these components had not been shown before on a farm digester. Farm digesters are different systems than municipal digesters. Municipal digesters are operated with different goals, and have a much larger operating staff than a farm level system will have. Also manure cannot be counted on to act as other materials like sewage sludge (biosolids). For farm digesters, the variation in particle size, its corrosive nature, and the ability to create biofilms and coatings on sensors show that cleaning and calibration could be an important maintenance issue.

7.0 Future Work

A large amount of previous research in anaerobic digestion has focused on the wastewater treatment industry. Wastewater treatment plants have a greater amount of resources to devote to anaerobic digesters, both in initial capital investment and ongoing operations and maintenance, than typical farms. They have more manpower to be able to grab samples and both the resources and regulatory obligation to analyze the samples, either on-site or by obtaining fast results from a nearby lab on a regular if not daily basis. A farm lacks these resources, and so the development of inexpensive sensing and computer equipment that can facilitate or perform various tasks is very important. It is also important to identify and document how such a system should be operated and maintained. How much time and money would it take for a farmer to calibrate a pH probe once a week, versus once a month, and what benefits would be gained? Should the farmer just wait until the pH seems to be incorrect before first performing a calibration? How often should the probe be cleaned?

To this point, the work has focused primarily on the impacts of an anaerobic digester on sensors, and the development of a data-acquisition and control routine in LabView for a pilot-scale system. This baseline research has recently been expanded to include remote monitoring of a farm digester. This farm-scale work will help to provide some understanding as to the necessary maintenance that a full-scale digester sensor system would require. This will give a better understanding of the long-term operation and maintenance costs associated with automated sensing and control systems for digesters.

Because most of the prior research dealing with remote monitoring, sensing, and controls have focused on the wastewater industry, some of the conclusions of this research may not be relevant to farm operations. While a number of the principles can be applied to the farm level, the two do not necessarily have the same overall goals in their use of digester technology.

Another reason this work is important is that manure handles very differently from other materials. The make-up of the solids is such that system components normally rated to handle the material actually may not be able to do so. For an example of this type of situation refer back to the clogging of the pump housing. This pump was

rated to handle 10% solids; however, clogging issues still occurred regularly at 8% solids. While this clogging first introduced itself at the inlet of the pump, the housing did eventually clog as well. The observation is that the solids in manure act as a very different type of material than sludges or vegetable pulps. The corn kernels and other undigested feed elements were able to stick to the sides and gradually accumulate straw fiber to create a matrix within the pump that led to its clogging.

One of the first steps that should be taken in order to further this research is to upgrade the lab-scale digester. As a research digester, all the probes should be capable of being removed without having to empty the digester. One of the shortcomings of the current design was that neither the pH probe nor the thermocouples could be removed without emptying about half of the digester. By being able to remove the sensors, they could be both cleaned and also calibrated on a regular basis. Easy access to sensors for inspection, removal, recalibration and replacement would be even more critical in farm-scale digesters, where the volumes and challenges associated with refilling are even greater. At any scale of digester, sensor maintenance is important to ensuring accurate long term results.

7.1 Programming Improvements

The program could also be upgraded and improved. The first change would be to store data less frequently. Data from a digester does not need to be stored every 5 or 6 seconds. This creates about 14,000 data points a day which can quickly become unwieldy for Excel and Minitab when one wants to analyze the results. Storing the average data of the previous 5 or 10 minutes would greatly reduce the amount of data managed. A 5 or 10 minute data interval would generate either 288 or 576 data points a day with the current sensor setup. Adding the new feature of remote monitoring to the lab digester would also be a great benefit to whoever was to operate it. Another programming improvement would be for the text file to save and empty program arrays every time the program were stopped so that no data is lost. This issue has been addressed in the remote monitoring program; however, it was not part of the current digester operational program. With the current version of the program, LabVIEW must be completely closed to clear the arrays.

Because of the challenges with manure, at this point I would not recommend making a lab digester fully automatic without 24 hour human surveillance. If a valve clogs or something goes wrong then the mess created could sit around. An operator should hopefully see the signs of any breakdown before it occurs and stop or can at least be present to clean it in a timely manner. If the digester had its own dedicated room with a containment system then perhaps automation would be a good idea, but that is not presently the case.

7.2 Control Work

For this project, automated control was only applied to the heating system during actual digester operation, but control should also be achievable for both the pH and feed stock. Most digester control systems have focused on altering the feedstock in response to the effluent concentration of COD and other regulated pollutants. For a farm operation, it makes more sense to use gas production as the process variable. The concentration of feedstock would then be altered based on the production of biogas. Unfortunately, the lab digester used in this research had such low biogas production that this control strategy could not be tested. Such a strategy should be thoroughly tested at the lab-scale before taking it a full-scale digester. This would help reduce the risk of upsetting an already operational digester.

A first step in digester feedstock control could be the use of a simple proportional control strategy. The digester could then be forced to deal with extreme levels of feedstock concentration, both high and low, under different antecedent conditions. The goal would be to see less variability in the biogas flow rate with the control system than without it.

7.3 Lab Digester Improvements

A prototype lab digester was constructed and utilized to perform this research. A number of things were learned from the prototype that would help in future design. It would be a good idea to go back and resize the tubing and valves. For both sets of tubing placed on the digester, adapters had to be constructed in order to make the ports on the pump match the diameter for the valves. Using the valves rather than purchasing was an

attempt to utilize resources already available to us. In hindsight it may have been a better idea to just purchase some new valves for use rather than rely on the old ones. Trying to force the old valves into the present use resulted in this mismatch of sizes.

With these improvements, it is believed that a pilot-scale digester of similar design could provide a valuable resource for performing future research. The investment would be minimal and hopefully would facilitate more anaerobic digestion research. This research could focus on manure digestion. The results could help educate farm digester operators in best practices and digester optimization. This information could make anaerobic digesters more attractive. Such research would not need to be confined to just controls or automation. Questions still exist about mixing. For example, “What type of mixing is best? What frequency of mixing is best?” These are important questions for optimizing farm digester operations.

Given the interest and economic incentives for treating food waste on farms, a farm digester research program should also embark on exploring how food waste mixed with manure affects digester performance. Is there an ideal ratio? Is there a point where food waste can become too large a component? A robust pilot-scale reactor may also allow for a larger scale test of digestion strategies than can be conducted in small reactors. Such a reactor could also be used to explore the application of new sensors to determine digester health and microbial growth.

An effective pilot-scale digester apparatus not only provides opportunities for better anaerobic digestion research, but could also create a great outreach opportunity. A pilot digester is small enough that it could possibly be placed on a trailer and taken to various sites. Farmers and others interested in anaerobic digestion could see a small digester and ask questions about it. The operator could explain how it would be similar and different from their larger on-farm system.

Such a digester also could provide Penn State and similar universities with another educational tool. Future students could see that there is potential for hands-on research and get to see the type of education they would be obtaining. Already, just during my time here, I have demonstrated the digester to many different students and shown the breadth of knowledge and the application you can gain in the Agricultural and Biological Engineering department.

With the remote monitoring feature comes the potential to reach vast new audiences around the world. Schools anywhere could log onto the website and see the performance of the digester, along with supplementary information such as the case study in Appendix B. They could then think about how much energy would be saved if we converted the methane to energy, and do calculations of digester operations and performance. By providing students with the input characteristics such as loading rate and VS concentrations, they could explore the digester's efficiency. If a simulation program were available they could alter the "virtual" digester and see how that changes things.

In short, the digester research described in this thesis, although not perfect, is a step to opening up many new and different opportunities to show off anaerobic digestion, and to educate the public in many ways. This helps highlight another lesser known form of alternative energy. The future of digester research is exciting, especially considering the desire of the country to move towards alternative fuels.

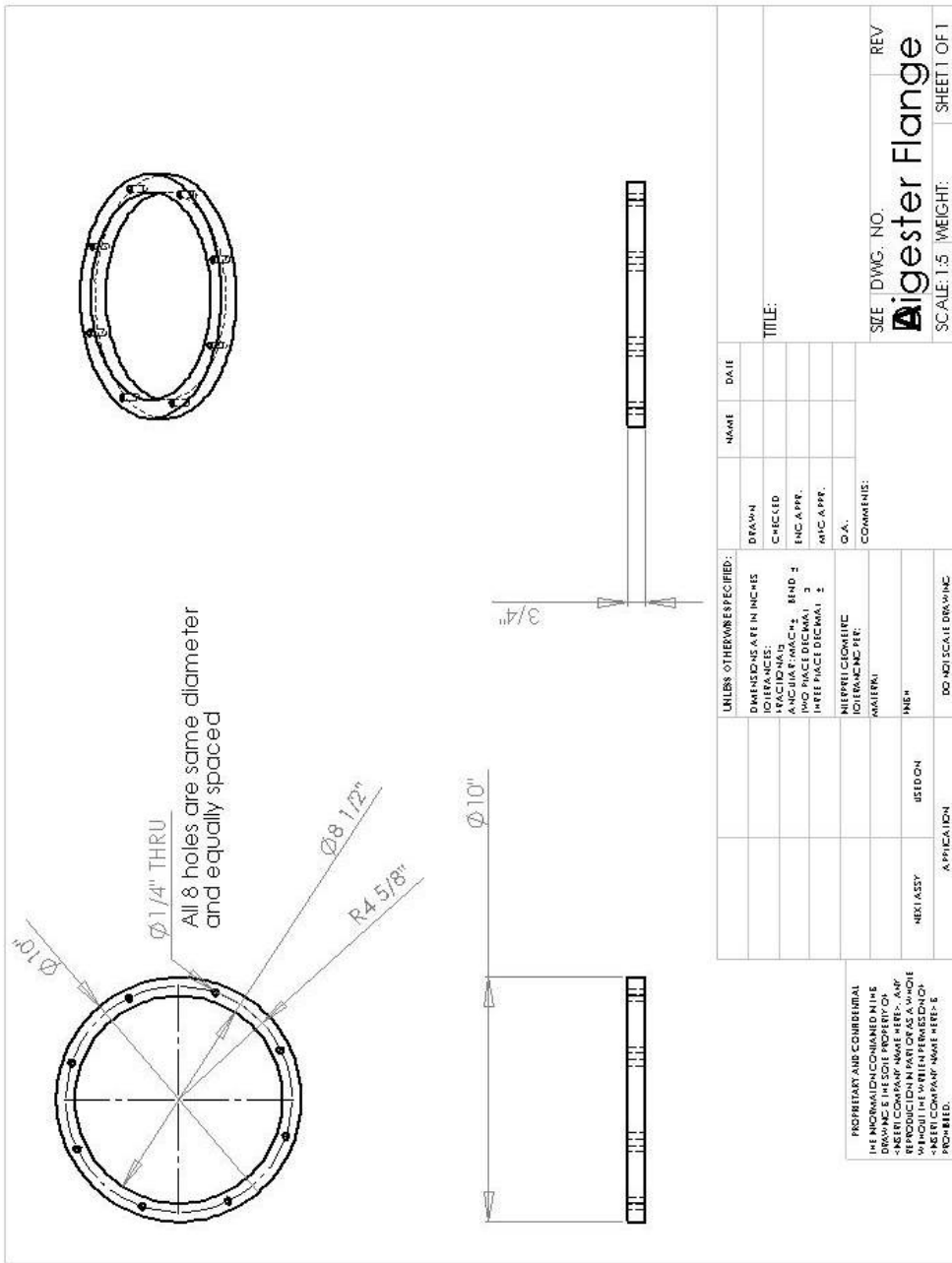
Appendix A

Lab-Scale Digester Drawings

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Main Digester Tank	Fabricated	1
2	Digester Flange	Fabricated	1
3	Digester Lid	Fabricated	1
4	Reducer	Purchased	1
5	Roof Entrance	Fabricated	1
6	Reducer	Purchased	1
7	Reducer	Purchased	1
8	Coupling	Purchased	1
9	Draft Tube	Fabricated	1
10	Digester Gasket	Fabricated	1
11	Tube Reducer	Fabricated	1

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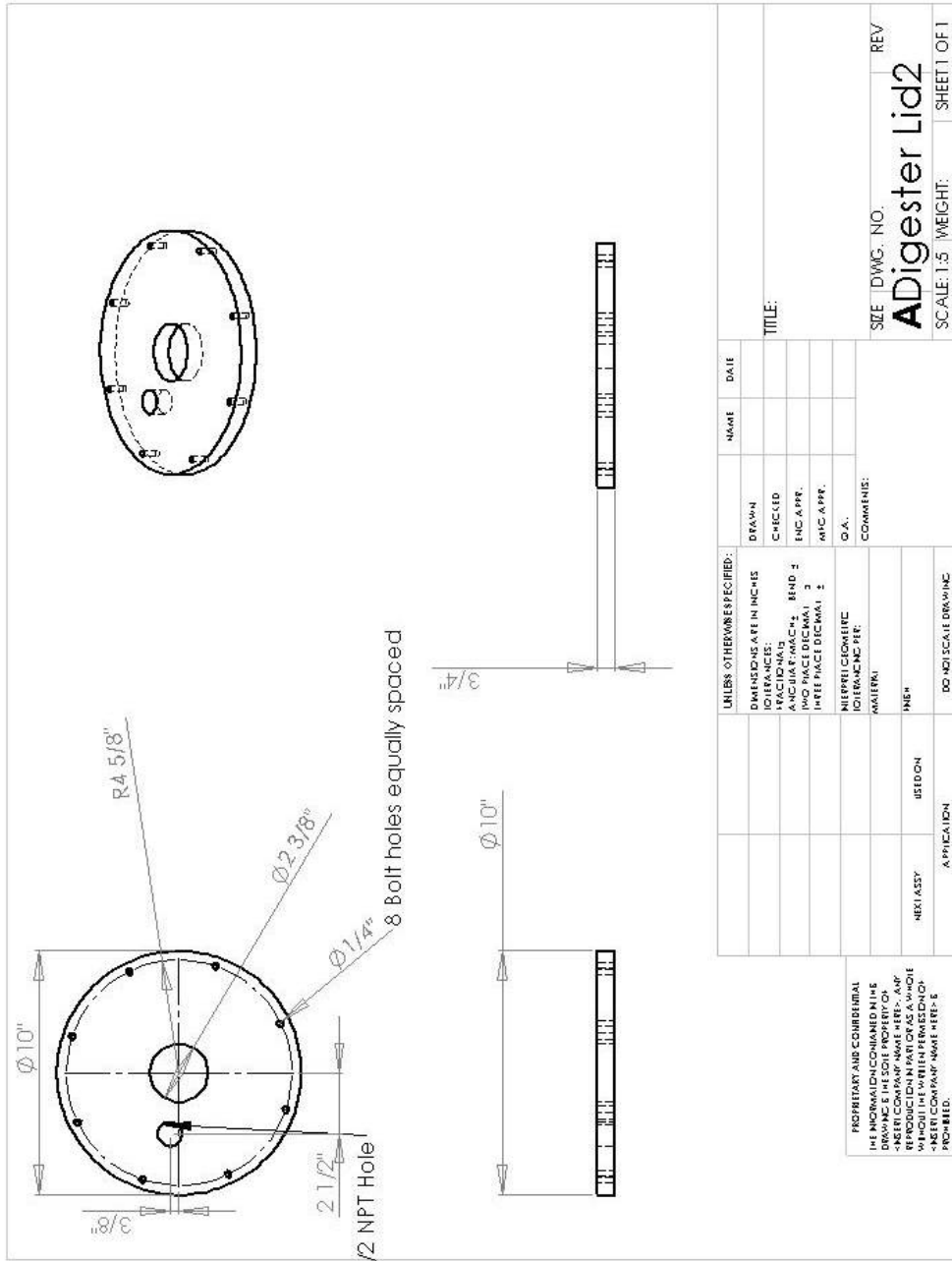
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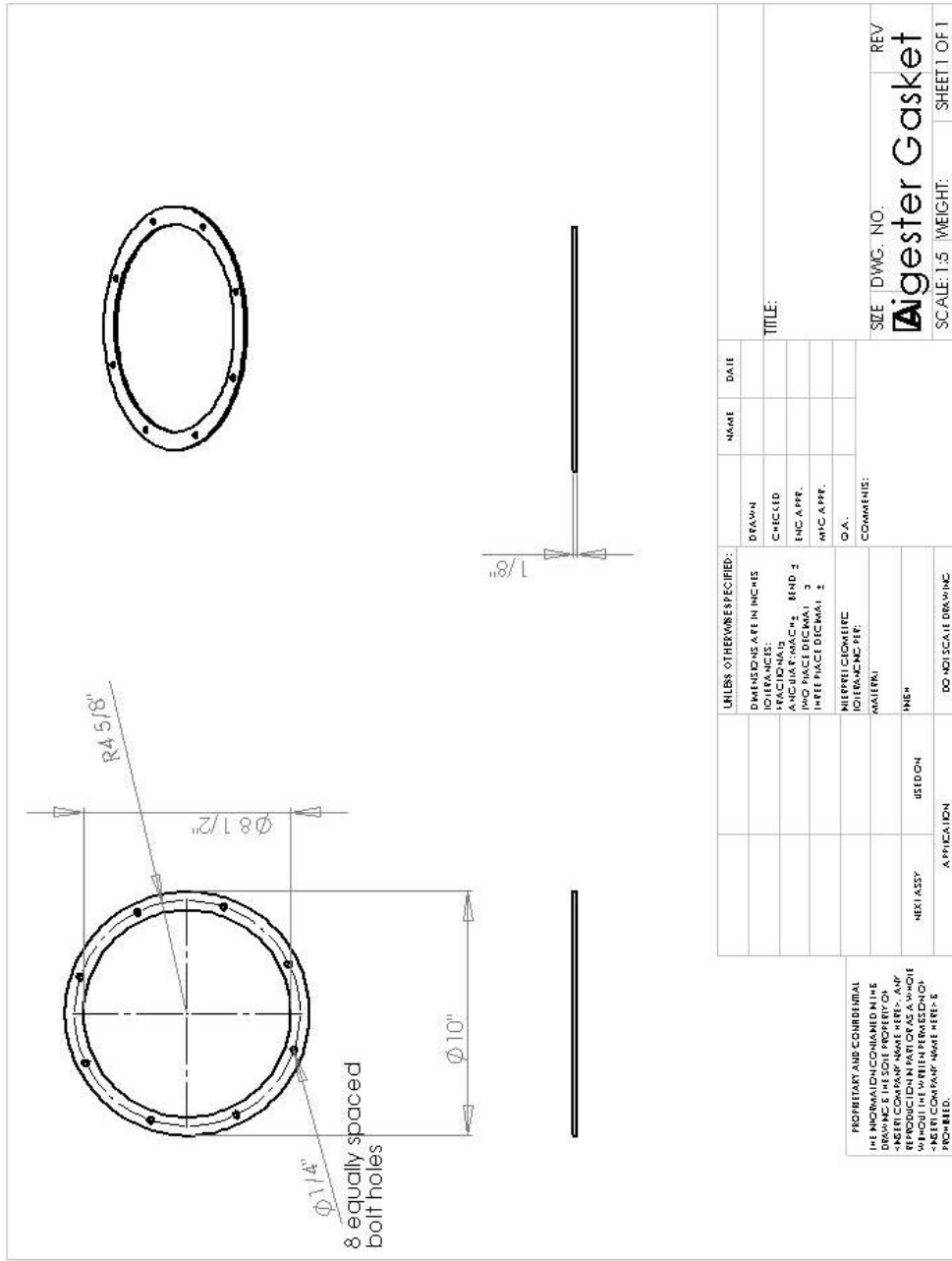
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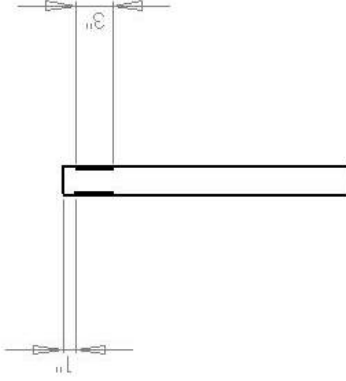
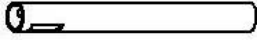
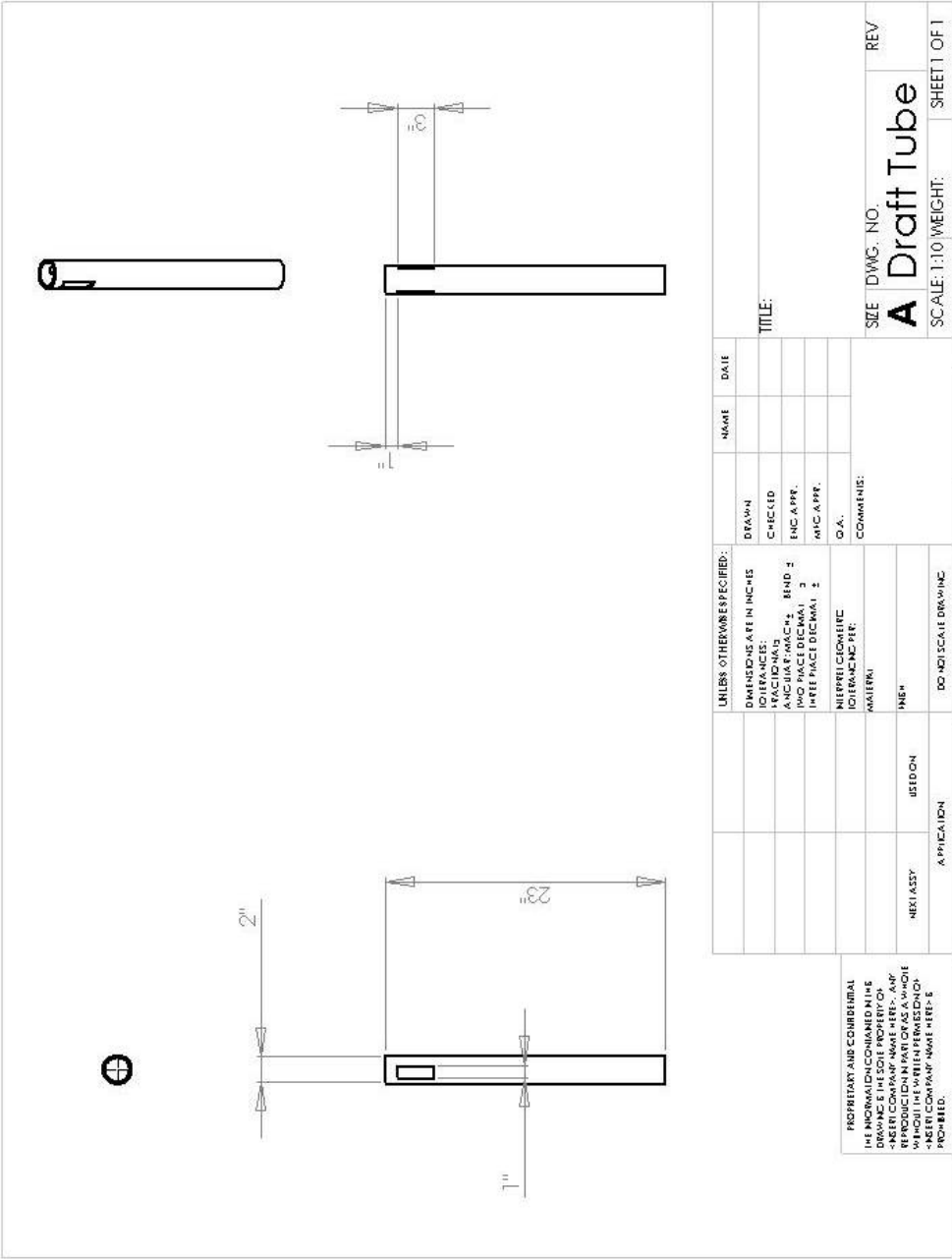


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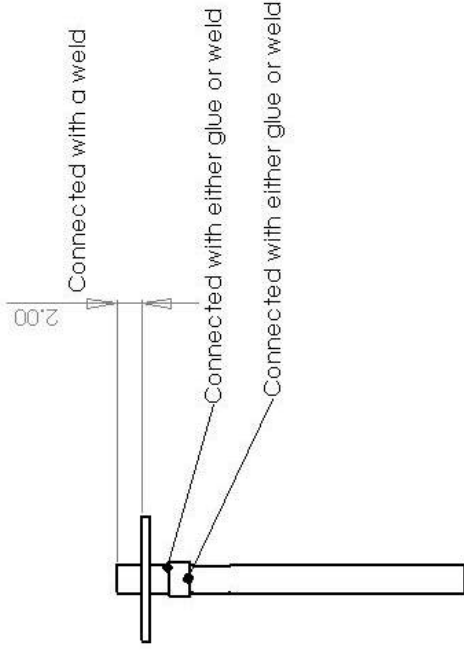
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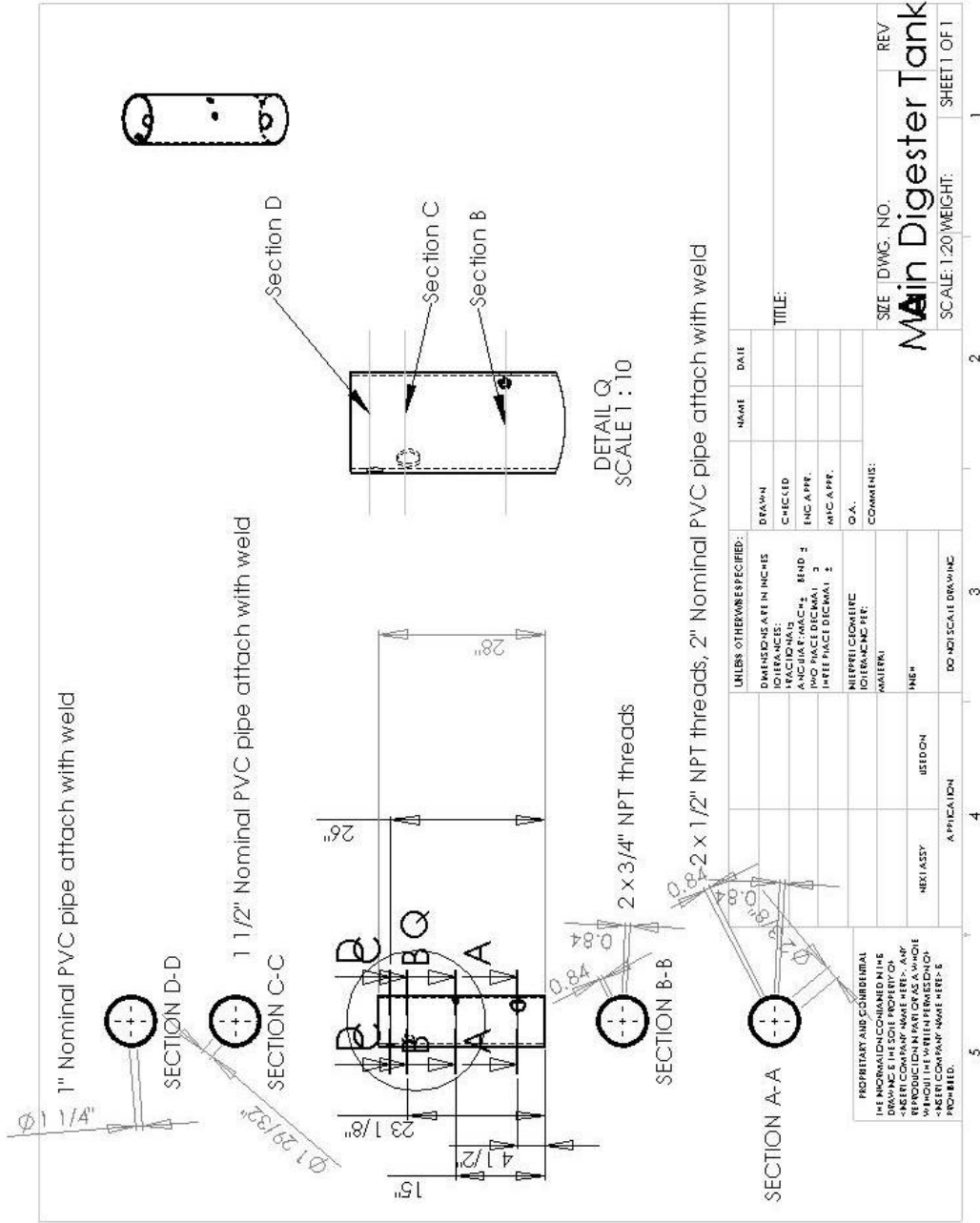
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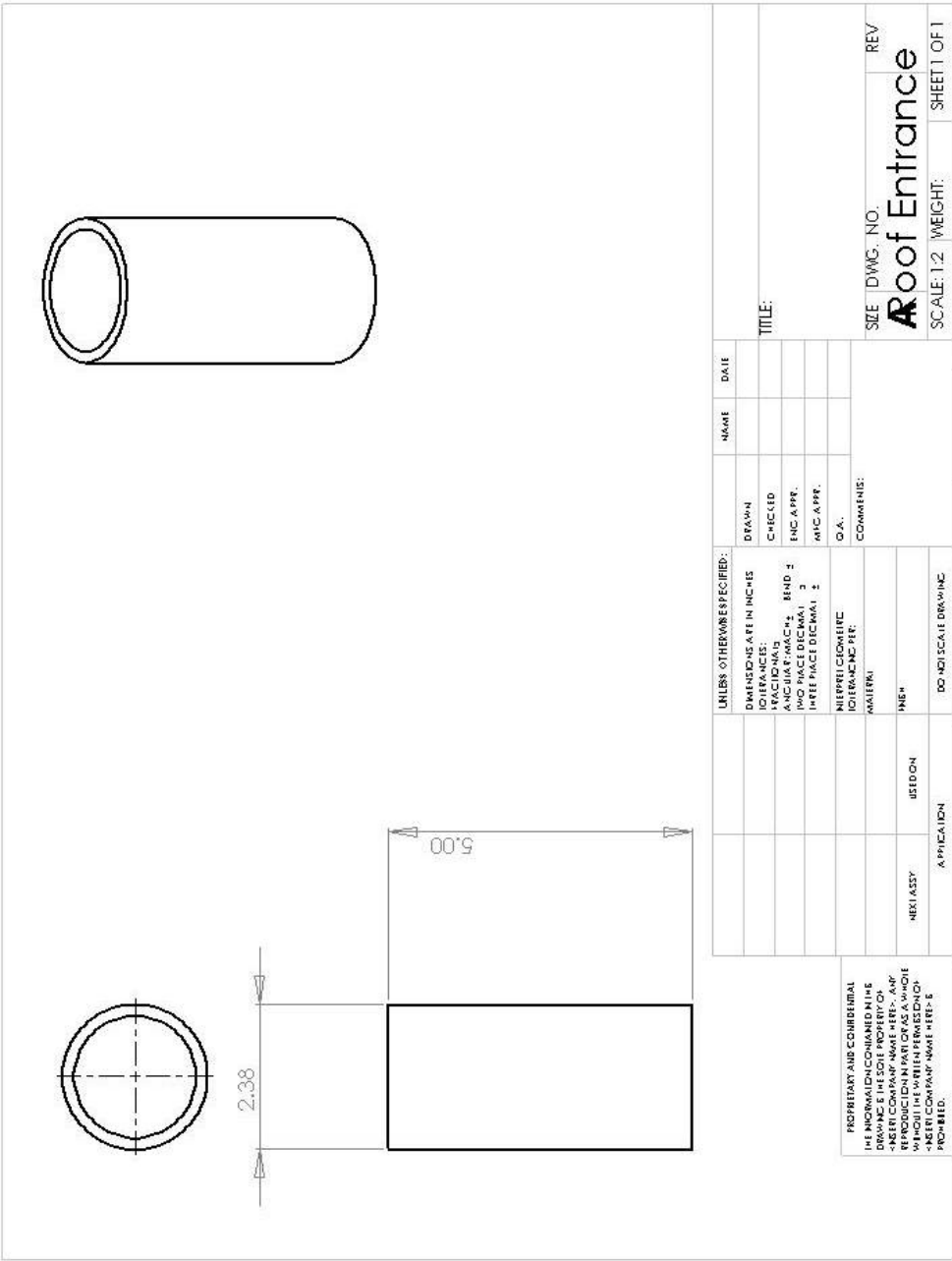
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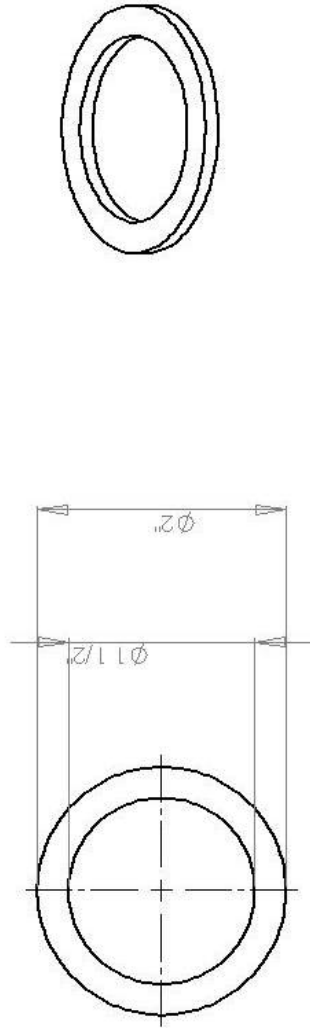
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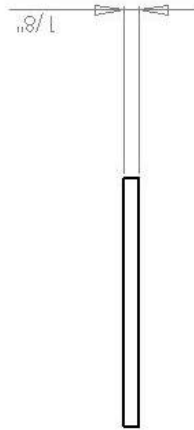
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Reducer will be welded to interior of coupling



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Appendix B

Penn England Case Study

PENNSYLVANIA STATE UNIVERSITY



Department of Agricultural
and Biological Engineering

Penn England Farm Case Study

Type of farm: Dairy
Name of farm: Penn England Farm
County: Blair
Digester designer: RCM Digesters
Digester Installer: Penn England Farm acted as General Contractor
Construction start date: October 8, 2005
Date digester became operational: August 17, 2006
Number of animals contributing manure to the digester: 720 milking + 80 dry
Housing system: freestalls
Type of bedding: dried digested separated solids
Manure handling system: alley scrapers to auger
Type of digester: mixed loop
Digester cover: insulated flat flexible
Digester temperature: mesophilic 100°F
Biogas uses: operate the CHP unit to produce electricity and heat
Biogas utilization equipment: engine generator set and flare
Heat recovery utilization: heat digester, hot water for milking parlor, genset radiator air used to dry manure solids
Power Purchase Agreement: Yes
2007 status of digester: operational

Introduction:

Penn England Farm is located in Blair County, Pennsylvania. The family operated dairy farm was started in 1979 with 75 cows. It was gradually expanded to its current size of 1,620 Holsteins in 1998. Presently, manure from 720 milking and 80 dry cows and milking center waste water goes to the digester. The remaining animals consist of 60 dry cows, 390 heifers and 370 replacement cows. The manure is continuously scraped from the freestall barn and augured into the 9,000 gallon digester influent holding tank. The milk parlor and holding pen are flushed 3 times per day and this flush water is mixed in the digester influent holding tank.

Penn England decided to put in the digester system for power production to reduce electricity costs on the farm. Odor control, nutrient management and farm expansion also were contributing factors into the decision of installing a digester. Members of the farm researched and also visited digester systems in New York, California, Wisconsin and Pennsylvania over a four year period. In 2004 a feasibility study and the grant application process started. RCM Digesters helped Penn England with the grant applications. After two large grants were awarded to the farm, excavation started on October 8, 2005. Work continued through the winter and spring of 2006. The proud moment came when the engine started running on biogas on August 17, 2006.

www.biogas.psu.edu 246 Agricultural Engineering Building, University Park, PA 16802 (814) 863-7960



Digester with flat cover

Digester information:

The digester designed by RCM Digesters is a mixed loop, heated, circular, partially above ground concrete tank, 80 feet in diameter and 16 feet in depth (manure level at 14 feet), with an internal dividing wall and has an insulated, flat flexible cover. The digester has a capacity of 525,000 gallons and is designed for 1,300 cows. It is designed to operate with 8 to 9 % solids and a hydraulic retention time (HRT) of 20 days at a temperature range of 98 to 104°F. Presently the digester is running with an HRT of 23 days with the percent solids unknown at this time and a temperature of 100°F. A hot water piping heat exchanger inside the concrete tank keeps the digester at the desired temperature. The tank exterior is insulated with 2 inches of re-manufactured rubber from recycled sneakers.



Floating insulation blanket

The digester cover consists of 4 layers: two - 60 mil HDPE (layers 1 and 4) and two - 2 inch rubber insulation blankets from recycled sneakers (layers 2 and 3). Environmental Fabrics manufactured the HDPE flexible 60 mil cover.

The internal dividing wall splits the digester into two chambers. Each chamber is mixed with a Baur, 12.6 kW mixer (18 inch diameter propeller) for approximately two hours a day. Every twelve hours one of the mixers runs for 50 minutes. A float controlled submerged manure pump in the influent holding tank, pumps 18,200 gallons of raw manure per day in batches of approximately 3,500 gallons per cycle four to five times a day through the 10 inch diameter PVC digester influent feed pipe into the digester. Parlor wash water of 6,000 gallons per day is also added to the influent tank and mixed into the manure.

Penn England monitored the digester system for two hours a day during the start-up phase. After steady state operation was achieved, monitoring takes approximately one hour a day; 45 minutes in the morning to take readings and grease the pumps and separator; at night, a 15 minute walk through to check all digester equipment. A log book is used to document monitoring, planned and corrective maintenance. During start-up, the oil was changed every 250 hours, then, based on engine oil analysis, upgraded to every 300 hours of engine operation with plans to extend to 350 hours. Digester internal and effluent temperatures, CO₂ content of the biogas, and influent and effluent pH are also monitored.

Biogas system:

The biogas leaves the digester through 6 inch diameter PVC pipe. There is a foam baffle separator used to condition the biogas. The biogas piping has gravity operated water removal drip pots that also provide over pressure relief protection. The piping travels underground downhill to the engine-generator set building.

Combined Heat and Power unit (CHP):

Once inside the engine-generator set building, the biogas is directed to a blower, then to the gas flow meter before entering the Caterpillar G342, 6-cylinder, 130kW, 440V, 3 phase engine purchased through Martin Machinery Inc. of Ephrata, PA. The engine generator runs 24/7, 365 days a year. Biogas is not treated in the engine-generator building before entering the engine. During the initial start up phase the engine generator set was producing 65kW. After 10 months of operation production has improved to 110 – 140kW, averaging 120kW. Heat recovery from the water and exhaust jackets of the engine are used to heat the digester and milking parlor, make hot water and dry manure solids from the FAN separator for bedding.



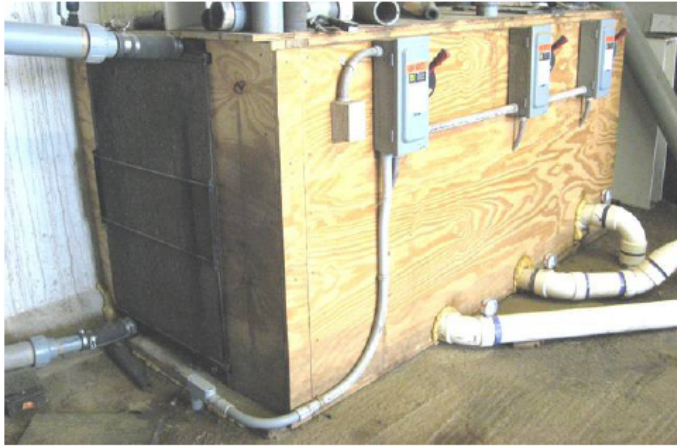
Combined Heat and Power Unit (CHP)

Power purchase agreement:

The engine generator set runs 24/7. Penn England has a power purchase agreement with Valley Rural Electric Co-operative (CO-OP) for 3.9 cents per kWh of any excess electrical power. At start-up, the CO-OP was not required to follow PA net metering guidelines. Since then, the CO-OP has followed the PA net metering guidelines and in December of 2006 the farm electrically connected (paralleled) with the utility making it possible to sell excess electricity generated or purchase electricity from the CO-OP when needed. The farm has been able to aggregate all their electric meters within a 2 mile radius of the digester. These meters are located at the dairy, tiestall barns, shop, trailer, employee building and the owner's residence.

Digester effluent:

A 10 inch PVC digester effluent pipe removes the digested manure and directs it to a 10,000 gallon effluent holding tank. A float controlled submerged manure pump in the effluent holding tank feeds the FAN separator in the upper level of the separated solids storage building. The solids travel from the separator across a conveyor belt and drop to the floor of the storage building. The solids are dried by hot air from the CHP unit auxiliary radiator installed in a wooden box with three blowers to direct the hot air through slots in the concrete floor. All of the dried digested solids are used for bedding for the cows. The liquid from the separator gravity flows to the approximately 4 million gallon manure storage pond.



Wooden box heat exchanger for drying manure solids



Separated solids drying on the slotted floor in the bedding storage area

Project costs:

The capital cost of the Penn England digester system was \$1.14 million. The farm owner acted as the general contractor and farm labor was used to build the system. A partial breakdown of costs is as follows:

digester \$141,370.00
power prime mover (CHP) \$135,000.00
biogas conditioning equipment \$50,000.00
switching gear, inter-connection fee \$155,000.00
designer, engineering, consulting fees \$85,000.00.

The farm received a Pennsylvania Energy Harvest Grant of \$280,500.00, a USDA Grant of \$203,725.00 and a MELF (grant or loan) of \$206,000.00. Penn England farm paid for or financed the rest of the \$480,275.00 needed for the digester project. Cost per head works out to be \$1,325.00.

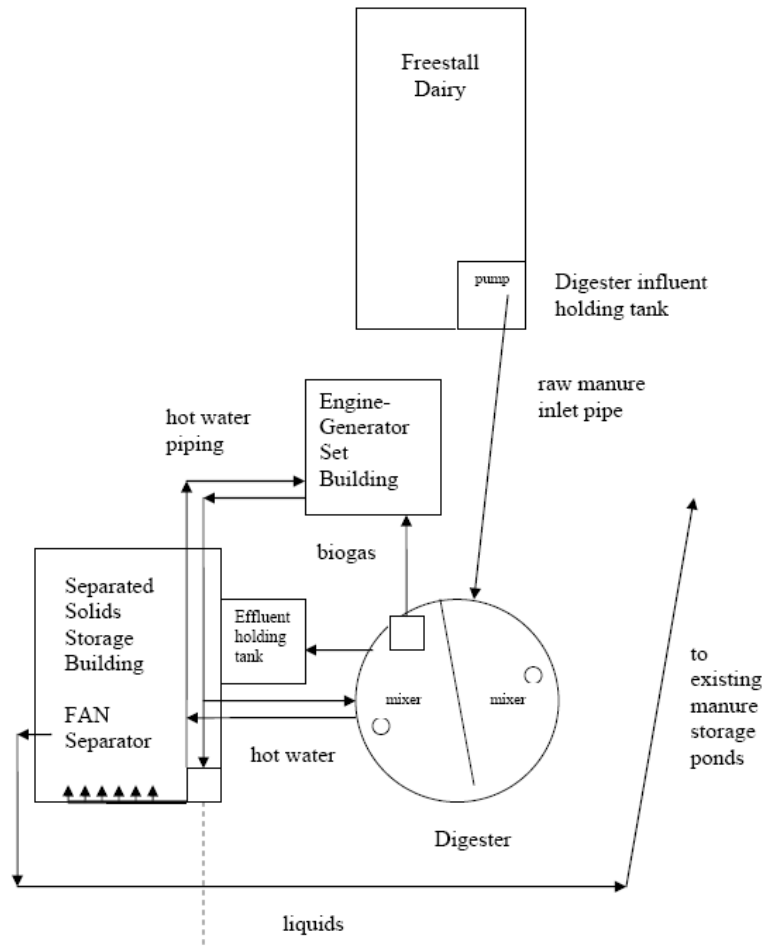
Operation and maintenance costs during the time period of August through December 2006 equals .0199 cent/kWh. Oil changes are performed on the engine every 300 hours of operation. A used engine oil sample is sent out to a laboratory for analysis.

Lessons Learned:

Lessons learned during the digester project include: build into the budget extra money to allow for unforeseen expenses and secondly, try to account for the electrical usage during the construction period.

The information obtained in this case study was collected by Penn State researchers, Deborah Topper and Patrick Topper during farm tours at the Penn England Farm and discussions with farm personnel during 2006 and 2007.

01/10/08



First Floor: The CHP unit auxiliary radiator wooden box heat exchanger is used to direct hot air under the floor to dry the separated manure solids for bedding.

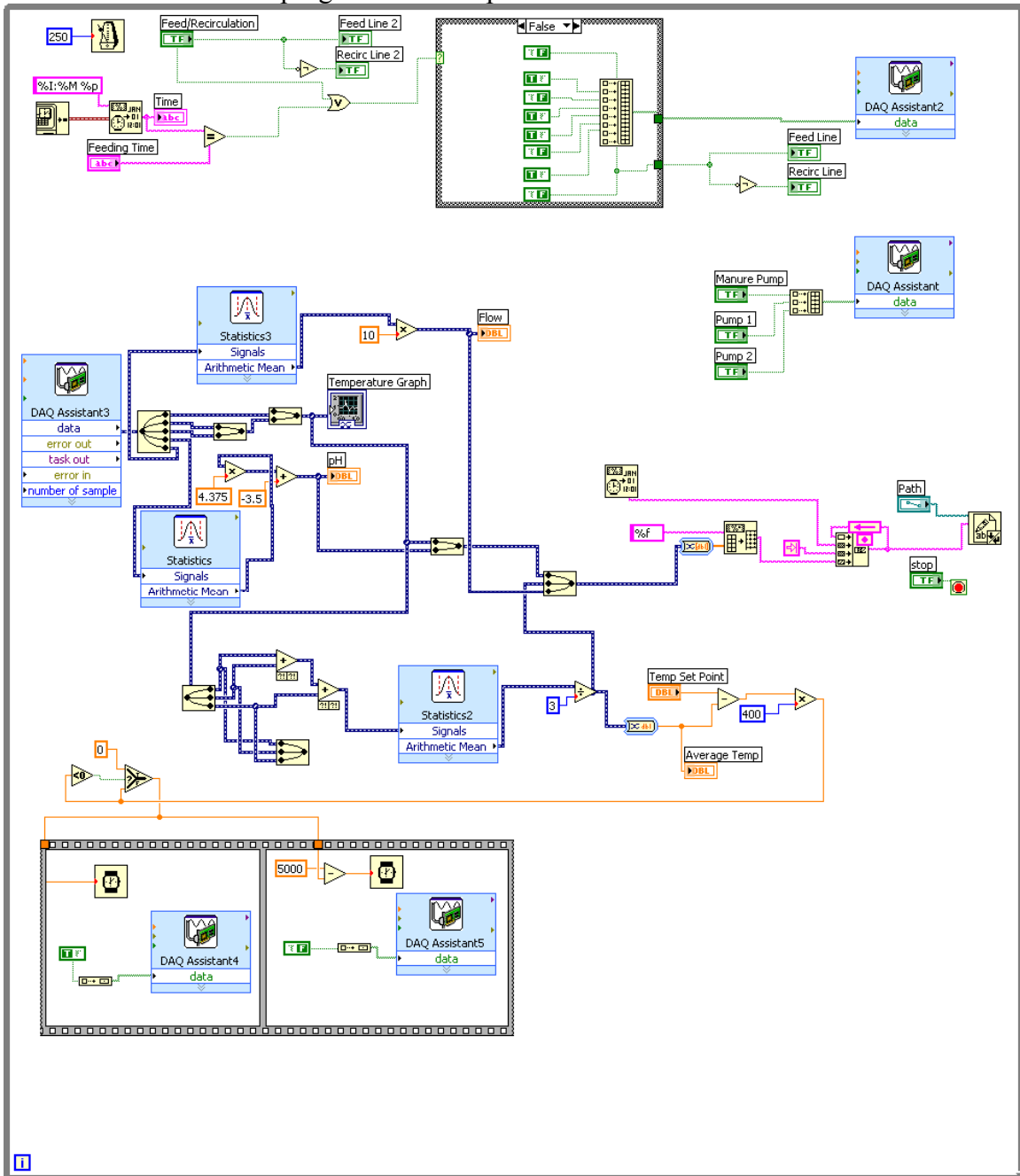
Second Floor: The Fan separator receives digested manure from the effluent holding tank. The solids are conveyed then dropped to the building floor and the

Schematic of Penn England Farm Anaerobic Digester System

Appendix C

Digester V3

The program used to operate the lab-scale reactor.



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