Wastewater Biogas Digester System for a Rural Residence in Barbados

Design Project Presented to

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Executive Summary

The purpose of this project is to design a small scale biogas wastewater digester for a rural residence in Barbados and present the project to various organisations in order to get funding for the implementation of the project."

A paradigm shift needs to occur wherein solid waste and wastewater will be recognized as resources instead of waste. Recovery-based, closed-loop systems that promote the conservation of water and nutrient resources while addressing multiple environmental issues must be supported. An ecological technology such as biogas digesters used for wastewater treatment could be favourable for Barbados' citizens and its environment.

The proposed system collects and stores the rainwater to feed the toilet.

- Rainwater harvesting allow Barbados' household to rely on a second source of water supply. (Groundwater being the principal source of water.)

The waste from the toilet travels to the biogas digester where other organic waste such as horse manure and crop are added and also decomposed by anaerobic bacteria.

- The collection of wastewater solves improper wastewater management issues such as degenerative effects on both public and ecosystem health and groundwater contamination. Barbados' climate offers the ideal conditions for the process; high ambient temperature and humidity and slightly alkaline water.

Two very useful products result from the anaerobic digestion. The first of which is biogas, a gas of high methane content (~60%) that can be used as a fuel.

- Our analysis shows a saving of $BB 1012.72 /year on cooking gas. As Barbados imports most of its fossil fuel, a local renewable source of energy is favourable for the economy.

The other product is the leftovers from the non-volatile organic and inorganic components of the feed. This product, acts as an excellent fertilizer.

- Our analysis shows a monetary equivalent of $BB 1295.72/yr in fertilizer.

The estimated cost for the entire ecological system is roughly 6 800 BB$. Considering the income and gas savings the system can be repaid in less than 3 years. Biogas in Barbados is a case where economics and environmental benefits are harmonious.

Acknowledgements

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Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

All around the world humankind is undergoing a radical transformation of its ecology. Resources are being consumed faster than ecosystems can restore them. The fossil fuel reserves of the planet are depleting at a fast rate. Changes need to be made. An ecologically sound solution needs to be implemented and enforced. Clean, renewable energy technology must be promoted and utilized. A paradigm shift needs to occur wherein solid waste and wastewater will be recognized as resources instead of waste. In order for such problems to be addressed, a new, holistic approach needs to be used. Leaders must analyze the problems from every possible angle in order to observe the largest scope and all of the interrelations and entanglement. People need to begin to consider all of the social, political, environmental, economic, and technical aspects of problems with an ultimate goal of sustainability underlying the research.

An ecological technology such as biogas digesters used for wastewater treatment could be favourable for Barbados' citizens and its environment. Only slightly ahead of the desert nations of the Middle East, Barbados is within the top 15 most water-scarce nations and has been considered water scarce since 1955. (FAO, 2003). As a water-scarce nation, it is even more important for Barbados to deeply consider and adopt technologies that look to provide sources of freshwater, reduce consumption rates, and protect established sources. The hybridization of rainwater harvesting and biogas digestion has the potential to satisfy all three goals along with offering a variety of other environmental and economic benefits.

The outline of the report is as follow. The project's objectives are presented in chapter 2. A clear identification of the problem is necessary in order to develop solutions that correspond precisely to the initial need. The report follows by presenting background information explaining the science behind the technology and offers the reader insights into how the technology can integrate into the infrastructure that already exists in Barbados. This second step can become very useful as sometimes solutions for the same or a similar problem have already been developed. Research in the literature can also help to find alternatives and ideas. The methodology presented in chapter 4 has laid as a foundation for the actual development of possible solutions. An outline of the examined case study will follow in chapter 5 and each aspect of the design will be explained in detail. Lastly analyses of the economic feasibility of the program will be included.

Chapter 2: Objectives

The objective of the project is to;

Design a small scale anaerobic wastewater digester system for a rural residence in Barbados .

The design of the digester will hopefully be implemented into a residence located in St-Andrew parish, Barbados. If all goes well, this will act as a pilot-project from which evaluations will be conducted and decisions for further dissemination can be planned.

Target site

The target household site will meet the following description:

a) Household without any or improper wastewater treatment.
b) Household with animal waste available.
c) Household without connection to the freshwater distribution system. (optional)
d) Household showing interest into sustainable living.

Use of the digester system

The digester system must fulfil the following tasks:

a) Collect at least enough water to supply the low flush toilet and any extra water that is required by the digester.
b) Produce enough biogas for daily cooking consumption
c) Protect groundwater contamination
d) Produce a high value crop fertilizer

The digester system

The digester system must meet the following specifications:

a) The rainwater harvester system must collect enough water to constantly supply the low flush toilet.
- Gutters must be size in function of the rainwater intensity.
- The tank(s) must store enough water for the driest month.
- A pump can be use if gravity not sufficient to bring water from the tank to the toilet.

b) The wastewater from the toilet must flow by gravity to the digester.

c) An opening for the animal waste and crop residue must be available to bring those organic materials into the digester.
d) The digester tank must;
- be sized in relation of the feed rate of organic material available and ideal retention time.
- withstand internal pressure created by the biogas.
- have an outlet for the gas that liquid cannot enter
- have an outlet for the carryover pipe.
- be safe, not harm any people or animals during the course of normal operation or in the case of malfunction.

e) The carryover tank must
- provide an adequate water column pressure onto the digester's contents.
- be protected from tampering.

f) The gas pipe must
- be connected to the household stove
- have an integrated water vapour collector.

g) Recycled material must be used when available.
h) Natural material such as bamboo must be used when available.
i) The cost of the whole system must be less than BB$ 10000.
j) The whole system must operate in a safe manner.
k) The owner of the digester system must understand the operating and maintenance daily tasks.

Chapter 3: Background

Different systems can be used for wastewater treatment. At the moment, most of the systems used worldwide are disposal-based linear system where excreta are seen as waste with no useful purpose (Sanitation Connection, 2005). This is a modern misconception. Fortunately, a recovery-based closed-loop system that promotes the conservation of water and nutrient resources has been growing over the previous three decades and is now considered an important management approach in countries where water shortages occur (Rose, 1999). According to the World Bank: "The greatest challenge in the water and sanitation sector over the next two decades will be the implementation of low cost sewage treatment that will at the same time permit selective reuse of treated effluents for agricultural and industrial purposes" (Rose, Looker, 1998). Technology that closes 'the loops' and create cyclical systems of resources instead of having open-ended systems where waste occurs is exactly what the world needs to begin researching and implementing. Even more profound would be technology that can perform that function while also addressing multiple issues. New designs are focusing on solving a given problem in a way such that other problems are reduced or solved as well, all while creating or progressing towards cyclical systems. It is these technologies that will be the catalysts in mankind's attempt to forage into sustainability. Biogas, through anaerobic digestion, tackles not only wastewater treatment but it also offsets pollution, provides a renewable source of energy and improves soil quality. Indeed these issues are all interrelated, and biogas is one area where all components meet in a serendipitous way.

3.1 Anaerobic Digestion

Biogas is a relatively old technology which harnesses the natural power of bacterial digestion of organic matter. Wastewater, and other effluent streams from industrial processes are nothing more than organic matter (combinations of C, N, S, O, H) in a presently 'undesirable' state. Bacteria can decompose such wastes into more simple molecules.

3.1.1 Anaerobic digestion Process

In anaerobic digestion, organic matter is decomposed by bacteria in the absence of oxygen. Anaerobic digestion occurs naturally in the environment and can also be used to process any carbon-containing material, including kitchen waste , paper, sewage, yard trimmings and solid waste.

The digestion can be described in four phases.

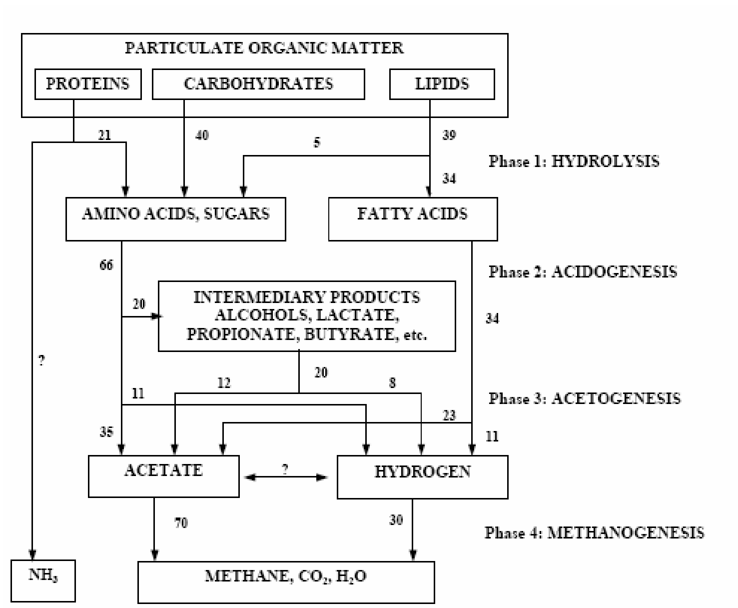


Figure 3.1: Microbiological Processes of Anaerobic Digestion.
(van Haandel and Lettinga, 1994).

Hydrolysis

In the first phase, the complexes organic molecules (proteins, carbohydrates and lipids) are broken down into soluble monomers (amino acids, fatty acids, glucose). Hydrolic or fermentive bacteria are responsible for the formation of monomers. Enzymes such as cellulase, protease, and lipase are excreted from the bacteria and catalyzed the hydrolysis. Complex feedstock such as cellulotic waste containing lignin is not recommended as it will slow down the hydrolytic phase. (Ostrem, 2004)

The hydrolysis of an organic waste to simple sugar can be represented by equation 1;

$$C6H10O4 + 2H2O \rightarrow C6H12O6 + 2H2^{+} \quad \textbf{(1)}$$

Acidogenesis

Following the hydrolysis is the acid-forming phase; the Acidogenesis. Acidogenic bacteria transform the soluble monomer into simple organic compounds, mainly short chain volatile acids, ketones and alcohols (eg. propionic, formic, lactic, butyric, uccinic acids, ethanol, methanol, glycerol, and acetone). (Ostrem, 2004) This step is completed by a variety of facultative bacteria operating in an anaerobic environment. If the digestion were to stop at this stage, the accumulation of acids would lower the pH and would inhibit further decomposition. (Hammer, 2004) The concentrations of organic compound produced in this phase differ with the type of bacteria as well as with culture conditions, such as temperature and pH. (Ostrem, 2004) The equation 2 below represents a typical acidogenesis reaction where glucose is transform to propriate. (Ostrem, 2004)

$$C6H12O6 + 2H2 \leftrightarrow 2CH3CH2COOH + 2\ H2O \quad \textbf{(2)}$$

Acetagenesis

The acetagenesis phase is often considered, with acidoenesis phase, to be part of a single acid forming stage. Acetagenesis take place through carbohydrate fermentation; long chain fatty acids, formed from the hydrolysis of lipids, are oxidized to acetate or propionate and hydrogen gas is formed. The hydrogen is critical to anaerobic digestion reactions. The hydrogen partial pressure needs to be low enough to thermodynamically allow the reaction to continue. The hydrogen scavenging bacteria, present in the digester, lower the concentration of hydrogen partial pressure and so, assure the conversion of all acids to occur. The concentration of hydrogen, measured by partial pressure, is an indicator of the health of a digester. (Ostrem, 2004)

In the reaction below (3), the free energy value of the reaction that converts propionate to acetate is +76.1 kJ, which is thermodynamically impractical. When acetate and hydrogen are consumed by bacteria, the free energy becomes negative and so the reaction toward to right side is favoured. (Ostrem, 2004)

$$CH3CH2COO- + 3H2O \leftrightarrow CH3COO- + H+ + HCO3 + 3H2 \quad \textbf{(3)}$$

Other key reactions in the acetogenic phase are the conversion of glucose (4), ethanol (5) and bicarbonate (6) to acetate.

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2\ CO_2 + 4H_2 \quad \textbf{(4)}$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \quad \textbf{(5)}$$

$$2HCO_3 + 4H_2 + H^+ \leftrightarrow CH_3COO^- + 4H_2O \quad \textbf{(6)}$$

The transformation of the organic material to organic acids in the acid forming stages cause a decrease in the pH of the system. This is favourable for the acidogenic and acetagenic bacteria that favour a slightly acidic environment but is problematic for the bacteria involved in the next stage of methanogenesis.

Methanogenesis

The acid-splitting methane forming bacteria known as methanogenesis or methane fermentation are strict anaerobes and are extremely sensitive to environmental condition such as temperature, pH, and anaerobiosis. In the methanogenesis, the bacteria convert the soluble matter into methane. About two thirds is derived from acetate conversion (7,8) or the fermentation of an alcohol (9), such as methyl alcohol, and one third is the result of carbon dioxide reduction by hydrogen (10).

$$2\ CH_3CH_3OH + CO_2 \leftrightarrow 2\ CH_3\ COOH + CH_4 \quad \textbf{(7)}$$

$$CH_3COOH \leftrightarrow CH_4 + CO_2 \quad \textbf{(8)}$$

$$CH_3OH + H_2 \leftrightarrow CH_4 + H_2O \quad \textbf{(9)}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \textbf{(10)}$$

The constancy of the digestion process depends on proper balance of the two biological processes. Sudden loading of organic matter or a quick rise in the temperature process will result of a build up of organic acids and the digester might generate foam as a result of overfeeding. (Hammer, 2004) Methanogenesis is the rate-controlling portion of the process because methanogens have a much slower growth rate than acidogens.

Consequently, the kinetics of the entire process can be described by the kinetics of methanogenesis.

Even though the anaerobic digestion process is described and can be considered to take place in four stages, the processes occur simultaneously and synergistically.

3.1.2 Parameters to consider in Anaerobic Digestion

As described above, anaerobic digestion process necessitates a complex interaction of several types of bacteria that must be in equilibrium to maintain constant biogas production. Changes in environmental conditions inside the digester can affect this equilibrium and so the constancy of the gas production. Regular monitoring of parameters such as; pH, temperature, C/N ratio, retention time, organic loading rate, bacterial competition, nutrient content, the presence of toxicants and solids content is necessitate.

pH

The pH level changes in response to biological conversions during the different processes of anaerobic digestion. A stable pH signifies system equilibrium and stability in the digester. Acceptable pH for the bacteria participating in digestion ranges from 5.5 to 8.5. However methanogenic bacteria will function better when the pH level is closer to neutral. (Hammer, 2004). The majority of methanogens function in a pH range between 6.7 and 7.4, and optimally among 7.0 and 7.1. Acid accumulation is the greatest potential for digester failure. This could happen if the organic matter loaded into the digester increased rapidly. The acidogenic bacteria would produce high amount of organics acids, lowering the pH to below 5, which is a fatal pH to methanogens. A decrease in methanogens will than turn to further acid accumulation.

The opposite, prolific mathanigenesis, could result in an increase in ammonia concentration and increase the pH above 8.0. At high pH, the acidogenesis functions will be slow down. (Lusk, 1998). Adding fresh solid content can help to solve problems associated with a low acidity level.

Maintaining an optimal and constant pH is especially challenging in the start-up phase of the process. The waste goes through acid forming stage before methane formation can start, lowering the pH. To raise the pH level, buffer such as calcium carbonate or lime must be added to the system. (Vlyssides and Karlis, 2003). Other substances like alkali, either sodium or potassium may be necessary to neutralize acids. Alkali induces swelling of particulate organics, resulting of the cellular substances more susceptible to enzymatic attack. (Baccay and Hashimoto 1984)

Temperature

Temperature is another critical parameter to maintain in a desired range. Anaerobic bacteria can live in a wide range of temperatures, from freezing to 70°C. However they thrive

within two ranges: the mesophilic range from 25°C (77°F) -40°C(104°F) and the thermophilic range from 50°C (122°F) to 65°C (149°F). The most favourable temperature for

mesophilic digestion is 35°C and so the digester must be maintained between 30°C and 35°C. (United Tech 2003) Figure 3.2 shows the rate of anaerobic digestion measured by gas production rate, growth rates and substrate degradation performance.

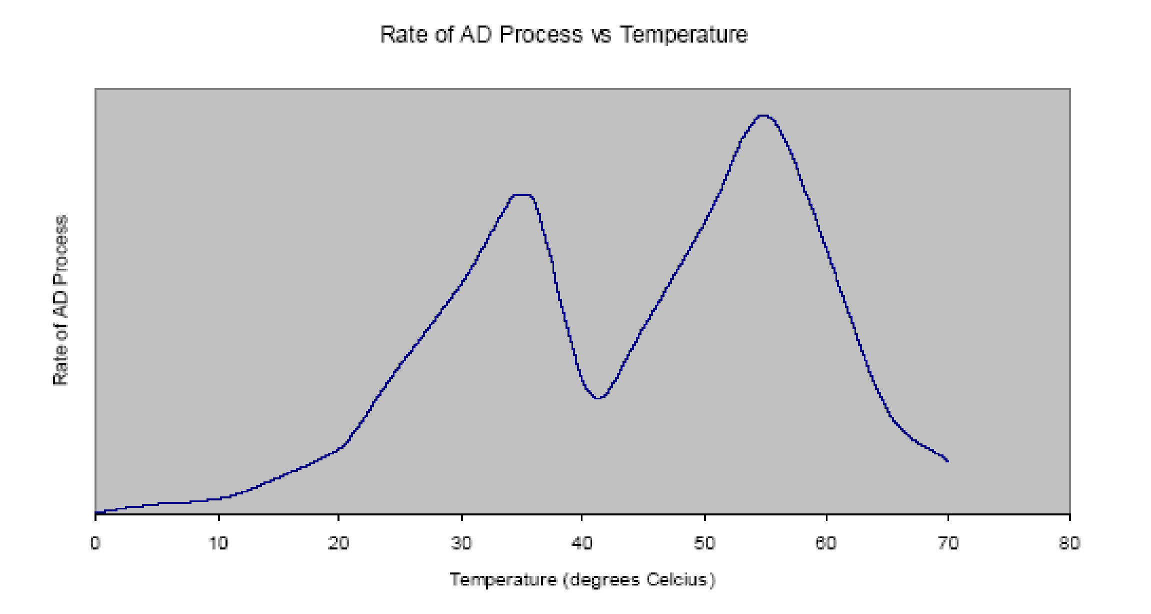


Figure 3.2: Rate of AD Process vs Temperature
(Ostrem, 2004)

In the Thermophilic digestion, higher loading rate, higher pathogen destruction and higher degradation of the substrate can be achieved. On the other hand, Thermophilic bacteria are more sensitive to toxins and smaller changes in the environment. It also required more energy since more heat is needed to maintain the desired temperature. The stability of the mesophilic process makes it more attractive for anaerobic digestion. Mesohilic bacteria are more robust and tolerate greater changes in the environment. The use of mesophilic process is recommended in digester where temperature can fluctuate greatly such as in small digester, poorly insulated digesters or digesters in cold weather.

C/N Ratio

The C/N Ratio is the measure of the relative amounts of organic carbon and nitrogen present in the organic resource (waste). This ratio can be monitor by keeping track of the amount and type of waste is entering the digester. Proteins are high in nitrogen content while most of the crops are high in carbon content. In composting process, the optimum C/N Ratio range between 20 and 30, with 25 being the ideal level. A low C/N Ratio (high nitrogen content) may result in accumulation of ammonia and cause the pH to rise above 8.5. Oppositely, in a high C/N Ratio, the mathanogenic bacteria will consume rapidly the nitrogen and this will lower the gas production rate.

Retention Time

Retention time is the time the organic resource stays in the digester. The average time its take for the feedstock to digest which is dependant on the type of organic material, the environmental conditions and the type of digestive bacteria will determine the retention time. Generally, retention time vary from 14 to 30 days for most dry process and can be as low as 3 days for wet processes. As reducing retention time reduces the size of the digester, there is reason to design systems that can accomplish complete digestion in short period of time, resulting in cost saving. In the scaling of the digester, the overall degradation rate, the gas productivity rate and the cost as to be balanced. Continuous mixing is a method for minimizing residence time so decreasing the volume of the digester. Inadequate mixing will result in stratified layers leading to less working volume. In an unmixed digester and continuously loaded, undigested material may exit reducing the efficiency. Other methods to reduce retention time are under research. Method such as introducing a surface where the bacteria can live permanently and not been flushed away with the digested material.

Organic Loading Rate

The last parameter influencing the digestion is the organic loading rate. A high organic loading rate demands more of the bacteria which may result that the acidogenic bacteria would multiply and produce acids rapidly. As the methanogenic bacteria take longer to reproduce, they will not be able to consume the acid at the same rate that it is produce, resulting to a decrease in pH. A constant slow organic loading rate is desired.

The monitoring of all those parameters inside the digester represents challenges especially at the start-up stage. Once equilibrium is reach and the optimum parameters are found for the specific conditions.

3.1.3 Benefits of Anaerobic Digestion

Biogas production

Biogas is somewhat lighter than air and has an ignition temperature of approximately 700°C. It consists of about 60% methane (CH_4)and 40% carbon dioxide (CO_2). It also contains small amounts of other substances, such as hydrogen sulphide (H_2S), forntunately, only to non-lethal concentrations. The methane content is higher the longer the digestion process. The methane content falls to as little as 50% if retention time is short. If this proportion falls below 50%, the biogas is no longer combustible. The first gas from a newly filled biogas plant contains too little methane and must therefore be discharged unused. The methane content depends on the digestion temperature. Low digestion temperatures give high methane content but less gas is produced.

Biogas can be used in many of the same ways as any other combustible gas, but it is mainly used for purposes such as; cooking fuel, lighting, refrigerators and to power an internal combustion engine. The calorific value of biogas is about 6kWh/m^3. (Sasse, 1988)

It is as cooking fuel that biogas has attracted the most attention. Practical values from India shows that a family of 5 comsumes around 850 to 2500 L of gas for cooking per day. A household burner will utilize between 200 and 450 L per hour. (Sasse, 1988) The gas stove needs to be adjusted to the proper gas/air ratioin order for effective combustion. Biogas lamps have low efficiency but can still be use in place without electricity. A gas lamp that offers a luminary equivalence to a 60W bulb will use 120 to 150 L per hour and a refrigerator will use 30 to 75 L per hour depending on the outside temperature. Gas-powered refrigerators also have a relatively low efficiency. The composition of the biogas varies day to day, as does the gas pressure. For those reason stable-burning jets are needed. (Sasse, 1988)

Wastewater treatment

Impact of improper wastewater sanitation

The constant growth of the global human population and the freshwater scarcity in the world necessitates adequate water management practices. Awareness has been put towards fresh water systems but unfortunately, the sanitation sector has not received the same attention (WHO, 1987).

The lack of domestic wastewater management in many regions presents a major challenge. The constant accumulation of human excreta and poor management associated with it directly contributes to the contamination of local availability of fresh water supplies. Furthermore, improper wastewater management has degenerative effects on both public and ecosystem health.

Diarrhoea associated with inappropriate water and sanitation management killed approximately 2.1 million people in the year 2000. It affects mostly the young and poor; 90% of which are children (Murray and Lopez, 1996). Sanitation represents the principal barrier for preventing human pathogens to enter the environment. In many parts of the world, wastes are often discharged into surface water, untreated or partially treated, and will potentially be affecting the health of all downstream users of the water (Sanitation Connection, 2006).

The transmission of diseases occurs through;

- directly, by contact with human excreta;
- directly through contaminated drinking water;
- directly through vegetables, shellfish or other food products exposed to contaminated water or soil;
- by accidental ingestion of contaminated water during swimming or recreational activities;
- by inhalation of aerosols or dust due to irrigation with wastewater, from scums, from showers or by other means;
- vector-borne transmission where the vector or the intermediate host breeds in water;
- by contact with animals and birds, both domestic and wild acting as a host for pathogenic bacteria and parasites;
- by direct contact with the organisms occurring in water bodies (for example Leptospira (spp.); and
- by secondary spread through contact with infected individuals.

(Sanitation Connection, 2006)

Improper management of wastewater is a menace for the environment; primarily for groundwater contamination and marine life. In many part of the world, when sanitary sewers are non-existent, on-site sewage disposal systems such as septic tanks are used. Unfortunately, when installed improperly or placed in poor geologic conditions, septic systems can have negative impacts on the environment. It has been shown that one-half of all septic tanks in operation are not functioning correctly. Nitrates and bacteria are the two major groundwater pollutants associated with septic systems. Figure 3.3 shows that sources of pollution occur when the contaminants move too rapidly through the soil and potentially into groundwater.

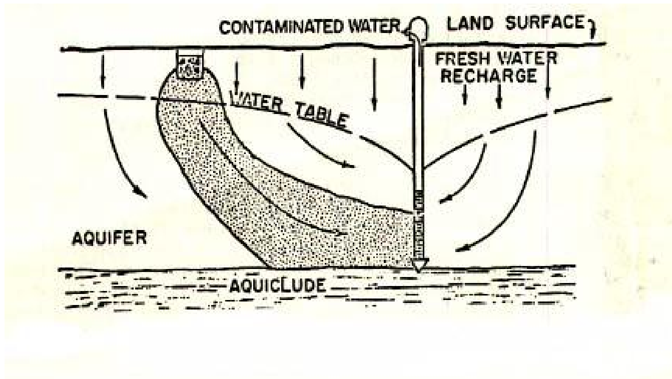


Figure 3.3: Contamination of groundwater.
(http://ewr.cee.vt.edu/environmental/teach/gwprimer/group03/sgwppollute.htm)

The soil absorption efficiency can be affected by many factors such as: climate, soil type, hydraulic conductivity, precipitation, porosity, etc. (Shawn et al. 1999) It is important to understand the hydrologic conditions and the geology of a terrain before installing a wastewater treatment facility. For instance, the island of Barbados has karstic coral reef topography: the water infiltrates through thresholds, sinkhole and dry valleys. The infiltration rate at which the water gets to the groundwater is rapid under discrete infiltration conditions. This allows the pollutants such as nitrates and bacteria found in human and animal excreta to move quickly through the groundwater and become a source of contamination. Since 1963, to protect wells from contamination, the Barbados Water Authority (BWA) has divided the island into 5 topographic zones. Depending on location, different legislation and regulation on septic tank characteristics have to be followed. For instance, in zone 1, no new houses can be developed, and wastewater must either be hooked up to the sewerage system or be treatment onsite. In zones 2-5 there are restrictions on the depth at which a septic tank can be installed, whereas in zone 5 there are no restrictions on domestic wastewater disposal. Harrison's Caves, one of Barbados most visited tourism attraction, is located in zone 1. Since it is an important source of revenue for the government, it is important to preserve it. To do so, the Ministry of Housing, Land and the Environment has created the Environment Special Project Unit (ESPU), encircling the surface where surface water infiltrates the cave. The ESPU is involved in different projects with particular focuses to assure the protection of the caves.

Another threat to the environment from traditional wastewater disposal methods takes place when the ground becomes saturated. Wastewater from sinkholes can permeate upwards with the watertable and make it all the way to the surface, at which point, runoff from rainwater disperses the contaminants into surface becoming a source of contamination as seen in figure 3.4.

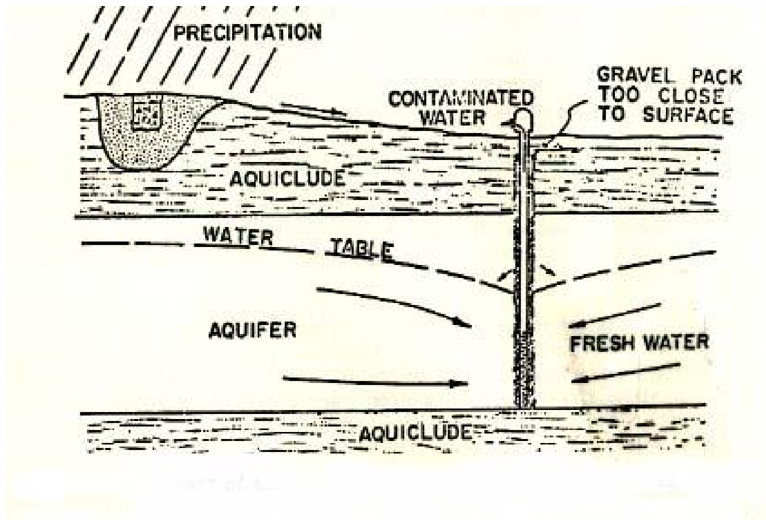


Figure 3.4: Surface runoff contamination.
(http ://ewr.cee.vt.edu/environmental/teach/gwprimer/group03/sgwppollute.htm)

In Barbados, when this type of situation occurs wastewater ends up in the sea contaminating the coastal area where the local population and tourists are swimming. This has a huge impact on human health as it increases the chances of infection and disease. Polluted beaches also affect the tourism industry as tourists come to Barbados to enjoy the beautiful beaches. If tourists develop a negative perception of Barbados' beaches, then Barbados' economy can be damaged through a decrease in annual visitors.

Impact on Marine Life

Pollution of the marine-environment concerns several governmental and non-governmental organisations around the world. (Ahmad, 1990;World Resource Institute et al., 1996).When related to wastewater, it occurs principally from offshore waste disposal and from the seepage of nutrients such as nitrate, and bacteria. In Barbados, the South Coast wastewater treatment plant only performs a primary screening and settling treatment, then directs the wastewater to a jetstream that alledgedly takes the waste far out to sea. Excreta has a high concentration of nutrients, and when in the sea, it promotes algal and bacterial growth, degradation of sea grass and coral reef ecosystems, decreased production of fish and larger aquatic life, and represents a risk to human health (UNEP, 2000). It is also important for the government of Barbados to work towards the conservation of marine life as they too represent important revenue from tourism. Beyond, just the economics, it is also important to maintain a high degree of biodiversity, through the protection of rare habitats such as coral reefs.

Biogas technology provides a potential solution that would address a good number of the problems that current wastewater practices in Barbados face. By maintaining the waste on the surface, biogas technology prevents or, at the very least, reduces the chances of dispersal into thr ground or into the sea. The technology is an alternative to septic tanks or sinkholes for those that live in rural areas where sewer mainlines do not extend, and it is also fitting for residences that exist within the zone-1 areas.

Fermentation slurry as fertilizer

Aside from the production of a useable energy source, and a means of treatment for wastewater, there are other important advantages to biogas digesters. The processed water can be used as a high-grade fertilizer, as a habitat for aquaculture, or many other purposes. During the digestion process, gaseous nitrogen (N) is converted to ammonia (NH3). In this water-soluble form the nitrogen is available to the plants as a nutrient. Also, the solid fermentation sludge is relatively richer in phosphorus (as appendix D demonstrates). A mixture of the solid and liquid fermented material gives the best yields. Compared with fresh manure, increases in yield of 5-15% are possible. Many of the pathogens in the feed are destroyed in the process, and there is more odor reduction than in other methods of waste-disposal. By conserving the useful organic matter on surface, there is less pressure to import such goods and, in general, the soil remains healthier and fuller.

Soil management practices influence grandly the productivity of a land. The maintenance of good soil organic matter (OM) content is an important management practise. OM has a positive effect on the stability of the soil structure. The OM is attracted to the charged soil particle and increase soil particle aggregation which makes water and air infiltration more favourable and decreases susceptibility to soil erosion. A source of food for the soil micro organisms and earthworms, OM also stimulates their reproduction. Soil organisms are very important in the health of a soil; they contribute to efficient nutrient cycling and produce substances that stimulate plant root growth and development. Good plant root in return contribute to stabilizing the soil and represent a more aggressive and productive plant. Finally, organic matter increases nutrient and water retention in the root zone. These imply less leaching, less runoff from the field, and this means improvement of the groundwater and of the marine life, less water for flooding and better soil moisture. Evidently, it is extremely important to farmers to have good soil organic matter content. By increasing the organic matter content of soil, one can decrease the amount of water needed for irrigation, reduce or even eliminate the need for chemical fertilizers, lower the chance of groundwater pollution, ameliorate the quality of marine life and increase crop yield.

3.1.4 Anaerobic Digester Types

A distinction is made between batch and continuous biogas digester plants. Batch plants are filled completely and then emptied completely after a fixed retention time. Large gasholders of a numerous digesters are required for uniform gas supply from batch filling. Continuous plants are filled and emptied regularly, normally daily. The feed material must be flowable and uniform.

Three main types of biogas plants exist: balloon plants, fixed-dome plants and floating-drum plants. The Ballon digester is the cheapest design. It consists of a plastic, usually polyethylene or red-mud, bag. This bag is used at the digester. It is elegant, and functional, but not durable. It can be designed to offer plug-like flow, which is ideal for designing for a specific retention time. Another advantage is that it can be transported on skids, which is often a useful characteristic. The plastic often collected pinholes and gas leakages will become more significant until the entire system must be discarded. The lifespan of a balloon digester is usually not more than 18 months.

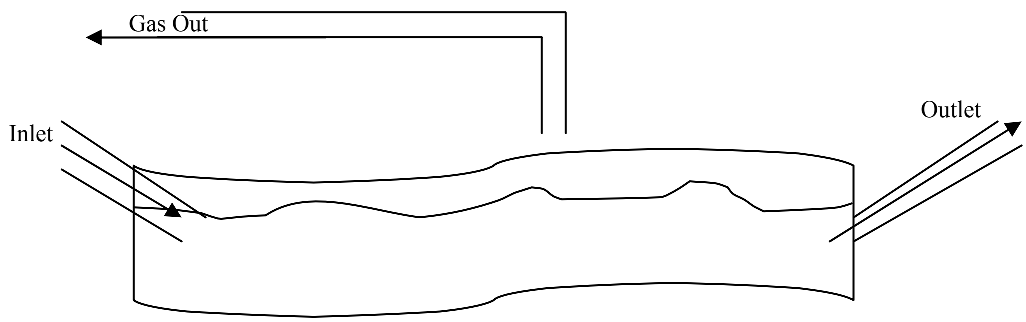


Figure 3.5: Balloon Digester sketch

The floating drum style consists of a open clylinder, usually underground, and usually made of concrete with another open cylinder, inverted and concentric within it. The advantage to this style is that the top cylinder has the ability to move up and down: depending on the pressure of the gas, it will adjust the volume as to maintain a constant pressure because the same force is being exerted on the gas from the weight of the drum itself. The top drum is typically made of ferro-cement has also be constructed of fibreglass in smaller scale instances. The problems with this design is that it is the most expensive type of design, it requires struts on which the drum will slide which are generally costly, there is leakage of methane through the area between the drum and cylinder, and retention times for the floating drum are generally longer as there is a degree of exposure between the digestive material and the atmosphere. A small degree of agitation can be achieved since the floating drum often has the ability to be spun around. This help methane production to a minute measure.

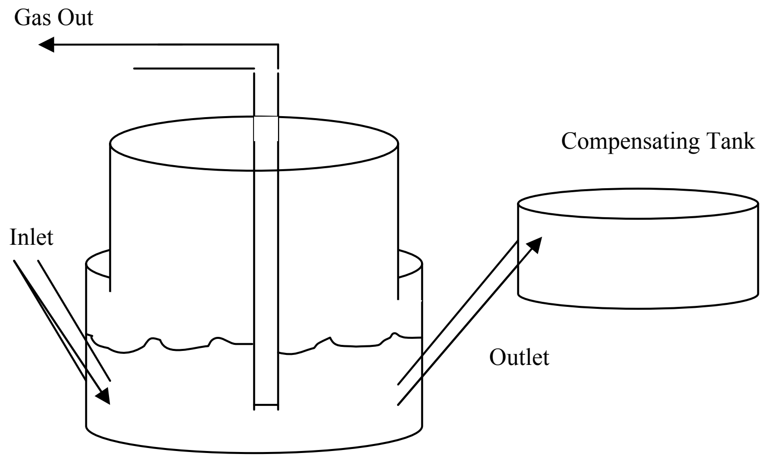


Figure 3.6: Floating drum sketch

Figure 3.7: Floating drum digester
(Richard Hoad Farm)

A fixed-dome plant consists of an enclosed digester with a fixed, non-movable gas space. The gas is stored in the upper part of the digester. When gas production starts, the slurry is displaced into the compensating tank. Gas pressure increases with the volume of gas stored, therefore if there is little gas in the holder, the gas pressure is low. Advantages of fixed-dome plants are low construction costs, no moving parts, no rusting steel parts (hence long life) and underground construction. However, plants are often not gastight (porosity and cracks), gas pressure fluctuates substantially and is often very high. Fixed-dome plants can be recommended only where construction can be supervised by experienced biogas technicians (Sasse, 1988).

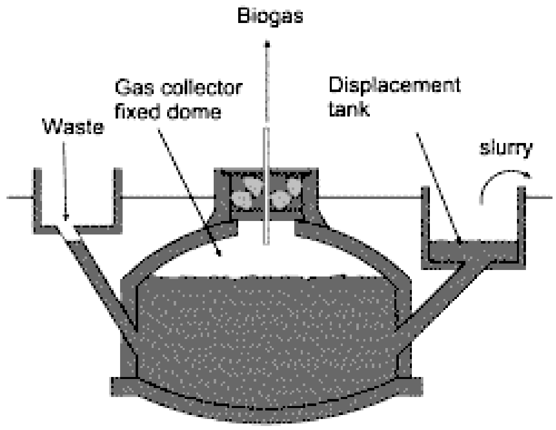


Figure 3.8: Fixed dome digester

3.2 A Brief History of Biogas in Barbados

From a technical standpoint, the Caribbean is an ideal location to host biogas. The ambient temperature range is within the ideal limits for mesophilic methanogenesis, being close to 30°C nearly all year round. As well, the propensity of locals to raise livestock offers a usable influent in the form of manure.

In 1980 the Deutsch Gesellschaft für Technische Zusammenarbeit (GTZ) began the Regional Biogas Extension Programme in the English speaking Caribbean in conjunction with the Caribbean Development Bank. The program concluded in 1989 after having constructed nine plants in Barbados of varying sizes.

Beneficiary	Location	Phone Number	Specs	Status
Julian Dottin	Gibbons Terrace, Christ Church	428-4505 # Not in Service	22 cattle (198?) Fixed Dome $20m^3$	Phone Number out of Operation
Arleigh Harding	Oldbury, St. Phillip	435-5713 # Not in Service	52 cattle (198?) Fixed Dome $20m^3$	Phone Number out of Operation
Richard Hoad	Morgan Lewis, St. Andrew	422-9083	42 cattle (1984) 2 horses (2005) Floating Drum $2X60m^3$	One unit is fully operational.
Husbands Farm	Kirton, St. Phillip	423-4023 # Not in Service	62 sows, 5 boars, 480 piglets (198?) Canal Design with separate gasholder $120m^3$	Phone Number out of Operation
Land Lease Development Project	Hector Bell, St. Lucy	439-8214 # Not in Service	50 cattle (198?) $20m^3$	Phone Number out of Operation
Trevor Gunby (Monterey Farms Ltd)	Oldbury Plantation, St. Phillip	435-5550 # Not in Service	200 000 poultry 600 pigs (198?) $100m^3$ w/ separate gasholder	Phone Number out of Operation
John Moss	Bloomsbury, St. Thomas	438-6118	7 goats, 10 pigs (198?) $15m^3$ canal w/ integrated gasholder	Last year gas collection has malfunctioned
Mary Moore	St. Simons, St. Andrew	422-9652	9 pigs, 30 poultry (1985) 10 pigs (2005) $8.5m^3$ floating drum	Recently gas collection has malfunctioned
Gay Reed (Barnwell Farm)	Rock Hall, St. Thomas	432-1787	500 pigs, 25000 poultry (1986). 725 pigs (2005) Red-mud plastic balloon. $2X75m^3$	Redone in concrete in 1989. Gas collection broke down in 1993. Used as septic carrier now. Waste is stored then pumped out and spread at Cow Williams field.

Table 3.1: Existing Biogas digesters in Barbados

Plants were also constructed in Guyana, St. Lucia, St. Vincent, and Dominica. Only four of the plants were monitored with intensive scrutiny, none of which were in Barbados. A total of 75 plants were constructed. The results of their studies were optimistic, but the necessary infrastructures for continued success were not in place when they left the

Caribbean. Progress was halted by; a lack of marketing techniques for the effluent (biofertilizer), the fact that there were no local engineers who could design and construct new plants, there were no local technicians who could professionally repair the plants, the general level of awareness amongst the populous was low and not promoted, financing techniques were not implemented to help the poorer farmers (the ones who they claimed would benefit the most from biogas) afford such technology. Jerome Singh of the Caribbean Development Bank also admitted that the German researchers became less involved over time and saw the project as more of a vacation than a study.

The reason for GTZ's departure without continuing development of biogas technology in the Caribbean are probably rooted in the institutional framework of GTZ. It conducts research in foreign nations and uses the findings at home. Once they had found what they wanted, there was no sense in them continuing research in the Caribbean. The department probably ran out of funds and funding was either not reapplied for or not bequeathed.

Since the departure of the GTZ-engineers there has not been a push from the government, an NGO (including the CDB), or an individual towards making more programs for biogas technology. To date, there has been no use of biogas technology using human waste as an influent. Although some were constructed, smaller scale biogas operations were not at the forefront of GTZ's dissemination program and were not studied to a high degree.

It could be time for a new generation of biogas plants in Barbados. Smaller, cheaper, more efficient designs that treat wastewater as well as manure could write a new chapter in the history of biogas in Barbados.

3.3 Future Potential for Biogas Wastewater Systems in Barbados

Wastewater treatment, soil upkeep, and energy production are extremely useful everywhere in the world, but especially in small, vulnerable, water scarce nation-states such as Barbados. Barbados is in the top-ten most water-scarce nations on a per capita basis. Because of this, the government is very concerned about issues of water reuse and conservation.

As a coral-based island, there is very little topsoil and minimal organic matter in what little soil there is. Barbadian farmers should be focused on looking into ways to keep the organic matter content high in their soils. Soil tests at the River plantation demonstrated that the soil has only between 0.1 and 0.2 % organic matter (OM) content. Oftentimes, readily available sources of OM are not used because they cause other problems. For instance, hydrologist and engineer for the Barbados Agricultural Development and Marketing Corporation [BADMC], Greg Marshal, stated that farmers won't spread chicken manure because of the weed seeds in it. This problem can be solved by biological treatment of the manure since the seeds would decompose. Many farmers compost their livestock's manure and use it as an organic fertilizer. This practice is more environmentally considerate than using inorganic sources of nutrients, but inefficient in many regards. Biogas technology can both concentrate the nutrient levels of the effluent and collect a fuel in the form of biogas.

Because of the geohydrology of Barbados, there is virtually no surfacewater from which to extract freshwater. Instead, groundwater acquifers are the source utilized *en masse.* The primary catchments, Belle and Hampton, are become more polluted with time, and they are believed to be over-exploited: diminishing in both quality and quantity. The lifespan these wells have for servicing Barbados' people and tourists is in question. Rainwater is becoming a more attractive source or freshwater, especially with new treatment techniques and uses for the water.

Rainwater collection and storage is a topic that has been discussed and implemented since the 1960's, when Michael Ionides first developed systems to catch rainfall in Sudan (Pacey et al, 1986). The concept behind rainwater collection is the collection of rainwater is as early as possible in the hydrologic cycle to ensure the best use of rainfall. This is ensured by collecting the rainfall before it runs-off to nearby rivers and streams, or lost to the groundwater, or even before evaporation occurs.

Modern techniques of water collection include exploitation of river systems and development of groundwater extraction techniques. This has taken a toll on the environment and is not a sustainable method of obtaining water in the long term. Also, it should be noted that these methods aren't applicable to many inland areas of the world. Many inland areas rely heavily on groundwater extraction; this practice is not sustainable because groundwater doesn't recharge itself and because the technology required extracting groundwater isn't applicable to many rural and developing areas of the world.

The principle of collecting and using precipitation from a small catchments area is referred to as rainwater harvesting. This is part of a general term called 'water harvesting'. In essence this is the collection and storage of any farmed water, including water obtained from runoff to be used for irrigation, water from creeks and streams and water from rooftops that is intercepted and used domestically. (Texas Water Development Board, 1997)

In the design of a rooftop water harvester, various factors need to be taken into account. The overall success of the design will depend on its economic, environmental and technical efficiency. The essence of appropriate technology is that equipment and techniques should be relevant to local resources and needs, to feasible patterns of organization and to the local environment. In order for the design to be realistic, the cost of the catchments system must not be greater than 10-15% of the cost of raw materials of the house to which is it attached. (Intermediate Technology Development Group, 2005) The technology used must be available locally and easily manipulated and maintained by the nearby people. The design also has to fit the environment; political and local customs must be known and respected. A social assessment should be carried out. Some important consideration such as existing rainwater catchments practices, opinions of local people about the usefulness and quality of water collected from the roof, the amount of time and money the people are willing to spend, need to be seriously considered before any design is to be made.

Energy demand is high globally, and fossil fuel prices are skyrocketing. Barbados must import most of its fuel. To run the electricity generators Barbados uses imported diesel, and for cooking fuel they import TexGas. The more energy that can be generated onshore, the more improvement there would be to the country's national product. There are natural gas reserves onshore, that are commingled within the producing oil wells, are distributed through domestic gas lines, but only to approximately 15000 homes, in primarily urban areas. There is still a need for native fuel sources to reach the rural communities and farmers. More environmentally friendly fuels, like biogas, are better for the environment too. They help reduce global warming because they are carbon neutral and, no methane is put into the atmosphere as would be the case if the wastewater was to decompose on its own. Biogas technology helps to address three key problems that face the world, generally, and especially Barbados. Barbados has an admirable policy towards the promotion of some one form of renewable energy. The government gives tax incentives to those who utilize solar water heaters and other solar powered devices. Another reason why solar power has become so widespread on Barbados is the fact that locally founded companies provide most of the parts required. Solar Dynamics, for example, is the forerunner of the solar power supplies in Barbados. Overall, however, Barbados still has a long way to go in the domain of renewable energy sources.

Exhibitors at the CWWA [Caribbean Water and Wastewater Association] Conference 2005 were advertising their technologies to the Barbadian government for solving some of the water and wastewater related problems facing Caribbean states, particularly Barbados. New Water Inc., a Barbadian firm that utilizes Zenon® technology, proposes a large scale water treatment reformation for Barbados. The plan involves an upgrade of the current Bridgetown and South Coast sewage treatment plants to tertiary levels and the construction of two more tertiary plants along the urbanized west coast of the island. The resulting treated water will be reused for purposes advised by the EPD, most likely irrigation of crops and/or golf courses, and aquifer recharge. Chances are that in the future a plan similar to what New Water Inc. is proposing will come into effect. The full sewerage system will service the more densely populated south and west coasts, but the more rural east, north, and central parts of the island will be largely bypassed. It appears the plan for a west coast line is almost for sure going to go ahead, an article in the Advocate on Monday December 5th, 2005 disclosed that the Inter-American Development Bank will fund the Barbados government with US$ 40 Million to aid in the construction of the pipeline(Cumberpatch 2005). The plans for the actual treatment facilities are, to date, not decided upon.

These areas are inhabited by small farmers, ranchers, and regular citizens. Areas designated as Zone 1 are not allowed to inject wastewater into the ground and must have a specified level of treatment of their wastewater, however enforcement of this regulation is marginal except for within the Environmental Special Projects Unit in the parish of St. Thomas, where aerobic digesters are beginning to become more ubiquitous. Zones 2-5 do not need treatment for their wastewater, and much of it is indeed injected into the ground. By and large, there is minimal treatment of wastewater outside of the serviced areas. This causes problems with the contamination of the groundwater aquifers and detrimental effects on the surrounding plants and soils. Arguably, even more important is the fact that lack of tertiary treatment leads to waste of potentially useful water. When wastewater is not reused the potential for a degree of relief of the stress on the supply of freshwater in Barbados is lost. Also, to maintain soil quality more fertilizer, often from inorganic sources, must be used to replenish the nitrogen and phosphate content in the topsoil.

Evidently biogas has the potential to play a major role in the future of Barbados and other Caribbean nations. It does not have to be limited to rural communities either. Another viably potential large-scale use of biogas in Barbados would be as a fuel for mass transportation. Buses are a dominant mode of transportation in Barbados and Sweden has demonstrated that large urban areas can utilize biogas for municipal transportation. This would require that the tertiary plants that are created for the urban areas incorporate anaerobic digesters to produce the biogas at a large enough rate. Yet another possibility for employing biogas in Barbados would be within the sugar-based food industries. Wastes from such manufacturing plants, have high sugar content, and are therefore good feeds for biological decomposition. Sources are plentiful in Barbados and management of such waste is a key issue within the industry.

A good example of how well anaerobic treatment plants can work in Barbados is Mr. Richard Hoad's farm. In the 1980s US Aid funded the construction of a digester for him through the Caribbean Development Bank [CDB]. At the time his farm consisted of 63 cows, all of whose manure was used as feed for the plant. Currently, he only uses two horses' manure as feed. Both now and then the digester provided enough gas to provide the house with adequate fuel for cooking and a sellable fertilizer, more effective than raw manure, although he no longer sells the effluent. ~20 years of cooking gas and counting, requiring minimal maintenance and the only labour involved is in the loading of the feed into the digester. Although his plant was designed and constructed by a German engineering firm (GTZ), there are other low-cost designs available today, some that require mostly 'off-the-shelf' parts or those from reused materials.

Barbados has a diminishing quality of groundwater, especially with regard to increasing nitrate levels. The Zoning Study relates that it is the only criteria which Barbados does not meet international standards in.

The following data was taken from the study conducted in 1998 regarding the Feasibility of the West Coast Sewerage Project.

Mean annual nitrate levels of the primary catchments are;

Well	**[NO^-_3]**
Belle	2-11 mg/L
Hampton	6-11 mg/L
W. Coast	5-8 mg/L

Table 3.2: Mean annual nitrate levels in catchments.
(Standley International, 1998)

The average trend over the years is as follows:

Year	**[NO_3^-]**
1977	0.5-2.5 mg/L
1987	5-7 mg/L
1992	5-8.5 mg/L

Table 3.3: Average nitrate trends.
(Standley International, 1998)

The increasing trend is partly due to the increased use of water closets but not a similar increase in sewerage. Where once the solid waste would remain relatively stagnant in a covered pit it now is being mixed with water and this increases its traveling velocity, and ergo that of the nitrates it contains.

Other factors that increase nitrate levels in Barbados' catchments are leaching and mineralization due to agricultural fertilizers.

Leaching accounts for 33 kg of N as NO_3^- per hectare-year because roughly 9.5% of a kg of $(NH4)_2SO_4$ creates nitrates and the same is roughly true for 12:12:17:2 fertilizer (Standley International, 1998).

Mineralization contributes ~250 kg N as NO_3^- per hectare-year (Standley International, 1998) but the land is only tilled once every 8 years on average. So on an annual basis there is only about 31.5 kg N per hectare-year.

The intended West Coast Sewerage Project and a potential expansion of the South Coast sewer mainline will help to protect the primary catchments. But the collection and accumulation of nitrates in the other, more rural catchments is still a concern. Although much of the East coast is zoned as class V, where infiltrating water will be ejected to the sea rather than into aquifers, there are still many zone I-IV areas as well.

Estimated expansion of sewerage services (2008-2010) will accommodate St. Michael, St. James, St. Peter, and Christ Church. As a simplification of an estimation of those who will be left without sewerage connections we shall estimate the entirety of the dwelling of the non-serviced parishes; St. George, St. Philip, St. Joseph, St. John, St. Andrew, St. Thomas, and St. Lucy. If anything the result is an underestimate of the number of dwellings not connected to the sewerage system by 2010.

Stats on Toilet Facilities in Dwellings (2000 census)
3026 total dwellings in Barbados.
Only 428 linked to sewer (all in St. Michael)

Parish	**Total Dwellings**	**W.C. not linked**	**Pit Latrine**
St. George	5562	4227	1198
St. Philip	7522	6128	1252
St. John	2727	1951	1252
St. Thomas	4016	3109	839
St. Joseph	2132	1518	579
St. Andrew	1617	1065	528
St. Lucy	3070	2363	620
Total	**26646**	**20361**	**6268**
	32.1% of all dwellings.	76.4%	23.5%

Table 3.4: Toilet facilites in toilets.
(Barbados National Census, 2000)

NB: W.C. not linked: Connected to suck-holes, absorption pits, or septic tanks.

Although, many of these residences are situated in zone 5 areas: where the surface water is believed to not travel into the groundwater and some residences surface water has a travel time of several years until it reaches the aquifers. So this overestimate is hoped to counteract the underestimate of the number of people bypassed by municipal sewerage lines.

There are several problems that hinder the potential of biogas in Barbados.
What is unclear at this point is whether biogas technology fits into the visions of any of the following classes; the local people who would be using the facilities, the government who would be responsible for the legislation and regulations, and any potential third parties who would provide materials or construction services.

Parts of Barbados' population see biogas as a step backwards. The general sentiment is that Barbados should emulate the 'developed world', not the 'developing world'. Those, like Richard Hoad, are perceived as eccentric individuals, not necessarily leaders. As well, nobody on the island yet uses wastewater to run biogas systems; only animal manure with added freshwater is used as feed for the plants that do exist. People may be wary in dealing with human excreta in any society because fear of diseases and general cultural unease with such a radical concept. These apprehensions tend to outweigh any personal benefits associated with saving of energy and fertilizer costs by using biogas.

Appropriate sources of funding for biogas digesters, obviously depends on the scale of the digester that is to be constructed. In the case of Barbados, the current targets for the use of biodigesters would be farms with livestock, individual or small community rural houses, and small rural industries. In the future, a large-scale wastewater treatment plant could be constructed that will service the more urbanized parts of the island where sewage collection infrastructure already exists or there is not enough available space to construct many small scale digesters. If such a large-scale endeavor were to be implemented funding would most likely be primarily from the government, possibly via the World Bank or the IMF, or through a BOOT program like the Ionics® Desalination Plant in Spring Garden, St. Michael. For the more current target of small-scale biogesters for private use, there are some different solutions as to how to fund such projects.

Financing of such small-scale treatment plants is arguably the most difficult piece to fit into the puzzle. Although the owners will save on energy and fertilizer costs and/or potentially sell some of the effluent as fertilizer, for small farmers like those on Barbados, the costs of construction can be outlandish for them to afford on their own. As well, NGOs and private corporations are less inclined to finance small-scale plants than they are larger ones because they would be unable to manage them, they must leave them more-or-less in the hands of the beneficiaries. Studies have shown that South Asian (India, Nepal, Bangladesh) people can often afford the plants with government micro-financing techniques like subsidies and/or loans, even some of the poorest farmers, but that is because labor and materials are much cheaper there than in the Caribbean.

The general sentiment among Barbadians is that the government is not as progressive as it could be. To paraphrase Dr. Don Marshall (a Barbadian professional and Research Fellow at the Sir Arthur Lewis Institute of Social and Economic Studies), 'the government's primary aim is to be re-elected and therefore abide by the demands of the masses and not necessarily for the good of the nation. Sugarcane farmer, Patrick Bethel, shares a common attitude towards the government. Local entrepreneur and independent bio-diesel producer, Handel Callender, believes that the government should do more to support small community-based projects that lead towards environmental sustainability, especially since they do not provide a lot of services (including wastewater disposal) to most rural areas in Barbados. There needs to be a push from a leader within the government, or a well established NGO that can force biogas technology into the foreground of energy issues. If there is a solid belief, then concepts can materialize rapidly. But without a strong driving force and publicity then the ideas are out of sight and fade into the background with time. Barbados currently lacks a leader who will espouse the concept, this is necessary before substantial change can occur.

Jerome Singh, a representative from the CDB led a study in 1993 concerning the possibility of biogas in the future of Barbados. The study concludes by recommending that biogas does have the potential to be an organized system in Barbados, but is only feasible for larger livestock farms; "Biogas production for generating cost effective electricity requires manure from more than 200 large animals." However if all that is needed is the generation of gas for cooking purposes, then smaller farms and ranches could be economic. He also cites the fact that safety is also a major concern when dealing with a flammable (and potentially toxic) gas as biogas; "A program may not be sustainable since it cannot occupy a biogas team full time.” There are a few other problems with certain types of manures too. Goat manure, for instance, requires dissolution through vigorous mixing before being fed into the digester because it will float on the surface otherwise, and thus not digest properly.

Chapter 4: Methodology

Literature Review

To best address the project topic and international location of the island, a variety of sources of information were necessary. Use of the following sources were utilized: internet sources, books , newspaper clippings, and journal articles.

Field Trips & Consultation

Field trips and consultations were important sources of information. Meeting with different people on the island allowed for custom-tailored information concerning Barbados, at the same time as expanding new and interesting issues relevant to the project of Anaerobic digestion. The summary and description of various interviews, meetings and consultations can be found in the Appendix A.

Design

The first step of the design process was meeting with the clients and visiting the future site. Discussing and understanding the clients' requirements was an important step of the design process. Brainstorming sessions between the designers was the next step. Research on existing designs was then conducted. Discussions and hand-drawings amongst the designers were composed until the designers were satisfied with the preliminary design.

The next step of the design process was the construction of a Matlab program calculating different parameters needed in the sizing of the tank. Drawings of the biogas digester system on Autocad were made. Those drawings will be useful in the construction process.

A list of materials was compiled and the designers searched for the best prices among the various suppliers on the island. A list of materials and costs can be found in chapter 6.

Subsequent to the design, the students wrote an official proposal and report and will be presenting the design to various organisations, including the Commission on Sustainable Development.

Chapter 5: Design of an Anaerobic Wastewater Digester System

Pilot project site

The future pilot project site is located in the district of St Andrew. Three families are getting together and are developing a low budget Eco Resort. They are planning to use strictly renewable energy, solar energy being the most important source of energy. There will be a community house where the system described below could be implemented. The system will be extremely benefit as organic food will be cultivated, prepare and serve to future client of the restaurant. With the actual system design, where the wastewater of 10 people, the manure of 2 horses and 2kg of crop a day will be feed to the digester, 3.5 m^3 of gas will be produce everyday. It is estimated that this amount of gas will allow 6 hours of cooking. The digested effluent will be use as fertilizer for the organic garden. As many locals and tourists will be passing to the Eco Resort, having a sustainable pilot project represents a great opportunity for the *Sustainable Development Commission*.

The design of the anaerobic wastewater digester system can be divided into 5 components; the rainwater collector, the toilet design, the plumbing from the house to the digester, the digester and the gas considerations. (figure 5.1)

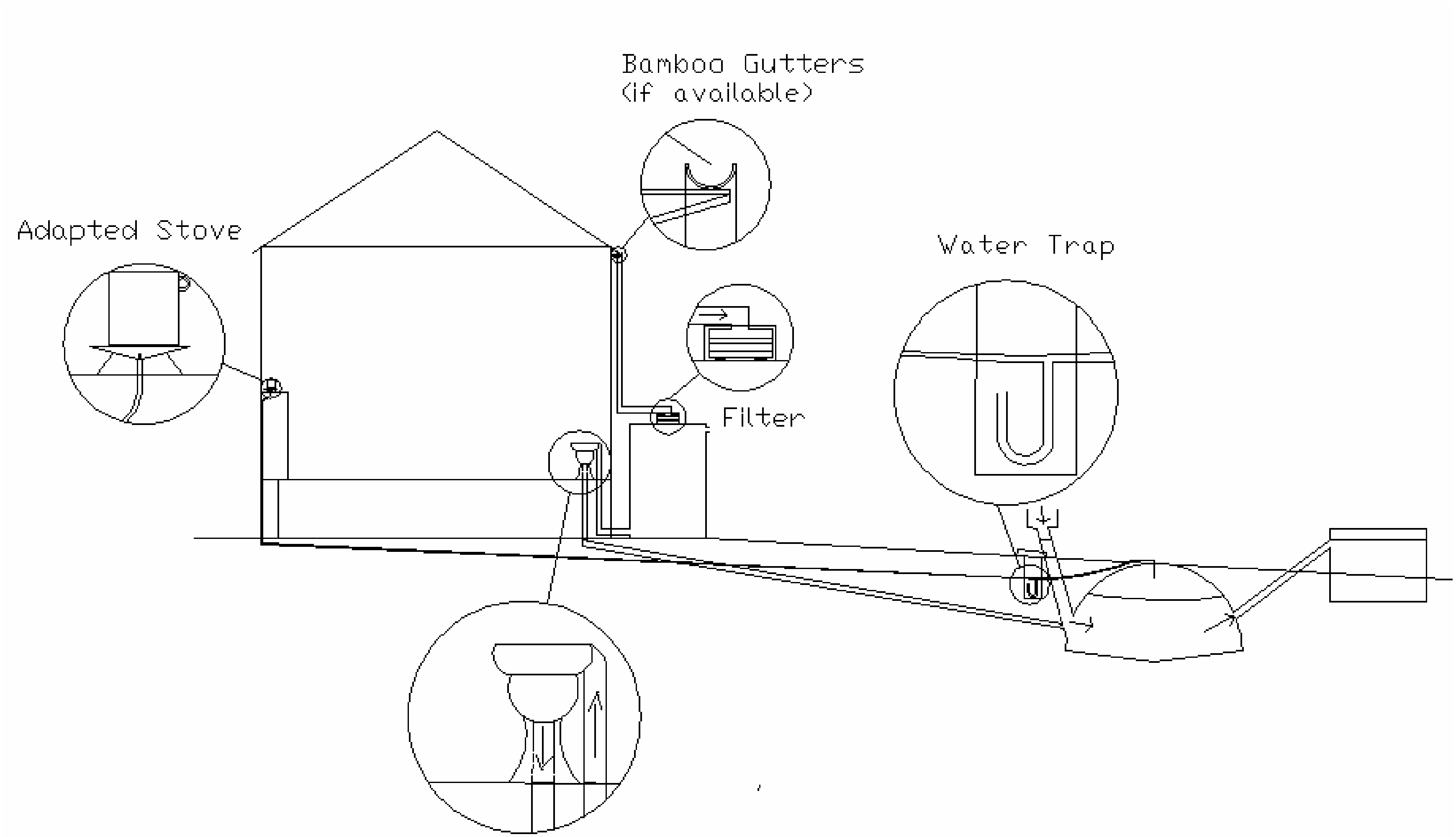


Figure 5.1: Overall AUTOCAD schematic of System with Directions of Flow.

5.1 Rainwater Collection

5.1.1 Design

The design consists of a catchments system, a storage system and a piping and pumping system to bring the water into to the home as needed.

The design criterion depends on the local climate and weather;

1. Daily rainfall measurements over 2-3 years form rain gauges about 2 km apart on the project area.
2. Estimates of the average and minimum monthly and annual rainfall.
3. A measurement of rainfall intensity and runoff in individual storms to ensure the design is adequate.

If anyone of these factors is not available, literature values, the internet and assumptions can be substituted in place.

Designing the storage tank;

1. An analysis of the rainfall data is done to measure the theoretical amount of water that can be stored.
2. The individual house is assessed to determine the daily and monthly water uses.
3. The cumulative supply vs. cumulative demand is plotted to size our storage tank.
4. The available materials are assessed in order to verify that the tank be large enough and strong enough to fulfill its purpose.

Piping and pumping system;

1. The pipes must be sized in order to carry the adequate amount of water in a given time. For example, if a 25mm/hr storm is normal for the month of August, then the pipes have to carry that amount to the storage tank.
2. Pipes have to be sized and fitted from the storage tank into the house. The pipes can be used in the kitchen or bathroom, for drinking water or hygienic purposes.
3. Pumping is done by the local people and has to be easily manipulated and low maintenance.

(Pacey. A. & Cullis, 1986)

The actual rainwater harvester design is for a Barbadian household located in the district of St-Andrew. The primarily goal of the water harvester is to fulfil the water requirement for the toilet system. Depending of the water quality, all extra water will be used for different purposes such as irrigation and bathing. The design will have 3 main storage tank and finally the delivery system.

The Catchment System

The first component of a catchment system is to know how much water will be collected. This depends on how much rainfall is expected in a year. As well, it is a direct function of the daily water needs. For our design, we need to know how much rainfall is expected in St-Andrew.

Janv	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
mm	Mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
66	28	33	36	58	112	147	147	170	178	206	97

Table 5.1: Average Rainfall depth in Barbados

(http://www.accessbarbados.com/barbados_climate.php)

This rainfall data is representative of a typical year, and can be used as an example when calculating rainfall.

The size of the roof is planned to be approximately 36 m^2(6m per 6m). Different roof material has been discussed. The roof material will influence the maximum amount of water that can be harvested. A metal roof will have a runoff coefficient of 0.9, which mean we assumed that 90% of the water falling on the roof will be harvested. In the actual design, the roof will most likely be made of grass. A grass roof will have a lower runoff coefficient, as more water will evaporate. We assumed a runoff coefficient of 0.6. Gutters will be attached to the roof. They will have a 2% slope toward the tank and will be comprised of plastic or bamboo. If bamboo available, the clients prefer the use of natural material. (Texas Water Development Board, 2005) made for the toilet, we will compare the toilet monthly water needs to the monthly rainwater that can be collected from the roof.

Water demand analysis:

If we take into consideration that on average, human produces 0,5Kg of waste per day. To have the ideal 8% solid waste in the digester, we need to add 0,75L per person per day. In the actual design, the number of toilet user is estimated to be 10. The water demand is presented in the following table:

Consumers	Number	Water demand (l/day)	Total demand (l/day)	Total demand (m^3/day)
Adult	10	0,75	7,5	0,0075

Table 5.2 : Water demand for the toilet.

With these parameters (i.e. rainfall harvested and water demand), we make a water balance table (table 5.3) to show the excess or deficit, which is needed in order to size the storage container.

Month	Rainfall (mm)	Rainfall (m)	Rainfall Harvested (m^3)	Cumulative Rainfall Harvested (m^3)	Monthly Demand (m^3)	Cumulative Demand (m^3)	Surplus (m^3)
Jan	66	0,066	1,4256	1,4256	0,225	0,225	1,2006
Feb	28	0,028	0,6048	2,0304	0,225	0,45	1,5804
March	33	0,033	0,7128	2,7432	0,225	0,675	2,0682
April	36	0,036	0,7776	3,5208	0,225	0,9	2,6208
May	58	0,058	1,2528	4,7736	0,225	1,125	3,6486
June	112	0,112	2,4192	7,1928	0,225	1,35	5,8428
July	147	0,147	3,1752	10,368	0,225	1,575	8,793
Aug	147	0,147	3,1752	13,5432	0,225	1,8	11,7432
Sept	170	0,17	3,672	17,2152	0,225	2,025	15,1902
Oct	178	0,178	3,8448	21,06	0,225	2,25	18,81
Nov	206	0,206	4,4496	25,5096	0,225	2,475	23,0346
Dec	97	0,097	2,0952	27,6048	0,225	2,7	24,9048
Total	1278	1,278	27,6048	27,6048		2,7	

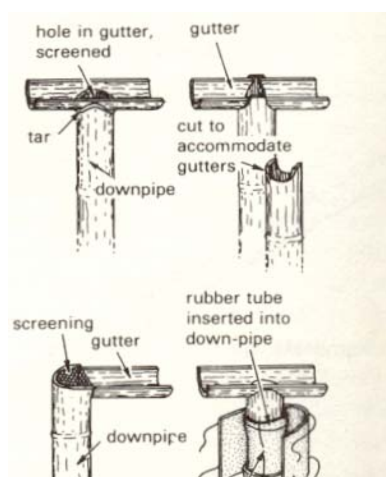
Table 5.3: A water balance based on the various parameters mentioned above.

Sample calculations (for the month of June):
Rainfall Harvested = runoff coeff. * Rainfall (m) * Roof area (m^2)
Rainfall Harvested = 0.6 * 0.112 m * 36 m^2
Rainfall Harvested = 2,42 m^3
Monthly Demand = Daily Demand * Number of days in the month
Monthly Demand = 0.0075 m^3/day * 30 days
Monthly Demand = 0,225 m^3

The amount of water is plenty for the toilet purposes. Even in the driest month, the possible amount of water harvested is more than the toilet demand. The size of the tank will need to be size in function of the amount of water needed for other purposes or in function to the maximum possible water that can be harvested.

Gutter

Gutters can be made in different sizes to trap different flow rates, and the cost will increase as the size increases. In our design, large diameter bamboo gutter will be the first choice. (Figure 5.2.) Plastic material will be used if bamboo material not available. Plastic gutters are widely used and widely available in developed countries. They come in standard sizes produced by many manufacturers. (Figure 5.3) Gutters can be made different sizes to trap different flow rates, and the cost will increase as the size increases. They can be made on site and attached to the roof or they can be bought pre-manufactured and attached on site.



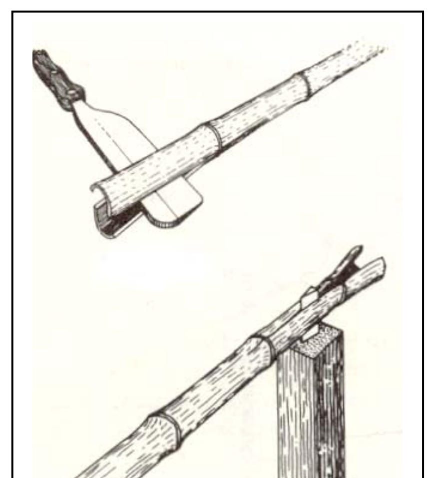


Figure 5.2: Bamboo Gutters
(Pacey. A. & Cullis, 1986)

Figure 5.3: Working with Bamboo
(Pacey. A. & Cullis, 1986)

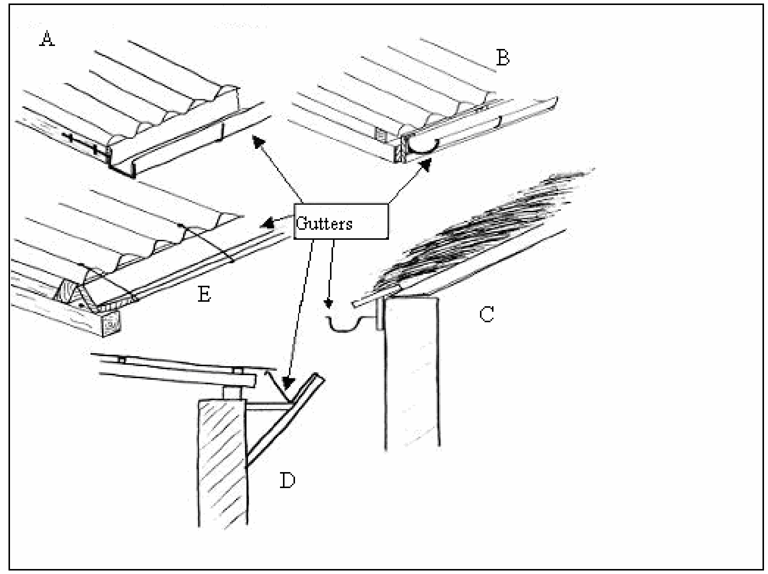


Figure 5.4: Different shape gutters
(Water for the World, 2004)

Appendix B shows alternative and cheap ways to harvest the water. Those ‘improvised water collection’ is seen in places such as Kenya.

The Filter System

Our filter will filter out sediments, leaves and dirt, and it will be attached to the tank. Proper filters can make rainwater into high quality water that is safe to drink and use on a daily basis. In general, rural areas will require less filtration than urban areas because of less pollution. Pollutant gases in urban areas that are emitted by industry and cars alike will rise into the atmosphere and rain will dissolve these gases as it comes down. Therefore in urban areas, the water will have to be filtered out for chemical contaminants, the pH will have to be corrected as well the regular sediments and dirt will have to be impurities that will make the water unfit for human consumption. Also animal droppings have to be removed and filtered before consumption.

Another aspect of the filtration system will be where to put it. Additional filters will cause a price increase, and therefore a balance will need to be achieved when dealing with cost vs. quality.

The filter system will be used to increase the quality of water. It will consist of three parts. They are:

a. the physical filter attached to the top of the tank
b. the first flush system
c. the addition of chlorine or bleach to the water to kill bacteria (if water use for potable water)

The filter system is designed to be low cost and low maintenance while increasing the quality of water available. However the water won't be excellent quality.

There will be a filter attached to the top of the reservoir tank entrance. It is simple and inexpensive to install and is easily cleaned. Our filter will be attached to the tank because it is the cheapest and easiest to use.

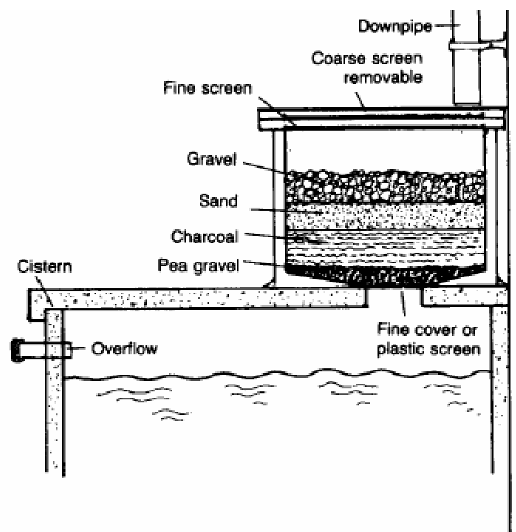


Figure5.5: The filter system attached to the tank.

simple jute bag, which is widely available and easy to use. It will trap the sediments that could runoff, such as dirt and dust, or pieces of leaves from nearby trees. The second layer is a fine screen which is a cheesecloth. It will serve to further trap any sediment that passes through the jute bag. The jute bag and cheesecloth are low maintenance, and are easily cleaned with a simple washing and can be replaced after cleaning. The third layer is gravel, the fourth sand, the fifth charcoal. Charcoal will clean the water further by absorbing organic substances and trapping them, either physically or with chemical bonds. The sixth layer will be made of fine gravel (pea gravel) and finally cheesecloth will be placed under this and it will be the last layer. See the diagram above to see the filter as it will be attached to the tank. The many layers of the filter will trap different size particles.

The second component of the filter system will be the 'first flush'. The first flush is the diversion of the first 40-45 l of water away from the storage tank, per rainfall event. The first flush system is a backup for the filter, as it will aid in the removal of large particles. This will lessen the load on the filter, and it will therefore require less maintenance. The first flush is attached to the gutters and will divert the water away from the cistern and drop it on the ground. This is used to remove any large sediments (such as leaves) or dirt.

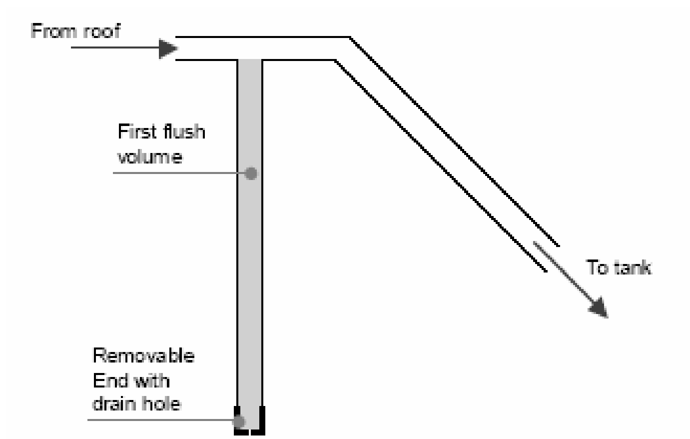


Figure 5.6: First Flush system; attached to the gutters
(Texas Water Development Board, 1997)

then less water will need to be flushed out, so the client won't have to remove and replace the plug as often.

Chlorine or bleach can be used to further disinfect the water. The bleach will be added in the home drinking supply if wanted. There won't be any chlorine added to the bathroom water, as it will be used for toilet flushing. Using bleach is relatively inexpensive, with an estimated cost of $0.02/m^3. This is less expensive than the cost of charcoal, and also less expensive than the cost of boiling water. Chlorine will protect against most bacteria, (for ex. *Giardia*), and it isn't harmful in the short-term. However, in the long-term there may be some adverse health effects, and so alternative way such as ozone disinfection should be considered.

5.1.2 Pump

The low flush toilet will used the collected rain water. The rain water will be store on ground level, this is cheaper than building a structure to elevate them. However, this design requires pumping the water from the tanks to the toilets, located higher than the tanks. The pressure required at the pumping facility is calculated by adding the following three items:

1. Pressure drop due to friction for 10 m length
2. The static elevation difference between the pumping facility and storage tank
3. The delivery pressure required at the storage tank

We can also see the calculation mathematically:

$$P_t = P_f + P_{elev} + P_{del} \qquad (11)$$

where P_t = total pressure required at pump
P_f = frictional pressure head
P_{elev} = pressure head due to elevation difference
P_{del} = delivery pressure at storage tank

The pipe bringing the water from the storage tank to the toilet reservoir is estimated to measure 30 feet (10 meters approximately) and will be 2 inches in diameter. These distances include estimations for minor losses such as 90° elbows.

To calculate the first term of the equation, P_f, we first need to calculate the head loss due to friction h_f. The Darcy equation may be used to calculate the pressure drop in water pipes as follows:

$$h = f \frac{L}{D}\frac{V^2}{2g} \qquad (12)$$

where h = frictional pressure loss, ft of head
f = Darcy friction factor, dimensionless
L = pipe length, ft
D = inside pipe diameter, ft
V = average flow velocity, ft/s
g = acceleration due to gravity, ft/s^2 = 32.2 ft/s^2

To find the value for the Darcy friction factor, we must know if the flow is laminar or turbulent. We can assume laminar flow, but to be certain, Reynolds number must be calculated:

$$R = \frac{VD}{\nu} \qquad (13)$$

where R = Reynolds number, dimensionless
V = average flow velocity, ft/s
D = inside diameter of pipe, ft
ν = kinematic viscosity, ft^2/s

Another way to calculate Reynolds number is:

$$R = 3162.5\frac{Q}{\nu D} \qquad (14)$$

where R = Reynolds number, dimensionless
Q = flow rate, gal/min
D = inside diameter of pipe, in
ν = kinematic viscosity, cSt

We know that to get a laminar flow, R must be equal or less to 2100. Also, we assume water has a viscosity of 1.0 cSt. The only unknown is Q. Plugging all the values back in equation (14), this gives us $Q \leq 1.3$ for laminar flow.

We want the flow rate to be 1.3 gal/min. Velocity is obtained through the following

$$V[ft/s] = 0.4085\frac{Q[gal/\min]}{D^2[in^2]} = 0.4085 \times \frac{1.3}{2^2} = 0.1327 \approx 0.13\, ft/s \qquad (15)$$

In order to calculate the friction loss in a water pipeline using the Darcy equation, we must know the friction factor Darcy friction factor f. This friction factor is a nondimensional number between 0.0 and 0.1. For laminar flow, the friction factor f depends only on Reynolds number and is calculated as follows:

$$f = \frac{64}{R} = \frac{64}{2100} = 0.03 \qquad (16)$$

Therefore, equation (12) becomes

$$h = f\frac{L}{D}\frac{V^2}{2g} = 0.03\frac{30\, ft}{2/12\, ft}\frac{0.13^2\, ft^2/s^2}{2 \bullet 32.2\, ft/s^2} = 1.42 \times 10^{-03}\, ft \qquad (17)$$

Another version of the Darcy equation is as follows:

$$P_m = 71.16\frac{fQ^2}{D^5} \qquad (18)$$

where Pm = pressure drop due to friction, psi/mi
Q = liquid flow rate, gal/min
f = Darcy friction factor, dimensionless
D = pipe inside diameter, in

By plugging all values in equation (18), we obtain $P_m = 0.144\, psi/mi$. Both the frictional pressure loss (h) and the pressure drop due to friction are very small and are therefore negligible. We can conclude that pressure drop due to friction for 10 m length of pipe can be neglected.

We will now calculate the second term in equation (11), P_{elev}. The pressure P in psi and liquid head h in feet for a specific gravity Sg are related by:

$$P = \frac{h \times Sg}{2.31} \qquad (19)$$

h = liquid head, ft
Sg = specific gravity of water

For our specific application, we assume the elevation difference is 10 feet (approximately 3 meters). The house is elevated 1 meter above ground, and we assumed the toilet tank is situated 2 meters on the floor. Here, Sg = 1. Therefore, by plugging all value back in equation (19) gives P = 4.33 psi, which we round up to 5 psi.

The final term in equation (11) is P_{del}, which is the delivery pressure at storage tank. We do not need a specific delivery pressure, since we have no time constraints. Therefore, it was assumed that delivery pressure is also 5 psi.

The total pressure at the pump can now be calculated. Since frictional pressure head was negligible, we need only consider P_{elev} and P_{del}. This gives us P_t = 10 psi.

Now that we calculated the total pressure required at the beginning of the pipeline to transport a given volume of water over a certain distance, we will now calculate the pumping horsepower (HP) required to accomplish this. The general equation used to calculate the water horsepower (WHP) is:

$$WHP = \frac{ft\ of\ head \times (gal/\min) \times specific\ gravity}{3960} \qquad (20)$$

where

$$ft\ of\ head = required\ pressure \times 2.31 = 10\ psi \times 2.31 = 23.1 \qquad (21)$$

Therefore,

$$WHP = \frac{23.1 \times 1.3 \times 1.0}{3960} = 0.0076\,HP \approx 0.008HP \qquad (22)$$

Assuming a pump efficiency of 80%, the pump brake horsepower (BHP) is:

$$BHP = \frac{0.03}{0.8} = 0.0365 \qquad (23)$$

This is an extremely small requirement, too little to justify the purchase of a pump. One alternative is to use a hand pump similar to the one shown in figure 5.7 to bring the water from the water catchments tanks to the toilet tank. This option will be discussed in the toilet selection. If in the future there are other pumping needs, such as for irrigation, then the 1 or 5 hp pump could also be used for the toilet filling purposes.

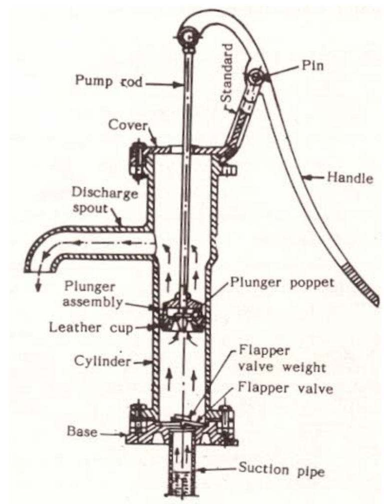


Figure 5.7: A typical hand pump that can be used to pump water (Michael, 1989)

5.2 Toilet design

One of the main challenges in our design project was the toilet design. Every time someone flushes, the water makes its way into the biogas plant. The problem lies in the fact that we require a solid to water ration of 1:1 to obtain a total solid content of 8-10%. To better understand this problem, we will first look at how a toilet works.

The three main systems that work together in a toilet are the bowl siphon, the flush mechanism and the refill mechanism. Figure 5.8 shows a cross section view of a toilet. The part we a most concerned with is the bowl and the siphon. Let's say you disconnected the tank and all you kept was the bowl. You would still have a toilet, since moulded into the bowl is called the siphon bowl (Brain, 2005).

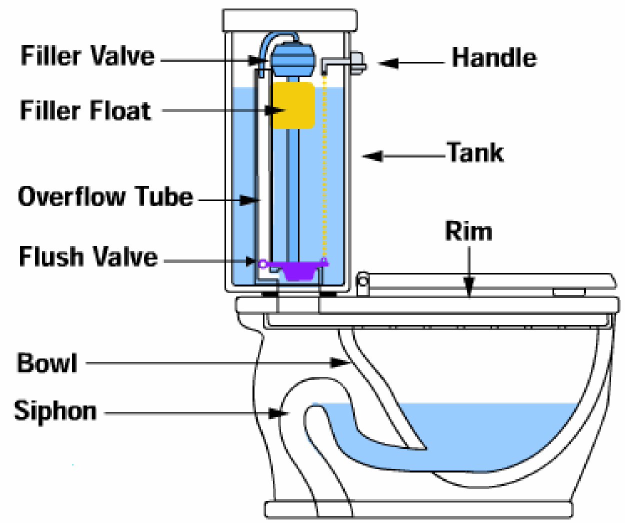


Figure 5.8: Cross-sectional view of a toilet.

If you were to pour a cup of water in the bowl, the water level in the bowl rises but the extra water immediately spills over the edge of the siphon tube and drains away. Now, redo the same experiment with a bucket of water containing approximately 2 gallons of water. You will notice that pouring this amount of water causes the bowl to flush, as if the water is sucked out of the toilet. What happened is that you poured enough water fast enough to fill the siphon tube. Once the tube was filled, the rest was automatic. The siphon sucked the water out of the bowl and down the sewer pipe. As soon as the bowl emptied, air entered the siphon tube, producing that distinctive gurgling sound and stopping the siphoning process (Brain, 2005).

The purpose of the tank is to act like the bucket of water described above. You need to get enough water into the bowl fast enough to activate the siphon. The tank acts as a capacitor: it holds several gallons of water. When you flush, all of the water in the tank is dumped into the bowl in about three seconds. When the flush lever is pulled it pulls up flush valves are called flappers. The flapper bulb is filled with air, so it wants to float, but the weight of the water on top of it seals it tightly against the discharge hole. Once it is pulled away from the hole, water flows under it and it floats. This holds it open, away from the discharge hole (Brain, 2005).

Immediately after a flush begins, the water level in the tank starts to go down, so the float starts to go down. The float then opens the fill valve and water from the house water pipe begins to flow into the tank. When the tank is almost empty, the flapper can no longer float and falls sealing the hole again. Now that the discharge hole is closed, the water coming in through the fill valve starts refilling the tank (How a toilet works, 2005).

Now that we have seen all the parts, we can understand the complete mechanism. Pushing on the handle pulls the chain, which releases the water from the tank into the bowl in about three seconds. This rush of water activates the siphon in the bowl. The siphon sucks everything in the bowl down the drain. Meanwhile, when the level of the water in the tank falls, so does the float. The falling float turns on the refill valve. Water flowing through the refill valve refills the tank as well as the bowl. As the tank refills, the float rises, and shuts off when it reaches a certain level. Should something go wrong and cause the refill valve to keep running, the overflow tube prevents a flood (How a toilet works, 2005).

Coming back to our design, the challenge is that we only require 0.7 liters of water per flush. This is based on calculation assuming each person flushing only once a day. Normal toilets use 2 gallons of water or more; even current low flush toilets still use 1.5 gallons, almost ten times too much water. The problem is that if we modify the toilet tank to only flush 0.7 liters, the siphon effect will no occur. There would be insufficient water discharged and the toilet would not work properly. Therefore, conventional toilets cannot be used along with the digester, or else there would be too much water in the tank.

adding pure undiluted horse manure or crop straight into the digester, without diluting it with water previously. This would bring our solid to liquid ration back to approximately 1:1.

The ideal solution is installing a toilet which does not use the conventional technology. We need a toilet where we can flush without adding water, or choose the amount of water to flush with. Such toilets can be found in RV trailers. They have separate knobs or pedal to flush and rinse. The Envirolet shown in figure 5.9 would be ideal for our application: it uses less than a pint of water per flush. However, it is manufacture in Canada and the United States and is expensive.

Figure 5.9: Envirolet Non Electric Low Water Remote 2/LW

A cheaper alternative to the Envirolet Low Flush toilet is using a toilet designed for boats. West Marine is a company specialized in boating supplies. They offer a wide variety of direct discharge toilets which use very little water. Located on page 530 of the online catalogue and shown in figure 5.10, this manual pumping toilet costs only us$149.99. This manual head toilet features a straight-forward design. The angled pump provides a

¾” inlet and a 1 ½” discharge.

Figure 5.10: Head Mate-Head toilet from West Marine. Page 530 of online catalogue.

The advantage of this design is that the toilet and pump are sold together as one unit. We not need a tank above the toilet. We can leave the reservoirs below the house and the hand pump will raise the water as it is needed. This toilet will provide the 1:1 water to solid content as well as solve the pumping problem.

5.3 Plumbing from the house to the Digester

Sewer systems are generally designed as gravity flow systems with a free water surface. This means that the sewer pipe may run full or partially full so that there is an air space above the water level: this is known as open water flow. Pumps are also used to provide the lift necessary from deep sewer locations to force the sewage to a higher elevation from which point gravity flow can continue. When a sanitary sewer system is flowing full, minimum velocities range from 2 to 2.5 ft/s. Strom sewers generally have a minimum velocity range of 3 to 3.5 ft/s. Therefore, we will use a velocity of 3.5 ft/s to determine the minimum slope required. The minimum velocity is required to prevent deposition of solids on the pipe wall (Menon, 2005).

Since sewer flow is open-channel flow, we can use the Manning equation for calculating the flows and pressure loss in sewer piping. The term slope is used to describe the hydraulic energy gradient in the sewer piping. The slope is a dimensionless parameter or roughness coefficient which depends on the type and internal condition of the piepe. The value of n ranges from 0.01 for smooth surfaces to 0.10 for rough surfaces. For sewer design, a Manning coefficient of 0.013 is generally used and we shall use this value (Menon, 2005). The general form of the Manning equation for open-channel flow is as follows:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \qquad (23)$$

where V = average velocity of flow, ft/s
n = roughness coefficient, dimensionless
R = hydraulic radius = wetted cross-sectional area/wetted perimeter, ft
(for a circular pipe flowing full, $R = (\pi D^2/4)/(\pi D) = D/4$)
S = slope of hydraulic energy gradient, ft/ft

It can be seen from the Manning equation that the slope of the sewer S is directly proportional to the flow velocity. Thus for a given pipe, flowing full, as the flow rate increases, the slope increases. When the pipe is not flowing full, the hydraulic radius R has to be calculated based on the actual wetted area and the wetted perimeter. Figure 5.11 shows a partially full sewer pipe.

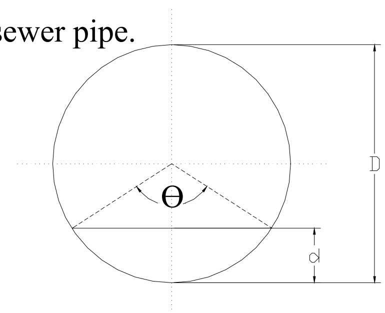


Figure 5.11: Partially full sewer pipe.

It can be seen from figure 5.11 that there is a relationship between the water depth d, the pipe diameter D, and the included angle Θ, as follows:

$$\cos\left(\frac{\theta}{2}\right) = \frac{D/2 - d}{D/2} = 1 - \frac{2d}{D} \qquad (24)$$

The wetted area A is calculated from

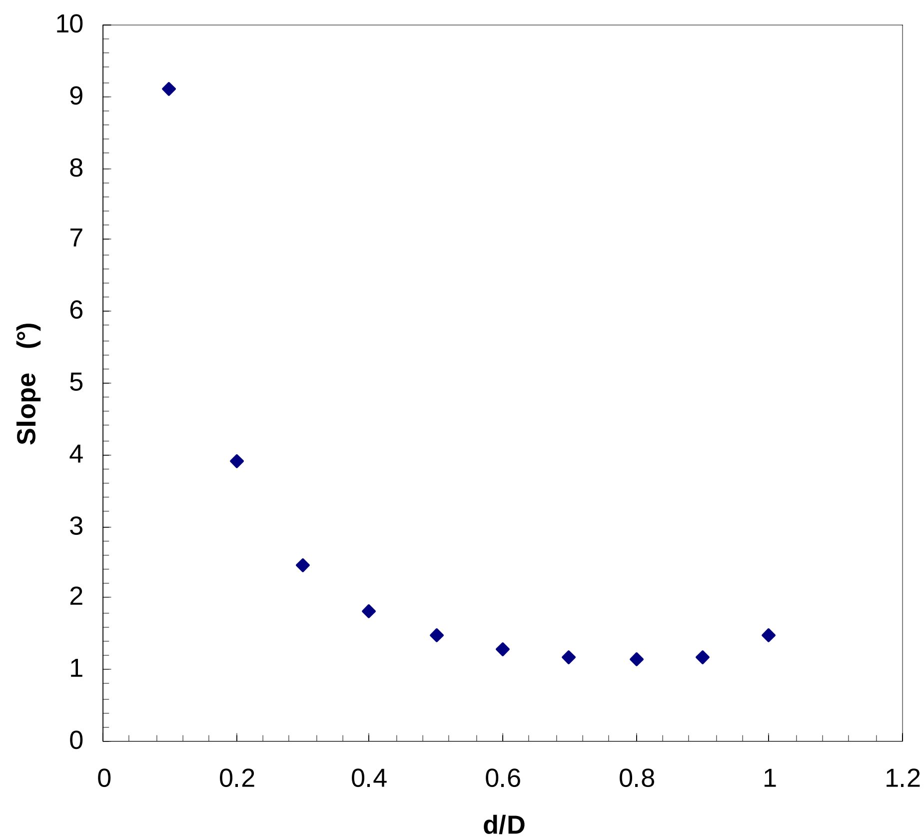
$$A = \frac{\pi D^2}{4}\left(\frac{\theta}{2\pi}\right) - \frac{1}{2}\left(\frac{D^2}{4}\right)\sin\theta = \frac{\pi D^2}{4}\left(\frac{\theta}{2\pi} - \frac{\sin\theta}{2\pi}\right) \qquad (25)$$

$$P = \frac{\theta}{360}\pi D \qquad (26)$$

Finally, the hydraulic radius R for the partially full sewer flow is calculated from

$$R = \frac{A}{P} = \frac{D}{4}\left[1 - \frac{180}{\pi}\left(\frac{\sin\theta}{\theta}\right)\right] \qquad (27)$$

Once the values for the hydraulic radius are found for the different d/D ratios, the required slope can be found by isolation S in equation (23). Figure 5.12 depicts the required angle needed for various depths of water flowing though our pipe. We must ensure the velocity is sufficient for the sewer to be self-cleansing for different. Thus the slope of the sewer must be checked for both full and partly full flow. Our pipe will be designed for the worst case scenario, i.e. when the pipe is running almost empty. According to Manning's equation, the require slope is of 9.1 degrees.



The pipe connecting the toilet to the biogas plant will be four inches in diameter. It will require a slope of 10° to maintain a velocity of 3.5 ft/s. The biogas plant will be approximately 5 meters away from the house or 16 feet approximately. Current prices for 4 inch diameter PVC piping is bds $ 40.24 for 19 feet.

5.4 Digester

The type of digester we opted for is the fixed dome. The fixed dome offers a constant volume in exchange for a constant pressure. The dome has been traditionally constructed out of concrete or ferrocement, but newer materials are being considered. Fiberglass and high density plastics can both withstand the pressures and are affordable. The dome is inconspicuous as it can be almost completely buried. It offers a good degree of the plug flow regime, and there is virtually no interface between the medium and the atmosphere so retention times are noticeably lower than in the floating drum. Leakages are seldom problems with the design. The drawback is that at low gas quantities, the only force that exerts pressure to get the gas to flow is the water column from the compensating tank. This means that at lower gas quantities there might not be enough pressure to get the gas to the stove or consumption point. This is a small price to pay for such an elegant and robust design. Also, agitation of the bulk is hard to accomplish compared to the floating drum.

The material chosen for the construction of the digester was fibreglass. Fiberpol Manufacturing Ltd, a company that operates out of Christ Church, Barbados, has experience constructing custom septic tanks from fibreglass. Traditional materials like concrete and ferro-cement require a technical expert on site, and a fair amount of time must be spent on each project. Fiberglass offers a less labour-intensive alternative and, considering the savings on labour costs is actually cheaper than concrete and ferrocement. Fiberglass can maintain pressures up to 150psi (Voyek, 2005), are watertight, gastight, and resistant to erosion, pests, and the elements. Contracting through a company like Fiberpol allows for mass production of digesters to become possible in the future, if cheap shape to produce and still performs the function.

Mixing

The digester should be completely mixed to ensure efficient digestion. Firstly, the mixing brings the raw influent sludge in contact with actively digesting sludge. It speeds up the digestion that the already existing bacterial population is brought into contact with new substrate. Secondly, the mixing ensures a uniform temperature throughout the digester. And thirdly, the mixing prevents accumulation of grit in the bottom of the digester and the build up of a scum layer on the top. Without a uniform environment in the digester, there would be pockets of sludge not degrading properly, potentially leading to undigested sludge leaving the digester and a decreased digestion rate.

Different types of systems are used, either mechanical mixing systems or gas mixing systems. Most modern plants use gas recirculation systems where digester gas is recirculated to diffuse through the sludge. Mechanical mixing systems are cheaper, but because of the very high cost of taking a digester out of use in case of maintenance or repair, the mechanical mixing systems are not cheaper in use than gas mixing systems. A new mixing system, draft-tube mixers, are energy efficient, and their use is recommended especially for egg-shaped digesters. For a small scale digester such as the one designed in this project, mechanical mixing was preferred over gas mixing for simplicity and cost.

Figure 5.13 depicts the concept for mixing the sludge inside the biogas tank. The mixer consists of a vertical shaft on which are attached metal blades that mimic fan blades. The blades are angled in order to displace more sludge and enhance mixing. On the bottom the shaft is resting on the fiberglass and is free to rotate in a collar. The collar offers sufficient space for sludge to come between the shaft and the collar. The top of the biogas tank is fitted with a bearing to allow for easy rotation and prevent any methane from escaping the tank.

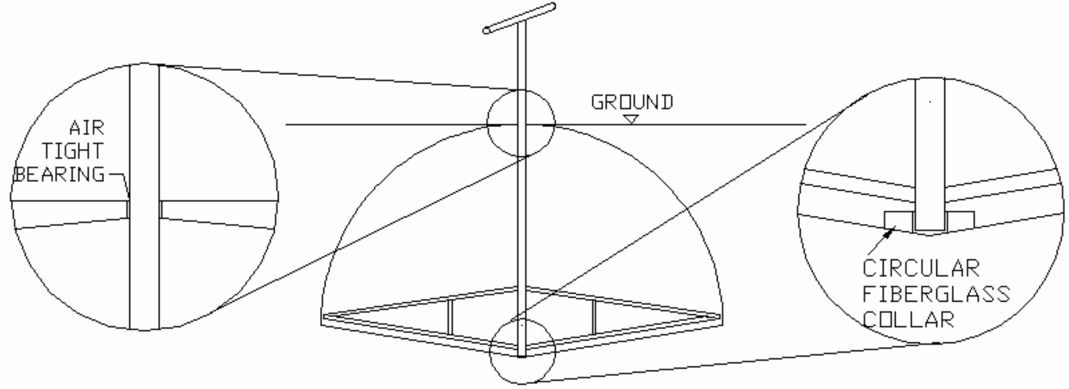


Figure 5.13: Cross-sectional view of the mechanical mixer.

5.5 MATLAB Program

The following section will describe (left column) the MATLAB program (right column).

The program was designed for sizing a plant based on what inputs the operator was planning on using as feed. In this way, the service becomes more universal, and plants can be produced *en masse* with more ease by the manufacture.

This syntax here allows the subfunction at the end of the function able to operate within the same script m-file.

```
% FUNCTION
function ted1 = main()

global Vg Hd

% Biogas Digester Volume Calculations
% User Inputs for Feed
```

User inputs of what animals/crop will be used as feed. Sources of data are from the GTZ text: *Biogas Plants* by Ludwig Sasse, GTZ, 1988.

```
males = input('Enter number of adult males residents\n');
females = input ('Enter number of adult female residents\n');
children = input('Enter number of children Aged between 7
and 14 years old\n');
cows = input('Enter number of cows\n');
pigs = input('Enter number of pigs\n');
horses = input('Enter number of horses\n');
sheep = input('Enter sum of sheep and goats\n');
cropwet = input('Enter daily kgs of crop waste\n');
chickens = input('enter number of chickens\n');

%Wet waste Masses
malewet = (males*170*.005);
```

This portion estimates the waste expected to be input from each of the animals that the user described in the previous section. Sources of waste/animal are (Local Government Engineering Department, Government of Bangladesh, Government of Bangladesh, http://lged.org/sre/Design%20Biogas%20Plant.pdf) and (Sasse ,1988).

```
femalewet = (females*140*.005);
childrenwet = (children*70*.005);
peoplewet = (malewet + femalewet + childrenwet)*.453592;
%[kg]
cowwet = (cows*10.586803);
pigwet = (pigs*3.401943);
horsewet = (horses*16.329325);
sheepwet = (sheep*1.8);
urine = ((males*1.75)+(females*1)+(children*.5)); %[kg]
```

chickwet = (chickens*0.045359);

Summation of all of the feed masses. →

totalwet = peoplewet+cowwet+pigwet+horsewet+sheepwet+cropwet+chickwet+urine; %[kg]

% Dry solids masses

Solid contents of each type of resource feed are estimated here.

maledry = (malewet*.27);
femaledry = (femalewet*.27);
childrendry = (childrenwet*.27);
peopledry = (maledry+femaledry+childrendry)*.453592; %[kg]
cowdry = (cowwet*.19);
pigdry = (pigwet*.21);
horsedry = (horsewet*.35);
sheepdry = (sheepwet*.30);
cropdry = (cropwet*.25);
chickdry = (chickwet*.35);
urinedry= (urine*.005);

Sum of solid contents of total influent. →

totaldry = urinedry+peopledry+cowdry+pigdry+horsedry+sheepdry+cropdry+chickdry; %[kg]

Desired volume for total influent based upon an optimal solid content of 8% as recommended by the Biogas Training Center (LGED, 2005)

influent = totaldry/0.08;

Amount of water that must be added daily to satisfy 8% criteria.

waterallowed = influent-totalwet; %[kg] ~ [L]

Q is the daily flow, calculated by summing up the added water and the amount of raw feed.

The total volume of the digester is the Q value multiplied by the retention time. It was determined that a RT of 40 days is best optimizing gas productivity while also considering material constraints.
Diameter and height are calculated based on the geometry of a hemisphere

```
Q = waterallowed+totalwet; %[L]

Vd = Q*40/1000 * 1.125; % [m3] 1.1 is safety precaution based on the chances of visitors and exceptional circumstances

Dd = ((((Vd)/3.14)*(3/2))^(1/3))*2; % Diameter of the digester

Hd = Dd/2;
```

Amount of gas expected per kg of feed (dry or wet depending on source (Sasse 1988) and (LGED, 2005)

```
% Gas and Energy Equivalent

gaspeople = (peoplewet*65);
gascow = (cowwet*270);
gassheep = (sheepdry*95);
gascrop = (cropdry * 275);
gaschick = (chickwet * 310);
smallbookgaspig = (pigdry*560);
gashorse = (horsedry * 250);
```

Sum of all gas values.

```
gastotal = (gaspeople+gascow+gaspig+gashorse+gassheep+gascrop+gaschick)/1000; %[m3]
```

The gas capacity coefficient of 0.7 is adequate for what typical Bajan uses of the gas would be (ie 3 meals per day) (Sasse 1988).

```
gascap = 0.7; % gas capacity factor p24,
```

Gas storage volume (Vg) is the volume within the digester occupied by gas. It is determine by multiplying the gas capacity coefficient and the total volume.

```
Vg = gastotal*gascap; % [m3]
```

To determine the number of moles we use the conversion at STP for ideal gases of ~40 mol/m^3.

```
% Given, by ideal gas law at expected conditions; 0.04 mol/L

n = 40 * gastotal; %[moles]

% To determine pressure in gasholder use of ideal gas law again
% Over the buildup period of 7 days assuming both the inlet and outlet are clogged and cannot be dislodged at such pressures
```

For safety considerations we use the buildup of gases over 7 days, assuming infinitely clogged inlet and outlet pipes, to determine the pressure at which to set the ERV.

Reuse of the ideal gas law to determine the pressure based on the volume of the gas storage area (Vg) →

```
maxP = 7*n*8.31*300/Vg/1000; % [kPa]  * realistic *
```

For the typical distances of pipelines between a the stove and the digester a water column (WC) of 1.35m will supply sufficient pressure to keep gas flowing to stove at daily low gas content.

```
WC = 1.35; %[m]
```

Use of the 'fzero' function to determine the height at which the gas storage volume begins within the digester volume. See function at end of script.

```
sol = fzero(@myfun1,1); % Must make fzero here to find height at which volume of cap is Vg this will then be Hpipe
```

The compensating tank where the effluent spills over into should have about the same volume as the gas storage volume. The bottom will be situated 0.3m above the line that divides the gas storage volume from the digestion volume. The height of the cylindrical compensating tank will be the difference between the water column height and the 0.3 m already accounted for, however an extra 0.2m will be added as a safety precaution in the event of no removal of the effluent.

```
bottom = sol + 0.3; %[m] bottom of comp tank
height = WC - 0.3;  %[m] Height on comp of pipe
top = bottom+height; %top of comp tank
Hc = height+0.2; %[m] safe height of comp tank to prevent spillover
```

Calculation for radius of compensating tank →

```
Rc = sqrt(Vg/(pi*height)); %[m] radius of comp tank
```

The mass of the solid biofertilizer in the effluent can be estimated based on an assumption of 5% solid matter in the effluent and $Q_{in} = Q_{out}$ →

```
mass = (Vd/40)*0.05*1000 % mass of solid fertilizer in kg, assuming ro_effluent = 1kg/L and dry content ~ 5%
```

```
% Calculations for CN ratio
```

The CN ratios for each type of feed have been gathered from (LGED, 2005).
The full CN ratio expected as a function of the masses of each type of feed will be summed together to determine to overall CN ratio of the influent.

```
CNpeople = 6; %compensated by urine N content as well
CNcow = 25;
CNpig = 13;
CNhorse = 25;
CNsheep = 30;
CNcrop = 40;
CNchick = 5;
```

Total CN ratio of feed CN ratios based on masses of individual input streams.

```
CNratio =
[(CNpeople*(peopledry+urinedry))+(CNcow*cowdry) +
(CNpig*pigdry) + (CNhorse*horsedry) + (CNsheep*sheepdry)
+ (CNcrop*cropdry) +(CNchick*chickdry)]/totaldry
```

Conversions, as used in Chapter 6 to determine the annual energy savings. Based on the following assumptions; 60% methane content in biogas, methane is sole combustible component of biogas, 604.96kJ/mol methane, 40mol of methane per L at standard T&P, monetary conversion is compared to the equivalent energy cost for TexGas (BB$ 0.06/MJ)

```
% Calculations for Annual Energy Savings

methanetotal = gastotal*.6; %60% methane content in biogas
methmoles = methanetotal * 40; % Moles of methane at given T and P
energyday = methmoles * 604.96; % Daily energy from combustion in kJ
energyyear = energyday * 365.25; % Inclusive of leap years
energysaving = energyyear * 0.00006; % $BB 0.06/MJ
```

Output to user of pertinent information
All heights use the base of the digester as the datum point

```
disp ('daily water to add to system (L) =')
disp (waterallowed)
disp ('Volume Digester (m3) =')
disp(Vd)
disp ('Diameter Digester (m) =')
disp(Dd)
disp ('Volume Gasholder(m3) =')
disp (Vg)
disp ('Height of Digester (m) =')
disp (Hd)
disp ('daily gas production (m3) =')
disp (gastotal)
disp ('daily solid fertilizer production (kg) =')
disp (mass)
```

Continued

```
disp ('height at which the carry over pipe should be
input into the digester from the bottom of the digester (m) =')
disp (sol)
disp ('height at which the bottom of the compensating tank will
be set from the bottom of the digester (m)')
disp (height)
disp ('height at which the bottom of the compensating tank will
be set (m)')
disp (bottom)
disp ('height of cylindrical compensating tank (m)')
disp (Hc)
disp ('radius of cylindrical compensating tank (m)')
disp (Rc)
disp('maximum pressure at which to set the ERV (kPa)')
disp(maxP)

disp ('annual energy savings (BB$) =')
disp (energysaving)
```

Program checks to make sure the calculated CN ratio is within the adequate range.
It checks to see if its below 20
If so it will tell the user to rerun the program with added crop waste.
It then checks to see if it is above 30
If so it will tell the user to rerun the program with removed crop waste.

```
if (CNratio <20)
 fprintf ('CN ratio is %2.0f and is too far below recommended
range of 20-30. Add more cropwaste to compensate and rerun
the program with the new inputs',CNratio)

elseif (CNratio >30)

   fprintf ('CN ratio is %2.0f and is too high above
recommended range of 20-30. Remove some of the
crop waste to compensate and rerun the program with the new
inputs ',CNratio)

else fprintf ('CN ratio is %2.0f', CNratio)

end
```

The function which is used to determine the height at which the volume above is equal to Vg.
Explanation of derivation is as follows:

```
                 ******    |    ******
cap
              ***         h|         ***

            **-------------+-------------** ----------
          ** \             |      c      / **
         *     \           |           /     *           sector
        *        \         |         /         *
       *           \    r-h|       /             *  cone
      *              \     |     /  r             *
      *                \   |   /                  *
     *                   \ | /                     *
     *                     + --------------------*-------------
     *                                             *
      *                                           *
      *                                           *
       *                                         *
        *                                       *
         *                                     *
          **                                 **
            **                             **
              ***                       ***
                 ******          ******
                       *********
```

```
           = 1/3 pi h [2r^2 - 2r^2 + 3rh - h^2]
           = 1/3 pi h (3rh - h^2)
Rearranged to
V_cap = 2/3 pi r^2 h - 1/3 pi (2rh - h^2)(r - h)
           = 2/3 pi r^2 h - 1/3 pi (2r^2h - 3rh^2
+h^3)
0 = [(pi*h)/3]  *[(3*Hd*)-(h^2)))-Vg]
```

Values of h are solved for and they represent the height at which the gas storage volume starts and 0.3m above which the bottom of the compensating tank is set.

```
function zz = myfun1(x)
%height of liquid layer in digester
global Hd Vg
zz =(((pi*x/3)*((3*Hd*x)-(x^2)))-Vg);

%Reference for function zz: Dr. Peterson, 2000,
http://mathforum.org/library/drmath/view/55253.html
```

MATLAB Scenario Inputs & Outputs

Inputs

Enter number of adult males residents
5
Enter number of adult female residents
5
Enter number of children Aged between 7 and 14 years old
0
Enter number of cows
0
Enter number of pigs
0
Enter number of horses
2
Enter sum of sheep and goats
0
Enter daily kgs of crop waste
2
enter number of chickens
0

Outputs

daily water to add to system (L) =
109.9312

Volume Digester (m3) =
7.2835

Diameter Digester (m) =
3.0306

Height of Digester (m) =
1.5153

Volume Gasholder(m3) =
2.2565

daily gas production (m3) =
3.2236

daily solid fertilizer production (kg) =
9.1044

height at which the carry over pipe should be input into the digester (m) =
0.7538

height at which the bottom of the compensating tank will be set (m)
1.0538

height of cylindrical compensating tank (m)
1.2500

radius of cylindrical compensating tank (m)
0.8271

maximum pressure at which to set the ERV (kPa)
997.2000

5.6 Gas Considerations

As mentioned previously, a fixed-dome plant consists of an enclosed digester with a fixed, non-movable gas space. When gas production starts, the gas pushes the slurry in the compensating tank. Gas pressure increases as the volume of gas increases; therefore if there is little gas in the holder, the gas pressure is low. An issue which is raised by this type of plant is high pressure inside the tank. If for some reason the pipe allowing the slurry to flow out of the tank into the compensating tank is clogged, high pressures inside the tank become a problem. For this reason, we must design an alternate outlet for the excess pressure to evacuate the gas inside the tank. Figure 5.14 shows one concept for a release valve for the methane.

The first concept is quite simple. When sufficient pressure builds up in the tank, it will push the ball which is resting on a funnel shaped cylinder up a little. This tiny displacement will allow the excess gas to exit the chamber. When the pressure re-establishes itself, the ball will fall back into place, sealing the hole and preventing any leaks. The funnel is covered and there is a vent on the side to allow the gas to escape. This cover keeps rain and water out of the funnel and out of the digester.

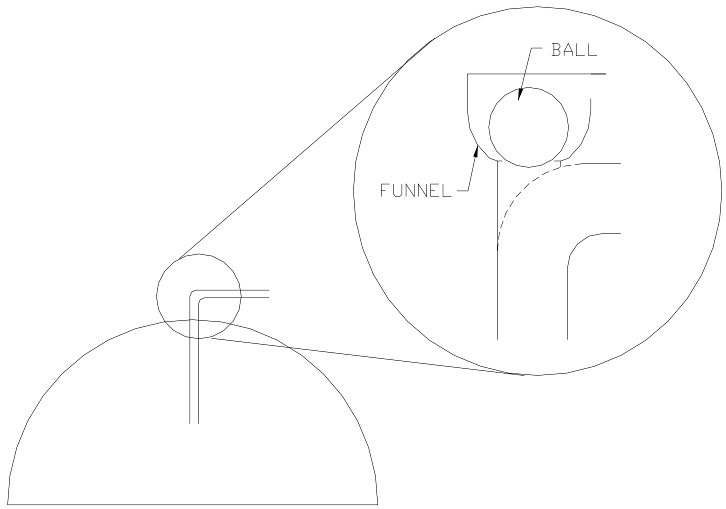


Figure 5.14: Ball and funnel idea for pressure release.

The ball must be designed based on the critical pressure. This was determined to be 1 MPa : it was obtained by calculating the amount of gas in the reactor after one week if no gas was able to escape. A free body analysis of the ball shows that when the critical pressure is reached, the weight of the ball (mg) is equal to the force pushing up on the ball. This for is simply the pressure inside the tank acting on the bottom surface area of the ball (FA). The area the pressure is acting on is the two inch pipe the ball would be resting on.

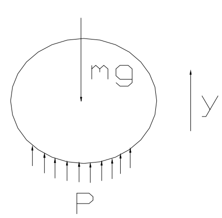


Figure 5.15: FBD of the ball.

The forces applied on the ball in the vertical direction are:

$$\sum F_y = 0 \;\therefore\; mg = F = PA \qquad (28)$$

$$P = 1MPa = 1000000\, N/m^2 \;\therefore\; F = PA = 1\times10^6\left[\frac{N}{m^2}\right]\cdot\frac{0.05^2}{4}\pi\left[m^2\right] = 625N$$

$$m = \frac{PA}{g} = \frac{625\left[kg\cdot m/s^2\right]}{9.81\left[m/s^2\right]} = 63.7\,kg = 140.5\,lbs$$

Therefore, we would need a 2 inch diameter ball to weigh 140 pounds. Let's consider a steel ball of the same dimension, with a density $\rho = 7.85\,g/cc$. The volume of the ball is $V = \frac{4\pi r^3}{3} = \frac{4\pi(2.5)^3}{3} = 65.4\ cm^3$. The weight of the ball is $w = \rho V = 7.85\left[g/cc\right]\cdot 65.4\left[cc\right] = 513.4\,g \approx 0.5\,kg$; no where near the required weight. Therefore, this option is not viable.

Another option to prevent excess pressure from building in the tank is having a clap on the end of the tube. Figure 5.16 shows the clap attached to the extremity of the pipe. The clap is free to rotate freely about its hinge. Only its weight is keeping it shut. Gaskets on the outer edge of the clap prevent any gas from escaping during regular operation.

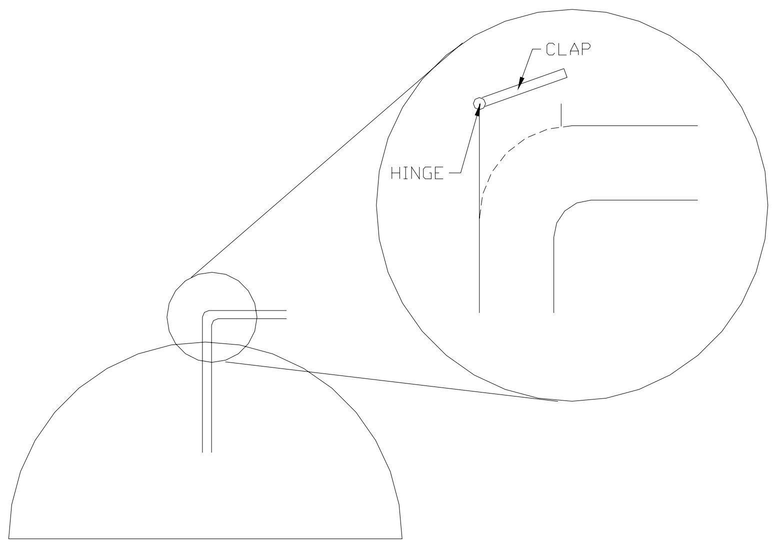


Figure 5.16 : Clap design.

Figure 5.17 shows the free body diagram of the clap. We notice that the moment taken about point O equals to zero when the weight for the clap equals the critical pressure, or when mg = FA.

The free body analysis of the clap, shows that once again the weight of the clap must equal upward force created by the pressure. We have seen previously that this requires the mass of the clap to be 63.4 kg, which is impossible.

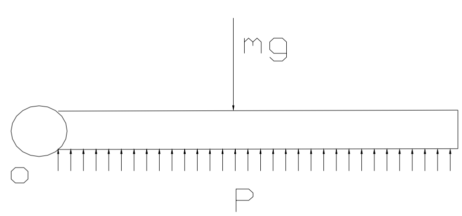


Figure 5.17: FBD of the clap design for releasing excess methane.

$$\sum M_O = mg\,{}^{L}\!/_{2} - F\,{}^{L}\!/_{2} \quad \therefore \quad mg = F = PA \qquad (29)$$

To resolve this problem we must add a rotational spring at the hinge which acts as a moment at point O. The new FBD and sum of moment equation becomes:

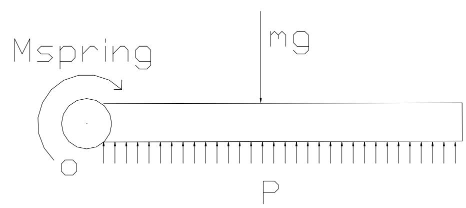


Figure 5.18: FDB of clap with a rotational spring located at the hinge.

$$\sum M_O = M_{spring} + mg\,{}^{L}\!/_{2} - F\,{}^{L}\!/_{2} \qquad (30)$$

$\therefore M_{sping} = F\,{}^{L}\!/_{2}$, since the mass of the clap is negligible

$M_{spring} = k\theta \rightarrow F\,{}^{L}\!/_{2} = PA\,{}^{L}\!/_{2} = k\theta$, Θ has been chosen to be 3°

$$\therefore k = \frac{PA\,{}^{L}\!/_{2}}{\theta} = \frac{1\times10^{6}[N/m^{2}]\cdot\pi(0.025)^{2}[m^{2}]\cdot 0.025[m]}{0.05rad} = 981.7[N\cdot m]$$

This means we need a rotational spring with a spring constant equal to 981 Nm. When the pressure reaches 1 MPa, the clap will open 3 degrees, enough to release the excess gas in the chamber.

5.7 Alternatives

In case of an emergency and the reactor can no longer accept more waster water, there has to be an alternative. Figure 5.19 shows what would happen if the digester stopped functioning for some unknown reason. All that has to be done is turn the valve and allow the waste water to fall into the storage tank. It is important to note that this is only a temporary solution while the digester is being fixed. Once the reactor is back in running order, the valve may be pushed back to its original position allowing the wastewater back into the biogas plant.

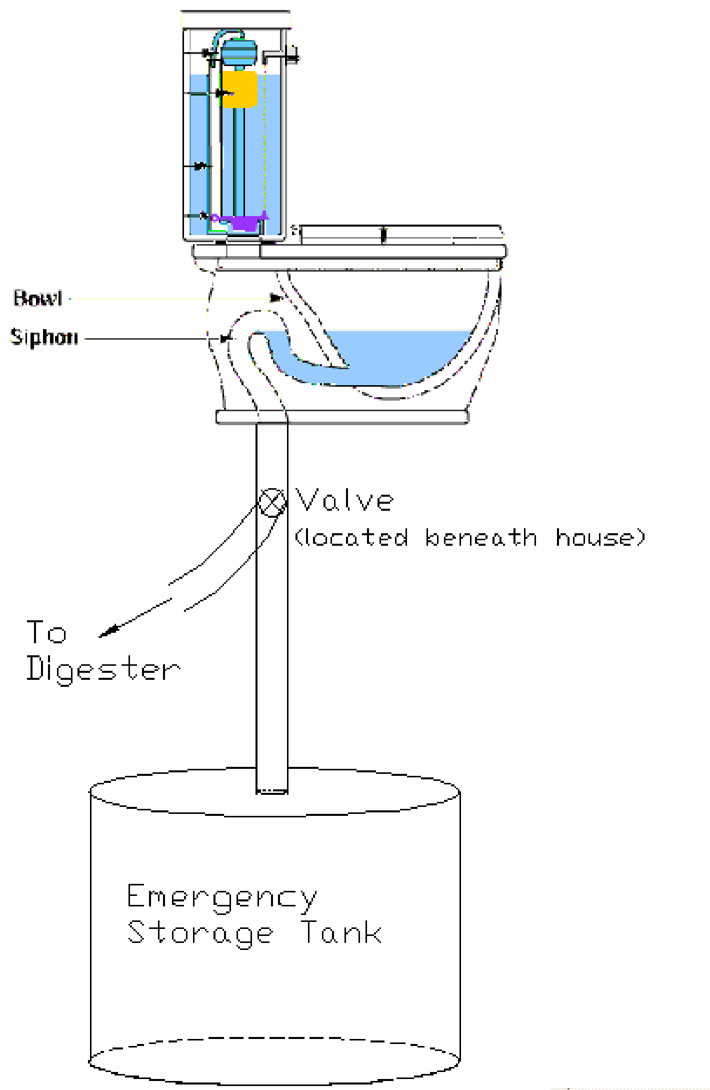


Figure 5.19: Emergency waste water collection mechanism.

Chapter 6: Economics

Economics is an important aspect of the evaluation of the feasibility of the system and its widespread use. Often the most difficult problem with implementing greener technologies is the cost involved in the construction of the equipment. Engineering is working within the monetary constraints to develop a system that performs the desired function without being economically detrimental to the country or the people. Hugh Sealy of the National Commission on Sustainable Development desired that the system cost less than BB$ 10 000. This was found to be not only very possible, but indeed pay for itself in less than 3 years.

6.1 Micro-level Analysis

Capital Expense

	Material	Specifications	Quantity	Price/unit	Price (Bd$)
Digester (option #1)	Bricks	4"*16"*8"	500 bricks	1,07$/bricks	535
	Cement		28 bags	18$/ bag	505
	Stone		2,24 m3	75$/m3	225
	Sand		2,38m3	70$/m3	210
	Coarse sand		2,38 m3	75$/m3	225
	Steel rods		15Kg		250*
	Labour		2 Missions	$800/mission	1600
	Total Digester				3550
Digester (option #2)	Fiberglass Tank		6m3		4000
Pipes	Gas pipe	1/2 inch PVC	196 ft	6.44$/ 19 ft	67
	Toilet pipe	4 inch PVC	196 ft	40.24$/ 19 ft	415
	Manure pipe	8 inch	19ft	130.22$/19ft	130
Rainwater Collector	Gutters	4 inch PVC	80 ft	18$/10ft	145
	Tank	Polyethylene	600 Gal		1130
Toilet	Water pipe	4inch PVC	19ft	40.24$/ 19 ft	40
	Toilet adaptor				300*
Stove	Stove adaptor				100*
Extra material	Nails, fitting,				500*
Total (option #1)					6375
Total (option #2)					6825

Table 6.1: Estimated cost of material for Biogas digester pilot project

* inferred estimation

In able to implement the biogas wastewater system described, resources and support need to be found. The National Commission on Sustainable Development has shown interest in supporting the project and possibly financing a pilot project. The table below represents an estimation of cost analysis. The budget analyzes a hemispherical, fixed-dome model, sized based on the outputs generated from the MATLAB program (section 5.5) for the expected inputs tp be used as feed. The rainwater collection, the toilet and the stove are sub-elements of the biogas reactor. The price analysis takes into consideration the whole system and labour.

There is a justification to lower the cost of the project and encourage reuse and recycling within the construction phase. Reused materials or excess, available material will be used if available. For example, gutters can be made from bamboo or other naturally occurring materials. However, for the sake of replication the cost stated was that of purchasable, standard material found in local store such as Semsco, Fiberpol, and Dacosta Mannings, and Trinidadian company Rotoplastics.

The digester can be designed and built using different materials. In the choice of the design, various factors need to be taken into account. The overall success of the design will depend on its economic, environmental and technical efficiency. The essence of appropriate technology is that equipment and techniques should be relevant to local resources and needs, to feasible patterns of organization and to the local environment. For our design, 2 options have been taking into consideration.

The first design is a traditional fixed-dome digester used in India and some Caribbean islands such as Guyana and Jamaica. We believe this design would not be the most suitable for the project because building the dome shape from bricks requires skill and costly labour and the material is not economical. Although, the design has proven to be successful in the past and it is replicable. Concerning labour cost of the option #1, skilled labour and supervision is needed to build a dome out of cement blocks. The Caribbean

Development Bank (CDB) offers the services of a biogas reactor professional to lead and supervise the construction at a subsidized rate of $BB 800 per 15-day mission. It will be assumed that no other labour is necessary other than the labour of the beneficiaries. It is estimated that 2 missions will be required to complete each system.

Digester options #2 is an innovative design. It is essentially a custom designed septic tank. The fibreglass tank (#2) can be custom made from Fiberpol, a manufacturing corporation based in Barbados. We have met with James Eldridge, a representative of Fiberpol, he is very interested to the whole project. The price he gave us is for a pilot project and no profit will be made out of this project. This is the most appropriate design.

The rainwater harvesting system can be constructed from tree-materials and used drums or barrels if available, and with adequate filtration.

Special toilets may have to be used in order to keep the ration between solids and water at an ideal state for biogas production to occur. Low flush toilets or other designs are often more expensive than conventional water closets. Ergo, the additional cost of the special toilet compared to a conventional toilet is an added cost of the project.

Most stoves have a manually adjustable regulator know to alter the ration between the air and gas for combustion. If it happens that there is an additional cost associated with such stoves vs. conventional stoves then this difference would be another added cost to the project.

Also, members of the student-team are prepared to come back for the months of May-August 2006, assuming they can find enough funds. They are interested in helping the coordinate the construction and implementation of the project. Using the fiberglass design, cost for manual labour should not be much. The price included with the fiberglass tank includes the construction time.

Monetary Benefits

To give an idea of what the savings will be on the system per annum we will evaluate:

I) Energy
II) Fertilizer
III) Water

For the system implemented based on 5 males, 5 females and 2 horses as input.

I) Energy

From the MATLAB program (Section 5.5), data based on literature for expected gas produced from the inputs yields a daily volume of gas produced. Estimating a methane content of 60% in biogas and an enthalpy of combustion of 604.96 kJ/mol for methane, table 6-1 can be completed.

Daily Gas Produced	3155 L
Daily Equivalent Methane	1893 L
Number of moles methane at STP	76.44 mol
Daily Energy Equivalent	**46 243 kJ/day**

Table 6.2: Energy equivalent.

To get a monetary value of the biogas, comparing it to a commodity typically used for cooking fuel, TexGas, is suitable because most of the population of Barbados uses TexGas for cooking. TexGas is composed of 30% propane (50.36 kJ/g) and 70% (49.15 kJ/g) butane.

TexGas Rate	$BB 2.97/kg
TexGas Energy Content	49 500 kJ/kg
Texgas Rate per Unit Energy	**$BB 0.06/MJ**

Table 6.3: Gas rate.

Converting the energy produced by the methane in the digester into terms of the cash cost of the equivalent cost of TexGas to supply the same amount of energy is described in Table 6-3.

Daily Energy Savings	**$BB 2.77/day**
Annual Energy Savings	**$BB 1012.72/year**

Table 6.4: Energy Savings.

II) Fertilizers

From the MATLAB program the daily volume of effluent generated was calculated based on literature data (Section 5.5). Estimating an effluent water content of 95% and a density equal to that of water it is possible to determine the daily solid biofertilizer produced.

Daily Volume of Liquid Effluent Generated	180 L/day
Water Content of Effluent	95%
Density of Effluent	1 kg/L
Daily Mass of Solid Fertilizer Produced	9 kg/day

Table 6.5: Mass of fertilizer.

DaCosta Manning is the primary supplier of fertilizers for small farmers. According to, unfortunately the most recent, 1989 Barbados Agricultural Census (Table 52A) the most commonly used fertilizer, especially among smaller farmers is 12:12:17:2 (12%N 12%P 17%K 2% Mg) fertilizer, its pricing are described in table 6-5.

Price of Commercial Fertilizer (bag)	$BB 4.73 for 2.00 kg
Price of Commercial Fertilizer (per kg)	$BB 2.365/kg

Table 6-6: Inorganic Fertilizer cost.

To estimate the price of the biofertilizer produced, the nutrient value can be utilized to equate the quality of it to that of conventional fertilizer. Of course nutrient content of the effluent will vary depending on such factors as feed material and frequency/intensity/duration of agitation. The literature/experimental figures give the following numbers which we will assume are adequate in this case.

The GTZ conducted a study on the Hoad Digester's effluent quality in the 1980s. At the time the digester was fed with cow manure. As well, a test for orthophosphates in the Hoad digester was carried out by the Bellairs Research Institute in 2005 to help determine the phosphorous content of the effluent.

Test	**Details**	**Content**
Nitrogen Content	GTZ, 1986, cow manure	2.5%
Phosphorous Content	Bellairs Reseatrch Institute, 2005 *inter alia* horse manure	1.4%

Table 6-7: Nutrient Analysis of Biofertilizer

Taking the averages of the phosphorous and nitrogen rations between the biofertilizer and the commercial fertilizer a rough estimate of the quality comparison between the two can be created. From this a price equivalence can be calculated.

Ratio of Biofertilizer to Commercial Fertilizer	2:12
Price of Biofertilizer	$BB 0.394/kg
Daily Fertilizer Income	**$BB 3.5475/day**
Annual Fertilizer Income	**$BB 1295.72/yr**

Table 6.8: Biofertilizer Economics

III) Water

Because the digester was designed on the basis of 10 people using it for their wastewater, the amount of water used to carry their solid waste is, at the minimum, the amount of water they save having to pay for. Table 6-8 outlines the water savings in monetary terms.

Average Flushes Per Person	2
Volume of water per flush	4 L/flush
Daily Water Consumption of Toilet	80 L/day
Price of Water	$BB 2.10/m3
Daily Water Savings	**$BB 0.168/day**
Annual Water Savings	**$BB 61.36/yr**

Table 6.9: Water Savings

IV) Total Savings and Total Savings per head.

Summing up the savings from each of the three categories, the total yearly savings of the system is outlined in Table 6-9.

Total Daily Savings	**$BB 6.49/day**
Total Annual Savings	**$BB 2369.80/yr**
Total Annual Savings per Head of Household	**$BB 236.98/yr per person**

Table 6-10: Total Savings

6.3.2 Overall Analysis

Capital Expenditure	BB$ 6825
Annual Income Equivalence	BB$2369.80/yr
Payout Period	2.88 years

Table 6-11: Overall Economic Analysis

This evaluation assumes that the plant is operating and productive at all times, which is not always the case. There is also a startup time of ~40 days before gas the gas can begin to be utilized.

Chapter 7: Recommendations

Recommended Evaluation Procedure

The present situation of the project is that the Commission on Sustainable Development, represented by Hugh Sealy, in conjunction with Travis Sinclair, the Chief Environmental Officer, will be evaluating our proposal and deciding whether to include the project into their Budget for 2006. Assuming all goes well, they will, in cooperation with the beneficiaries, construct the project in 2006. Our proposal also includes methods for evaluating the success of the project over the next few years. We recommend they scrutinously monitor the project with both our criteria and new criteria defined by people more attuned to local concerns. Depending on how the project is evaluated it will be the Commission's decision on how to proceed with more widespread dissemination of biogas plants across Barbados. But, in either the event of a 'failure' or 'successful' outcomes we recommend some other considerations for the potential of biogas in Barbados that future students at the Bellairs Research Institute can look into.

Arguably, the most important aspect of this project will be determining if it is or is not a success. Gauging its degree of success will determine what kind of role it will have in Barbados' future.

The Criteria for considering the pilot project 'successful'.

- Positive social reaction to 'humanure' concept
- Useful function of biofertilizer
- No contamination of crops by use of biofertilizer
- General contentment of beneficiaries and positive effect on their quality of life
- Technical success
    - Minimal 'downtime' (<5%)
    - Sufficient gas production (>80% expected)
    - Minimal signs of degradation

In order to measure some of these factors some methods need to set in place. For example, for each time the system is 'shut-down' for repairs, the duration for which it was offline must be recorded scrupulously. Any sales of the biofertilizer, or amounts administered to cropland should also be recorded. The beneficiaries should be surveyed once every 3 months for comments on issues relating to the plants technical performance and their sentiments towards how it has impacted their quality of life. Technicians should also inspect the condition of the equipment once every 3 months to monitor how the equipment is weathering the elements.

Future Research/Projects

There are a variety of potential futures for Barbados that biogas digesters can play a role in. Replications of the design produced, for single family homes with livestock, could be made widespread. However a number of obstacles will need to be addressed first. The The costs are generally unaffordable for the targeted population. The government could conceivably make contracts with Fiberpol and other equipment suppliers that would reduce marginal costs through economies of scale. It would be interesting to test the robustness of the design to determine how feasible it would be to mass-produce a certain number of specific sizes. The MATLAB program could be used to determine which pre-made size best fits the optimal size description. If the concept works without malfunction, then custom-fit digesters would not be necessary, and costs would be brought down tremendously. The government could also offer special credits for financing and/or allow for special conditions on loans for biogas plants (ie taking livestock as a collateral), possibly through some sort of Agricultural Development Bank. Market forces could also play a role if the government were to promote research in the field of biogas, entrepreneurship in the area could thereby increase competition and lower prices. The next obstacle is more difficult to change. The lifestyles of the targeted group must be ones such that the inputs will be consistent and managed strictly, ones that are stable and sedentary, and ones that accommodate for time spent tending to the digester.

Another possible future places less reliance on the individuals and more on the state. By incorporating larger, community scaled, digesters the state (or potentially private enterprise) can operate the plants. The economics of larger digesters will also allow for more treatment techniques that will prevent potential problems and make the process more efficient. For example a simple separation technique could account for excess water being input into the system. Also, the lifestyles of the people need not accommodate for as much time being devoted to the upkeep of the system, instead government employees can be hired to maintain and service the equipment. People will still need to manually input their livestock manure into the digester, and regulations will need to be abided by so that the authorities know exactly what is going into the system.

First and foremost there are some potential design considerations that could drastically improve the productivity of the system that we have not had adequate time to evaluate but deserve assessment in the future. These are;

- heating of the digester through solar or geothermal means so as to maintain an environment conducive to the growth of thermophilic methanogens
- the incorporation of a solar drying bed into the system, wherein from the compensating tank the effluent will spillover into a shallow tank with a large area where the water can be evaporated to produce a solid fertilizer free of biological contaminants.

Should the case that methane emissions are reduced by using biogas technology be proven, then anaerobic digestion systems could be considered 'carbon sinks' in the Kyoto Protocol. For every ton of methane not released into the atmosphere, they could obtain ~22 carbon credits which then could be sold to developed nations in exchange for money. This money could go towards subsidizing or promoting the construction of more biogas plants. This is another example of a positive feedback scenario that would benefit Barbados in multiple ways.

There is much to be learned from the experiences of those Barbadians who currently own or have owned biogas digesters in the past. There is the potential to collect information and compose a report of their 'best-practices' and how they dealt with problems they encountered with their systems. It will be very beneficial if the 2nd generation of biogas digesters don't fall victim to the same mistakes made in the 1st generation. The owners give a negative impression on the idea of a symposium or group meeting, however they generally don't seem to mind presenting a written report themselves or being interviewed (however we found it difficult to comprehend their statements due to language barriers).

One of the recommendations that both Richard Hoad and Gay Reed mentioned was the creation of a biogas digester at the C.O. Williams Dairy Farm in Waterhall could be great for the community. The cows' stalls are already set up so that manure is easy to be collected, and the scale of gas production could be enough to provide cooking gas for the entire community.

Another approach would be to investigate the potential in the industrial sector. The Bacardi rum distillery in Puerto Rico has had success in implementing an anaerobic digester to treat the liquid waste from the distillery. The same success could be replicated in the Mount Gay or the Malibu distilleries, the Banks brewery, and/or local fruit juice manufacturers.

The Caribbean Development Bank holds copies of the reports generated by the GTZ. Their final study was published in 1989, summarizing their major findings. It could be worthwhile to repeat their evaluations of the biogas plants, now 16 years later, to see if their conclusions still hold. Evaluation from economic as well as environmental, social, and technical standpoints of all of the biogas plants that have been constructed in Barbados will be helpful in determining what constitutes an effective design and what improvements in the implementation process lead to more successful use of the plant.

Any of these recommendations could be potential projects for future students at the Bellairs Research Institute to explore. But there must be some initiative from either an NGO or governmental institution to push forward this technology. Dr. Ronald Gehr describes the need for a 'local champion' to endorse the technology and make changes happen from within the boundaries of the country. Without careful consideration and implementation of the work students do, their could be not fruition of their plans, and without guidance from a permanent and overseeing institute, the work the students do could be frivolous and unheeded.

Social Difficulties to be Tackled

There are some social hurdles that must be overcome if biogas is to become a viable and widely accepted part of Barbadian society. Firstly, people must come to grip with the fact that biogas is not a 'third world' technology. It may be old, but considering that the world must change its attitudes towards energy production and use it is actually a progressive step that more wealthy countries are using too. Secondly, people should accept the fact that human excrement is not much different than animal manure and it can be treated in the same manner. Irrigating land with treated human feces, a similar process as utilizing a composting toilet, should not be considered a social *'faux pas'*. Biogas is a great example of how wealthier nations are not good role models for the developing world. Countries like India, Nepal and China are smarter for using such a technology and more nations should look to them for guidance in the field, not the irresponsible west. This change in ideologies should be explained to the rural farmers, along with the personal and environmental benefits of using biogas.

What may need to be considered is a forum in which representatives from all stakeholder camps get together to discuss the potential and come to an agreement on how the technology should be implemented into Barbadian society. BANGO [Barbados Association of Non-Governmental Organizations] representative Roosevelt King believes that grassroots campaigns are often the ones who fill the void left by government and the private sector, including in the realm of renewable energies. There is a degree of interest at all levels, but whether the acceptance of the responsibilities that parallel the benefits of installing biogas plants is present is still questionable. The successful widespread implementation and use of biogas systems has the potential to solve a variety of issues that face Barbados today. But, as the government does not hold a position that instigates change, and the private sector does not seem to be selling any designs of the technology, it appears that King is correct; grassroots groups must change themselves first and force the larger players to take notice. BANGO could assist in getting their message out, and publicizing the progress that they are making. If there is enough development that the government does see the potential, they could begin to make incentives for using the technology, much as they do with solar panels. This cycle of positive feedback could lead to a more sustainable future in Barbados, both environmentally and economically.

Chapter 8 Conclusion

Barbados is a scientifically ideal location for biogas technology. The environmental benefits provided by biogas technology are necessary steps towards a sustainable future. Biogas technology creates an economical boon out of what people currently categorize as wastes. There is a history of biogas in Barbados, from which many lessons have been learned and much experience can be gained for the future generations.

The designs provided in this report, compliment the economic, environmental and scientific findings to make biogas an even more feasible and accessible technology to the Bajan people.

There is a lot of work yet to be done to make widespread biogas use a reality in Barbados. The first step is acquiring funding for the pilot-project, but the end result could be global use of the biogas wastewater systems with Barbados as a leader in the area and a role model for both the developed and developing nations of the world.

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Appendix A:
Interviews, Meetings and Consultations all through the Project

Date	Location	With Whom Meeting Held	Purpose of Meeting
Sept. 12	Coral Reef Hotel, Holetown, St-James	Sam Nielands, New Water Inc Environmental Engineer	To learn about small scale tertiary wastewater treatment plant.
Sept. 19	Bridgetown Wastewater Treatment Plant, Bridgetown, St. Michael	Mr. Lowe, tour guide and operator	To receive an overview of the facilities and operations of a secondary wastewater treatment plant.
Sept. 20	South Coast Wastewater Treatment Plant, Chris Church	Mr. Joseph Griffith, Operations manager and Mr. Luther, Chief Engineer	To learn about different wastewater treatment plant facility implemented in Barbados.
Sept. 20	Christ Church	Peter Gittens	To talk about the possibility of designing small scale wastewater biogas reactor for his future house.
Sept. 26	Bellairs Research Institute, Holetown, St. James	Dr. Gisela Frias	To discuss about incorporating the concept of Globalization in the final project report and discuss about some interview techniques.
Sept. 27	Household of Richard Hoad, St-Andrew	Richard Hoad, Biogas digester owner	To learn about his biogas digester system and discuss about our design.
Oct. 3	Future Center,	Handel Callender, Biodisel producer	To talk about his experience on the implementation of an eccentric project in Barbados. Difficulties encountered.

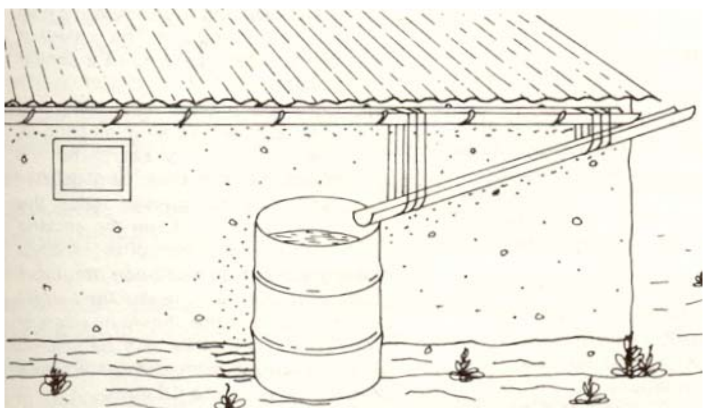
Date	**Location**	**With Whom Meeting Held**	**Purpose of Meeting**
Oct. 10	Hilton,	CWWA Conference (Caribbean water and wastewater annual conference)	Discussing about our design to different member of the conference. Learning about other wastewater treatment technology.
0ct. 17	Caribbean Development Bank, Pine….	Jerome Singh, Project Manager	To discuss past and present biogas digester projects in Barbados and the rest of the Caribbean.
0ct. 18	Classroom, Bellairs Research Institute, Holetown, St. James	Dr. Bonnell, professor for the BFSS internship project	To discuss progress to date and any problems encountered; to ask for advice & recommendations
0ct. 19	Classroom, Bellairs Research Institute, Holetown, St. James	Hugh Sealy, Sustainable Development Commission Director	To discuss about our design and procedures involved in the implementation of a pilot project.
0ct 21	Classroom at Bellairs Research Institute, Holetown, St. James	Mid-term progress presentation with Colleagues and Professor Bonnell	To present the progress and future goals of the project. Gathering feedback from colleagues and Professor Bonnell.
Oct 25	Classroom, Bellairs Research Institute, Holetown, St. James	Travis Sinclair, Senior Environmental Officer, Minister and Hugh Sealy, Sustainable Development Commission Director	To presented our project and look at the visibility of getting funding from the Sustainable Development Commission for the implementation of a future pilot project.
0ct. 31	Manning Hardware Store, Speisthown		To get material prices.

Date	Location	With Whom Meeting Held	Purpose of Meeting
Nov. 3	Client Household Bathsheba, St. Joseph	Peter Gittens, Anthony	To present our primary design and gather feedbacks.
Nov 7	Classroom, Bellairs Research Institute, Holetown, St. James	Nicole and Handel Callender, Future Center	To discuss about the Energy Day exhibition that will be held in Bridgetown.
Nov 14	Classroom, Bellairs Research Institute, Holetown, St. James	Mr. James Eldridge, Fiberpol Manufacturer	To discuss the cost of a fiberglass tank.
Nov. 18	Independent square, Bridgetown	Energy Day	To present to the general public and various organizations our Small Scale Biogas Wastewater Digester system.
Nov 21	Pig Farmer, Rock Hall, St. Thomas	Gay Reed	To visit a large scale, canal style biogas digester
Nov. 21	Resident/Pig Farmer St. Simon's, St. Andreww	Mary Moore	To visit a small scale, floating drum biogas digester.
Nov. 22	Household, St-Andrew	Graeme Reeves, Future owner of Eco House	To Discuss the possibility of having a biogas digester that would be feed with chicken manure and that produce gas for melting the wax of his candle business.

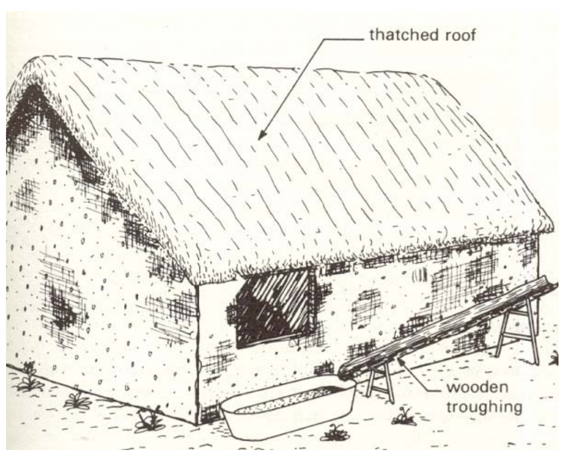
Date	**Location**	**With Whom Meeting Held**	**Purpose of Meeting**
Nov. 22	Pilot project site, St-Andrew	----	Site visit and rainwater sample taken from the existing rainwater harvester. Analysis of the water will be conducted.
Nov 25	Hoad Digester, Morgan Lewis, St. Andrew	Richard Hoad	Collect sample for tests and discuss opinions on biogas educational programs.
Dec. 5	Ministry of Agriculture, Planning Unit Top Rock, Christ Church	Emiline Marcus-Burnett Economist	To collect agriculture census data for macro analysis.
Dec. 7	Bellairs Research Institute Classroom	Dr. Robert Bonnell	Conclude project details.

Appendix B: Alternative design for rainwater harvesting

(Pacey. A. & Cullis, 1986)



(Pacey. A. & Cullis, 1986)



(Pacey. A. & Cullis, 1986)

Appendix C: Barbados Energy Day, Nov 18, 2005 Presentation.

On Nov 18, 2005, we had the opportunity to partake in the Barbados National Energy Day in Hero's square, Bridgetown. We shared a display stall with Counterpart Caribbean, with Handel Callender et al. This was a good event to get the word out on renewable energies, and show other people in the field some of our findings.

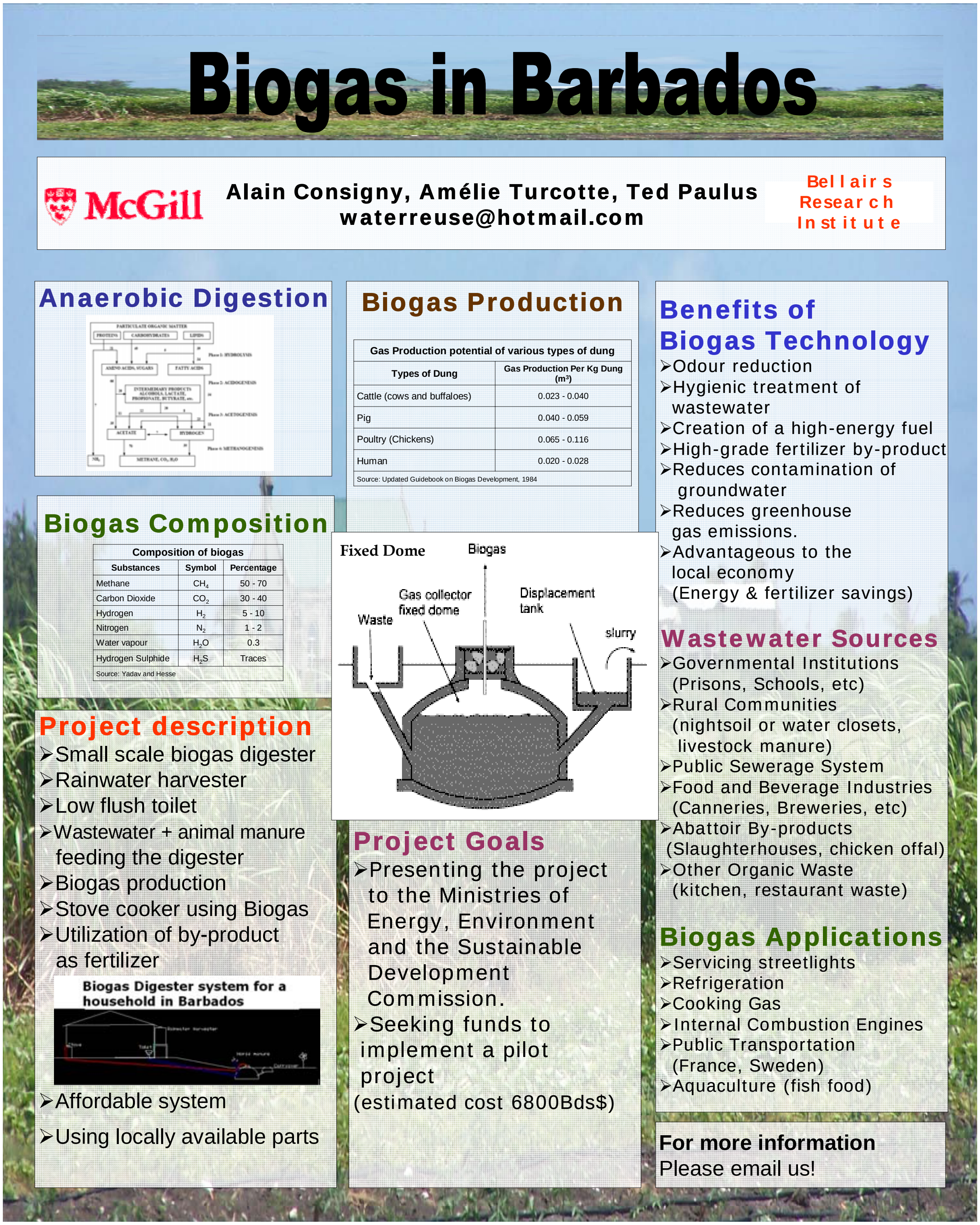


Figure E1: **Small scale of the Poster prepared for the exhibition**

Patron: Sir Neville Nicholls
Chairman: Dr Basil Springer

COUNTERPART CARIBBEAN at The Future Centre

Edgehill, St. Thomas, Barbados, W.I.
Phone: 246-425-2020 Fax: 246-425-0088
E-mail: futurecentre@sunbeach.net

21 November 2005

Mr Alain Consigny, Ms Amelie Turcotte and Ted Paulus
Bellairs Research Institute
Holetown
St James
Barbados

Dear Alain, Amelie, and Ted,

We would like to sincerely thank you for your support of our Ministry of Energy "Energy Week" exhibit held in Heroes Square on Friday November 18, 2005, by offering your BioMass project to be part of this exhibit.

Our exhibit was focused on renewable and alternative energy sources, with the information you provided on your project being an interesting and viable alternative for the public of Barbados. We feel, overall, the day proved to be successful with many patrons making requests for more information on each of the areas included in the exhibit.

Your inclusion was an integral part of our display and we were more than happy to have you on board. Your project could well be the alternative Barbados could look to in the reduction of the use of crude oil to run the current electricity generation plant.

We wish you well with the remainder of your project and studies here in Barbados, and look forward to hearing of your continued successes.

Thank you, once again for your support, and may you have a successful remainder of 2005.

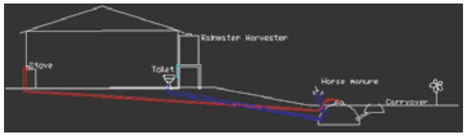
Kindest Regards,

Chapter 2 Nicole Garofano

Nicole Garofano
Volunteer Administrator

We do not inherit the earth from our fathers, we borrow it from our children!

Biogas Digester System for a household in Barbados



Clean, renewable energy technology must be promoted and utilized. A paradigm shift needs to occur wherein solid waste and wastewater will be recognized as resources instead of waste.

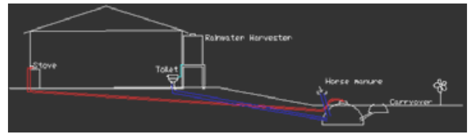
An ecological technology such as biogas digester used for wastewater treatment could be favourable for Barbados' citizens and its environment.

Need more information on Biogas technology? Email us!

Alain Consigny (alain.consigny@mail.mcgill.ca)
Amélie Turcotte (Amelie.turcotte@mail.mcgill.ca)
Ted Paulus (edmund.paulus@mail.mcgill.ca)

McGill Bellairs Research Institute

Biogas Digester System for a household in Barbados



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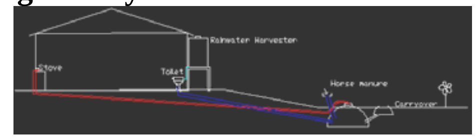
McGill Bellairs Research Institute

Biogas Digester System for a household in Ba



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Ted Paulus (edmund.paulus@mail.mcgill.ca)

McGill Bella Rese Instit

Figure E2: Handouts for the Presentation

Appendix D: Contact Dossiers

Jerome Singh
Finance Officer, Engineer
Caribbean Development Bank
Wildey, St. Michael
(431-1600

Experienced in many aspects of biogas in the Caribbean, especially in Barbados. Familiar with design and financing of plants. Worked in conjunction with the Deutsch Gesellschaft für Technische Zusammenarbeit (GTZ) in the 1980s during their Biogastechnology Regional Extension Programme. Holds copies of the GTZs publications on the topic and CDB studies.

Richard Hoad
Farmer
Morgan Lewis, St. Andrew
422-9083

Owner of a 75m^3 floating drum biogas digester. Formerly a dairy cow farmer, now primarily a goat farmer. Continues to gather and utilize the gas for domestic cooking. An environmentally conscientious individual. A pragmatic person.

Dr. Hugh Sealy
Engineer / Chairman
New Water Inc. / National Commission on Sustainable Development
426-5008

A leader and intellectual. A champion for sustainable development in Barbados. Attempting to bring together NGOs and the government to work together on environmental problems and surmounting goals that would benefit the people. Holds a lot of literature on water reuse technologies, practices, and policies.

Mary Moore
Resident/Pig Farmer
St. Simon's, St. Andrew
555-5555

The owner of a small scale, floating drum biogas digester. An elderly woman who is very generous and holds much practical knowledge concerning the operation of the digester.

Sam Nielands
Engineer
New Water Inc.
Gables Haggat Hall, St. Michael
234-4484

Environmental engineer, focused on wastewater treatment. Knowledgeable about the different service and material providers on Barbados and how to obtain specific parts.

Emiline Marcus-Burnett
Economist
Ministry of Agriculture, Planning Unit
Top Rock, Christ Church
555-5555

Holds much documentation and studies conducted on livestock enumeration and farmer practices.

James Eldrige
Engineer
Fiberpol Manufacturing Inc.
Newton Plantation, Christ Church
428-2920

Manufactures fibreglass septic tank and water storage tank.

Peter Gittens
Local farmer
St Andrew
261-9261

Instigator of the household scale biogas digester system. Interested into implementing the project on his land.